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Challenges for drought assessment in the Mediterranean region under future climate scenarios

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This review is a collaborative effort initiated during a workshop on droughts held in Montpellier in April 2019. Y. Tramblay coordinated the review and wrote the early draft, A. Koutroulis coordinated section 2.1, L. Samaniego coordinated section 2.2, S. M. Vicente-Serrano coordinated section 3.1, F. Volaire coordinated section 3.2, M. Le Page coordinated section 3.3, Aaron Boone coordinated section 3.4, and M.C. Llasat coordinated section 3.5. M. Turkes, D. Pulido-Velazquez, K. Cindric Kalin, R. Trigo and M. Turco contributed to section 2.1, M. Grillakis, R. Trigo and D. Renard contributed to section 2.2, L. Hanich, J.-P. Vidal and D. Pulido-Velazquez contributed to section 2.3, P. Greves and N. Martin contributed to section 3.1, J.L. Dupuy, H. Davi, M. Cailleret, N. Martin, J. Martinez-Vilalta, F. Mouillot, A. Vilagrosa and M. Turco contributed to section 3.2, C. Albergel and M. Zribi contributed to section 3.3, J. Polcher, L. Jarlan and P. Quintana-Segui contributed to section 3.4, and D. Pulido-Velazquez, S. Burak, M. Turco and R. Trigo contributed to section 3.5.

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Index of acronyms:

Drought indicators:

AED: Atmospheric evaporative demand
CDD: Consecutive Dry Days
GRI: Groundwater Resource Index
SGI: Standardized Groundwater level Index
SPEI: Standardized Precipitation Evaporation Index
SPI: Standardized Precipitation Index
PDSI: Palmer Drought Severity Index

Models and remote sensing products:

CMIP5: Coupled Model Intercomparison Project - Phase 5
EDII: European Drought Impact Inventory
EO: Earth Observations
GCM: General Circulation Model
GHM: Global hydrological model
LSM: Land Surface Model
RCM: Regional Climate Model
RCP: Representative Concentration Pathway
NWP: Numerical Weather Prediction
SWOT: Surface Water Ocean Topography
NUTS: Nomenclature of Units for Territorial Statistics

Vegetation indices:

NDVI: Normalized Difference Vegetation Index
NDWI: Normalized Difference Water Index
EFFIS: European Forest Fire Information System
FAPAR: Fraction of Absorbed Photosynthetically Active Radiation
FWI: Fire Weather Index

Climate indices:

AMO: Atlantic Multidecadal Oscillation
AO: Arctic Oscillation
EA: Eastern Atlantic pattern
MO: Mediterranean Oscillation
NAO: North Atlantic Oscillation
SCA: Scandinavian patterns

Abstract

Droughts can have strong environmental and socio-economic impacts in the Mediterranean region, in particular for countries relying on rain-fed agricultural production, but also in areas in which irrigation plays an important role and in which natural vegetation has been modified or is subject to water stress. The purpose of this review is to provide an assessment of the complexity of the drought phenomenon in the Mediterranean region and present various perspectives on drought in the present and under future climate change scenarios. The projections of various model experiments on future climate change scenarios strongly agree on an increased frequency and severity of droughts in the Mediterranean basin. Nevertheless, given the complexity of the phenomenon, with different types of droughts and complex interrelated impacts, significant future uncertainties remain. For example, uncertainties are stronger for hydrological droughts than meteorological droughts due to human influences and water withdrawal. Significant drought impacts are expected in the future, in particular for developing countries in the southern and eastern parts of the Mediterranean basin. To improve the resilience and adaptive capacities of societies and environments faced with drought, we aim to provide an overview of the key issues in research on climate change impacts on droughts, with a specific focus on the Mediterranean region, in order to: i) redefine more meaningful drought metrics tailored to the Mediterranean context, ii) better take into account vegetation and its feedback on droughts, iii) improve the modelling and forecasting of drought events through remote sensing and land surface models, and iv) promote a more integrated vision of droughts taking into account both water availability and water use. This overview reflects the complexity of the problem and the need to combine scientific research with adaptation solutions to deal with drought in the future.

1. Introduction

Droughts can be considered as Earth system phenomena that cover a number of meteorological, hydrological and biophysical processes with socio-economic implications (Wilhite and Pulwarty, 2017). Drought generally originates as a meteorological phenomenon, in which periods of low precipitation may produce water scarcity in various parts or the whole of the hydrological cycle (McKee et al., 1993), which in turn affects crops (Chaves et al., 2003) and various environmental systems (Vicente-Serrano et al., 2020a). This ultimately cascades into diminished resources for mankind. This canonical vision of drought can be modulated by a number of other processes, such as increased atmospheric evaporative demand (S. M. Vicente-Serrano et al., 2020a) and evaporation (Teuling et al., 2013), which amplify the water deficit, or increased snowmelt, which compensates for it. Biophysical processes can likewise be more or less affected by water deficits (McDowell et al., 2008), and the vegetation response to droughts can also affect water availability through the modulation of evapotranspiration (Swann, 2018). Finally, humans have developed means to mitigate the impact of droughts through hydraulic infrastructures (Lorenzo-Lacruz et al., 2010), irrigation (Pinilla, 2006), planting more adapted plant species or crop varieties, etc. Thus, droughts can be seen as a process by which the continental water cycle is put into an extreme state and stresses all the other dependent systems (Wilhite et al., 2007). This cascade of processes leading to droughts amplifies the complexity thereof, which explains the great difficulty the scientific community has in quantifying (Vicente-Serrano et al., 2013) and forecasting (Pozzi et al., 2013) droughts and predicting their impacts. This complexity and uncertainty is exacerbated even further under future climate change scenarios due to the complex underlying processes driving drought (Cook et al., 2018; Dai et al., 2018; Scheff, 2019).

The largest Mediterranean climate region on Earth is found in the Mediterranean Basin, due to the topographical features of the western subtropical regions of continents. The Mediterranean climate is defined as a mid-latitude temperate climate with a dry summer season. Precipitation has a marked annual cycle, with hardly any precipitation in summer, and also a spatial gradient, with values decreasing toward the South (Lionello 2012). The high temporal variability of Mediterranean climate at seasonal and inter-annual scales is due to the transitional situation between temperate, cold mild-latitudes and the tropics, causing significant circulation changes between winter and summer, and the association with several large-scale atmospheric oscillations/teleconnection patterns..

Mediterranean droughts, in particular those occurring during the wet season, can have a strong impact on water resources by lowering groundwater levels and water available in dams and reservoirs (Lorenzo-Lacruz et al., 2017, 2013; Raymond et al., 2016). Low water availability can affect multiple economic sectors, wild biodiversity, and agricultural production, in particular for countries relying mostly on rain-fed agriculture such as the countries of North Africa or Middle-East (Turkes et al., 2020; Schilling et al., 2020). Indeed, the reduction of soil moisture at key phenological stages of crop growth can be detrimental (Pascoa et al., 2017; Pena-Gallardo et al., 2019); likewise, low groundwater level and reservoir storage can also affect crop performance, as well as the survival of all agro-ecosystems during the summer dry season (Guerrero-Baena and Gómez-Limón, 2019). The past changes in droughts in the mediterranean region are difficult to assess, due to limited records with regards to the strong inter-annual variability of precipitation (Vicente-Serrano et al., 2020b). There is much more consensus on the possible future evolution of droughts in the region, with both climatic (Dubrovský et al., 2014; Hertig and Tramblay, 2017; Turkes et al., 2020) and hydrological (Forzieri et al., 2014) scenarios suggesting an increase in drought frequency and severity. Therefore, it is necessary to identify the potential impacts of future droughts in order to develop better adaptation strategies.

The entire society of the Mediterranean has over the millennia developed techniques to harvest water excess during winter to preserve it for the dry summers when enough energy is available for plants to grow (Mays, 2004). Generally, hydrological basins are strongly modified and affected by large water regulation and water management is largely impacted by the frequent droughts that affect the basin. In addition, vegetation coverage has been strongly affected by changing human pressure during centuries. Both issues are real challenges posed to geophysical science. Climate change and its impact on droughts will pose a systemic challenge to society. The Mediterranean basin now concentrates approximately 500 million habitants in countries with various levels of development with a stark north/south contrast. Besides, it is one of the regions with more tourists from affluent countries and refugees from sub-Saharan and Middle East countries, two additional external drivers that are putting extra pressure on the limited agricultural and water resources available. The distribution of water resources in the Mediterranean is also very heterogeneous, causing numerous supranational and international conflicts mostly in transboundary basins and regions with water transfers between basins that may aggravate due to droughts or changes in ecosystem service supply (Gleik, 2014; Schleussner et al., 2016, Cramer et al., 2018). Indeed, the Mediterranean region is considered one of the regions of the globe with the highest socioeconomic exposure to droughts that is likely to be exacerbated in the future (Gu et al., 2020). Drought can also pose a threat to human health, mainly as an indirect indicator of the impacts of other extreme climatic events, such as atmospheric pollution and/or heatwaves (Salvador et al., 2020). There are competing interests for water resources in this densely populated region: irrigation, human water reserve for seasonally dense touristic population, ecosystem conservation, consuming water at the expense of the other services, among others. There is also a strong pressure on surface water resources and drought is an additional stressing factor in aquatic ecosystems. Drought also exacerbates aquifer overexploitation, which is a very significant issue in the Mediterranean area (Leduc et al., 2017). The groundwater component is also crucial for an appropriate mitigation of droughts due to the importance of aquifer status to satisfy water demands during droughts (Carmona et al., 2017). There is a crucial need to deepen the understanding between anthropogenic effects and the effects of climate change in monitoring land surfaces (vegetation, humidity). This aspect is essential in a very anthropogenic Mediterranean context for a better characterization of drought and its evolution.

There is a peculiarity of the Mediterranean water cycle with dry spells matching the highest evaporative demand and hottest temperatures, which is leading to critical thresholds of leaf temperature for plant functioning putting plants close to their physiological limit to resist drought in many areas. The Mediterranean region is very unique from a biogeographical perspective, as it is at the interface between temperate and dryland biomes, and contains many elements of the temperate flora that reach the southern limit of their distribution there. This also makes the Mediterranean the most fire prone of temperate ecosystems. Crop productions in dryland cultivations are already strongly determined by the inter-annual variability of droughts in the region, in particular for Southern countries of the basin. The spatial variability of plant types and landscapes make regional generic drought indices misleading at local scale. Many areas are at the interface between very different functional types and land cover types, including forest, shrubland and, in some extreme cases, bare ground with very sparse vegetation. Drought may be a major factor of alteration in the composition and health of the ecosystems in the future. At the same time, the causes underlying current drought impacts on vegetation dynamics are particularly difficult to unravel. Mediterranean vegetation has been modified for millennia and recent changes in management and land-use, very different in the North and South of the Mediterranean due to different socioeconomic contexts, make it difficult to isolate climatic impacts and attribute current episodes of vegetation dieback (Doblas-Miranda et al., 2015). Consequently, a main challenge on Mediterranean droughts is to understand its effect on plant and ecosystem communities, the strategies of drought survival and their trade-off with productivity across different species and its collateral effects on the vulnerability faced to other disturbances such as wildfires or desertification processes. Droughts will put limits for vegetation development especially in dry and semiarid areas, and management of these areas will increase in importance to avoid declining processes and tree mortality. Climate change impacts will be a strong incentive to adapt their management according to socio-economic contexts, and to provide relevant physiological traits to breed better adapted varieties of crop species.

The purpose of this review is to provide an exhaustive inventory of the current challenges in assessing droughts and their impacts under climate change scenarios in the Mediterranean region. Various definitions of drought exist, most often classifying it as meteorological, agricultural/environmental or hydrological, depending on its impact (Mishra and Singh, 2010; Wilhite et al., 2007). Consequently, we use the same categories: the available climate scenarios for meteorological droughts are presented in section 2.1, agricultural droughts in section 2.2 and hydrological droughts in section 2.3. We acknowledge that additional drought types could be conceived, for instance by considering the propagation of drought impacts to the socio-economic system (e.g. reflecting the deficit in water demand satisfaction (Guo et al., 2019; Linés et al., 2018; Mehran et al., 2015; Bachmair et al., 2016; Shi et al., 2018), but the literature available for these integrated definitions is still scarce. In the second part of this review, we provide a discussion of current research issues to improve our understanding of the various processes associated with droughts and highlight future research needs. The need to consider atmospheric evaporative demand in the assessment of drought severity is discussed in section 3.1, while section 3.2 examines the vulnerability and resilience of vegetation in the face of drought. The research perspectives of monitoring drought through remote sensing are presented in section 3.3, and the modelling of droughts to improve forecasting is presented in section 3.4. Finally, the importance of linking together drought indices, models and impacts is discussed in section 3.5.

2. Current drought scenarios for the Mediterranean

2.1 Meteorological droughts

Meteorological drought is a phenomenon associated with prolonged and abnormal moisture deficiency. It is usually described by the magnitude and duration of precipitation deficit with respect to the long-term climatology, often analyzed with statistical indicators like the Standardized Precipitation Index (SPI) (McKee et al., 1993). The SPI is particularly useful for drought monitoring, enabling the identification of different drought types and drought impacts on various systems. Besides precipitation, atmospheric evaporative demand (AED), i.e. the demand of the atmosphere for water, is included in several drought metrics like the Palmer Drought Severity Index (PDSI) (Guttman, 1998) and the Standardized Precipitation Evaporation Index (SPEI) (Vicente-Serrano et al., 2010). Yet it should be noted that each drought index may have some drawbacks. The SPI index, despite its simplicity and wide use, does only account for water supply without AED that could affect the water balance. The PDSI, and its self-calibrated version, show important problems of spatial comparability among regions with different characteristics (Guttman et al., 1998). The SPEI, accounting for water supply and AED, can be sensitive to the method to compute atmospheric evaporative demand (Beguería et al., 2014). Droughts effects most often cannot be apprehended only by these meteorological indices, their management also requires agricultural and hydrological indicators (Van

Lanen et al., 2016; Bachmair et al., 2016). Meteorological drought indices are commonly employed in the Mediterranean region when the severity and duration of a specific drought event needs to be quantified and placed in a long-term perspective (Cindrić et al., 2010; García-Herrera et al., 2019; Ionita et al., 2017; Sousa et al., 2011). Alternatively, dry spells defined as consecutive sequences of dry days are generally used when it comes to drought risk assessment (Rivoire et al., 2019; Vicente-Serrano and Beguería-Portugués, 2003). Regardless of the indicator used, it is of paramount importance to account for the non-stationary nature of climate variables under future climate scenarios (Mukherjee et al., 2018) and to consider the timescale of drought and its statistical properties (Vicente-Serrano et al., 2019a) for improved drought assessments in the context of climatic change.

Large-scale climate variability over the Mediterranean Basin is strongly associated with circulation patterns such as the Arctic Oscillation, the North Atlantic Oscillation, the East Atlantic Pattern and the Scandinavian Pattern, which control moisture fluxes and determine the patterns of wet and dry conditions over the Western and Eastern Mediterranean Basins (Lionello, 2012; Sahin et al., 2018). Based on long-term precipitation observations, some studies suggest that anthropogenic emissions have contributed to the increase in meteorological drought in the Mediterranean (Gudmundsson and Seneviratne, 2016; Hoerling et al., 2012). It must, however, be stressed that historical precipitation trends are not statistically significant over the whole domain (Raymond et al., 2016; Vicente-Serrano et al., 2020). Drought studies extending to before the industrial era suggest drying trends over the Mediterranean Basin that have reached extreme levels over the last few decades (Cook et al., 2016; Hanel et al., 2018; Markonis et al., 2018). Recent droughts in the eastern Mediterranean after 1998 and Syria in 2007-2011 (Kelley et al., 2015) were the largest in intensity and duration over the last few decades or even centuries. Based on long-term reconstructions and modeling approaches, drying trends are attributed to increased anthropogenic forcing (Marvel et al., 2019). Moreover, the increase in drought severity in various countries of the Mediterranean basin suggested by multiple studies (Caloiero et al., 2018; Fniguire et al., 2017; Jacob et al., 2018; Markonis et al., 2018; Raymond et al., 2019; Sousa et al., 2011; Spinoni et al., 2017; Turco et al., 2017a) is mostly related to the observed increase in atmospheric evaporative demand (Vicente-Serrano et al., 2014) since precipitation has not changed substantially over the long term (Hanel et al., 2018; Vicente-Serrano et al., 2020b), and precipitation records since the middle of the 19th century indicate several drought episodes equivalent in severity and duration to those recorded in the last few decades (Vicente-Serrano et al., 2020b). Thus, under the dominant stationary precipitation conditions, the most evident change would be the increased severity of recent drought events caused by higher atmospheric evaporative demand (García-Herrera et al., 2019), which would explain the general drying assessment based on soil moisture models and drought indices that include this variable in calculations (Markonis et al., 2018; Marvel et al., 2019). Studies based on the impacts of drought on forests (Carnicer et al., 2011), pasture lands (Vicente-Serrano et al., 2012) and water resources (Vicente-Serrano et al., 2014) support the increased influence of the AED on drought severity in the region.

Potential shifts in large-scale circulation under climate change will place substantial pressure on the Mediterranean hydro-climate (Barcikowska et al., 2018; Wang et al., 2018). There is relatively high agreement on a decrease in Mediterranean precipitation in future scenarios, which could be explained by a gradual northward shift of the winter jet over the North Atlantic, leading to a northward transport of air moisture away from the Mediterranean (Putnam and Broecker, 2017). The projected decline is strongly related to the level of global warming and the induced changes in the regional circulation of remote drivers (Zappa and Shepherd, 2017). In the case of weak circulation changes, the response is unclear, especially for a lower level of global warming, while in a high-impact scenario with amplification of regional circulation, the reduction in wintertime Mediterranean precipitation could locally reach a rate up to 0.2 mm $day^{-1}K^{-1}$ of global warming (Zappa and Shepherd, 2017). Simulations from a high resolution GCM (Barcikowska et al., 2018) suggest precipitation changes of up to −50% in some regions of Northwest Africa and up to −20% and −25% over the west coasts of the Balkan Peninsula and Turkey, respectively, by the end of the 21st century. Polade et al. (2017) note a similar drying pattern (12% average reduction, ranging from +1% to −38%) over the same period based on 30 CMIP5 GCMs. Consistent with this decline in precipitation, climate models project an increase in the duration and intensity of droughts in the Mediterranean during the 21st century, based on different scenarios and metrics (Daliakopoulos et al., 2017; Dubrovský et al., 2014; Ozturk et al., 2015; Ruffault et al., 2014; Spinoni et al., 2018; Vrochidou et al., 2013). These projected changes in the duration of meteorological droughts may affect large parts of the Mediterranean region (Deidda et al., 2013; Lionello and Scarascia, 2018; Marcos et al., 2017; Raymond et al., 2019; Turkes et al., 2020) and present a high signal-to-noise ratio under the RCP8.5 concentration pathway (Orlowsky and Seneviratne, 2013; Prudhomme et al., 2014). According to the same scenario, a significant increase in the frequency of Mediterranean droughts is projected even under the ambitious mitigation targets of 1.5°C and 2°C global warming, with droughts projected to occur 5 to 10 times more frequently compared to the recent past (Naumann et al., 2018). For instance, Polade et al. (2015) used projections of precipitation from 28 CMIP5 global climate models forced by RCP8.5 to study changes in dry day frequency. They found an increase of up to 30 more dry days for the period 2060–2089 relative to 1960–1989 over the Mediterranean Basin. As a result, more than 80% of the projected annual precipitation change in the Mediterranean region can be ascribed to increases in the occurrence of dry days rather than to changes in precipitation intensity. Based on a set of higher resolution transient climate simulations under the RCP8.5 scenario (Koutroulis, 2019; Koutroulis et al., 2019; Wyser et al., 2016), Mediterranean areas are expected to experience increases in time under severe and extreme drought (Figure 1). The magnitude of the changes is higher for long-term (SPI48) than short-term (SPI6) meteorological droughts and escalates with the level of global warming. These changes are not projected to be homogeneous over the entire Mediterranean basin, with the western half showing a tendency towards more frequent severe droughts, with stronger agreement among ensemble model members. However, most model experiments overestimate the observed precipitation decrease (Knutson and Zeng, 2018). Considering changes aggregated at the country level, at 1.5^{o}C above pre-industrial levels, 30% of the land of Morocco is projected to face an increase of approximately 10% to 20% in time under severe (long-term) drought, with a multi-model agreement of over 80% (Table 1, supplementary material). At 2^{o}C of global warming, the drying signal (>10% in time under severe (long-term) drought) is present for over 30% of Morocco, Portugal, Spain, Montenegro and Albania, while at the high end of 4^{o}C the drying signal is more robust for the majority of the Mediterranean countries. By the end of 21st century, the extent of the current Euro-Mediterranean climate zone is projected to shrink by 16% (157,000 km^2) under RCP8.5, equivalent to half the size of Italy (Barredo et al., 2018). The extent of the Mediterranean arid zones is expected to increase more than twofold, covering an area of almost 400,000 km^2. An increase in aridity over the northern Mediterranean implies transitions from dry sub-humid and humid to semi-arid, while over the southern Mediterranean these transitions are towards dryer arid and hyper-arid types (Koutroulis, 2019; Ozturk et al., 2018).

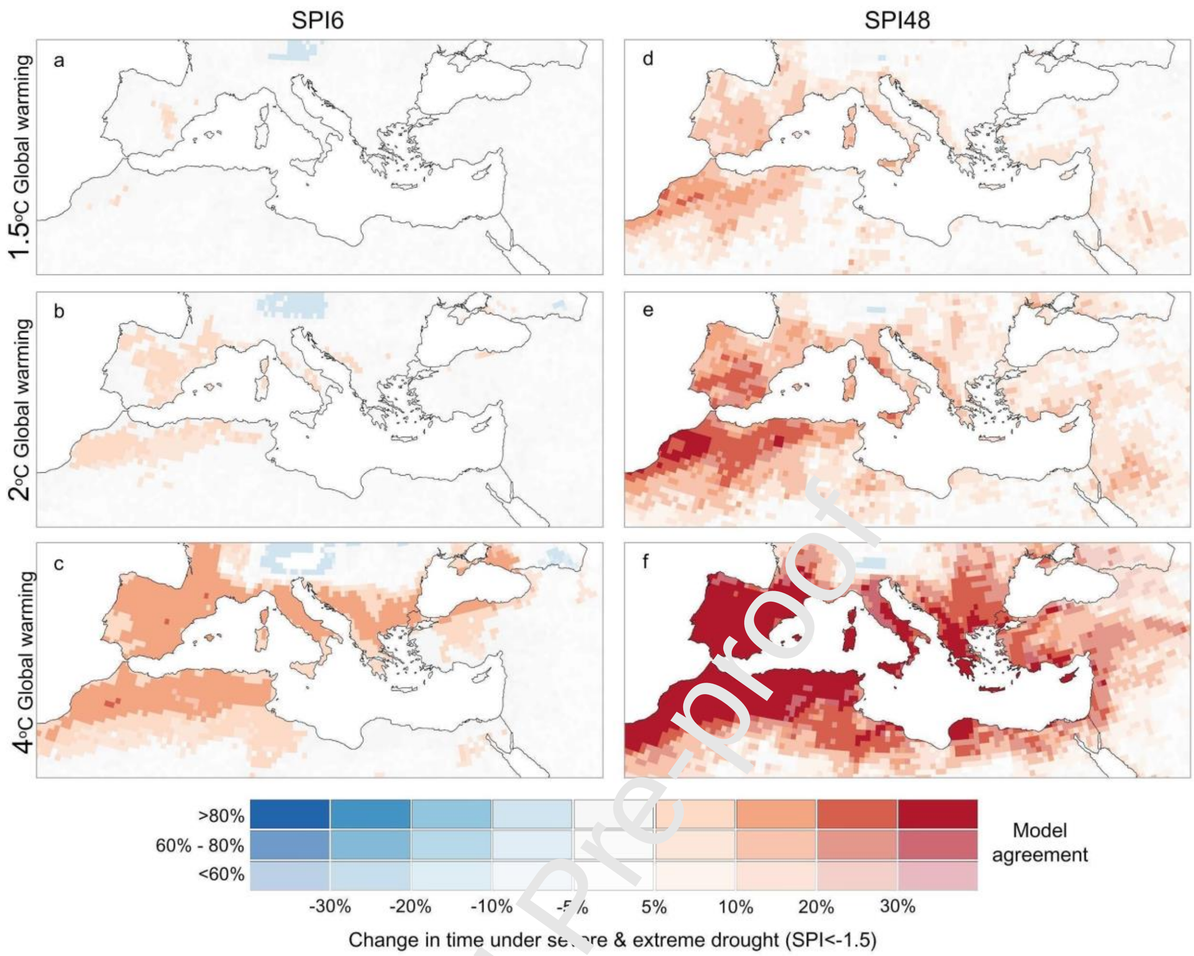

Figure 1. Mediterranean areas projected to experience increases in time under severe and extreme drought (SPI<-1.5). Changes are shown for short timescale (SPI6 – a, b, c) and long timescale (SPI48 – d, e, f) droughts for specific levels of global warming (1.5 °C, 2 °C and 4 °C above preindustrial levels) relative to the baseline period (1981-2010). SPI calculations are based on a set of higher-resolution transient climate simulations under the RCP8.5 scenario (Wyser et al., 2016). SPI statistics are calibrated on the reference period (1981-2010) and used for the SPI calculations for the future periods. Color saturation denotes the agreement among ensemble members and color hues show the magnitude of change.

Changes in droughts can also be caused by changes in rainfall characteristics in terms of seasonality, dry spells and precipitation intensity. There are numerous studies on dry spells concerning the Mediterranean region, particularly those covering datasets from the second half of the 20th century across individual countries, selected regions (e.g. Iberian Peninsula, different parts of the Mediterranean) or the whole of Europe. There are generally two groups of studies dealing with dry spells: i) those that model dry spells via theoretical probability distributions, providing spatial patterns with different return levels (Rivoire et al., 2019; Serra et al., 2016; Tramblay and Hertig, 2018), and ii) those in which observed and projected changes in dry spells are analyzed. In particular, the maximum duration of dry spells (according to a 1 mm threshold) has been widely analyzed in the context of climate change since it is part of the core set of indices of extremes (Lionello and Scarascia, 2018; Raymond et al., 2019). With regard to observed climate change, in general, a drying trend has been found in the Mediterranean region with a growing duration of dry spells, particularly in the cold season (Zolina et al., 2013), 2013). Such positive trends occurred at the expense of wet periods, with the Iberian Peninsula experiencing the strongest shortening of wet periods. Regional simulation experiments (Brogli et al., 2019) suggest that the causes of drying in the Mediterranean differ depending on the season and are probably linked to the dominant seasonal precipitation formation mechanisms: winter precipitation is predominantly caused by synoptic processes while locally formed convective precipitation is more abundant in the summer. The relationship between dry spells during winter and synoptic patterns has been examined by a number of studies (Raymond et al., 2016; Tramblay and Hertig, 2018), revealing an association between these episodes and anticyclonic blocking conditions 1000km to the northwest, which bring non-saturated cold air masses. Dry spells are also associated with positive anomalies in the NAO and to a lesser extend in the MO. With regard to future projections, over 90% of the CMIP5 models predict a notable drying of the Mediterranean, most likely associated with a lengthening of dry spells (Polade et al., 2017). The area could experience up to 30 more dry days per year by the end of the century (Polade et al., 2015). For the temperature targets of 1.5°C and 2.0°C, the small size of the CMIP5 ensemble does not provide enough information to quantify changes in weather extremes, due to a low signal-to-noise ratio. In response to this, Sieck et al. (2020) used regional climate simulations driven by a large GCM ensemble to quantify changes in the number of Consecutive Dry Days (CDD) for 1.5°C and 2.0°C of global warming. Their results suggest statistically significant shifts towards more frequent, longer dry periods in the Iberian Peninsula for both warming targets, while for the rest of the Euro-Mediterranean area, similar changes are simulated for the 2.0°C global warming level. Comparable patterns are emerging from the regional climate model simulations carried out under Euro-CORDEX and Med-CORDEX (Raymond et al., 2019). The results show an increase in the number of very long dry spells, from + 3 to +31 events (according to RCP4.5 and RCP8.5), with a parallel increase in mean duration and spatial extent for the period 2066-2100 compared to the recent past (1971-2005). Furthermore, future drought changes could be determined not only by the changing frequency of dry days but also by precipitation intensity on wet days. Several studies demonstrate that the future relationship between temperature and precipitation intensity is close to Clausius-Clapeyron scaling (Bao et al., 2017) at temperatures below a regionally varying threshold that is determined by the level of moisture deficit (Drobinski et al., 2018). These changes in rainfall intensity (mm/h) on the sub-diurnal scale could potentially lead to increased surface runoff and thus make rainfall events less efficient for water resources.

Although significant progress has been made in the scientific field of meteorological drought, the impact of climate change on drought requires further investigation because of the underlying complexity of the relationship between the two. Several questions have yet to be studied. A comprehensive analysis of the mechanisms behind the change in the duration of dry episodes should also involve temperature regimes during dry periods, which are particularly important for analyzing the impacts of extremely long dry periods (Zolina et al., 2013). Recent studies stress that direct climate model outputs contradict the signals of increasing dryness simulated by offline impact models due to incorrect assumptions under increasing atmospheric CO2 that do not account for changes in water use efficiency (Betts et al., 2015; Greve et al., 2019, 2017; Huang et al., 2015; Milly and Dunne, 2016; Peters et al., 2018; Yang et al., 2018). Furthermore, the first results from the new generation of CMIP6 global climate models (Eyring et al., 2016) present higher equilibrium climate sensitivity with respect to the CMIP5 range. Scientists will need to investigate the magnitude and trends of future drought in response to this greater likelihood of reaching higher levels of global warming, while also taking into account the potential changes triggered by abrupt and irreversible climate changes (Pascale et al., 2016). Finally, it should be noted that model consensus on Mediterranean drying does not necessarily imply more confidence since false confidence in robust projections could stem from common errors or deficiencies in physics parameterizations (Pascale et al., 2016).

2.2 Agricultural droughts

Soil moisture is a fundamental variable, acting as a switch and integrator of various water fluxes interlinked in the soil-vegetation-atmosphere system (Koster, 2004; Seneviratne et al., 2010; Teuling et al., 2013) and regulating energy flows and biogeochemical cycles, and thus plays a key role in plant growth. Along with topography, soil hydraulic characteristics and rainfall rate, the prevailing soil moisture conditions control the proportion of rainfall that percolates, runs off, or evaporate from the Earth's surface and drive many vegetation processes. Soil moisture also integrates precipitation and evaporation over periods of days to weeks, thus introducing memory into the coupled soil-vegetation-atmosphere system. This makes the water stored in the topmost, unsaturated surface layer of the Earth one of the most important water resources, supplying natural vegetation and non-irrigated crops with the water they need.

Rain-fed agriculture is crucial for the economy in several Mediterranean countries, accounting for more than 90% of cultivated areas in Algeria, Morocco and Tunisia (Schilling et al., 2020), 57% in Turkey, 64% in Italy and 56% in Portugal (Jacobsen et al., 2012). As a result, long and/or intense droughts during the rainy season can have serious consequences for crop production and agricultural revenues. The lack of soil moisture is at the forefront of drought issues, as it affects crop growth and yields, and is thus called *agricultural drought* (Ciais et al., 2005). Agricultural drought is caused by the combination of a lack of precipitation (meteorological drought) with the AED. The socio-economic impacts associated with agricultural drought can be severe, as they often accumulate slowly and over a long time and may persist for years after the end of a meteorological drought (Vrochidou et al., 2013). Since the 1960s, drought events have been one of the main drivers of crop failure in the world (Cottrell et al., 2019), with a significant impact on the world economy and food security. The projected increase in the frequency, intensity and extent of drought will likely exacerbate the pressure on rain fed agricultural production in Mediterranean drylands and strain livelihood systems (Bird et al., 2016; Bouras et al., 2020). More frequent drought, in particular during summer, threatens the sustainability of multiple agroecosystems characterizing this region. Agroecosystems relying on rain fed trees for example may suffer from increased mortality due to gas embolism. The availability of water is one of the most important factors that determine plant growth. This is why the best-known effect of water deficit on crops, worldwide and in the Mediterranean region, is the reduction of yield. The magnitude of this reduction varies with species and variety. For food legumes (lentils, chickpea and fava beans), an experiment conducted in Syria showed that yield reduction due to drought ranged from 56 to 64% on average across three seasons (Karrou and Oweis, 2012). Wheat and food legumes are expected to be among the most affected by projected more frequent and severe drought events; along with barley, they are the most dominant species in Mediterranean cropping systems, playing a major role in feeding people and livestock (Karrou and Oweis, 2012). Water availability also depends on soil storage. Larger negative impacts from drought are usually expected on light soils (with a high proportion of sand) with lower water-holding capacities. The magnitude of drought-induced yield reduction also depends on the growth stage: when droughts occur during key phenological stages, irreversible damage or physiological disorders may occur (Pena-Gallardo et al., 2019; Vicente-Serrano et al., 2013). For instance, water stress induces tiller losses during the early stages of cereal growth, while a decline in carbon assimilation and grain hampering could occur if drought coincides with the reproductive and grain-filling stages. High temperatures (above 30°C) associated with drought are also particularly harmful for yields of all crops during the pollination phase. In addition to reducing yield, the distribution of rainfall and the timing of dry spells create a high level of uncertainty for farmers regarding if and when to sow seeds. Water deficit after sowing can not only lead to seed mortality and thus loss of cropland area and crop failure, but farmers may even decide not to sow at all, since small-scale farmers may wait for well-distributed rainfall events at the start of the season to seed.

Agricultural drought is affected by both climate change and human activity on land, but also direct human influences on the hydrological cycle. For the Mediterranean region, studies indicate a historical decrease in soil moisture, particularly in southeastern Europe, southwestern Europe and southern France, as well as a substantial increase over western Turkey (Kurnik et al., 2015; Samaniego et al., 2018; Sheffield and Wood, 2008). Similarly, Mariotti et al. (2015) indicate a progressive decrease in total soil moisture in the Mediterranean region based on CMIP5 historical runs. Nonetheless, century-long reconstruction of soil moisture should be interpreted with care in the absence of validation data. Based on Samaniego et al. (2018), a global warming increase of 3 K instead of 1.5 K would lead to an increase of 44% (± 24%) in soil-moisture drought area in the Mediterranean (i.e. regions enduring severe droughts where SMI < 0.2), and consequently 42% more people would be affected by droughts by the end of the century. The longest droughts in all of Europe are projected to occur in this region, with durations exceeding 7 months/year (using the period 1971-2000 as a reference for the SMI quantile estimation).

In order to derive a consistent multimodel ensemble for SMI, the simulated SM of every RCP-GCM-LSM combination was transformed into SMI (Samaniego et al., 2013). The reference empirical SM CDF for a given RCP-GCM-LSM combination was based on the period 1971-2000 (Samaniego et al., 2018). Once the SMI for a given ensemble member is obtained, the drought duration is calculated by tallying the number of months per year in which the SMI is less than the 20% quantile. This quantile implies that the simulated SM in a given cell and simulation will be exceeded 80% of the time. The ensemble mean drought duration is then estimated as the average of the 60-member ensemble. It must be emphasized that the representation of land cover and land use is of crucial importance for these kinds of climate projections. Future studies should also include gridded land cover and land use fields representing socio-economic scenarios to be able to better represent land cover change and dynamic vegetation (CO2 fertilization hypothesis) in land surface models. Unfortunately, at the time of this study this information was not available. Figure 2 shows the evolution of the ensemble mean drought duration in the Mediterranean region (months/year) based on the simulations of 4 LSMs (Noah-MP, mHM, PCR-GLOBWB, and VIC) and 5 bias-corrected GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) under three RCPs (2.6, 6.0, 8.5). The simulations on which this figure is based were reported in Samaniego et al. 2018, 2019. It should be noted that the estimation of the SMI for the period 2001-2099 uses the historical SM reference (i.e. no adaptation of the CDF). This figure 2 clearly shows the magnitude of the changes from the beginning to the end of the century for the Euro-Mediterranean region. Under the RCP2.5 scenario, the DD will peak at mid-century and reach around 6 months per year at a few locations in the Iberian Peninsula and eastern Greece. Under RCP6.0, the ensemble DD will reach 6 to 7 months per year by the end of century for large portions of both regions. Under RCP8.5 the situation will be drastically different. Large changes will be observed in the Iberian Peninsula by midcentury (around 6 to 7 months per year). By the end of the century, the whole Mediterranean will endure severe droughts for 8 or more months of the year. This unprecedented increase in drought duration highlights the severity of the expected changes. With such results and given current technologies, it is hard to imagine how large-scale agriculture and the supply of water to millions of people will be feasible. In a similar work, Grillakis (2019) analyzed soil moisture simulations for Europe from the JULES Land Surface model driven by four GCMs under the RCP2.6 and RCP6 scenarios. The results indicated that exceptionally low soil moisture would become substantially more frequent in the Mediterranean region in 2100. A key finding was that the unprecedented drought events of the historical period, which had an unforeseen spatial extent and duration of up to 3 years, are expected to occur up to twice per decade in the future, regardless of the degree of mitigation.

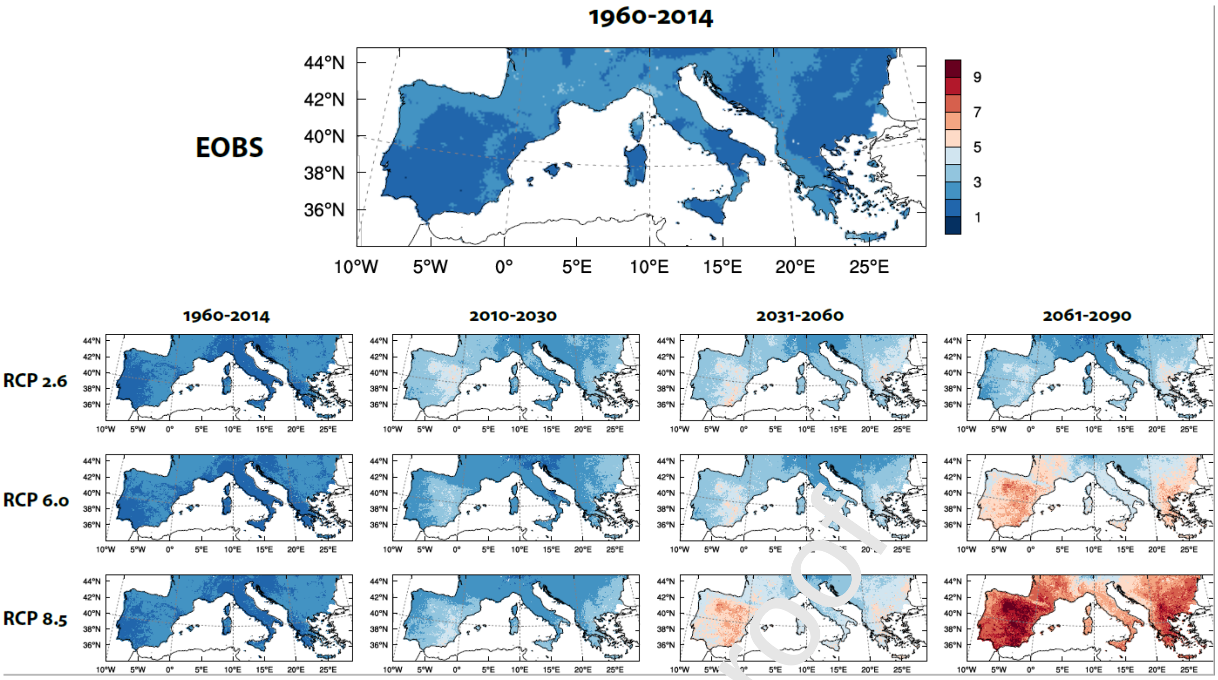

Figure 2: Multi-model ensemble mean drought duration (months/year) obtained with historical observations (E-OBS) during the period 1960-2014 and with for RCP 2.6, 6.0, and 8.5 for three periods: near future (2010-2030), mid-century (2031-2060) and end of century (2061-2090) for the northwestern Mediterranean region.

2.3 Hydrological droughts

Hydrological drought refers to low flow periods with a streamflow or groundwater level deficit under "natural" conditions. Related indicators often include the annual minimum of a streamflow average taken over several consecutive days. Assessing natural flow conditions in a specific location requires removing the anthropogenic influences (e.g. reservoir management, water transfers, abstractions for various anthropogenic uses like irrigation and drinking water, etc.) from the observed streamflow series. Naturalization thus requires additional data on anthropogenic influences, which are usually greater during the summer low-flow period, when water demand around the Mediterranean is at its highest, notably for irrigation. Strong collaboration with the social sciences is therefore needed to improve our understanding and modelling of hydrological droughts in the Anthropocene (Kreibich et al., 2019; Van Loon et al., 2016).

Historical discharge records indicate an increased frequency of low flows in Southern Europe (Stahl et al., 2010), in particular in France (Giuntoli et al., 2013), Spain (Coch and Mediero, 2016; Lorenzo-Lacruz et al., 2013) and Turkey (Cigizoglu et al., 2005), and an overall decrease in water availability over the Euro-Mediterranean domain (Gudmundsson et al., 2017). However, low-flow trends can be influenced by multidecadal variabilities (Hannaford et al., 2013) such as the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) (Giuntoli et al., 2013). In addition, the expansion of forests in headwaters and of irrigated lands in the lowlands mostly explains the decrease in streamflow in the region (Teuling, 2018; Vicente-Serrano et al., 2019a). Thus, the increase in hydrological droughts downstream of the main irrigation areas is greater than higher upstream (Vicente-Serrano et al., 2017a, 2017b).

Marx et al. (2018) provided future scenarios with a combination of 3 hydrological models driven by 5 GCMs under RCP 2.6, 6.0 and 8.5, with low flows described as the percentile of daily streamflow exceeded 90% of the time. They observed a decrease for Euro-Mediterranean areas (France, Spain, Italy, the Balkans and Greece) ranging from 12% under +1.5 K warming to 35% under +3 K warming. Similar results were obtained by Quintana-Seguí et al. (2011) for French Mediterranean basins; using different downscaling methods, they found a reduction of up to 20% in the annual monthly minimum under the A2 scenario for the middle of the 21th century. Smiatek et al. (2014) observed that summer low flows in the Jordan river basin could be reduced by between 15% and 25% towards the end of the 21st century. Using an ensemble of Euro-CORDEX simulations for +2° and +4° scenarios, Papadimitriou et al. (2016) found that the intermittent flow regime of the Guadiana River (south of the Iberian Peninsula) will intensify in these climate change simulations. Overall, most studies conducted with hydrological models forced by climate models indicate an extension of the low-flow period during summer (Forzieri et al., 2014; Prudhomme et al., 2014), accompanied by an increased frequency of flow intermittency, in France (Lespinas et al., 2014), Italy (Fiseha et al., 2014; Piras et al., 2014; Senatore et al., 2011), Spain (Majone et al., 2012), Portugal (Mourato et al., 2015), and Morocco (Marchane et al., 2017; Tramblay et al., 2013). With regard to basins influenced by snow, several studies report a general decrease in snow amounts and increasing snowmelt, implying a changing contribution to river runoff that could impact the seasonality and magnitude of low flows (Marchane et al., 2017). In their study on the Durance River in southern France, which is regulated by large reservoirs, Andrew and Sauquet (2017) found a decrease in mean annual renewable water resources, with a decrease in summer low flows, associated with a greater pressure on water demand, using ENSEMBLES regional climate models with the A1B scenario up to the year 2050. Schneider et al. (2013) applied the WaterGAP model and 3 GCMs under scenario A2, with a time horizon of 2050, to find an increase in discharge intermittency in the Mediterranean basins of Southern Europe, likely exacerbated since large amounts of water are already withdrawn for irrigation purposes. Grouillet et al. (2015) used an integrated modelling framework that considers both hydrological processes and water demand to study the Ebro (Spain) and Hérault (France) basins. They found that a future increase in human activities (tourism, agriculture, etc.) and the consequent increase in water demand may have a greater impact on water availability than climate changes, even under RCP8.5. Over the whole Mediterranean, water demand is already high and may increase greatly in the future, in particular in North Africa, thus affecting water resources and subsequently low flows (Droogers et al., 2012; Milano et al., 2013).

A few drought indices are focused on groundwater. Bloomfield and Marchant (2013) developed a methodology based on the SPI approach that uses the monthly groundwater level time series to estimate a Standardized Groundwater level Index (SGI). Mendicino et al. (2008) introduced a Groundwater Resource Index (GRI), which is derived from a distributed water balance model. This index is used in a multi-analysis approach for monitoring and forecasting drought conditions and has been tested in the Mediterranean region. For example, Lorenzo-Lacruz et al. (2017) showed high correlation between aquifer levels and the Standardized Precipitation Index on the island of Mallorca (Spain). These groundwater variables will be affected by climate change in the future. Semi-arid Mediterranean areas show significant reductions in future potential recharge. For example, a 12% decrease in net aquifer recharge over continental Spain is estimated for the horizon 2045 under the most pessimistic concentration pathway, RCP8.5 (Pulido-Velazquez et al., 2018a). The spatial distribution of this decrease is quite heterogeneous, and the standard deviation of the annual mean recharge will increase by 8% on average in the future. Nevertheless, although the probability is low, an increase in rainfall variability, as expected under future scenarios, could increase recharge rates for a given mean rainfall because the number of extreme events may increase. For some RCMs, the simulations predict total recharge increases over the historical values, even though climate change would produce a reduction in the mean rainfall and an increased mean temperature (Pulido-Velazquez et al., 2015). However, the current generation of land-surface components in climate models does not reproduce well groundwater recharge, and precipitation intensity is also strongly biased in climate simulations. Overexploitation of groundwater is another important factor, with an even greater effect of lowering groundwater levels than climate change in many Mediterranean areas (Leduc et al., 2017). Reductions in groundwater recharge and levels, independently of the drivers, might produce significant hydrological impacts, especially in systems with higher vulnerability such as the coastal aquifers, in which salt-water intrusion could be exacerbated (Pulido-Velazquez et al., 2018). The groundwater component is also crucial for an appropriate assessment of operational droughts, due to the fact that aquifer levels have a significant influence on the availability of water to satisfy demands in Mediterranean areas (Carmona et al., 2017).

The assessment of the impact of climate change on river discharge and subsequently on low-flow indicators requires a modelling chain linking climate models, downscaling and/or bias-correction methods, and hydrological models. Mediterranean regions are a hot spot for changes in low flows (Giuntoli et al., 2015), with a large increase in low flow days simulated from a multimodel ensemble combining various GCMs and global hydrological models (GHMs). However, it has also been demonstrated that over the Mediterranean region, the largest contribution to the total uncertainty is related to the GHMs (Giuntoli et al., 2015). Similarly, Vidal et al. (2016) analyzed the uncertainties of the hydro-modelling chain used to simulate low-flow changes in two snow-influenced catchments in the French Southern Alps. They found a large influence of internal large-scale and small-scale climate variability, and a large contribution to the total uncertainty of the hydrological modelling structure. Lespinas et al. (2014) observed that for various types of Mediterranean basins, the hydrological scenarios are sensitive to the choice of the potential evapotranspiration formulation in the conceptual models that are still widely used for this type of climate change impact assessment. Moreover, these models do not include the possible feedback effects of land cover, for example the impact of forest cover on long-term hydrological droughts.

3.0 Research perspectives

3.1 The need for drought indicators that include atmospheric evaporative demand

Projections based on precipitation indices suggest an increase in the frequency and severity of droughts in the Mediterranean region at the end of the twenty-first century (Martin, 2018; Orlowsky and Seneviratne, 2013). Other studies based on drought metrics that include the atmospheric evaporative demand project a stronger increase in dryness in the region than the precipitation-based metrics (Dai et al., 2018; Naumann et al., 2018; S. M. Vicente-Serrano et al., 2020a). The rationale behind these findings is that the AED would increase water scarcity in various usable water sources and in vegetation, although the authors suggest that in the last few decades, increased AED does not correspond to a reduction in water resources and/or vegetation activity (Scheff, 2018), the role of the AED is particularly relevant during drought periods given increased plant stress and direct evaporation from surface water bodies (Vicente-Serrano et al., 2020).

At present, there is a scientific debate on the use of drought metrics that include AED with future climate projections (Scheff, 2019, 2018; Zang et al., 2020). This is in part due to the fact that the formulation of potential evapotranspiration in AED indices can have a strong influence on the magnitude of changes in drought indices, with a potential overestimation of the temperature effect (Sheffield et al., 2012). This is also because there are large uncertainties regarding the combined effect of AED, soil drought and CO2 on vegetation responses to climate change. Such uncertainties are primarily linked to runoff outputs from global climate model projections that suggest more limited drought trends than offline drought indices that use AED calculations based on the meteorological outputs of the GCMs (Greve et al., 2017; Milly and Dunne, 2016; Roderick et al., 2015). However, as pointed out by Barella-Ortiz et al. (2013), offline computation of AED with climate model outputs can be problematic since it neglects several factors, in particular the surface conditions. This issue could be partly explained by the inclusion of CO2 effects in the GCMs (Lemordant et al., 2018; Roderick et al., 2015; Swann, 2018). These effects would increase the water-use efficiency of vegetation, at least partially compensating for the radiative effects of CO2 on air temperature and vapor pressure deficit (VPD). This seems to agree with both paleoclimatic reconstructions (Scheff, 2018) and observations globally (Yang et al., 2018).

In the Mediterranean region, streamflow variability is mostly governed by precipitation, the influence of AED being much smaller (Vicente-Serrano et al., 2014; Vicente-Serrano et al., 2019b). Therefore, the influence of AED on drought severity could be limited in comparison to that which is suggested by meteorological drought indices like the Standardized Precipitation Evapotranspiration Index (SPEI) and the Palmer Drought Severity Index (PDSI) that consider AED. It is true that from a purely hydrological point of view, these meteorological drought indices could overestimate the role of AED in humid regions and periods characterized by high precipitation (Vicente-Serrano et al., 2019b). Nevertheless, here we provide arguments to justify why in the Mediterranean region, drought severity is expected to increase as a consequence of the rise in AED projected for the end of the twentieth-first century by the GCMs (Scheff and Frierson, 2015; Vicente-Serrano et al., 2019b).

First, it should be noted that drought affects different systems, and consequently, there are different drought types: hydrological, agricultural and environmental, all affected differently by AED. Here, we establish a difference between the influence of AED on hydrology (streamflow and reservoir storages) and on vegetation. From a hydrological point of view, and independently of the possible uncertainties regarding the role of CO2 in future scenarios (Kolby Smith et al., 2016; Piao et al., 2007), the Mediterranean region is characterized by strong modifications in natural vegetation in both the north and south of the basin (Chebli et al., 2018; García-Ruiz et al., 2011; Gerard et al., 2010; Sluiter and de Jong, 2007) and the creation of large irrigated lands that consume a large amount of water in the summer (García-Ruiz et al., 2011; Pinilla, 2006; Serra et al., 2014). In the Mediterranean basin, water is mainly generated in the headwaters of the mountain areas (Viviroli and Weingartner, 2004). In the north of the basin (i.e. Southern Europe), mountain areas have been affected by an extensive abandonment of traditional agriculture and livestock over the last century (Lasanta et al., 2017), making the dominant land cover forest and shrubs (García-Ruiz et al., 2015), which consume a large amount of water in comparison to the traditional crops and pastures (García-Ruiz and Lana-Renault, 2011). Such a decrease in runoff for these areas could be amplified by the projected increase in vegetation cover related to high CO2. However, in future trends, the increase in vegetation cover due to high CO2 is highly uncertain and strongly depends on model formulation (Keenan et al., 2011; Mankin et al., 2019).

Given the current human pressure, this process is expected to continue in the future, with an increase in the leaf area, the length of the vegetative periods, and the altitudinal expansion of the forests, even though precipitation shows a decrease in future projections, since Mediterranean mountains are humid areas in which precipitation is not the main constraint for vegetation activity and growth (Gazol et al., 2017; Keenan et al., 2011; Vicente-Serrano et al., 2015). Under these land-cover scenarios with increased AED, water losses by plant transpiration would increase given the larger leaf area and because CO2 fertilizing effects would not entirely compensate for the effect of the projected increase in temperature and VPD (Vicente-Serrano et al., 2019b), reducing the available "blue water" in comparison to the "green water" used by plants. Thus, recent studies have suggested that increased leaf activity and the lengthened vegetative periods would compensate for the possible hydrological effects of the CO2 fertilization hypothesis (Frank et al., 2015). During periods characterized by precipitation deficits, which are projected to increase in the Mediterranean (Hertig and Tramblay, 2017; Raymond et al., 2019), the hydrological effects of the AED would be even more critical for water generation since the percentage of "green water" would increase.

In addition to the greater implications for mountain headwaters, there are also hydrological consequences in sub-humid and semi-arid Mediterranean areas. Although runoff generation is small in these areas, there are large reservoirs to supply irrigated lands (García-Ruiz et al., 2011; Lorenzo-Lacruz et al., 2010; Morán-Tejeda et al., 2012). In these reservoirs, the increased AED projected in future scenarios would noticeably increase direct water evaporation (Friedrich et al., 2018; Martínez-Granados et al., 2011), reducing the available water for human uses, which is much more critical during periods of precipitation deficits. In addition, irrigated lands are expected to increase water demand given the traditional irrigation approaches, in which direct evaporation is very strong, and crops would also evaporate more in response to the increased AED (Fader et al., 2016). The strong alteration of river regimes and streamflow magnitude (Vicente-Serrano et al., 2017a) and the increase in hydrological drought severity downstream of the main irrigation polygons (Vicente-Serrano et al., 2017a, 2017b) paint a pessimistic picture under scenarios of AED increase. In the south of the Mediterranean basin (North Africa), the effects of AED on hydrological drought severity are expected to be different since vegetation coverage has strongly decreased and is expected to continue to do so in the future as a consequence of increased population pressure (e.g. in the Atlas mountains) (Aguilar et al., 2016; Chebli et al., 2018). Under these conditions, the effects of an increased AED would be small given the constrained plant transpiration, but the hydrological effects in the middle and lower parts of river courses would be similar to those in the north of the basin due to the increased demand in the irrigated lands (Fader et al., 2016).

From the agricultural and environmental points of view, there are significant uncertainties related to the possible effects of CO2. A number of experimental studies have supported the hypothesis of CO2 fertilization affecting the water-use efficiency of vegetation (Drake et al., 1997; Dusenge et al., 2019), including typically Mediterranean plant species (Andreu-Hayles et al., 2011; Osborne et al., 2000). This suggests that plants would be more resistant to water deficits in future climate scenarios, but these fertilizing effects of CO2 are not very clear during periods of precipitation deficits characterized by low soil moisture (Peñuelas et al., 2011). A number of experimental studies have suggested that due to stomatal closure in response to low soil moisture, the effect of elevated CO2 would be negligible under drought (Allen et al., 2015; Bachofen et al., 2018; Duan et al., 2015, 2014; Morgan et al., 2004; Xu et al., 2016); given that precipitation deficits are projected to be more frequent and severe in the Mediterranean region, this could be a critical issue since an AED driven purely by atmospheric conditions would clearly increase plant stress and the severity of environmental and agricultural droughts (Vicente-Serrano et al., 2019b).

The influence of the AED on plant stress is complex. Mediterranean vegetation is not expected to be negatively affected by increased AED during periods of high precipitation and sufficient soil moisture (Vicente-Serrano et al., 2019b). However, during periods of soil moisture deficits, vegetation would be further stressed by an increased AED. The negative role of AED in vegetation stress has been suggested by a number of studies on both humid (Vicente-Serrano et al., 2015) and water-limited (Joffre and Rambal, 1993; León-Sánchez et al., 2016; Pumo et al., 2010) areas of the Mediterranean, and long term observational analysis also suggests an increased negative role of AED trends. Carnicer et al. (2011) showed that defoliation rates in the forests of northeast Spain have noticeably increased in areas in which precipitation has not changed but the AED has strongly increased over the last few decades (Vicente-Serrano et al., 2014a). Similar mechanisms have been suggested in arid steppe areas of northeast Spain, which show a tendency towards degradation (Vicente-Serrano et al., 2012). Overall, the vegetation greening trends that had been reported through 2010 are now being reversed, and this effect seems partly related to increased atmospheric drought globally (Yuan et al., 2019).

Therefore, the use of drought metrics that use AED to define drought severity in future climate scenarios seems to be highly recommendable. In this sense, the Standardized Precipitation Evapotranspiration Index (SPEI) (Beguería et al., 2014; Vicente-Serrano et al., 2010), the Standardized Evapotranspiration Deficit Index (SEDI) (Kim and Rhee, 2016; Vicente-Serrano et al., 2018) and the Evaporative Demand Drought Index (EDDI) (Hobbins et al., 2016; McEvoy et al., 2016) could account for the possible effect of the increased AED on hydrological, agricultural and environmental drought conditions in the Mediterranean under future climate change scenarios. Each of these indices could include the possible CO2 effects via the modified FAO-56 Penman-Monteith equation by Yang et al. (2018). These indices would have clear applications in assessing agricultural and environmental drought impacts, but also possible hydrological applications (e.g. hydrological drought downstream of big reservoirs and irrigation polygons). Along with other possible metrics based on modeling approaches, these indices can be useful for better understanding drought severity and related drought impacts in the Mediterranean region under future climate change scenarios. However, since vegetation plays a major role in water balance, its differential response to climate and land-use change factors can greatly affect the projections based on AED indices alone. With this in mind, AED indices should also be compared to functional indices that account for vegetation processes.

3.2. Predicting the future of Mediterranean agro-ecosystems under intensifying drought

By the year 2100, current anthropogenic climate change will likely alter ecosystems in the Mediterranean in a way not seen for the past ten millennia and will lead to the substantial expansion of drylands and deserts in much of southern Europe and northern Africa (Guiot and Cramer, 2016). Beyond the urgent need for effective mitigation, we must understand vegetation vulnerability, resilience and the capacity for adaptation to increasing drought intensities. In the Mediterranean basin, land use as measured by the Global Drylands Assessment is dominated by agroecosystems: forests (21%), grasslands or rangelands (26%), and crops (35%), including perennials like vineyards and fruit trees, forage species and annual cereal crops. Under both the greater incidence of summer droughts, which may become up to 40% more frequent by 2100 (Spinoni et al., 2018), and increasing population, the amount of water available for agriculture is declining drastically. The research priorities are therefore (1) to advance the understanding of the mechanisms involved in the response of agroecosystems to longer and more intense drought, (2) to develop indicators that act as early warning signals of the impact of drought on vegetation, and (3) to improve projections of future drought impact on rain-fed agroecosystems in order to inform long-term adaptation strategies.

Given the diversity of agroecosystems in the Mediterranean, one current challenge is to develop 'agro-ecological drought' indices that are better linked with drought impacts. These indices should be generic enough to assess the levels and impact of water stress across various agroecosystems and to scale up the assessment of drought from any type of plant community to the landscape level (Figure 3). This may be possible by accounting for (i) water balance processes within the soil-plant-atmosphere continuum, which allows the soil water available to plants to be quantified, (ii) plant functional responses to drought through key phenological, morphological and physiological traits that represent the diversity of short- and long-term plant drought strategies, and iii) ecosystem-level adjustments of plant density/species composition to accurately partition surface runoff, transpiration and evaporation (Tague et al., 2019).

The modelling of soil water available to plants can be improved through process-based water balance models (Cáceres et al., 2015; Mouillot et al., 2001; Rambal, 1984; Ruffault et al., 2013), but this will require more knowledge of the interactions between the various soil layers, the types of soil and vegetation, and the contribution of groundwater to tree water uptake (Barbeta et al., 2015; Carrière et al., 2020), in particular through plant rooting strategies (Cabon et al., 2018a, 2018b; Mouillot et al., 2001). They should also account for the effects of fluctuating water consumption and runoff due to leaf area dynamics (Cáceres et al., 2015), species competition for water (Longepierre et al., 2014), and species succession over time after disturbance or land cover change (Mouillot et al., 2002). Remote sensing data should be incorporated into monitoring and modelling efforts since it can be used to monitor spatial and temporal processes and benchmark or parameterize models that simulate the effect of drought on forests, grasslands or field crops, as described in section 3.3, and can thus constitute an early warning signal (Le Page and Zribi, 2019; Liu et al., 2019). Combined with process-based vegetation models (McDowell et al., 2015) that include energy balance developed specifically for complex agroecosystems, remote sensing data refines the simulation of water fluxes for the heterogeneous land surface characterizing most Mediterranean agroecosystems.

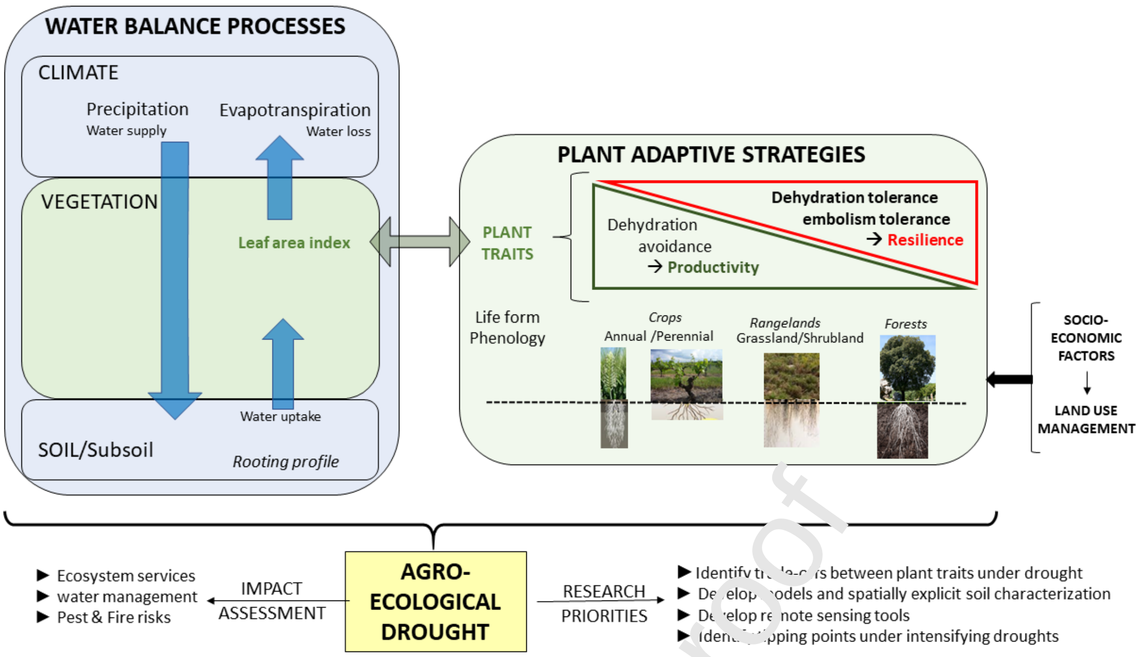

Figure 3: Developing agro-ecological drought indices. Improving the prediction of drought impacts entails better combining water balance models with the identification of traits involved in plant adaptive strategies under drought.

Coupling physiological knowledge of relevant traits with an estimation of water balance is the key to translating generic estimates of soil water content into species-specific estimates of plant stress. Generic process-based or species-specific models that include plant traits and ecoclimatic indicators should be used to investigate crop and natural vegetation productivity and sustainability under different climatic scenarios (Caubel et al., 2015). Due to the multiplicity of traits that contribute to drought resistance and drought survival, the study of trait coordination (Rosas et al., 2019) and the identification of general trade-offs (e.g. production versus resilience) is very promising (Martin-StPaul et al., 2017). For instance, dehydration avoidance is the main drought resistance (i.e. maintaining production under moderate drought) strategy in major annual crops. The trade-offs between such traits associated with maintaining production under moderate drought (dehydration avoidance) and traits associated with survival under severe drought (dehydration tolerance and embolism tolerance) need to be better identified for a wide range of plant types (Volaire, 2018). This is the case for summer dormancy (Volaire et al., 2016), which confers high dehydration tolerance and persistence on some Mediterranean perennial grasses (Volaire and Norton, 2006) and putatively on other shrubland species such as *Periploca* sp. and *Witthania* sp. Advances need to be made in the simulation of these traits and strategies, the effects of vegetation structure on the soil water balance (Mouillot et al. 2001, Cáceres et al., 2015), hydraulic processes (Martin-StPaul et al., 2017; Sperry et al., 2016), and the direct impact of droughts on the growth of organs (Guillemot et al., 2017; Lempereur et al., 2015; Zribi et al., 2016) and the modification of their architecture (Chaubert-Pereira et al., 2009), including root foraging (Cabon et al., 2018b). Models should explicitly account for regeneration dynamics in perennials (Martínez-Vilalta and Lloret, 2016), which are affected by summer soil surface drought (Chamorro et al., 2017), and winter drought for desiccation-sensitive seeds such as *Quercus ilex* acorns.

Plant traits and extreme events associated with tipping points that lead to significant plant mortality and drastic changes in plant function should be identified (Martinez-Vilalta et al., 2019) and integrated into monitoring efforts and refined predictive models. The factors triggering mortality under drought have been relatively well explored in trees with regard to their hydraulic system (Choat et al., 2018), but far less in herbaceous or shrubland species (Lens et al., 2016; Volaire, 2018). Long-term studies showed that plant recovery capacity relies on the mobilization of carbon and nitrogen reserves, especially in perennial species (Norton et al., 2016), and is highly associated with former growth patterns (Cailleret et al., 2017; Limousin et al., 2012). We must also consider nutrient limitations and their interaction with plant hydraulic limitations (Gessler et al., 2017). To understand longer-term impacts and vegetation-atmosphere feedback in a Mediterranean context, it is essential to account for the interactions with pests, pathogens and fire at the landscape scale. Plant mortality processes interact with biotic attacks, which should also be subject to further investigation (Anderegg et al., 2015), for example in Aleppo pine forests, which are widely distributed throughout the Mediterranean and have been recently affected by various types of diseases (Morcillo et al., 2019). Forest wildfires are probably one of the most widespread disturbances in these ecosystems (Batllori et al., 2019; Moreira et al., 2020; Pausas and Vallejo, 1999). The recovery of species and ecosystems after the combination of fire disturbance and drought may lead to significant changes in ecosystem characteristics and their ability to face new perturbations, with relevant effects on land degradation and desertification processes (Batllori et al., 2017; Trumbore et al., 2015).

Although the current literature indicates a strong link between droughts and fires (Gudmundsson et al., 2014; Russo et al., 2017; Turco et al., 2017b), droughts alone are not sufficient to predict burned area values across all regions (Turco et al., 2017a). A relatively short period of drought is presumably needed to provide a sufficient amount of biomass for burning (fuel load) in a wildfire. Recent findings have confirmed the effects of live fuel moisture content on fire behavior, inviting further attention to the prediction thereof (Pimont et al., 2019; Rossa and Fernandes, 2018). The response of plants to drought varies among species and biomes (Martin-StPaul et al., 2017; McDowell et al., 2015; Vicente-Serrano et al., 2013), and when applying the widely used Fire Weather Index (FWI) system, the influence of drought on plants is implicitly assessed via moisture codes originally developed for dead fuels. These moisture codes do not account for plant-specific responses, and the same is true for other drought indices. So far, most approaches to predicting fire hazard have been based on empirical drought indices that are not adapted to multispecies predictions (Ruffault et al., 2018) and rarely account for fuel limitations - a crucial driver of the fire-weather relationship (Turco et al., 2017a). Process-based modelling approaches coupling water balance with plant traits at the global (Hantson et al., 2016) or local level (Cáceres et al., 2015; Mouillot et al., 2002), as well as the global database of seasonal plant moisture content (Globe-LFMC) (Yebra et al., 2019), should improve these fire hazard indices by providing direct estimates of fuel quantity and moisture content. One of the possible direct consequences of the trends towards warmer and drier conditions in the future is an increase of burnt area due to forest fires (Dupuy et al., 2019). However, the quantitative evidence indicates that fires have been decreasing over the last few decades in the Mediterranean (Turco et al., 2017a), probably due to increased fire-suppression efforts (Moreno et al., 2014; Ruffault and Mouillot, 2015). Indeed, in recent decades, fire management strategies have improved through new technologies and experience, even though climate drivers would have probably led to an opposite trend (Batllori et al., 2013; Fréjaville and Curt, 2017; Turco et al., 2014). Nevertheless, the increase in societal exposure to wildfires in recent years (Bowman et al., 2017), along with climate change effects, may overcome the current fire prevention efforts; as a result, more and different fire management approaches must be considered to increase our resilience towards future Mediterranean forest fires (Turco et al., 2019).

Finally, it is crucial to take into account the socio-economic context driving past and current land use and vegetation dynamics, in particular for forests (Doblas-Miranda et al., 2015) and rangelands/grasslands, including old abandoned crop fields, which are strongly affected either by overgrazing and soil degradation or undergrazing (shrub encroachment) in the southern and northern areas of the Mediterranean basin, respectively (Vigan et al., 2017). The socio-economic context influences management practices such as tree density in agroforestry (Cabon et al., 2018b; Fader et al., 2015; Gavinet et al., 2019; Joffre et al., 1999; Vilà-Cabrera et al., 2018) and the selection of species with high water use efficiency and resistance to drought in agriculture (Latiri et al., 2010), which in turn play a role in promoting drought resilience. In conclusion, we argue that unified agro-ecological drought indices would provide policy makers and stakeholders with information needed to optimize rain- and water-use efficiency and manage the trade-offs between various ecosystem services on different spatial and temporal scales.

3.3 Challenges in drought monitoring through Earth observation

The modelling of terrestrial variables can be improved through the dynamical integration of observations. Remote sensing observations are particularly useful in this context because they are now unrestrictedly available at a global scale, with high repetitivity. Many satellite-derived products relevant to the hydrological and vegetation cycles are already available. They allow drought to be analyzed through statistical anomalies with respect to the long-term mean (Bijaber et al., 2018; Jiao et al., 2019; Le Page and Zribi, 2019; Mariano et al., 2018; Sánchez et al., 2018). The recurrent problem in using EO for drought analysis is the short duration of individual sensor time series. Longer series could allow better separation of anthropogenic effects from climatic effects (Garonna et al., 2016). In this context however, various products try to increase the length of records by taking into account measurements from different sensors and blending them together. The ESA Climate Change Initiative (CCI) exploits over 40 years of archived and emerging satellite observations to develop long-term, global data records that describe the evolution of key components of the Earth system. To monitor changes across the oceans, atmosphere and land environment, Essential Climate Variables (ECVs) provide the empirical evidence needed to advance scientific understanding of the climate and address the impacts of a changing world. For example, the ESA CCI Soil Moisture algorithm generates a 40-yr consistent worldwide product (1978-2019) by merging soil moisture retrieval from active and passive microwave-based products (Dorigo et al., 2017, Gruber et al., 2019). The capabilities of satellite Earth observation have been steadily improving and cover multiple aspects related to drought: precipitation (TRMM, GPM-IMERG...), vegetation development (MODIS, SPOT, Sentinel...), vegetation stress (Landsat, MODIS...), surface soil moisture (ASCAT, SMOS, SMAP...), water level in lakes and rivers (JASON, SWOT), groundwater storage (GRACE), and snow cover (MODIS, Sentinel). The raw reflectance measurements are processed to obtain biophysical products such as the LAI (Leaf Area Index) and fAPAR (fraction of Absorbed Photosynthetically Active Radiation) of crop cover (Weiss et al., 2004), surface characteristics like LST (Land Surface Temperature), or soil characteristics like SSM (Surface Soil Moisture). All land surface variables cannot be observed from space but some advanced products such as evapotranspiration estimates can be obtained by using LST to solve the surface energy budget with some simplifying assumptions (Courault et al., 2005; Martens et al., 2017). The decrease in precipitation gauges around the world has also encouraged the generation of precipitation products derived from EO, mainly relying on estimates from thermal infrared and passive microwave sensors. For example, the Global Precipitation Measurement (GPM) mission has provided a continuous global record since the year 2000 and will surely benefit from future passive microwave missions (Skofronick-Jackson et al., 2017). In recent years, there has been an increasing use of low resolution satellite surface data (e.g. SMOS) to improve precipitation products, such as the SM2RAIN product (Brocca et al., 2019). The development of high-resolution operational soil moisture products could also be extremely useful in retrieving precise precipitation products in this complex context (Caracciolo et al., 2018).

Besides the physically based variables, several vegetation indicators based on remote sensing have been proposed. The well-known NDVI (Normalized Difference Vegetation Index), which uses red and infrared reflectance, is an indicator of chlorophyll content in vegetation (Tucker, 1979), the NDWI (Normalized Difference Water Index) uses the near-infrared and red bands to indicate the water content in the surface layer of soil and vegetation (Gao, 1996), and plant stress is analyzed by the difference between air temperature and surface temperature (Kustas and Anderson, 2009). The indices for soil surface water content are generally derived from passive or active microwave measurements (Kerr et al., 2016). With a lifetime of 20 years, the Moderate Resolution Imaging Spectrometer (MODIS) on the satellites Terra (1999) and Aqua (2002) represents the most emblematic mission related to drought studies (Justice and Townshend, 2002). MODIS offers 36 spectral bands ranging from 0.4 to 14.4 mm with resolutions ranging from 250 meters to 1 kilometer. Anomaly indices using remote sensing of biophysical parameters can be computed from a single product (Amri et al., 2012, 2011; Chakroun et al., 2015; Kogan, 1995) or from a combination of several products, like in the Vegetation Drought Response Index (Brown et al., 2008) or the Drought Severity Index (Mu et al., 2013). These indices have shown a strong potential to characterize droughts, for example the beginning and end of a drought event. The combination of these indices provides us with a better understanding of the chronology of a drought event, in which a rainfall deficit in turn leads to soil moisture deficit and lower water storage. Plant water stress can be identified in the early stages with fluorescence (the future FLEX mission). A decrease in plant transpiration causes an increase in land surface temperature, which will be captured with a high temporal resolution on future LST missions (e.g. Indo-French mission TRISHNA and the ESA-LSTM. Finally, a prolonged deficit of water affects the development of vegetation, which is visible through common optical Earth observations.

EO from remote platforms presents several challenges. The cost of platforms has long been a constraint to EO, and thus a trade-off between spatial, temporal and spectral resolution was necessary. This constraint has been diminished by the advent of satellite constellations (for example, the two Sentinel-2 satellites allow a revisit time of 6 days at a resolution of 10 meters, with 13 spectral bands) and nanosatellites (the CubeSats of private company Planet Labs can cover the entire planet with a spatial resolution of 1 meter). New sensors are being developed with higher spectral, temporal and spatial resolution to capture more precise signals (Schimel et al., 2019). Technical improvements in sensors allow resolutions of less than one kilometer to be achieved with geostationary satellites (e.g. the ABI sensor on the GOES-R platform, or the MTG FCI sensor, expected in 2022), thus greatly improving the revisit time of NDVI-like observations at this resolution. The launch of the Copernicus constellations (in particular Sentinel-2), which allow acquisition with a high spatial and temporal resolution, could enable a significant leap forward in the analysis of agricultural drought. The SWOT mission (Surface Water Ocean Topography), with an expected launch date of April 2022, will provide global observation of the changing water level of rivers and lakes with a vertical accuracy of 10 cm and a spatial resolution of 100 meters. Other experimental satellite missions will add additional observations for drought monitoring. For example, the BIOMASS mission expected in 2022 will carry a P-band SAR designed to determine the amount of biomass and carbon stored in forests. The EarthCARE mission planned for 2022 will advance our understanding of the role that clouds and aerosols play in reflecting incident solar radiation back into space and trapping infrared radiation emitted from Earth's surface, while the Aeolus satellite launched in 2018 carries a Doppler wind lidar to measure wind profiles around the globe. Finally, sensor improvements can be combined with techniques such as data fusion or spatial disaggregation, which improve the original spatial resolution. With these recent operational multi-sensor products characterizing various parameters, we are surely moving towards analyses based on multi resolution indicators to better refine the specific contexts of each region. Indeed, this type of data will allow a much finer analysis of the effects of drought through a precise evaluation of the anthropogenic component. This means taking into account human-made impacts, including the expansion of urban areas, land cover changes, the extension of irrigated areas, and changes in agricultural practices. EO can provide a good interpretation of these changes, especially through the use of classification algorithms. Analyzing agricultural drought could be performed at the plot scale which is more suited to the needs of managers and decision makers. This data will also be very important in monitoring mountainous areas, in particular in terms of snow cover, which is often highly fragmented in semi-arid areas (the Atlas Mountains for example) and during drought periods.

Earth observations (EO) are mostly focused on surface or near-surface properties and several key surface variables for drought monitoring are not directly observable from space including the root-zone soil moisture or evapotranspiration fluxes. Sensor data or products are thus used jointly with dynamic land surface models (LSMs) through data assimilation technics. Data assimilation techniques combines EOs and LSM allowin to spatially and temporally integrate the observed information into LSMs in a consistent way (Reichle et al., 2007,Albergel et al., 2017). We refer to Land Data Assimilation Systems (LDASs) as the framework where LSMs are driven by and/or ingest such observations generating improved estimates of the land surface variables (LSVs) (Kumar et al., 2018). Several LDASs now exist from point to global scale, amongst them are the Global Land Data Assimilation System (GLDAS, Rodell et al., 2004), the Carbon Cycle Data Assimilation System (CCDAS, Kaminski et al., 2002), the Coupled Land Vegetation LDAS (CLVLDAS, Sawada and Koike, 2004, Sawada et al., 2015) and more recently the U.S. National Climate Assessment LDAS (NCA-LDAS, Kumar et al., 2018) as well as LDAS-Monde (Albergel et al., 2017, Bonan et al., 2020) to name a few. These LDASs either optimize process parameters (e.g., CCDAS), state variables (e.g., GLDAS, NCA-LDAS, LDAS-Monde) or both (e.g., CLVLDAS). Assimilated Earth Observations (EOs) generally include satellite retrieval of surface soil moisture, snow depth and snow cover, vegetation, as well as terrestrial water storage. The recent advances in remote sensing observations including improved spatial and temporal resolution (Copernicus constellation) and new water stress detection technics such as sun induced fluorescence (e.g. Duveiller et al., 2020) will open new perspectives for LDAS-based drought monitoring systems (e.g. Norton et al., 2019).

3.4 Improvements in land surface modelling in semi-arid Mediterranean regions

Land surface models (LSMs) were originally designed for implementation in numerical weather prediction (NWP) models to provide interactive lower boundary conditions for atmospheric radiation and turbulence schemes, and thus they compute the fluxes of heat, mass and momentum between the land and the atmosphere on the required convective (turbulent) and radiative timescales (i.e. resolving the diurnal cycle). In the past two decades, LSMs have evolved considerably to include more physical and biological processes in order to meet the growing demands of both the research and the user communities (van den Hurk et al., 2016). They increasingly include processes such as photosynthesis and the associated carbon fluxes and vegetation phenology: biomass evolution, net primary production, aerosol emissions, soil moisture prediction, surface runoff and exchanges with groundwater and rivers, and snow pack dynamics. LSMs thus provide integrated simulations of atmosphere-land interactions by closing the water and energy budgets.

These models have been especially developed to be coupled with atmospheric models, within Numerical Weather Prediction (NWP) systems, regional climate models and general circulation models, in order to predict different variables (evapotranspiration, soil moisture, leaf area index…) of the Earth's surface. They can also be used offline, that is, not coupled to the atmosphere, typically forced by a gridded database of meteorological variables (Habets et al., 2008). Offline applications are appropriate for long-term monitoring of droughts (Vidal et al., 2010). Furthermore, they can be used with or without data assimilation of soil moisture or vegetation properties (Albergel et al., 2018). As a result, they are versatile tools that can be applied in different contexts and at various spatial scales and resolutions. Yet both the model inputs (precipitation and other climate variables, land use, soil types, vegetation characteristics...) and the model structures can strongly affect the simulations (Quintana-Seguí et al., 2019). Since LSM parameterization is typically applied at spatial resolutions that range from 100 m to GCM grid resolutions (upwards of 10^5 m), it treats unresolved scale-dependent processes as a function of some grid-average state variable though a combination of conceptual models, empirical relationships, theory, and fundamental mathematical laws. Generally speaking, the research community has a fundamental knowledge of how to model certain surface processes using very detailed approaches, however, such numerical modeling must strike a sometimes delicate balance between computational usage or efficiency, the ability to accurately define input parameters, and the complexity of the physical parameterization. LSMs have therefore been developed to include what are deemed to be first-order processes (or even only those for which there are reasonable estimates of the input parameters in order to avoid adding additional large uncertainties into the system). As our understanding of processes, computational resources and the availability of observational or satellite data sets increases, complexity and realism are added. In addition, methods for optimally combining observations with LSMs are continuously improving.

LSMs are formulated in terms of the energy and mass balances extending from the surface (including vegetation) downwards through the vegetation rooting depth in order to capture the processes most pertinent to representing land-atmosphere exchanges. In terms of drought, some recent studies have added improved physics to better model such conditions. For example, Garcia Gonzalez et al. (2012) showed the improvements in LSM simulated soil moisture and evapotranspiration due to the incorporation of water vapor transfer into an LSM for semi-arid sites. Ukkola et al. (2016) showed that the accurate representation of vertical water fluxes, plant water stress and soil properties were of paramount importance for representing droughts in particular. More LSMs intended for use in NWP models are including explicit vegetation canopy processes; for example, Napoly et al. (2017) showed the improvements for a Mediterranean site in terms of surface fluxes (notably the Bowen ratio) and radiative transfer. A very important recent development has been the explicit modelling of plant hydraulics to improve the way these models simulate the impact of drought on gas exchange (Eller et al., 2020). Some LSMs used within GCMs have even recently moved to using multi-layer vegetation canopies (Naudts et al., 2015) in order to further improve the analysis of radiative transfer, represent the turbulent fluxes explicitly rather than using an assumed within-canopy profile, and provide a more consistent and realistic coupling between the vegetation and various different aspects of the carbon cycle and plant dynamics (thus potentially improving the simulation of the impact of increased future droughts on both vegetation and climate). But despite an ever-improving representation of the aforementioned physical processes in LSMs, there are some issues related to their ability to represent atmosphere-land interactions in semi-arid Mediterranean environments (Samaniego et al., 2017). For example, LSMs have some difficulties in capturing the spatial heterogeneity of semi-arid environments, and thus their performance can vary greatly from one site to another with similar characteristics (Hogue et al., 2005). Quintana-Seguí et al. (2019) showed that the timescales of drought propagation, from precipitation to soil moisture, are highly dependent on LSM model structure. Barella-Ortiz and Quintana-Seguí (2019) observed that drought representation in RCMs is better for precipitation than for soil moisture, showing that the land-surface component presents more uncertainties.

It is generally accepted that LSM soil moisture must be rescaled in order to be compared to in-situ observations. For example, Quintana-Seguí et al. (2019) used a quantile-based index in order to obtain a coherent multi-model estimate of soil moisture. Vidal et al. (2010) and Samaniego et al. (2018) have shown that this procedure helps to derive extremely consistent drought indicators based on simulated runoff or soil moisture. The reasons why LSMs may reproduce soil moisture differently (Wang et al., 2009) can be manifold. First, they define soil moisture differently depending on their vertical resolution, sub-grid assumptions and pedo-transfer functions, which results in different ranges of soil moisture values. In addition, the LSMs can rely on different land cover or soil property maps (e.g. USGS, ESA, ECOCLIMAP…). Global comparisons of these products derived from remote sensing and/or local surveys and built on various classification schemes and validation methodologies indicate several inconsistencies between different products (Congalton et al., 2014; Dai et al., 2019). Therefore, a better harmonization of these maps is necessary, as noted by Grekousis et al. (2015). The problem is particularly complex in the Mediterranean region, where most natural areas belong to transitional land cover classes of mixed vegetation. Indeed, Mediterranean vegetation types include forests, shrublands and rangelands, and mosaic types of habitat are very common, forming complex patterns created by variations in soil, topography, climate, fire history and human activity over several millennia (Geri et al., 2010). Consequently, the pedo-transfer functions used to derive the LSM parameters can result in highly contrasting situations (Samaniego et al., 2017) across different land cover maps, even without considering land cover changes that can occur on the timescale of climate simulations. Several studies indicated the need to perform a sensitivity analysis of LSM parameters to identify those that it is most important to calibrate for a given landscape (Cuntz et al., 2016; Demaria et al., 2007) and to upgrade the representation of the physical processes in these models (Clark et al., 2017).

A significant source of the surface heterogeneity of the Mediterranean landscape in LSMs, which modulates surface fluxes and state variables, is the inclusion of anthropogenic processes. For the land surface outside urban zones, this includes reforestation and agricultural practices such as irrigation. And obviously, the water needs for irrigation can be influenced by the intensity or longevity of droughts. The inclusion of irrigation in an LSM is not straightforward, since irrigation is difficult to detect and to quantify at the plot scale over large areas. There are essentially two aspects: mapping irrigated areas, and representing the physical process and impacts of irrigation. Different approaches have been proposed to map irrigated areas. One such approach, based on the compilation of national or regional databases (Portmann et al., 2010), is increasingly being used by the LSM community. However, data timestamping may vary between regions, and these products are only available at relatively coarse spatial scales. LSMs are increasingly incorporating more realistic representations of irrigation, for example explicitly modeling different methods such as sprinkler, gravity and drip (Lawston et al., 2015). Therefore, including anthropogenic aspects such as irrigation in LSMs is of critical importance for accurate future projections of water resources and modifications to the global water cycle (Harding et al., 2015). Some studies have suggested that an accurate representation of irrigation can increase forecast skill using a coupled LSM-atmospheric model (Ozdogan et al., 2010). However, Sorooshian et al. (2012) showed that the atmospheric response to irrigation depends to a certain degree on the details of the irrigation scheme employed in the LSM. It is also likely that other physical parameterizations in an atmospheric model would contribute to this response.

LSMs offer a physically-based estimate of drought in comparison to purely statistical methods, and thus they can also offer insights into drought impacts on and interactions with various components of the land-atmosphere system. Hao et al. (2017) give a comprehensive overview of different regional to global scale drought monitoring systems and their methodologies, including those based on LSMs. For example, Sheffield et al. (2012) present a system for monitoring past and present hydrological drought using an ensemble of LSMs (in this way, model uncertainty can be estimated). In terms of agricultural drought, Crow et al. (2012) found that there was not much added value in using LSMs over a simpler index such as the API (Antecedent Precipitation Index) in monitoring applications to predict the impact of soil dryness on the future state of vegetation. However, they did determine that there was some added value for LSMs in terms of the simulated mean root zone soil moisture, and for certain periods of the growth season. Many studies have suggested that the most promising way forward for LSMs is to adopt data assimilation strategies in order to incorporate remote sensing products such as soil moisture and LAI and thus provide improved soil moisture and vegetation states (Albergel et al., 2018).

3.5 Linking indices, models and impacts to better adapt

3.5.1 Indices and impact databases

Standard indices describing drought, such as the SPI and SPEI, are most often defined separately from impacts. For example, according to McKee et al. (1993), a drought is arbitrarily considered "severe" with SPI values below -2, whereas more relevant thresholds could be identified on the basis of potential impacts on different sectors: agricultural productivity, water demand satisfaction or reservoir levels. Depending on the climatic zones and types of agricultural crops, the sensitivity to a rainfall deficit and high evapotranspiration rates could vary greatly. Therefore, to produce robust scenarios for droughts and in particular for their potential impact, there is a need to jointly analyze different drought indicators and also include potential vegetation changes that can modulate ET. The scientific literature presents a large variety of indices for assessing operational and/or socio-economic droughts (Guo et al., 2019; Shi et al., 2018) by analyzing different variables. The availability of drought impact databases is of great importance to the development of functions linking impacts to drought indices. Wang et al. (2019) applied machine-learning techniques to examine potential links between multiple drought indices (SPI, SPEI, Soil Moisture, NDVI) and impact data (financial, livestock, yield). They found different patterns of correlation depending on the type of drought impact and the location (city level), with SPEI6 showing the highest correlation for all types of impacts. Sutanto et al. (2019) employed a detailed impact database to develop a methodology capable of forecasting drought impacts several months in advance, using machine-learning techniques to examine relationships between drought indices from hydro-meteorological forecasts and drought impacts.

To provide a pan-Mediterranean assessment of drought impacts, there is a need to develop country-scale databases on the effects of droughts in multiple areas (agricultural production, forests, reservoir levels, economic impacts…), similar to the databases currently being developed for flood impacts (Vinet et al., 2019) and Globe-LFMC, which combines national-scale live fuel moisture content and covers several Mediterranean countries (Yebra et al. 2019). As noted by Hayes et al. (2011), globally, there is a lack of direct and indirect drought impact data. The European Drought Impact Inventory (EDII) (Stahl et al., 2016) is one of the initiatives aiming to fill this gap, but improvements must still be made with regard to Southern Europe (Blauhut et al., 2015), and it does not include countries on the eastern and southern borders of the Mediterranean region. The impact of droughts on vegetation and agricultural production can be assessed using remote sensing data (e.g. NDVI) as a proxy (Vicente-

Serrano et al., 2013). Global or regional databases (Le Page and Zribi, 2019) can be used for this purpose, but information on agricultural yields, hydropower production, water abstraction, and the socio-economic impacts of droughts needs to be gathered from a variety of sub-national, national and international agencies (Kreibich et al., 2019), a task that is not always straightforward, even for neighboring countries, since this type of data may be accessible at different spatial and temporal resolutions. For instance, the European Union created a standardized hierarchical geocode that refers to country-specific administration units, the Nomenclature of Territorial Units for Statistics (NUTS). Statistical data in Europe is most often referenced by these NUTS subdivisions, but spatially, they are not comparable in size (Blauhut et al., 2015). NUTS administrative units have been increasingly used to evaluate the potential impact of droughts on fires in Southern Europe (Turco et al., 2017, 2018). As noted by Kreibich et al. (2019), due to the different mechanisms by which droughts can cause direct or indirect damage in different sectors, the information needs to be filtered to correctly attribute drought impacts. In addition to classical databases, there is an increasing use of the media coverage of extreme events (e.g. with droughts in Catalonia (Llasat et al., 2009) and with floods and other hydrometerological hazards in Portugal (Pereira et al., 2018)). Recently, a drought impact database was created for the countries of the Danube river basin (including a few Mediterranean countries) for the period 1981 to 2016 (Jakubínský et al., 2019). The data was obtained from select national newspapers and periodicals in each country, and drought reports were classified into five categories based on the most affected sector (agriculture, forestry, soil system, wildfires and hydrology). This type of approach could be useful in building retrospective databases of drought impacts via the data mining of online media archives. Despite the challenges associated with the elaboration of such impact-related databases, they would be useful in translating future droughts scenarios in terms of impacts tailored to national institutions and local management agencies.

3.5.2 The challenge of adaptation measures

The anticipated impacts of future droughts on agriculture encourage complementary irrigation in areas where surface water is unavailable, increasing the pressure on the already over-exploited groundwater resources in the region. Likewise, recurrent droughts will also increase the use of ground water given the already observed extension and intensification of irrigated tree crops in the Mediterranean area. Multiple adaptation pathways should be investigated to counterbalance the negative effects of droughts on food production. A shift in planting dates and a change in species or variety cultivated are among the most commonly cited climate-change adaptation measures (Mijatović et al., 2013). Temperature rise may reduce the duration of crop cycles even more, which would call for a reassessment of the choice of seed varieties by farmers. At present, long-lifecycle wheat varieties are not well suited to the semi-arid Mediterranean region because the grain-filling phase coincides with severe temperatures and water stress periods occurring in late spring. In light of the shortening crop cycle, longer duration and drought-tolerant varieties could become increasingly rewarding in a changing climate. In addition, the adoption of more water-efficient cropping systems can reduce water losses from runoff and evaporation. The use of water harvesting, mulching and new tillage practices could also contribute to meeting these challenges and help counterbalance the higher water demand of crops caused by increasing drought in the future. Agroforestry, a traditional system that involves integrating woody vegetation (trees or shrubs) into crop and/or animal production systems, dominates Mediterranean landscapes (Salvati and Ferrara, 2015). Agroforestry offers multiple benefits, including the control of soil erosion by reducing surface runoff, which could be particularly relevant for vineyards and olive trees planted on the drought-prone, sloping land of the Mediterranean basin (Durán Zuazo and Rodríguez Pleguezuelo, 2008). Agroforestry also has a positive effect on soil fertility and biodiversity, but may not always promote woody biomass production as much as forestry or pasture alone (Torralba et al., 2016). Therefore, adaptation to increased drought stress on ecosystems and on the delivery of services should involve not just one solution, but a combination of solutions.

A precipitation deficit does not necessarily affect vegetation or agricultural production: years with low yield may be explained by multiple factors such as temperature, reservoir levels, type of culture, etc., but also depend on the presence of dam management, the agricultural water demand and existing water transfers (water trade). When management strategies are implemented, the impacts of droughts can be strongly influenced by these adaptation measures (Pulido-Velazquez et al., 2011). Consequently, the impacts of drought can be complicated to assess and quantify if the management prescriptions are unknown. The early identification and application of drought-management measures is essential to reducing the operational, socio-economic and environmental impacts (Estrela and Vargas, 2012). Over the last few decades, a lot of effort has been devoted to improving drought forecasting, but due to the complexity of this natural hazard (see above), predicting future droughts episodes remains challenging. As a result, many new studies focus on drought risk assessment in water resources systems (Haro et al., 2014). An assessment of operational and socio-economic droughts that takes into account the management strategy put in place would require a dynamic modelling framework that integrates real time climatic, hydrological and management models (Escriva-Bou et al., 2017; Pulido-Velazquez et al., 2011; Van Loon et al., 2016). An integrated multidisciplinary quantitative assessment, addressing not only the natural system, but also socio-economic and legal boundaries, is required to develop suitable integrated management models to aid in the assessment and decision-making processes (Van Lanen 2016; Escriba-Bou et al., 2017). Water allocation is one of the most important management issues in the Mediterranean countries, where inter-basin water transfer projects have been the preferred approach (Carmona et al., 2017). The decision-making process for water allocation needs measurable, comparable and reliable tools in order to be able to make trade-offs when facing conflicting issues (Burak and Margat, 2016). However, further efforts are needed to develop more pertinent management models, in particular taking into account the prediction of meteorological and hydrological droughts, in order to meet the requirements for inter-basin allocation. A decision support system can be useful in the analysis of this issue (Pedro-Monzonís et al., 2016). In this sense, accounting frameworks such as Water Accounting Plus (WA+) can provide valuable information since they integrate local water availability and consumption information, as well as related local socio-economic issues and priorities (Hunink et al., 2019). Water accounting provides an essential foundation for good water governance, which is widely recognized as the major weakness in water resource management in most developing countries.

Recent advances in seasonal weather forecasting have provided valuable information for better anticipating water- and climate-related risks. Examples of such advances on a regional scale include the management of hydrological extremes (Pappenberger et al., 2015; van den Hurk et al., 2016), as well as the European Forest Fire Information System (EFFIS) (Di Giuseppe et al., 2016). Further studies have highlighted the benefits of seasonal forecasts of water resources at the watershed level (Grillakis et al., 2018; Marcos et al., 2017), although they also outline the need for greater forecast skill and larger lead times. Changing hydro-climatological conditions in the near and distant future, especially with regard to extreme events such as droughts, pose major challenges to long-term water planning and management. Ensuring a sufficient and cost-effective supply of water to households, industries, and farmers requires robust assessments of previous practices and how they can be adapted to future conditions. However, both historical and projected climate data is subject to major uncertainties, often not permitting a conclusive analysis of commonly implemented or potential water management strategies and adaptation actions. In addition, water planning requires estimates of future water demand, under both stressed and average conditions. Similar to the projections of changing natural conditions and water supply, estimates of anticipated sectoral water demands are highly uncertain due to unclear future socio-economic development and technological advances.

Nonetheless, given recent efforts to account for human activity and interventions in drought and aridity assessments (Van Loon et al., 2016), long-term water planning requires estimates of both future water availability and water demand. Additionally, changes in the intensity, duration, and frequency of droughts and in the mean hydro-climatological conditions need to be considered to address potential future water scarcity. The Mediterranean region was shown to be especially vulnerable to anticipated water scarcity (Greve et al., 2019; Schewe et al., 2014; Veldkamp et al., 2017). Parts of the Mediterranean, especially southern Iberia, Italy, and the southern and eastern Mediterranean countries, are already under severe water stress due to unsustainable usage of available water resources (e.g. overexploitation of coastal aquifers, extraction of fossil water resources). Given both anticipated climate change and socio-economic growth, water scarcity will continue to increase in the next decades. However, the uncertainties associated with these projections are vast, thus preventing robust water planning. Large-scale interventions aimed at addressing increasing water stress (such as dams, reservoirs and increased water trade and transfer) are both costly and irreversible, and pose major challenges to water planning in this region due to the high uncertainty of the projections. To avoid maladaptation, modular planning that accounts for potential additions and reversals needs to be considered, especially when it includes options with a lower environmental impact (green infrastructure). In addition, the current unsustainable approaches to distributing and allocating water among users may require a total rethinking of water policies in order to drastically reduce water use by humans and the implementation of transformational strategies for agricultural and industrial water usage (Greve et al., 2015). Addressing increasing water scarcity further requires robust water governance and institutional infrastructure, which is especially important in the context of differing upstream and downstream water needs (Veldkamp et al., 2017).

4. Conclusions

There is a consensus on the increase in droughts over the past decades and in future climate scenarios for most parts of the Mediterranean basin. Recent studies have made substantial progress in understanding drought in the Mediterranean and the effects of climate change, but further research is needed because of the uncertainty that remains in regional climate responses, that could be tackled by the recent advance in climate modelling taking advantage of increased spatiotemporal resolutions and a better quality of observations. Under the dominant stationary precipitation conditions, the most evident change is the increased severity of recent drought events caused by higher atmospheric evaporative demand (García-Herrera et al., 2019), which would explain the general drying assessment based on soil moisture models and drought indices that include this variable in calculations (Markonis et al., 2018; Marvel et al., 2019). Studies based on the impacts of drought on forests (Carnicer et al., 2011), pasture lands (Vicente-Serrano et al., 2012) and water resources (Vicente-Serrano et al., 2014) support the increased influence of the AED on drought severity in the region. Future climate scenarios indicate that there will be a growing impact of droughts on various economic sectors, particularly in developing countries in the southern and eastern Mediterranean. This same climate signal of increased drought frequency and severity translates into soil moisture and hydrological droughts, but with increasing complexity due to non-linear vegetation responses and the influence of human activities in the face of approaching hydrological drought. The uncertainties are manifold, stemming from the modeling chain used to assess the impact of climate change on low flows and the strong interactions between water use and the baseflow component in rivers. Along with the increased urban development across all Mediterranean countries, these findings call for the implementation of urgent mitigation measures and for more integrated approaches to drought modelling and forecasting closer to the actual socio-economic impacts and actors. The existence of uncertainties in the evaluation of future climate change impacts should not be an excuse for delay or inaction in the implementation of adaptation measures, especially in the Mediterranean region, which has been identified as one of the most vulnerable areas according to several socio-economic factors, and in particular in countries on its southern and eastern shores (Milano et al., 2013, Schilling et al., 2020).

The Mediterranean region is confronted with demographic pressure and associated expansion of urbanization, this situation calls for more water supply and consequently impose tremendous constraint on the limited and fragile water resources of the Southern and Eastern countries, in particular. These prevailing conditions expected to worsen in the face of climate change will have a negative impact on the sectoral water distribution and use. This governance concern is very likely to be further affected by transboundary water issues prevailing in the southern and eastern Mediterranean countries, because the dilemma is to overcome the structural imbalance between increasing water demand and degradation/decrease of water resources due to both natural and anthropogenic stress while ensuring self-sufficiency in meeting agricultural, industrial and domestic water needs at national scale. This is crucial for regional peace and welfare since 38% of available fresh water resources is transboundary (Burak and Margat, 2016). This increases the importance of the rate of dependence with regard to external resources which is high in certain countries varying between 97% and 43% dependency ratio. Managing the structural drought inherent to most of the southern and eastern rim countries may provide an expertise that may help mitigate drought impacts. Future research needs to be extended on the mediterranean region as a whole, more specifically, on selected representative locations covering the mediterranean basin countries without exception. A great challenge is related to the availability and the development of homogeneous datasets between the different mediterranean regions that will require substantial efforts. Recent progresses in seasonal weather forecasting are expected to provide reliable data on climate-related risks and consequent impacts on water resources. This approach consolidated with water accounting efforts is expected to provide better foresight related to water and climate related risks and formulate robust adaptation measures to increase resilience in the water-scarce regions of the Mediterranean countries.

The standard approach to drought analysis relies on standardized drought indices, but recent research calls for the development of generic agro-ecological drought indices that take into account the atmospheric evaporative demand, which is expected to increase with temperature. This would require a better estimate of vegetation evapotranspiration, which is likely to evolve under ongoing climate change and direct human impacts. Better knowledge of vegetation dynamics is crucial to assessing the resilience of the Mediterranean landscape in the face of changing drought occurrence and better evaluating the likelihood of widespread drought-induced forest mortality and its potential interactions with wildfires and forest pests. These research challenges could be addressed by the development of new remote sensing data products for high-resolution monitoring of the mixed vegetation patterns that are typical of the Mediterranean region. The monitoring of new variables, higher repetitivity and longer time series could help to better constrain several components of land surface models, which are useful in monitoring droughts in an integrated manner. There is probably a need for a shift from index-based analyses to impact-based studies in order to achieve a better understanding of drought processes related to socio-economic activities (Kreibich et al., 2019). Adaptation to the forthcoming changes is a major challenge for the region and calls for an integrated appraisal of droughts, including a realistic representation of water available in soils, drought propagation, feedback from vegetation cover, and human influence during these events.

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SUPPLEMENTARY MATERIAL

Table 1: Fraction of land area projected to experience increases in time under severe and extreme drought (SPI<-1.5), for short term (SPI6) and long-term (SPI48) timescales, reported at the country level. Values included in the table are constrained to a multi-model agreement of over 80% from a set of higher-resolution transient climate simulations under the RCP8.5 scenario. Changes are calculated for specific levels of global warming (1.5 °C, 2 °C and 4 °C above pre-industrial levels) relative to the baseline period (1981-2010). Countries are shown in alphabetical order.

	SPI6									SPI48				
Global warming	1.5°C			2°C			4°C			1.5°C			2°C	
Change in time under severe & extreme drought	10% - 20%	20% - 30%	>30%	10% - 20%	20% - 30%	>30%	10% - 20%	20% - 30%	>30%	10% - 20%	20% - 30%	>30%	10% - 20%	20% - 30%

(SPI<-1.5)														
Albania	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	36%	*0%*	*0%*	*0%*	*0%*	*0%*	36%	*0%*
Algeria	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	16%	*0%*	*0%*	2%	*0%*	*0%*	6%	8%
Bosnia & Herzegovina	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	67%	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Bulgaria	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	58%	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Croatia	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	7%	*0%*	*0%*	*0%*	*0%*	*0%*	4%	*0%*
Cyprus	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	25%	*0%*
Egypt	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
France	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	46%	*0%*	*0%*	*0%*	*0%*	*0%*	7%	*0%*
Greece	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	30%	*0%*	*0%*	*0%*	*0%*	*0%*	4%	*0%*
Israel	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Italy	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	44%	*0%*	*0%*	3%	*0%*	*0%*	10%	6%
Jordan	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Lebanon	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Libya	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	1%	*0%*
Montenegro	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	83%	*0%*	*0%*	*0%*	*0%*	*0%*	33%	*0%*
Morocco	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	49%	1%	*0%*	31%	4%	*0%*	18%	33%
North Macedonia	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	91%	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Palestinian Territory	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Portugal	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	48%	*0%*	*0%*	3%	*0%*	*0%*	33%	13%
Serbia	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	37%	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Slovenia	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Spain	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	87%	*0%*	*0%*	2%	*0%*	*0%*	21%	22%
Syria	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Tunisia	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	35%	*0%*	*0%*	*0%*	*0%*	*0%*	21%	*0%*
Turkey	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	9%	*0%*	*0%*	*0%*	*0%*	*0%*	1%	*0%*

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Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: