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Seasonal Predictions and Their Applications in the Mediterranean Region: Part I—Sources of Predictability and Prediction Skill

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ABSTRACT

The capability to predict climate fluctuations from sub–seasonal–to–decadal timescales would yield large and significant socio–economic benefits. On the other hand, our limited understanding of the mechanisms and processes responsible for predictability and systematic model errors hampers our ability to simulate and forecast climate variability. As a result, current forecast quality remains relatively unsatisfactory, particularly in the mid-latitudes and in the Mediterranean basin. In recent years, several research studies and collaborative projects have been conducted in order to improve the skill of forecasting systems and the quality of the data and climatic information they produce. This effort has led to substantial advancements in understanding Mediterranean climate variability and its drivers, as well as to improvements in the capability to provide reliable climate predictions for this region. The main objective of this paper is to review and discuss the current understanding of climate variability and sources of predictability in the Mediterranean basin and surrounding areas, to assess the current capability of climate prediction systems in order to provide skilful predictions in this region to feed services in relevant socio-economic sectors. Examples of advanced tools and innovative methodologies recently developed to enhance predictions, both in terms of forecast skill and of the quality of the data they provide (e.g., sub–sampling and bias correction), will also be discussed.

1 | Introduction

This paper is the first of a two-part review on climate prediction in the Mediterranean region. Part I synthesises the scientific foundations of predictability, including key sources, teleconnections, and the performance of current prediction systems across different time horizons. Part II (Gualdi et al. 2025) focuses on the development and use of climate predictions as actionable information, showing how probabilistic forecasts can be transformed into tailored climate services for sectors such as energy, water, transport, and agriculture. Together, the two parts provide a comprehensive view from the physical basis of climate predictability to its translation into operational services supporting resilience in the Mediterranean region.

In general terms, climate forecasts (or predictions—the two terms will be used synonymously) refer to activities aimed at anticipating the occurrence of climate anomalies in the relatively near future, ranging from a few weeks (sub-seasonal) to the upcoming seasons (seasonal) and extending to the coming years and decades (multi-annual and decadal).

Climate predictions are increasingly becoming a fundamental element in decision-making processes, especially in the context of adapting to climate change (WMO 2016). The importance of using forecasting tools is even more accentuated in regions where the signal of climate change and its related impacts are particularly intense and concerning, such as the Mediterranean area.

The Mediterranean region, defined here as the domain including the Mediterranean Sea and its surrounding lands, is inhabited by over 500 million people spread across ~30 countries in Africa, Asia, and Europe. Its climate is shaped by the interaction between mid-latitude and subtropical circulation regimes and the complex morphology (mountain ranges and land-sea contrasts) that characterises it. This area has been identified as one of the most responsive to climate change (Lionello 2012), therefore, understanding and being able to predict its climate variations has enormous socioeconomic implications.

To date, very little has been done to fully explore the potential of climate forecasts and their applications in the Mediterranean basin. It is known that seasonal forecasts at mid-latitudes suffer from low skill levels, and this generally holds true for the Mediterranean region as well. However, some studies have shown that several cutting-edge forecasting systems demonstrate some ability to predict interannual or multiannual variability of the North Atlantic Oscillation (NAO, e.g., Scaife et al. 2014a; Athanasiadis et al. 2017; Nicolì et al. 2023), which in turn is known to have a strong influence on the climate of the Mediterranean (e.g., Trigo et al. 2002). Similarly, there is evidence that predictable tropical phenomena like ENSO (El Niño Southern Oscillation) might have an impact on the Mediterranean, enhancing the predictability of the regional climate (e.g., Shaman 2014; Martija-Díez et al. 2021).

These results suggest that improving current climate forecasting capabilities for the Mediterranean is possible, particularly by increasing our understanding of the physical processes involved in predictability, improving simulations of remote phenomena and their teleconnections with the region, and refining the representation of local mechanisms influencing regional variability.

In recent years, the importance of maximising societal benefits from climate predictions (and more generally, climate information) has been recognised by working more closely with stakeholders and end-users. Numerous projects and initiatives aimed at developing and improving end–to–end climate forecasts and services have been launched, demonstrating how predictions can become directly usable by decision-makers in various sectors (e.g., MedGOLD, Dainelli et al. 2022). Additionally, projects such as MEDSCOPE have developed methodologies and tools (Pérez-Zanón et al. 2022) for creating prototype climate services that meet the specific needs of users in sectors of relevance in the Mediterranean region (Sánchez-García et al. 2022).

The purpose of this article is to review and discuss the current understanding of climate variability and sources of predictability in the Mediterranean basin and its surrounding areas, and the ability of climate prediction systems to provide skilled forecasts. In general, the terms "source" and "driver" are related but not synonymous. In this article, the term 'source' refers to the components or processes that generate and maintain predictable signals within the climate system while 'driver' is seen as the physical mechanisms that force changes in the climate system (e.g., "drivers of variability").

Climate predictions can be broadly divided into dynamical and statistical. The former use numerical models based on the equations of physics that describe the behaviour of the Earth system components, producing forecasts by simulating their evolution from a given initial condition. The latter use statistical relationships, derived with varying levels of methodological complexity—now increasingly incorporating approaches based on Artificial Intelligence—from observed data, linking meteorological and climatic variables over specific regions. For example, a statistical relationship that links anomalies in the sea surface temperature (SST) of the Tropical Atlantic observed in late spring with precipitation anomalies recorded in the Sahel region during the African monsoon (Folland et al. 1991. Further examples of statistical methods for seasonal forecasting can be found, for instance, in Mason and Mimmack 2002; Eden et al. 2015; Hao et al. 2018; Zellou et al. 2023; Gyu-Ri Lee et al. 2024). While dynamical climate forecasts are a relatively recent endeavour, statistical methods have been in use since the late 1800s (e.g., Normand 1953). However, it is with the advent of dynamic forecasts that climate predictions, especially over longer timescales, have grown significantly. For this reason, this review paper will focus primarily on dynamic forecasts, although references and examples of systems based on statistical models and their results will not be lacking in the discussion.

Various factors have enabled recent substantial advances in dynamical climate forecasting. One element is the development of increasingly advanced numerical models, thereby improving their ability to represent the dynamics underlying climate system behaviour. This development has been supported by the ever-greater availability of computational resources and observations. The former are essential for increasing the complexity and the resolution of the models and, thus, their capacity to represent phenomena fundamental to the dynamics of the climate. The latter are crucial to better understand the nature of the dynamics at play and to enhance the ability to initialize forecasts more adequately.

Nowadays, climate predictions, primarily produced using dynamic models, are operationally conducted across all timescales, from sub-seasonal to decadal by several centres grouped into programs coordinated by the WMO (https://community.wmo.int/en/wipps-web-portal), the North American Multi–Model Ensemble (https://www.cpc.ncep.noaa.gov/products/NMME/), the Copernicus Climate Change Service (C3S, https://climate.copernicus.eu/seasonal-forecasts) and the Climate Centre of the Asia-Pacific Economic Cooperation (APCC, https://www.apcc21.org/content/clpre?lang=en). (See also Supporting Information, Appendix 1). However, seasonal predictions have likely reached the greatest level of maturity, both in terms of forecast quality (thanks to a better understanding of the processes underlying predictability at this temporal scale and the improved skill of these forecasts across large regions of the globe) and their application in climate services. Thus, this review focuses mainly on seasonal predictions.

The core of a dynamical seasonal forecasting system is a climate model, typically including atmosphere, ocean, land, and sea ice components. The model is integrated over time, starting from initial conditions (I.C.s) that represent the state of the system, which are particularly crucial for the components containing the most significant sources of predictability. By accurately initializing the ocean and land states, it is possible to predict how critical boundary conditions for the atmosphere, such as SST, soil moisture, and snow and vegetation cover, will evolve over the coming months and years. It is the simulation of the evolution of these slowly changing components that allows for the prediction of atmospheric circulation patterns several months in advance.

The most common approach to initialization in a prediction system is through analysis based on data assimilation techniques (e.g., Stammer et al. 2016). The analyses that produce the I.C.s are generally conducted separately for the individual components of the system. As a result, there is often no coupling between the I.C.s for the various parts of the Earth System, thus creating an imbalance in the model's initial state. New methodologies, such as (weak or strong) data assimilation coupling, offer promising approaches to reduce this imbalance and the associated initial shock in the forecasts (Penny et al. 2017).

In forecasting activities, one must adequately consider the chaotic nature of the climate system (Slingo and Palmer 2011), which manifests in the well-known behaviour whereby even the smallest, seemingly insignificant changes in the I.C.s (or in the formulation of the model used) can substantially influence a forecast. Consequently, producing deterministic forecasts of the climate system's evolution is impossible. Instead, ensemble forecasting is required, where multiple predictions are generated simultaneously through simulations starting from suitably perturbed (initial) conditions. These ensemble forecasts allow the assessment of the probability of the occurrence of certain anomalous conditions, and the members' spread provides an estimate of the forecast uncertainty.

By decomposing temporal variability into signal (predictable) and noise (unpredictable), filtering out the latter through ensemble averaging has proven to be a highly effective method for revealing the underlying signal (e.g., Christiansen 2019, and references therein).

The size of the ensemble is a crucial factor influencing predictive skill and reliability: the larger the ensemble, the greater the filtering effectiveness, signal extraction efficiency, and overall prediction skill (e.g., Kumar et al. 2001; Manzanas et al. 2022; Han et al. 2023). Thus, predictive skill typically improves as ensemble size increases due to the reduction of unpredictable noise. Eventually, it approaches the predictable limit, where a sufficiently large ensemble has effectively eliminated all noise (e.g., Scaife et al. 2014b; Athanasiadis et al. 2017). Furthermore, with a sufficiently large ensemble, techniques such as subsampling the best-performing ensemble members (e.g., Dobrynin et al. 2018; Dobrynin et al. 2022) can be employed to further refine ensemble properties and improve forecast quality.

In most state-of-the-art forecasting systems, ensemble sizes generally range between 10 and 50 members. A further increase in the number of ensemble members can be achieved by combining forecasts from multiple systems (e.g., Palmer et al. 2004), leading to the creation of so-called super-ensembles or multi-model ensembles.

Numerical models can provide an extremely high volume of data and information, and therefore, for the predictions to be usefully applicable, it is necessary to identify which results and aspects of the forecasts are most relevant to the issue at hand (Torralba et al. 2017; Manzanas et al. 2019). It must also be considered that the variables produced by models are generally affected by bias and systematic errors and are available only at spatial scales too coarse to be of practical use. Therefore, most often, many variables must be carefully bias-adjusted, and it is necessary to apply downscaling techniques before the forecast outputs can be used for regional or local applications.

In addition, to allow users to interpret and apply the information provided correctly and to have confidence in the results, it is essential that the forecasts are always accompanied by a thorough evaluation of their quality and skill. Various evaluation/verification techniques have been developed, based on different types of metrics, both deterministic and probabilistic (WMO 2018).

To adequately account for the initial shock and model drifts (e.g., Shukla et al. 2018), the skill of forecasts is generally evaluated based on forecast lead time, that is, depending on the temporal distance from the start date of the forecast. The forecasts are expressed in terms of predicted anomalies for each lead time, calculated against a climatology also expressed in terms of lead time. This climatology is computed from an ensemble of past forecasts (hindcasts) which, once appropriately averaged for each month and lead time, provide the means against which to calculate the anomalies.

This article provides an overview of the current capability to produce skilled forecasts in the Mediterranean area, discussing their characteristics and possible applications in the production of climate services for relevant socioeconomic sectors. Section 2 discusses the main sources of predictability at seasonal scales, focusing on those relevant to the Mediterranean region. Section 3 briefly discusses the skill of the forecasts that some of the main international seasonal forecasting programs (illustrated in Supporting Information, Appendix I) provide for this region. Section 4 offers a summary and conclusion. Finally, a more extended evaluation of the forecast skill, discussion of the advantages of the multi-model approach, and examples of tools to enhance the prediction quality (e.g., sub-sampling and bias correction) are provided in Supporting Information (Appendices II, III, and IV).

2 | Main Drivers of the Mediterranean Climate Variability

The main drivers of climate variability and sources of predictability for the Mediterranean basin are discussed starting from the fastest and least predictable processes associated with atmospheric variability, and then moving to slower, more predictable processes, such as those determined by the interactions of the atmosphere with the land surface, ocean, and sea-ice.

2.1 | Atmosphere

Atmospheric circulation over the North-Atlantic Euro-Mediterranean sector (NAEM) is dominated by four main teleconnection patterns, particularly during winter, which influence surface Euro-Mediterranean climate (e.g., Trigo et al. 2002; Josey et al. 2011): NAO (e.g., Mikhailova and Yurovsky 2016; Mellado-Cano et al. 2019), Scandinavian (SCA; Bueh and Nakamura 2007), and East Atlantic/West Russian (EA/WR; Lim 2015). The summer NAO also exerts a distinct influence on the Euro-Mediterranean surface (Folland et al. 2009; Bladé, Liebmann, et al. 2012; Bladé, Fortuny, et al. 2012). Lledó et al. (2020) used a seasonal multi-model framework to show that the NAO, SCA, EA, and EA/WR patterns can be skilfully predicted in winter, spring, and summer.

Several studies have reported skilful forecasts of the winter NAO and subsequent climate conditions over northern Europe at seasonal (Scaife et al. 2014a) and decadal (Athanasiadis et al. 2020; Nicolì et al. 2023) timescales. However, translating this skill into improved predictions of surface climate over the Euro-Mediterranean region remains challenging (Tsartsali et al. 2023). The seasonal predictability of the winter EA pattern has been recently assessed, showing significant skill and prospects for prediction of its teleconnection to regional temperature and precipitation (Thornton et al. 2023).

Mid-latitude weather and climate is also modulated by circumglobal (Rossby) wave trains that propagate along the Northern Hemisphere (NH) trapped within the westerly jet streams acting as a waveguide. These have been well documented both for winter (Branstator 2002) and summer (Ding and Wang 2005), following theoretical considerations (Hoskins and Ambrizzi 1993; Ambrizzi et al. 1995). These quasi-stationary wave trains, mainly characterised by wavenumbers 5 and 7, have been shown to impact temperature and precipitation over the Euro-Mediterranean during summer, including extremes such as heatwaves and droughts (e.g., Wolf et al. 2018; Kornhuber et al. 2020). Model representation and biases (Luo et al. 2022) as well as seasonal forecast skill (Beverley et al. 2019) of these summertime circumglobal teleconnections have been reported.

The stratosphere is also considered a driver of regional climate variability and a possible source of predictability, particularly during winter with the presence of the polar vortex—a deep, large-scale cyclonic circulation in the extratropics that is radiatively induced but subject to dynamical modulation by upward-propagating and breaking planetary waves. Interannual variability of the wintertime polar vortex in the NH is governed by annular, wavenumber-0 anomalies associated with the strengthening/weakening of the westerly flow, and to a lesser extent by wavenumber-1 anomalies related to horizontal displacements of the cyclonic circulation; all having an impact on the tropospheric circulation over the NAEM region (Perlwitz and Graf 2001; Palmeiro et al. 2020). Intraseasonal variability is dominated by sudden stratospheric warmings (SSWs), which represent severe wave-driven disruptions of the polar vortex leading to its slow-down, stop, and eventual reversal. Apart from wavenumber-1 displacement SSWs, there are also splitting SSWs linked to wavenumber-2 anomalies and elongation of the polar vortex. The surface signature of the major SSWs projects strongly on a negative NAO pattern, with its resulting effect on NAEM surface temperature and precipitation (e.g., Palmeiro et al. 2015; Ayarzagüena et al. 2019; Baldwin et al. 2021).

The anomalous lack of upward-propagating wave activity from the troposphere into the stratosphere may lead to (sudden) polar vortex intensifications, whose imprint at surface resembles a positive NAO pattern and its related anomalies (e.g., Baldwin and Dunkerton 2001; Limpasuvan et al. 2005; Kuroda 2008). The polar vortex-NAO relationship can also be influenced from the tropics via the Quasi-Biennial Oscillation (QBO), that is, leading mode of interannual variability in the tropical stratosphere characterised by alternating, descending easterly (EQBO) and westerly (WQBO) winds (e.g., Baldwin and Dunkerton 2001). The stratospheric tropical-extratropical teleconnection and subsequent downward propagation to the NAEM tropospheric circulation is mediated by the Holton-Tan effect (e.g., Anstey and Shepherd 2014): the EQBO (WQBO) phase tends to deflect upward-propagating planetary waves to high (low) latitudes, leading to more (less) wave-breaking there, thus weakening (strengthening) the polar vortex and showing a negative (positive) NAO-like anomaly at surface.

Lastly, the interannual variability of the final, irreversible breakup and warming of the polar vortex, which determines the springtime transition from the cyclonic flow in winter to the anticyclonic flow in summer, has also been shown to affect surface circulation and storm-tracks over the Euro-Mediterranean region (e.g., Butler et al. 2019).

2.2 | Land Surface

Land-atmosphere interactions play a crucial role in seasonal predictability by influencing patterns of temperature, precipitation, and other meteorological variables (Halder et al. 2018). These interactions involve exchanges of energy, moisture, and momentum between the land surface and the overlying atmosphere, which can modulate circulation patterns. Understanding these interactions is essential for accurately predicting seasonal climate variations, as they can amplify or attenuate the signal of natural variability. Additionally, land surface conditions, such as soil moisture, snowpack, and vegetation cover, can act as memory mechanisms, influencing subsequent weather and climate patterns, further enhancing the predictability of seasonal atmospheric conditions. The current state of knowledge on land-based sources of predictability, with a focus on the Mediterranean, is discussed here.

2.2.1 | Soil Moisture

Soil moisture refers to the amount of water present in the soil, and it can play a significant role in the regional climate system. This holds for regions characterised by both a strong coupling between land and atmosphere, and a substantial soil moisture memory (Dirmeyer and Halder 2017). The Mediterranean region has long been identified as a hotspot of land–atmosphere coupling (Seneviratne et al. 2006). In this semi-arid region, the limited soil moisture availability exerts control on the evapotranspiration rate, which in turn affects boundary layer processes and ultimately near-surface temperature and precipitation (Seneviratne et al. 2010). Consistently, Hirschi et al. (2011) showed that soil moisture deficit favours the occurrence of hot days as well as the duration of heat waves in Southeast Europe. The severe spring heatwave that hit southern Spain and North-West Africa in April 2023, for example, was preconditioned by dry soils that contributed to its amplification and persistence, as demonstrated in Lemus-Canovas et al. (2024). The authors suggest also that information on soil moisture could significantly contribute to the seasonal forecasting of such extreme heat events across western Mediterranean. Accordingly, a realistic soil moisture initialization in forecast systems, therefore, is expected to enhance atmospheric predictability for up to 3 months, especially for summer forecasts (Guo et al. 2011).

While the value of soil moisture initialization for the subseasonal predictability over southern Europe has been demonstrated (van den Hurk et al. 2012; Seo et al. 2019), several early studies following the second phase of the Global Land–Atmosphere Coupling Experiment (Koster et al. 2010, 2011) suggest that a realistic initialization of the land component in seasonal prediction systems during boreal spring significantly improves the summer (JJA) forecast skill over Europe and the Mediterranean (Douville 2010; Materia et al. 2014).

Soil moisture initialization improves the temperature prediction skill in the Balkans region, when combining summer forecasts from multiple dynamical systems (Ardilouze et al. 2017). Prodhomme et al. (2016) also find that realistic soil moisture I.C.s in spring lead to improved forecast skill of JJA extreme temperature indices over Southern Europe. For example, their model better captures the precipitation deficit and warm temperature anomaly patterns during the extreme summer of 2003 in Western Europe, particularly in the southern part of the affected region.

More recently, a new perspective on the climate impact of soil moisture in the Mediterranean area has emerged from two companion studies investigating the effect of extreme soil moisture conditions on subsequent temperature (Materia et al. 2022) and precipitation (Ardilouze et al. 2022). Dry soil moisture anomalies in May tend to persist throughout the warm season, with dry soils during this month likely to sustain early summer heatwaves and rainfall deficits. Conversely, wet soil anomalies in spring reduce the occurrence of hot days in summer and increase local precipitation anomalies and persistence.

These results are often model-dependent in terms of amplitude and affected sub-regions. The coupling between surface processes and atmospheric dynamics and thermodynamics is complex and involves significant uncertainties, stemming from limitations in model representation and availability of suitable reference datasets for comparison. Figure 1, from Knist et al. (2017), illustrates the uncertainty in the strength of land–atmosphere coupling in the Euro–Mediterranean basin.

Beyond the seasonal horizon, deriving well-balanced and realistic soil moisture and temperature I.C.s from a weakly coupled data assimilation system leads to skilful summer temperature and precipitation prediction at the interannual timescale across Europe, especially south of 50°N (Shi et al. 2022).

2.2.2 | Snow Cover

Over mid-latitudes, the snow cover extent exhibits large interannual variability, and the snowpack interacts with the atmosphere through various processes. Due to its high emissivity, high albedo, and low thermal capacity, snow has a strong impact on the surface radiative balance, especially in boreal autumn and spring, when solar radiation is significant (Peings et al. 2011; Xu and Dirmeyer 2013a). In spring, beyond its radiative effect, snow absorbs energy for melting and subsequently for the evaporation of meltwater that infiltrates the soil (Xu and Dirmeyer 2013b).

In boreal autumn, anomalous extensions of the Eurasian snow cover favour the upward propagation of tropospheric Rossby waves, which can weaken the stratospheric polar vortex in early winter (e.g., Cohen et al. 2014). Ultimately, this may amplify the negative phase of the Arctic Oscillation, leading to anomalous near-surface conditions over Europe (e.g., Kolstad et al. 2010).

Hence, with large interannual variability, long-lasting memory and various atmospheric coupling processes, snow cover meets the three *sine qua non* conditions to act as a potential source of climate predictability.

The extent to which the variability of boreal autumn snow cover drives the winter atmospheric circulation has been extensively studied but remains poorly understood. The teleconnection between snow cover anomalies and jet stream variability or/and the Arctic and North Atlantic oscillations shows little stationarity and a low signal-to-noise ratio (Henderson et al. 2018). This was recently highlighted by a multi-model study demonstrating the relatively limited ability of S2S forecast systems to capture the observed connection between autumn Eurasian snow cover and troposphere-stratosphere coupling pathways (Garfinkel et al. 2020). Yet, in a sub-seasonal predictability study focused on the exceptionally cold winter of 2009/2010 in Europe, Orsolini et al. (2016) highlighted the role of the anomalously thick Eurasian snowpack in December I.C.s in accurately predicting the onset and persistence of a tropospheric circulation pattern resembling the negative phase of the NAO. They could also demonstrate the simulation of a stratospheric pathway underpinning this snow-NAO coupling.

Further supporting the link between autumn Eurasian snowpack and prevailing negative NAO in winter, Brands et al. (2012)

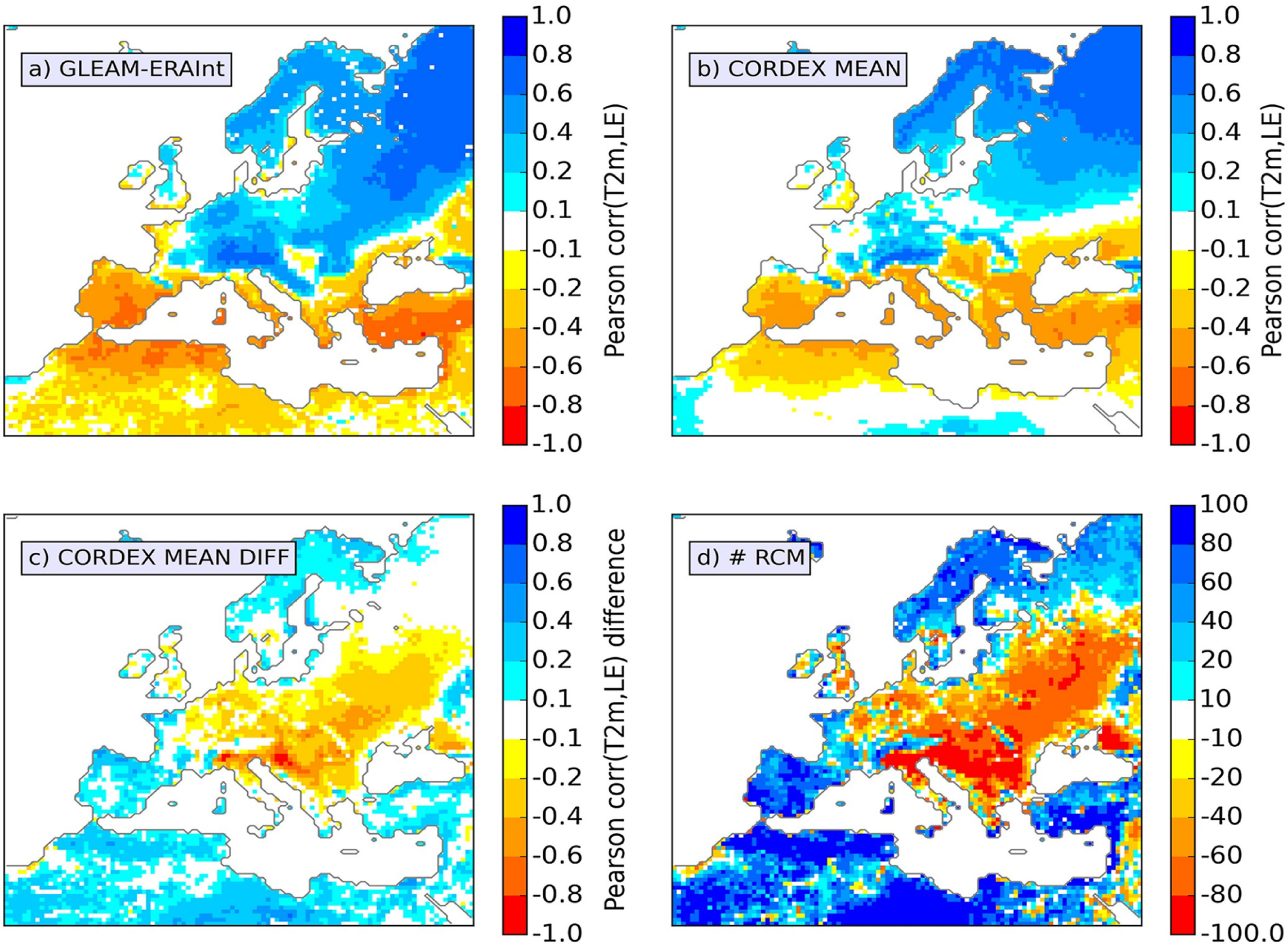

FIGURE 1 | (a) Correlation of summer (JJA) 10 day averages of latent heat flux (LE) and 2 m air temperature (T2m) for the years 1990 to 2008 for GLEAM (LE) and ERA-Interim (T2m), (b) for the ensemble mean of 16 Regional Climate Models (RCM) from EURO-CORDEX, (c) for the difference of Figure 1b minus 1a. (d) Percentage of RCMs that simulate stronger (red) or weaker (blue) coupling strength than GLEAM-ERAInt. Figure from Knist et al. (2017).

find high predictability of wintertime (DJF) Iberian Peninsula precipitation anomaly with an empirical model based on a single predictor: the Snow Advanced Index which measures the rate of increase of the Eurasian snow cover in October. Yet, the relationship between snow cover and NAO was found to be affected by multidecadal variability (Douville et al. 2017), highlighting the limitations of using a Siberian snow cover index as a predictor of the wintertime circulation across Europe.

Finally, a recent multi-model study suggests that an increase in October snow cover precedes high-pressure anomaly and suppressed precipitation across the western Mediterranean in November–December (Ruggieri et al. 2022), although significant differences in atmospheric patterns between models warrant a cautious interpretation.

In spring, pioneering predictability studies have highlighted the added value of prescribing reanalysed snow cover boundary conditions to improve the near-surface temperature variability (Schlosser and Mocko 2003) and potential predictability (Douville 2010) in climate models. Peings et al. (2011) showed that a realistic snow initialisation in early March improves both potential and actual spring temperature predictability across central Europe, including the north-eastern part of the Mediterranean basin. However, they did not find any increased forecast skill for large-scale atmospheric circulation patterns.

2.2.3 | Vegetation

Using observations, Green et al. (2017) found that the vegetation growth in the Mediterranean, driven by radiation and precipitation, is accompanied by increased latent and sensible heat fluxes. This results in a deeper boundary layer and reduced cloud cover, leading to increased incoming solar radiation. This positive feedback loop suggests that a substantial share of atmospheric variability relates to vegetation processes, which could thus contribute to seasonal predictability.

Weiss et al. (2012) showed that prescribing observed leaf area index in their forecasting system enhances the potential predictability of the summer surface evaporation, particularly in the Eastern Mediterranean. They also found a positive impact on the June-to-August 2 m air temperature (T2m), although the absolute potential predictability remains weak for this variable.

Alessandri et al. (2017) conducted potential predictability studies using a prescribed leaf area index to assess the impact of improved vegetation cover parameterization. At seasonal timescales, their results show enhanced potential predictability of winter temperature over the western part of the Mediterranean basin, and of summer precipitation, mostly in the eastern part of the basin. The latter finding should be interpreted with caution given the very scarce rainfall affecting that region in summer.

Few studies have explored the contribution of vegetation to seasonal prediction skill. At the sub-seasonal timescale, Koster and Walker (2015) found that incorporating an interactive phenology scheme into their prediction system slightly improved warm-season T2m forecasting skill on a global scale, though not significantly in the Mediterranean region.

2.3 | Ocean

2.3.1 | Mediterranean Sea

Although the Mediterranean Sea is a relatively small component of the global ocean, and its SST variability is significantly influenced by large-scale atmospheric circulation patterns (e.g., Xoplaki et al. 2003), its role in the climate system, both at regional and hemispheric scales, is far from being passive (e.g., García-Serrano et al. 2013; Yan and Tang 2021).

At seasonal-to-interannual timescales, the Mediterranean Sea inherently acts as a source of heat and moisture linked to the atmospheric circulation above (e.g., Josey et al. 2011), leading to temperature and precipitation anomalies in the surrounding region.

SST variability in the Mediterranean Sea has an impact on the regional climate, affecting the probability and intensity of European heat waves (Feudale and Shukla 2007, 2011) and changes in the West African monsoon (WAM; Rowell 2003).

Mediterranean SST variability affects large-scale (Haarsma et al. 2009) and small-scale (Drobinski et al. 2020) summertime thermal lows, potentially associated with continental-scale wave patterns and extreme temperature events (Ferranti and Viterbo 2006; Fischer et al. 2007).

The atmospheric response to summer-autumn SST anomalies in the eastern Mediterranean modifies temperature-advection over the region (García-Serrano et al. 2013). Observations (Polo et al. 2008) and model simulations (Fontaine et al. 2010) suggest that SST variability in the eastern Mediterranean can influence the Sahelian rainfall in summer, affecting thus the inter-tropical convergence zone (ITCZ) and circulation over North Africa (Fontaine, Roucou, et al. 2011; Fontaine, Gaetani, et al. 2011).

SST anomalies over both the eastern (García-Serrano et al. 2013) and western (Black and Sutton 2007) Mediterranean have been shown to impact regional climate during summer-autumn, and downstream atmospheric circulation in the NH (García-Serrano et al. 2013). The regional and hemispheric influence of eastern Mediterranean SST anomalies has also been reported for winter (Li 2006).

At decadal-to-multidecadal timescales, SST variability in the Mediterranean Sea is strongly related to the Atlantic Multidecadal Oscillation/Variability (AMV; e.g., van Oldenborgh et al. 2012; see next subsection). The low-frequency variability of Atlantic-Mediterranean SST has been shown not only to influence the Euro-Mediterranean climate in summer (Mariotti and Dell'Aquila 2012) but also to enhance the NAO-induced hydroclimate response during winter (Suárez-Moreno et al. 2022).

2.3.2 | Atlantic Ocean

At seasonal-to-interannual timescales, SST variability in the Atlantic Ocean is dominated by the North Atlantic Tripole (NAT) and Tropical Atlantic Variability (TAV). The NAT pattern corresponds to the oceanic fingerprint of the NAO, being maximum during winter; although it is now well accepted that these SST anomalies can feedback onto the atmosphere and help the NAO to persist beyond the meteorological limit of ~10 days (see Kushnir et al. 2002 for review). Several studies have shown that the anomalous tripole-like SST structure generates an atmospheric response that projects on the NAO (Rodwell et al. 1999; Peng et al. 2002; Kucharski and Molteni 2003; Bellucci et al. 2008). Their results indicated that this feedback onto the atmosphere is positive: namely, the NAO polarity of the response is the same as that forcing the SST anomalies. The same findings apply to the extratropical dipole-like SST anomaly (Ferreira and Frankignoul 2005; Deser et al. 2007; García-Serrano and Haarsma 2017) and to the monopole SST anomaly in the subtropics (Terray and Cassou 2002; Losada et al. 2007).

While encouraging for predictability, all this modelling evidence focuses on the feedback of the NAO-induced SST anomalies. What is critical for seasonal forecasting is the predictive role of those SST anomalies and their persistence, which can be initialized in the forecast systems. Previous observational studies have identified the North Atlantic Horseshoe (NAH), during late summer and autumn, as a good predictor for the early-winter NAO (e.g., Czaja and Frankignoul 2002; Rodríguez-Fonseca and Castro 2002; Frankignoul and Kestenare 2005; García-Serrano et al. 2008). This lagged relationship is robust under different methodological approaches (Frankignoul et al. 2011) and stationary (Gastineau and Frankignoul 2015). One modelling study has confirmed the influence of the NAH-NAT transition on the development of a subsequent NAO in early winter (Cassou et al. 2004).

The TAV shows two leading modes coupled to deep convection (ITCZ) in the Tropical Atlantic (Ruiz-Barradas et al. 2000): the Atlantic zonal mode or Atlantic Niño, in which the Bjerkenes feedback operates via changes in the trade winds, the thermocline slope, and redistribution of heat in the equatorial region; and the Atlantic meridional mode, where the wind-evaporation-SST feedback is at play and whose amplitude is dominated by the Subtropical North Atlantic (SNA). The SST anomaly associated with the SNA overlaps with the NAH pattern during summer-autumn and with the NAT during winter, thus representing a suitable predictor for the early-winter NAO (Czaja and Frankignoul 2002; Frankignoul and Kestenare 2005) and related precipitation anomalies

(Rodríguez-Fonseca and Castro 2002; Rodríguez-Fonseca et al. 2006; García-Serrano et al. 2008).

The Atlantic Niño peaks in boreal summer, although it yields a secondary maximum in November–December (Okumura and Xie 2006). The influence of the summer Atlantic Niño on the WAM and other tropical basins has been widely reported, but its potential teleconnection to the Euro-Mediterranean region has been barely tackled, even if observations (García-Serrano et al. 2008) and models (García-Serrano, Losada, and Rodríguez-Fonseca 2011; Losada et al. 2012) indicate that it might have a detectable impact on the regional climate.

More attention has been devoted to the summer-autumn evolution of the Atlantic Niño and its predictive role on the NAEM atmospheric circulation in early-winter. Covariance analysis suggests that this lagged relationship projects on the East Atlantic (EA) pattern (Frankignoul and Kestenare 2005; Haarsma and Hazeleger 2007), while modelling studies indicate that the associated cyclonic anomaly at midlatitudes may result from a direct, tropical-extratropical wave propagation (Drévillon et al. 2003; Peng et al. 2005) or an indirect circumglobal wave activity trapped into the westerly jets (Haarsma and Hazeleger 2007; García-Serrano, Losada, and Rodríguez-Fonseca 2011). Finally, to the best of our knowledge, there is no study addressing the atmospheric response to the winter Atlantic Niño.

At decadal-to-multidecadal timescales, the Atlantic SST variability (AMV) is characterised by a basin-wide pattern arguably related to the Atlantic meridional overturning circulation (AMOC; Knight et al. 2005; Dijkstra et al. 2006), although their relationship can be non-stationary in time (Bellucci et al. 2022).

Over the Atlantic, the atmospheric response to winter AMV SST anomalies projects on the NAO (Peings and Magnusdottir 2014), with a positive AMV leading to a negative NAO, where both the subpolar (Gastineau et al. 2016) and subtropical (Davini et al. 2015) components of the SST pattern have been suggested to play a key role. Troposphere-stratosphere coupling (Omrani et al. 2014) and ocean–atmosphere coupling (Peings and Magnusdottir 2016) have also been found to be important in this NAO-like atmospheric response, although there seems to be uncertainty and model dependency (Ruggieri et al. 2021). The AMV prediction skill is dominated by the subpolar SST component (García-Serrano et al. 2012), which provides decadal predictability to the North Atlantic jet stream (Strommen et al. 2023).

The AMV influence on the Euro-Mediterranean climate appears to be robust in summer (e.g., Mariotti and Dell'Aquila 2012), including its hydrological cycle (Nicolì et al. 2020). It is also significant in spring and autumn (Sutton and Dong 2012), and detectable in winter both in observations (Gastineau and Frankignoul 2015) and models (Gastineau et al. 2013).

2.3.3 | Tropical Pacific Ocean

The interannual variability in the tropical Pacific is dominated by El Niño-Southern Oscillation (ENSO; e.g., Deser et al. 2017), whose periodic fluctuations in SST, atmospheric circulation and precipitation influence the global climate (see Alexander et al. 2002 for review). The circulation patterns associated with ENSO induce anomalies in the Indian Ocean that, in most cases, lead to basin-wide warming or cooling (Deser et al. 2010). In other cases, they can trigger Indian Ocean Dipole events (Saji et al. 1999), which, as discussed further below in Section 2.3.4, in turn induce teleconnections that may interact with those of ENSO itself. For this reason, the impacts of the interannual variability in the tropical Pacific and Indian Ocean and their teleconnections with mid-latitudes are strongly interconnected.

ENSO is the most important driver of climate variability at seasonal and interannual timescales (Manzanas et al. 2014). It exerts a significant influence on the NAEM sector (Brönnimann et al. 2007), thus representing an important source of predictability for the region. In Mariotti et al. (2002), the ENSO impact on Euro-Mediterranean precipitation was assessed by linear correlation with the Niño3.4 index throughout the seasonal cycle; an analysis that has been continuously revisited, adding also the impact on surface temperature (e.g., Brönnimann et al. 2007; Yang and DelSole 2012). The robustness, stationarity, linearity, and timing of the ENSO teleconnection with the NAEM sector remain under investigation, and here, only a brief review is provided.

In spring, the ENSO impact on NAEM precipitation is largest, with negative anomalies over the western Mediterranean and positive anomalies over north-eastern Europe related to El Niño; opposite sign for La Niña (Mariotti et al. 2002). This dipolar precipitation pattern is associated with a wave-like circulation anomaly arching from the tropical Atlantic (Lorenzo et al. 2011), whose source could be the zonally compensated anomalous diabatic heating from the tropical Pacific (García-Serrano et al. 2017).

In summer the ENSO influence is weak, with only a marginal increase in precipitation over central Europe (Mariotti et al. 2002) and colder conditions over the western Mediterranean (Brönnimann et al. 2007; Yang and DelSole 2012) during El Niño, and the opposite for La Niña. Little investigation has been devoted to exploring the mechanisms underlying this remote connection, but results suggest that a zonally-propagating wave-train could be responsible (Martija-Díez et al. 2021).

Autumn is the other season with the largest ENSO impact on regional precipitation, showing wetter conditions during El Niño events over most of the Mediterranean basin, with the opposite sign for La Niña (Mariotti et al. 2002; Brönnimann et al. 2007). The anomalies associated with this teleconnection appear to involve a wave-like pattern triggered from the Central American-Caribbean area and crossing the North Atlantic (Shaman and Tziperman 2011).

During winter, particularly late winter, the ENSO teleconnection to the NAEM sector is weak but linear for El Niño and La Niña, robust, and stationary over the past 300 years (Brönnimann et al. 2007). It manifests as an atmospheric circulation anomaly characterised by a meridional dipolar pattern, resembling, but dynamically distinct from the NAO (Brönnimann et al. 2007;

García-Serrano, Rodríguez-Fonseca, et al. 2011; Rodríguez-Fonseca et al. 2016; Mezzina et al. 2020).

Importantly, recent studies (e.g., Ayarzagüena et al. 2018; King et al. 2018, 2021; Zhang et al. 2019; Abid et al. 2021; Joshi et al. 2021; Benassi et al. 2021; Molteni and Brookshaw 2023; Zhang and Jiang 2023) have highlighted that the winter ENSO teleconnection exhibits a strong intra-seasonal variability: in early winter (November–December), the atmospheric circulation related to El Niño (La Niña) shows a pattern dominated by cyclonic (anticyclonic) anomalies at subpolar latitudes, while in late winter, the circulation projects on the canonical pattern described above, which resembles the negative (positive) phase of the NAO. Both tropospheric (e.g., García-Serrano, Rodríguez-Fonseca, et al. 2011; Mezzina et al. 2020, 2022) and stratospheric (Ineson and Scaife 2009; Bell et al. 2009) pathways have been shown to be at play in this dipole-like canonical pattern during late winter.

Low–frequency modulations of the ENSO–NAEM teleconnection have also been reported. López-Parages and Rodríguez-Fonseca (2012) and López-Parages et al. (2016) found that the impact of ENSO on the regional precipitation in early spring tends to become stronger and more significant during the negative phase of the AMV.

2.3.4 | Tropical Indian Ocean

The role of the Indian Ocean variability as a possible source of teleconnections, and thus of predictability, on a planetary scale has emerged especially after the identification of the so-called Indian Ocean Dipole (IOD; Saji et al. 1999), which can concur with ENSO events but can also occur independently from them. An increasing number of studies based on both observations and models have investigated and highlighted the link between Indian Ocean SST anomalies and NAO, and consequently, variability in the NAEM region, at various timescales (Hurrell et al. 2004; Hoerling et al. 2004; Bader and Latif 2005; SanchezGomez et al. 2008; Molteni et al. 2015, 2020; Hardiman et al. 2020; Abid et al. 2023 and references therein).

In winter, the intra–seasonal transition of the ENSO-NAEM teleconnection can be due to the action of Rossby waves triggered by precipitation anomalies in the tropical Indian Ocean induced by IOD events concurrent with ENSO (Molteni et al. 2020; Abid et al. 2021, 2023; Joshi et al. 2021; Molteni and Brookshaw 2023; Sabatani and Gualdi 2025). Abid et al. (2021) managed to disentangle early- and late-winter teleconnection patterns between the tropical Indo-Pacific and NAEM. Using both reanalysis and modelling data, they found that in early autumn, the anomalous diabatic heating produced during the peak of IOD anomalies triggers a Rossby wave-train originating from the subtropical South Asian jet region, which extends north-eastwards and eventually reaches the North Atlantic region, producing an atmospheric anomaly pattern that resembles the positive phase of the NAO.

The dynamics and propagation of these Rossby waves can be either entirely tropospheric, as shown in Scaife et al. (2017), Mezzina et al. (2020), Joshi et al. (2021), or involve stratospheric paths as in Domeisen et al. (2019), Walsh et al. (2022). With the progression of the season, in late winter, the ENSO anomalies in the central-eastern Pacific become the main source of the teleconnection, inducing the canonical pattern in the NAEM region described above (e.g., Brönnimann et al. 2007).

In summer, the precipitation signal migrates from the equatorial Indian Ocean northwards, reaching the Indian subcontinent and initiating the summer phase of the Asian monsoon. The triggered teleconnection directly affects the eastern Mediterranean through a mechanism first described in a seminal paper by Rodwell and Hoskins (1996). Using an idealised model, they theorised how the high–pressure and dry conditions that characterise the Mediterranean summer are the result of the interaction between westward-propagating Rossby waves, generated by the diabatic heating produced by summer monsoon precipitation in southern Asia, and the mean westerly flow north of it. This dynamical mechanism, named "desert-monsoon mechanism", has been further discussed in observations (e.g., Tyrlis et al. 2013) and state-of-the-art GCMs (e.g., Simpson et al. 2015).

2.4 | Sea Ice

Arctic sea-ice variability and change have long been considered potential drivers of climate variability and a source of predictability in the NAEM region, but with considerable discrepancies between observational and model results, pointing at a key role played by atmospheric internal variability, which makes the debate still ongoing and leads to a number of published research articles (e.g., Cohen et al. 2014; Screen et al. 2018; Smith et al. 2019 for review). Here only a summary of evidence relevant for the Euro-Mediterranean atmospheric circulation and surface climate is provided.

Sea-ice anomalies have a strong impact on heat and moisture fluxes, which make plausible to influence local and large-scale atmospheric circulation. As it was the case for North Atlantic SSTs (see Section 2.2.2), the response of Atlantic sea-ice concentration (SIC) to the winter NAO atmospheric forcing, which consists of a dipole between Davis Strait-Labrador Sea and Greenland-Barents Seas, can feedback onto the atmosphere displaying a NAO-like pattern; although in this case the feedback is negative—that is, the polarity of the NAO changes sign, which appears to be consistent in observations (Strong et al. 2009; García-Serrano et al. 2015) and model simulations with prescribed SIC changes (Deser et al. 2004, 2007; Magnusdottir et al. 2004). Acting instead as a predictor, the emerging picture is that SIC anomalies over the Barents-Kara Seas can lead to a NAO-like pattern with a 1–/2-month lag, where sea-ice reduction in November is accompanied by a negative NAO phase in winter (Scaife et al. 2014b; Dunstone et al. 2016; García-Serrano et al. 2017); although other timings have also been reported (Nakamura et al. 2015, 2016; Sun et al. 2015). In these studies, the dominant teleconnection mechanism is a stratospheric pathway, with wave activity over Eurasia inducing first the anomalous state of the stratospheric polar vortex that subsequently propagates downwards. Model bias in ice-ocean coupling (Strommen et al. 2023) and/or model diversity in the atmospheric background flow (García-Serrano et al. 2017) could help to explain the uncertainty/non-robustness of this linkage in several studies.

More in general, pan-Arctic sea-ice loss is associated with amplified warming at polar latitudes that modifies the meridional temperature gradient, which appears to robustly show an atmospheric response projecting on a negative NAO pattern in winter, according to the largest multi-model assessment of atmosphere-only simulations so far (Smith et al. 2022) and in agreement with a suite of different coupled sensitivity experiments (Screen et al. 2018).

Pan-Arctic sea-ice variability has also been suggested to be a precursor for summer atmospheric circulation and rainfall anomalies over Europe; in particular, with sea-ice reduction linked to a weakening of the North Atlantic westerly jet and wetter/drier conditions over central-western Europe/Mediterranean basin (Screen et al. 2018).

Figure 2 provides a schematic overview of the main drivers of climate variability that influence the Mediterranean region, either locally or remotely through teleconnections, and that represent key sources of predictability for this area. The figure is not intended to be exhaustive of all the processes affecting the Mediterranean, but rather to highlight the most relevant ones, particularly those discussed in this section, that play an important role in determining predictability at the seasonal timescale in the region.

3 | Seasonal Prediction Systems and Their Skill in the Mediterranean Area

At present, several international programs are dedicated to the operational production of multi-system seasonal forecasts, which are conducted using results from different prediction systems (see also Supporting Information Appendix I). One of the reasons supporting the multi-model approach is that, as shown, for example, in Palmer et al. (2004), combining ensemble forecasts from different systems into a multi-model ensemble forecast allows for increased skill (see Appendix III of the Supporting Information for a more in-depth discussion).

The growing attention and the increasingly widespread operational activities for producing seasonal forecasts are mainly driven by their potential to provide information about climate anomalies several months in advance, thereby supporting decision-making processes across a variety of socioeconomic sectors. However, forecasts can be useful only if they are skilful, that is, they show an improvement compared with a trivial reference forecast based, for example, on climatology or persistence.

A robust estimate of the performance of forecasting systems can be obtained by systematically comparing a set of retrospective forecasts (or hindcasts) with observations to derive statistical skill measures. Numerous methods for estimating the skill of seasonal forecasts can be found in the literature, quantifying different aspects of forecast quality, such as resolution, discrimination, reliability, and sharpness (Mason 2018; Wilks 2011; Toth et al. 2003 for a review).

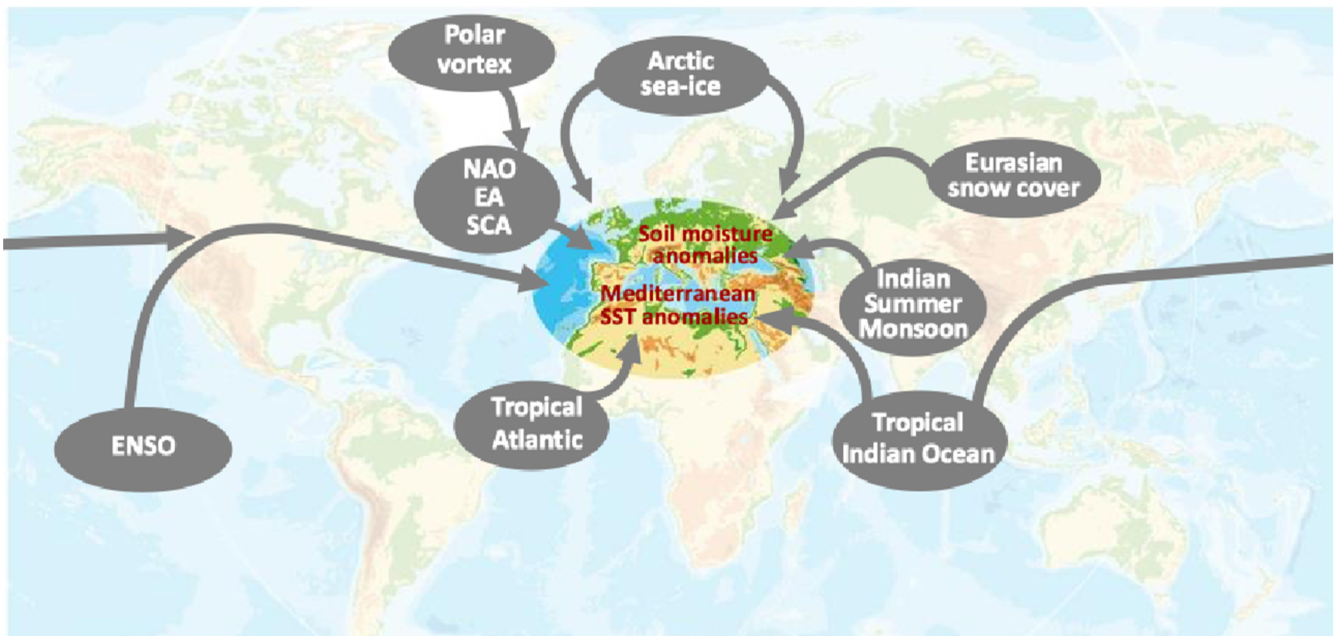

FIGURE 2 | Schematic diagram of the main sources/drivers of Mediterranean climate variability and predictability at seasonal-to-interannual timescales, showing local (coloured) and remote (grey-white) interactions. The former (local) correspond to soil moisture/vegetation and the Mediterranean Sea. The latter (remote) illustrate teleconnections from low latitudes, including the tropical Pacific (ENSO), tropical Atlantic (Atlantic zonal mode or Atlantic Niño, and Atlantic meridional mode), and tropical Indian (basin-wide, IOD, Indian Summer Monsoon) basins; and from middle-high latitudes, including Arctic sea-ice, Eurasian snow cover, tropospheric circulation (NAO, EA, SCA, EA/WR patterns) and stratospheric circulation (SSWs and stratospheric pathways). Details about the processes involved and other sources/drivers can be found in Section 2.

The skill of seasonal prediction systems has been investigated in numerous studies at different spatial scales and considering a single or an ensemble of forecasting systems, different variables, seasons and lead times. We here review the recent literature focusing on the skill of forecasts in the Mediterranean region, mainly for the prediction of a few essential climate variables and extreme events. More discussion on skill for the main teleconnection indices and a selected set of climate indicators is provided in Supporting Information (Appendix II).

3.1 | Essential Climate Variables

In climate prediction, T2m, total precipitation, low-level winds, and solar radiation are among the most carefully considered variables due to their relevance in socioeconomic applications (Hemri et al. 2020), including agriculture (Rodriguez et al. 2018; Roudier et al. 2016; Ramírez-Rodrigues et al. 2016; Ouedraogo et al. 2018), hydrology (Terzago et al. 2023; Yuan, Roundy, et al. 2015; Yuan, Wood, and Ma 2015; Demirel et al. 2015), or renewable energy production (Goodess et al. 2019; Lledó et al. 2019).

3.1.1 | Temperature and Precipitation

Several studies have assessed the skill of seasonal prediction systems, either for single models (e.g., Johnson et al. 2019; Fröhlich et al. 2021 among many others) or within a multi-model framework, by evaluating their ability to forecast seasonal T2m and precipitation anomalies. Kim et al. (2016) analysed the skill of the WMO Multi-Model Ensemble (MME) at the global scale and over selected regions, for the hindcast period 1981–2010. They found that the systems contributing to the MME were generally able to capture the observed climatological patterns and seasonal variations in temperature and precipitation, although systematic biases were found, mainly located in mid- or high-latitude regions.

The prediction skill of both individual models and MME varies with season and region, with the best performance by the MME forecasts for the Tropics, where predictions are strongly influenced by ENSO. Over the tropical oceans, the temporal correlation coefficients of both T2m and precipitation were found to exceed 0.9, but they gradually decrease towards higher latitudes. North Eurasia as well as South-Eastern Europe and Eastern Mediterranean show relatively low skills in all seasons compared with other regions (Kim et al. 2016).

The skill of the T2m and precipitation anomaly predictions produced by the C3S multi-model system for the Mediterranean region was analysed by Calì Quaglia et al. (2022), considering results from individual models and their combination in MME. As shown in Figure 3, the C3S MME shows a generally better skill at predicting winter (DJF) and summer (JJA) temperature anomalies compared with precipitation anomalies in the same seasons, although with varying correlation patterns. The MME has been found to have the best agreement in terms of anomaly correlation with ERA5 precipitation, while a forecast based on the persistence of the anomaly had the best results in terms of anomaly correlation with ERA5 temperature. Individual forecast systems and MMEs outperform a reference forecast based on climatology in terms of accuracy of tercile-based forecasts up to lead time 5 months and in terms of discrimination up to lead time 2 months. All seasonal forecast systems are found to outperform elementary forecasts based on persistence in terms of accuracy and sharpness (Calì Quaglia et al. 2022).

3.1.2 | Wind Speed and Solar Irradiance

The increasing demand for clean and renewable power and, consequently, the growing importance of wind and solar energy have led to a boost in the interest in predictions of near-surface wind speed and solar irradiance. In recent years, several studies have been published to assess how low-level wind and solar irradiance characteristics may be impacted by climate change (see Jung and Schindler 2022, for a review), whereas a smaller number of works have investigated the capability to predict these variables on a seasonal timescale (e.g., Torralba et al. 2017).

Crespi et al. (2021) showed that ECMWF5 wind speed seasonal forecasts over Europe tend to overestimate the ERA5 reference in all seasons and across the entire domain, especially in sea areas, with an error distribution that remains fairly invariant across seasons. Noteworthy, simple bias adjustment based on quantile mapping was found to be particularly effective in removing such biases (Crespi et al. 2021).

Other studies analysed the skill of a set of three C3S forecasting systems at predicting seasonal–mean wind speed and solar irradiance in Europe (e.g., Bett et al. 2022; Lledó et al. 2022). For both variables, the skill appears patchy, even though the uncertainty in the reanalysis products typically used as reference data is quite large (e.g., Ramon et al. 2019). However, where some skill exists, simple post–processing methods based on linear regression techniques can be used for forecasting gross wind or solar energy generation (Bett et al. 2022).

3.1.3 | Ocean Heat Content and Sea-Surface Temperature

One of the major components of seasonal predictability in both the ocean and the atmosphere is Ocean Heat Content (OHC), whose anomalies typically persist for several months. The importance of OHC lies in the fact that an accurate representation and prediction of subsurface heat contribute to skilful predictions of SST, which is a key driver of many atmospheric circulation patterns and teleconnections. The ability of state-of-the-art seasonal forecasting systems to predict OHC is still under investigation (McAdam et al. 2022). Globally, two state-of-the-art seasonal forecasting systems (CMCC-SPS3 and ECMWF-SEAS5) showed skilful seasonal predictions of OHC in the upper 300-m across a range of forecast start times and seasons. The dynamical systems appear to outperform simple anomaly persistence forecasts in the Tropics. In contrast, inadequate prediction performance was found in the subpolar regions and areas dominated by sharp fronts, which should be the focus for further improving the skill of climate forecasting systems (McAdam et al. 2022).

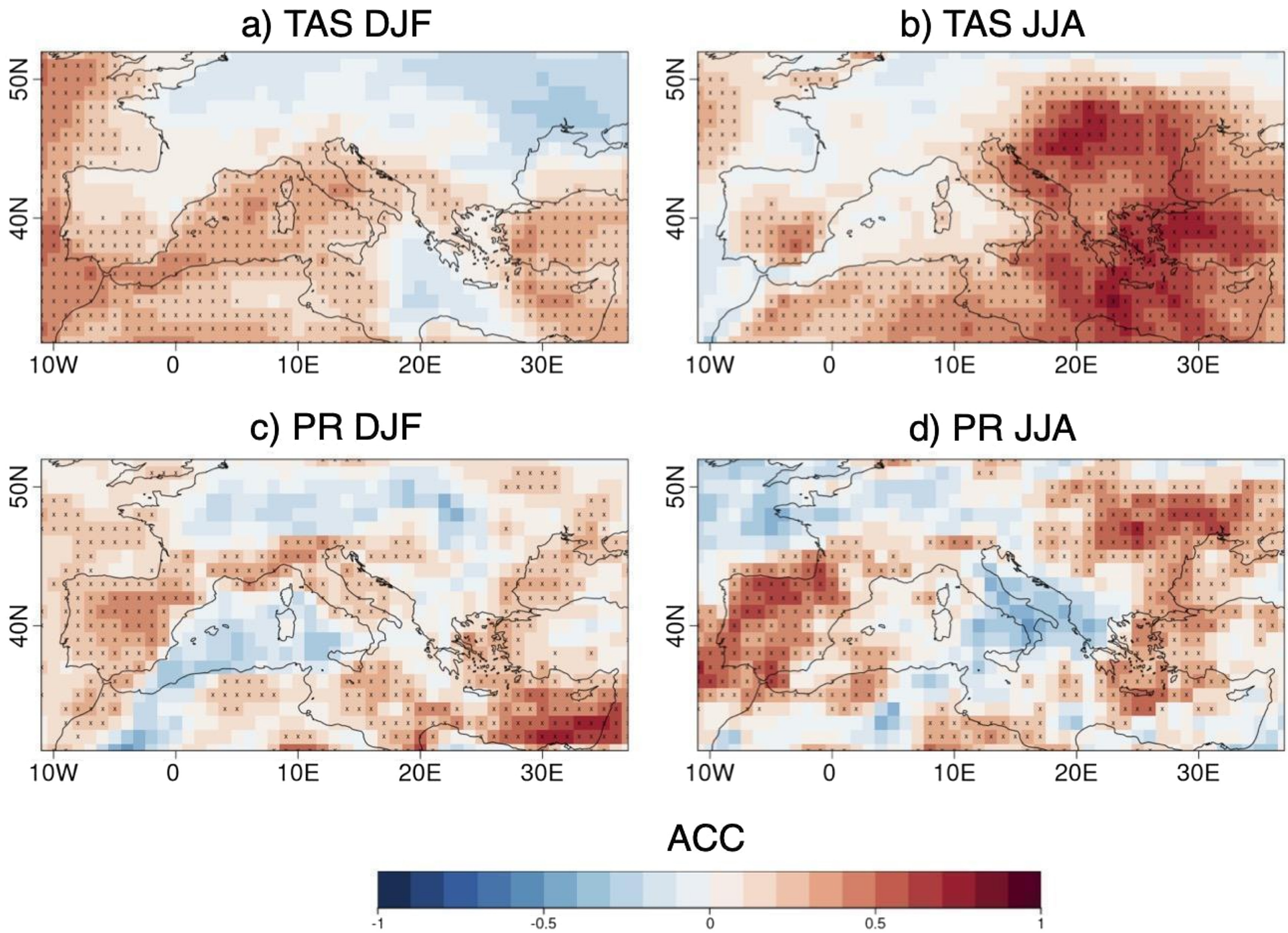

FIGURE 3 | Anomaly correlation coefficients of winter (DJF) and summer (JJA) near-surface air temperature (TAS) and total precipitation (PR) forecasts based on the ensemble mean of 5 forecast systems (namely European Centre for Medium-range Weather Forecast System 5 (ECMWF), Météo France System 6 (MF), UK Met Office GloSea5-GC2 (UKMO), Centro Euro-Mediterraneo sui Cambiamenti Climatici SPS3 (CMCC) and Deutscher Wetterdienst GCFS 2.0 (DWD)) with respect to ERA5 reference. Significant correlations (95% confidence level) are indicated by stippling. Forecasts are initialised on November 1st (left panels) and May 1st (right panels) and refer to the hindcast period 1993–2014. Figure adapted from (Calì Quaglia et al. 2022).

3.2 | Extreme Events

Aside from their ability to predict deviations from seasonal averages, seasonal forecasting systems are truly useful when they can also predict impactful events, such as extremes. While forecasting extreme precipitation events on seasonal timescales remains quite challenging, recent studies have demonstrated that forecasting systems exhibit some capability to predict extreme temperatures and heatwaves. For example, Prodhomme et al. (2022) evaluated the prediction skill of heatwave indices over Europe in the ECMWF-SEAS5 prediction system, showing that it outperforms a simple statistical model over the Mediterranean and Eastern Europe regions.

Torralba et al. (2024) investigated the potential of four C3S seasonal forecasting systems, and their combination into a multi-model ensemble, to provide useful information on the frequency and magnitude of the night-time heat waves (NHWs) in the Euro-Mediterranean region, during boreal summer. The characterisation of the NHWs has considered the effect of humidity. This is an important factor at night-time because the humidity combination with above-normal night-time temperatures poses a high risk to human health by impeding the body's recovery from daytime heat exposure. Their results (Figure 4) have revealed that the considered forecasting systems can represent the interannual variability of the magnitude and frequency of NHWs in Southern Europe, Eastern Europe, and the Middle East. Hence, in these areas, predictions can help to better anticipate and manage the risks associated with summer NHWs. Nevertheless, there are regions in Northern Europe where the value of the forecasts for the representation of the NHWs is still limited. The improvement of the seasonal predictions in these regions requires a better understanding of the physical mechanisms involved in the occurrence of the NHWs.

Marine heat waves (MHWs), defined as prolonged periods of extremely warm sea temperatures, have received much attention in recent years due to the serious consequences they can have on ecosystems (Wernberg et al. 2013) and marine services, such as fish farming (Gamperl et al. 2021). Generally, studies investigating the characteristics of MHWs and their

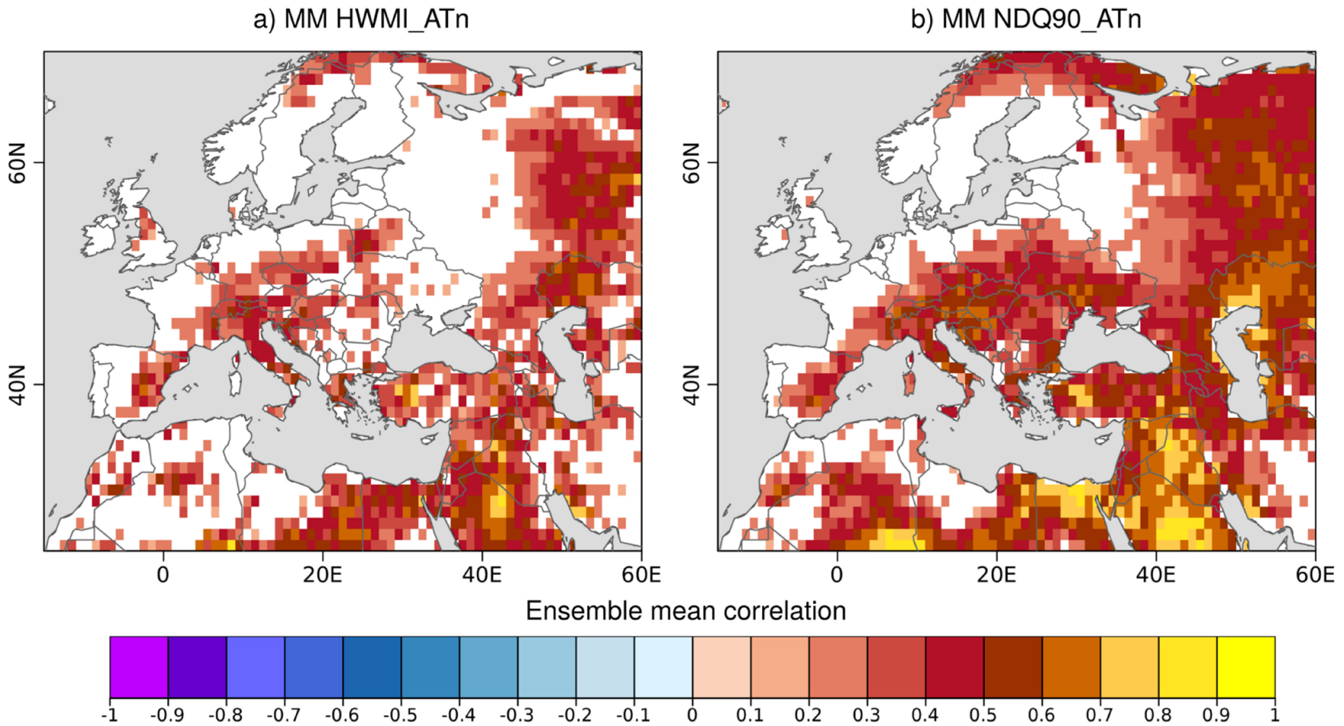

FIGURE 4 | Ensemble mean correlation for the seasonal predictions of the heat wave magnitude index (HWMI) and NDQ90 based on the apparent temperature at night (ATn) for the multimodel combination at the grid point level. The seasonal forecasts were issued on the 1st of May and the observational reference is ERA5. The analysis corresponds to the 15MJJA season in the 1993–2016 period. White colour has been used to mask regions with non-statistically significant correlations at the 95% confidence level. Adapted from Torralba et al. (2024).

predictability have mainly focused on SST-based event indicators, showing that the seasonal frequency and duration of MHWs can be predicted with operational state-of-the-art forecasting systems (e.g., de Boisséson and Balmaseda 2024). In these studies, the prediction of the occurrence of MHW events, the number of MHW days per season, their intensity and spatial extent are derived from seasonal SST forecasts and show a useful skill in predicting the occurrence of surface MHWs globally for the two seasons following the start date. The highest forecast skill is found in the El-Niño region, the Caribbean, the north-eastern extratropical Pacific, and the south-western extratropical basins, but is not as good for other mid-latitude basins, including the Mediterranean Sea (de Boisséson and Balmaseda 2024).

On the other hand, marine heatwaves damage marine ecosystems and services with effects identified mainly below the ocean surface. To create a truly user-relevant sensing system, therefore, it is necessary to provide predictions of the subsurface ocean state. McAdam et al. (2023) demonstrated the feasibility of seasonal predictions of subsurface marine heat waves using upper ocean heat content, validating extreme surface and subsurface temperature events predicted by an operational dynamic seasonal prediction system against satellite observations and an ocean reanalysis. In their study, McAdam et al. (2023) show that indicators of summer extreme events (number of days, maximum intensity, and number of events) of subsurface temperatures are predicted more skilfully than surface equivalents across much of the global ocean and particularly in the Mediterranean basin.

4 | Summary and Conclusion

This paper has reviewed the primary drivers of climate variability and the main sources of predictability in the Mediterranean region, focusing on their importance for seasonal forecasting. The Mediterranean climate variability is influenced by the intricate interplay of land-atmosphere–ocean interactions, with key contributors to regional predictability given by soil moisture, snow and vegetation cover, and SST variability.

Oceanic drivers, such as the SST anomalies in the Mediterranean Sea, but particularly in the Atlantic and tropical Indo-Pacific oceans, provide additional sources of variability and possibly predictability. Despite significant progress in understanding how SST variations in remote oceanic regions may influence the Euro-Mediterranean climate, forecasting remains constrained by the limited ability of climate models in reproducing the observed teleconnection processes.

Future work aimed at systematically assessing the predictability gains associated with the various drivers, including potential interactions and regional differences. Such an effort would improve our understanding of the underlying sources of predictability in the Mediterranean and help enhance the skill of current seasonal prediction systems over the region.

The paper has also briefly discussed the characteristics of multimodel climate prediction systems. The skill of these systems in predicting essential climate variables, such as temperature and precipitation, varies significantly across regions and seasons. Generally, MMEs consistently outperform single-model ensembles by aggregating diverse outputs and compensating for individual model biases. While MMEs generally perform well in the Tropics, challenges persist in large portions of the mid-latitudes, particularly in the Euro-Mediterranean region, and especially for precipitation. In contrast, the prediction of temperature, including extremes such as heatwaves and marine heatwaves, has shown encouraging results.

While advances in post-processing techniques, such as bias correction and downscaling, have improved forecast usability (see also Supporting Information Appendix IV), further efforts are needed to enhance model performance and forecast reliability. Artificial intelligence (AI) offers transformative potential for addressing these challenges. AI can enhance bias correction, refine downscaling methods, and improve teleconnection modelling by uncovering complex, nonlinear relationships among climate drivers. Traditional identification of teleconnections has relied on linear methods, which may fail to capture non-linear, conditional, regime-dependent, or multivariate interactions (e.g., ENSO–QBO coupling, MJO phase dependencies, or threshold sea-ice effects). AI approaches have the potential to uncover these non-linear and conditional dependencies, helping to identify when and under which background states these relationships contribute to predictive skill. In this sense, AI is intended to complement predictive systems, for example, by informing hybrid models or adaptive bias-correction schemes that can adjust teleconnection patterns either online (during forecast integration) or offline (through post-processing), depending on the application.

Notably, in recent years there has been an extraordinary effort to exploit AI methods to directly produce seasonal forecasts (e.g., Slater et al. 2023; Materia et al. 2024; Camps-Valls et al. 2025). The preliminary results of these developments, which are being updated at an extremely rapid pace, indicate that such methods will soon become essential components of forecasting activities at these timescales.

In conclusion, significant progress has been made in understanding and predicting Mediterranean climate variability, yet critical gaps remain in accurately capturing regional anomalies and extremes. Future research should especially focus on improving the modelling of tropic-extratropic teleconnections to fully exploit the predictability of the variability phenomena of the tropical oceans, particularly the Indo-Pacific. The improvement of the models' ability to correctly simulate teleconnections is certainly linked to the reduction of the systematic errors that still affect dynamical models. Many recent studies (e.g., Tsartsali et al. 2023) indicate the combination of dynamical models with statistical systems (possibly based on machine learning) as the most promising way to improve climate forecasts in this region. This integrated approach could represent a key tool to address the vulnerability of the Mediterranean to climate variability and support decision-making in vital sectors such as agriculture, water management and disaster preparedness. In a companion article to this one, some examples of forecasting applications in these crucial sectors for societies in the Mediterranean region will be discussed.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Appendix I-IV** Supporting Information.