Mediterranean Drought: Regional Exceptional Datasets

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To define such drought events and their characteristics, separate analyses based on three drought indices were performed at 12-month timescale: the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), and the Reconnaissance Drought Index (RDI). A multivariate combined drought index (DXI) was developed by merging the previous three indices for more understanding of droughts' features at the country and subregional levels. Principal component analysis (PCA) was used to identify five different drought subregions based on DXI-12 values for 312 Mediterranean stations and a new special score was defined to classify the multi-subregional exceptional drought events across the Mediterranean Basin (MED). The results indicated that extensive drought events occurred more frequently since the late 1990s, showing several drought hotspots in the last decades in the southeastern Mediterranean and northwest Africa. In addition, the results showed that the most severe events were more detected when more than single drought index was used.

climate change | drought event | Mediterranean basin | meteorological drought | SPEI | SPI | RDI | DXI

1. Climate Change and the Growing Risk of Drought Hazard

Climate change, in combination with accelerated population growth, has been described as the biggest human threat of the 21st century, putting natural systems and, thereby, sustainable human and environmental resource development at increased risk [1]. The intensive climate extremes are projected to result in a change in water availability, exacerbate carbon losses in terrestrial ecosystems, and further raise water vapor content in the atmosphere, thus amplifying the warming impacts and increasing mega-droughts worldwide [2][3][4]. Drought is one such recurring, widespread, complicated, costliest and disruptive climate extreme that frequently occurs as a result of differential responses to climate warming in different climatic regimes [5][6][7]. Recently, drought has begun to be seen not as a purely natural hazard, but partially as a result of human action, which has altered many of the characteristics of drought [1][8]. One-fifth of the global destruction caused by natural disasters can be attributed to droughts [9], where the dramatic population and economic growth has resulted in increasing demand for water that substantially intensified the frequency of global drought events [10]. Pandemics can potentially exacerbate drought impacts [11], as it was found that drought is among the most obvious reasons for displacement and disturbance during the coronavirus pandemic [12][13]. Droughts in the 21st century are identified as multifaceted, challenging natural disasters [14][15] and are characterised by longer duration, higher severity, larger spatial extent and hotter temperature that can potentially result in many deleterious impacts on ecological security, with non-linear

alterations in ecosystem functions and resilience [3][4]. Systematic reviews [16][17] have indicated an accelerated transition to a more arid climate over several areas as the result of an increased tendency of frequent and intense droughts. Meanwhile, human-induced global warming and rapidly expanding human populations have already influenced water availability and storage, increasing pressure on water supplies, affecting the long-term ecosystem and increasing their sensitivity to droughts [4][18]. As a result of 1.5 to 2 °C global warming, two-thirds of the world population will experience increasing droughts; the drought magnitude is likely to double in 30% of the global land by the end of this century [19][20]. An important part of drought problem is that its current definitions refer to the drought only from the perspective of human dimensions, focusing primarily on meteorological, agricultural, socioeconomic and cultural impacts without addressing its ecological dimensions [21]. The occurrence of widespread drought in developing and developed societies has underscored the sensitivity of all communities to this natural hazard. It is not easy to know whether the drought frequency is increasing, or rather the community exposure to it. This tendency appears to be accelerating as a result of the increasing demand on both local and regional water resources [22]. The socioeconomically devastating impacts of frequent drought events have recently resulted in several global assessments of future drought conditions to better support populations and improve management plans in order to reduce direct and indirect cascading drought impacts [23][24][25]. Combining the natural and human dimensions of drought is one of the most fundamental steps in addressing the increased risk of drought in the 21st century [18][26].

2. Drought, Climate Change and the Mediterranean Context

The MED is identified as one of the most responsive hotspots of the climate system in the face of increased dryness at global warming levels beyond 1.5 °C [27]. The IPCC 1.5 degree Special Report (SR15) has pointed out that the increased anthropogenic warming in the MED has contributed to increased drying in the northern hemisphere mid-latitude areas including the MED [28][29]. Furthermore, with global warming of 2 °C, desertification is also predicted to occur in the MED by the end of the 21st century, resulting in an expansion of areas with significant decreases in water availability, with an accompanying increase in aridity, driving irreversible terrestrial biodiversity loss and affecting the Mediterranean ecosystem carbon storage in the coming decades [30]. The MED experienced more frequent and severe meteorological and hydrological droughts in recent decades, which is in line with the expected trend towards high frequencies of drought periods in a future warmer climate [31][32]. Above 2 °C, the MED could become more vulnerable to drought, calling for the development of a variety of adaptation mechanisms and the pursuit of drastic adaptive responses to cope with these extreme climate events, including mitigation strategies in addition to radical changes in the social structure and human communities [33][34]. The complexity of the Mediterranean climate, with its high rainfall variability and its unequal seasonal distribution in addition to the observed dynamical and physical atmospheric process complexities [35][36], produced the conditions that have led to the high sensibility and vulnerability of this region to droughts [37]. Droughts are not spatially coherent in the MED [38] demonstrating different spatial patterns even at the regional scale [39][40].

The main goal of our study is the identify and characterise meteorological drought events over the MED by constructing a robust list of the most relevant drought events that occurred in the MED between 1975 and 2019,

and analysing these events. The severity, intensity, spatial extent, peak month, area involved at peak month and the frequency of drought occurrence are the essential characteristics that we have investigated. Compared to the existing drought datasets, we have provided some important developments and novelties that include a new and detailed database of drought episodes over the MED. The importance of this dataset is that it deals in details with the drought events in the Eastern Mediterranean and Middle East (EMME), where drought studies are still relatively few. Based on quality-checked and homogenised data, three drought indices were applied in order to obtain detailed information and better understanding of drought events' features over the MED in addition to formulating a strong dataset of these events, taking into account the impacts of both precipitation (PP) and temperature (TEMP). The obtained drought events records have specific entries at both the country and subregional scales, which can then be used to extract the main drought characteristics for each subregion.

The remainder of this paper is structured into five main sections. In Section 2, we present the input data, study area and the selected drought indices. The main characteristics of different drought events and the new applied system for classifying the drought events are also demonstrated in this part. Section 3 displays the analysis results and discussion and describes, separately: the database structure; the collected records at the country and subregional scales; the biggest constructed drought events; and the drought dynamics in terms of large-scale teleconnection patterns. Finally, Section 4 derives some conclusions from the main results and includes some critical research questions for evaluating future studies of drought in the region.

3. Conclusions

This study has provided a comprehensive dataset of exceptional meteorological drought events over the Mediterranean during the 1975–2019 period that contains hundreds of constructed drought events at the national and subregional scales. Three drought indices were computed at 12-month accumulation scales and a new combined indicator was obtained (DXI-12) as the average of these three indices to identify the meteorological drought due to both rainfall shortage and climatic water balance. The drought event databases are identified by monthly series of the DXI-12 at the national and subregional scales. Based on the drought-event dataset, we have also investigated in detail the main characteristics of the obtained drought events in different subregions across the MED, including duration, severity, intensity, spatial coverage, peak month, area involved at peak month and the frequency of drought occurrence. This new approach has proved to be effective in detecting the most relevant Mediterranean drought events at the national and subregional scales as it is based on data obtained with high-quality control, a multi-indicator method, and a strong statistical setting. The evaluated drought quantification, which includes these three indices, gives a more reasonable estimation of water demand as a result of including evapotranspiration. Generally, our newly developed DXI-12 provides better information about drought identification and more realistic characteristics of dry spells compared to a single drought index and, thereby, provides a better tool for monitoring water resources, especially in semi-arid and arid ecosystems. According to the results presented in this study, the MED is shown to be a region that is water-stressed and prone to severe and exceptional droughts. The drought episodes show that the EMME and most areas of the NA and southern Europe, including south Italy and Spain, underwent a drying phase during the study period, with the highest drought severity and intensity from

the late 1990s onwards. These findings are in line with recent scientific literature [28][41]. The combination of individual indicators depicts the spatial extent of a drought situation across the MED and gives an overview of the drought drivers. The DXI-12 indicates that droughts over the MED were mainly driven by temperature increases with the inherent increase in the PET, particularly in the humid area, whereas rainfall did not change appreciably. A new grade classification approach for identifying the most relevant extreme events is identified by the three-dimensional array (severity, intensity and spatial coverage). The new classification approach and database extracted from combined indices the time series have listed twenty-four multi-region big drought events, which were previously documented. The new classification has allowed us to discover the most hotspots that have displayed the highest severity and intensity and included the largest area over the MED. The significant trends towards larger drought areas and higher drought severities and intensities in all subregions and mainly occurred in the EMME. Although the actual precipitation anomalies exhibit relatively large effects on drought occurrence, we can also conclude that the rapid warming of the MED in recent decades presents a relatively greater role in determining droughts than that of precipitation variations in several areas, especially in the Balkans and west Turkey.

In this paper, we have detected several drought hotspots that have tended to experience more severe, intense wide and more long-lasting drought events between the subperiods 1975–1996 and 1997–2019 in all subregions. Dynamically, the region lies at a crossroads of large-scale influence from the Atlantic Ocean and the Mediterranean Sea, which results in regionally severe and prolonged droughts. Dynamically, the region is a junction of regional influence from the Mediterranean Sea, Europe, and Asia, as well as large-scale influence from the Atlantic Ocean and the Mediterranean Sea. A complex range of atmospheric circulation patterns influences have been shown to have at least some influence on the droughts of the MED, both nationally and regionwide, particularly the WeMO and the EATL/WRUS.

The WeMO pattern and the EATL/WRUS appear to play the strongest role in forcing wide droughts at the subregional scale, including the two widest and most devastating droughts of the last 40 years (1999–2001 and 2007–2012). A relative role is played by the NAO and ULMO in the NA in these episodes; in addition, a relationship between the SCAND and the area in drought in western and the Adriatic is found. The drought event datasets produced by this study still need to be improved in some respects. The extension of the data to drought events to include more historical data is significant for studies of climatic dynamics and ATPs in order to understand the long-term variation of droughts and develop monitoring and forecasting tools to help to adapt to and mitigate drought. Moreover, including realistic socio-economic data will strongly improve the prospects for drought risk assessment in the future as many combined meteorological, hydrological, and social drivers contribute to drought occurrence. Finally, these constructed exceptional drought events at the national and subregional scales can help researchers and relevant stakeholders in dealing with the multitude of such drought events and assess their risk by investigating the correlation between the severity and duration of each event and documented impacts in different sectors. As an initial possible application, we are planning to exploit this dataset in exploring the synergy and combination between these exceptional droughts and heatwaves across the MED.

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