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P. Quintana Seguí, E. Martin, E. Sanchez, Mehrez Zribi, M. Vennetier, S.M.
Vicente-Serrano, Jean-Philippe Vidal

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Drought: observed trends, future projections

Pere QUINTANA-SEGÚ
Ebro Observatory, Spain

Eric MARTIN
IRSTEA, France,

Enrique SÁNCHEZ
University of Castilla-La Mancha, Spain

Mehrez ZRIBI
UMR CESBIO, France

Michel VENNETIER
IRSTEA, France

Sergio VICENTE-SERRANO
Spanish National Research Council, Spain

Jean-Philippe VIDAL
IRSTEA, France

Introduction

Drought quantification is difficult since a drought is usually identified by its effects or by its impacts on different types of systems, but no single physical variable can be measured to quantify drought. Droughts are also difficult to pinpoint in time and space since their onset, ending, duration, magnitude, and spatial extent are not easy to define. Thus, drought is often quantified indirectly using indices, which are often based on meteorological, hydrological and/or remote sensing data, and physical models help us understand the relevant processes and make predictions. In this sub-chapter, we describe and discuss drought in the Mediterranean together with some relevant processes, and comment on possible future scenarios.

Description of drought

Mediterranean meteorological droughts

The most popular drought indices are those based on meteorological data, such as the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al. 2010) which is obtained using data of precipitation and atmospheric evaporative demand (AED). SPEI informs on the severity of dry conditions and makes it possible to quantify different types of drought and the possible impacts of droughts in a number of sectors. SPEI also makes it possible to identify the main drought episodes that have affected a given region.

As a representative example, figure 1 shows the spatial distribution of the 12-month SPEI in December 2005. In 2005, severe drought conditions were recorded in the west of the Iberian Peninsula, southeast France and extensive areas in Turkey, whereas humid conditions prevailed in the eastern part of the Iberian Peninsula, parts of Italy and the Balkans. This is the common pattern of drought occurrence found in the Mediterranean region, which is characterized by marked spatial variability of drought events, even for the most extreme episodes recorded in the region.

Temporal variability of droughts is also strong. Changes in the average SPEI for four large areas of the Mediterranean region follow very different patterns. In the Iberian Peninsula, the main drought episodes occurred in the 1940s and 1950s and between 1990 and 2012. In Italy and southern France, the main droughts occurred in the 1940s although very strong droughts were also recorded in the 2000s and from 2010 on. In the eastern Mediterranean area, there was a

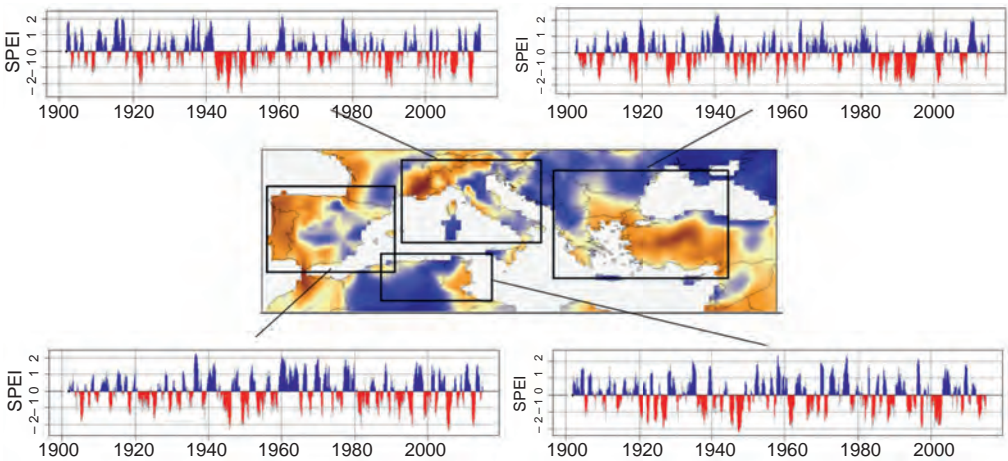


Figure 1

Spatial distribution of the 12-month SPEI in December 2005 (Red indicates dry conditions and blue humid conditions). The average evolution in the SPEI in four representative regions between 1901 and 2014 is also shown. Red: dry conditions, Blue: humid conditions.

Source: S.Vicente-Serrano using data from the Global SPEI database (<http://sac.csic.es/spei/database.html>)

succession of drought events in the 1930s but the most severe drought events were recorded between 1980 and 1995, a period characterized by extremely severe long lasting droughts. Finally, in northern Tunisia and in Algeria, droughts event have been recorded in different periods but no grouping the drought events in particular decades.

Long term reconstruction of past hydrological droughts

Hydrological droughts are those related to river flow deficits. Historical meteorological and streamflow observations around the Mediterranean are generally limited to the last few decades and therefore offer a too small sample of extreme events to properly explore their long-term evolution as constrained by both natural variability and recent anthropogenic climate change (Giuntoli et al. 2013). However, recent advances in the reconstruction of the global atmospheric circulation from the late 19th century on provides relevant information on drought precursors that can be translated into local precipitation and streamflow deficits through dedicated hydro-meteorological modeling (Caillouet et al. 2016). Applying these modeling steps to a large set of near-natural catchments over France allowed a better understanding of the individual drought and low-flow events that happened throughout the 20th century. Results revealed drought clusters in specific decades like the 1940s or the 2000s and more widespread events occurring since the 1950s. They also recall somewhat forgotten extreme events like those in 1893 that affected a large part of France, or in 1878 that only affected the Mediterranean coastal area (see fig. 2). Such benchmark events, possibly prefiguring standard 21st century droughts, can therefore inform robust climate change adaptation strategies for water resources management.

Drought processes and impacts

Specific Mediterranean drought processes

At least during the warmer months, evapotranspiration is limited by the availability of water, as solar radiation is abundant and water scarce. A good knowledge of soil moisture is thus very important because it determines the availability of water for evapotranspiration. At the same time, vegetation is well adapted to this situation, with strategies to obtain water from deeper soil layers (long roots) along with strategies to better tolerate water stress. Unfortunately, *in situ* observations of soil moisture are rare, but remote sensing is revolutionizing our knowledge of soil moisture and vegetation conditions over large areas, enabling progress in monitoring.

With climate change, an increase in temperature, in the length of the summer dry period and in its extension is expected. This will exacerbate the impacts of drought, as a very dry soil stimulates the sensible heat flux, which can interact

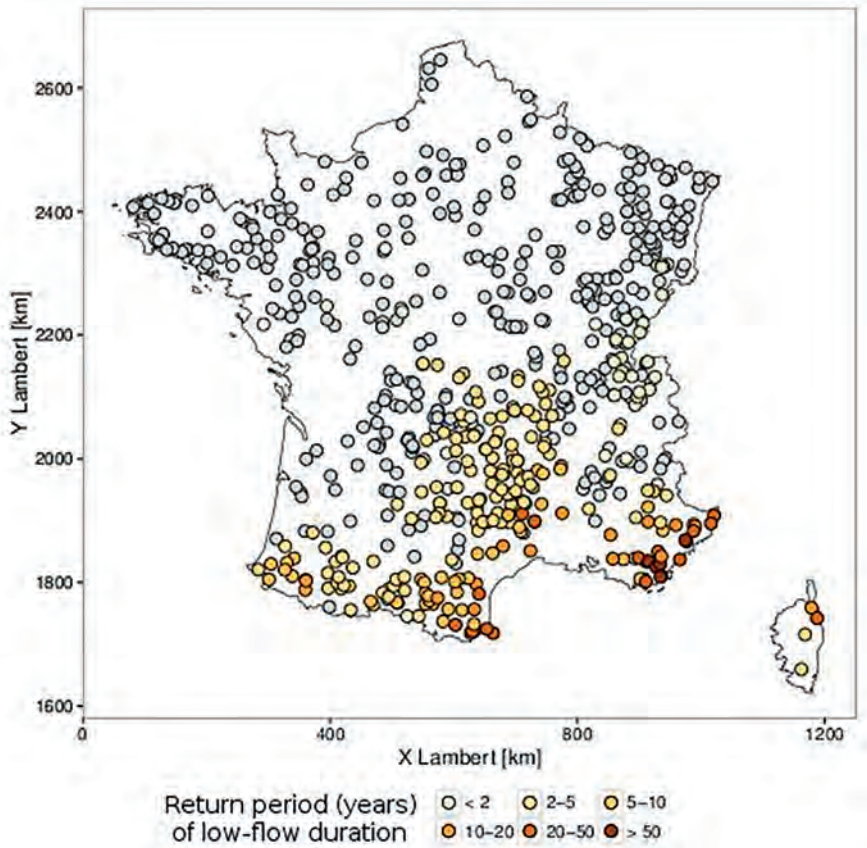


Figure 2
1878 low-flow duration in southern France.
Reconstructed by Caillouet et al. (2016).

with the atmosphere, intensifying heat waves. The vegetation will be water stressed for longer periods too.

In this context, the action of man can also be a vulnerability factor. If climate change increases demand for irrigation, the water available for natural vegetation might decrease due to a drop in the water table caused by pumping water for irrigation, thereby amplifying the above mentioned effect, thereby creating an environment where extreme droughts could thrive.

Drought and vegetation, as seen using remote sensing techniques

Meteorological drought indices, such as SPEI, are difficult to use in areas with few or no meteorological stations, or in regions with a short period of measurements, which is the case in many Mediterranean areas. Furthermore, even if meteorological indices can be correlated, for instance, with agricultural

Box I Impact of drought on tree growth and health

Increasingly long and severe droughts threaten Mediterranean forests. After decades of improved productivity in the 20th century, since the 1980s, there has been a progressive north-south downward growth trend (Sarris et al. 2011) that reached the northernmost Mediterranean areas at the beginning of the 21st century (Girard et al. 2012).

Thanks to higher temperatures, the growth season starts earlier in spring and ends later in the fall. Some species such as Aleppo pine even show shoot growth and flower development throughout winter. But these additional growing periods are more than offset by the longer stop of growth in summer due to increasing aridity (Adams et al. 2015). This shift in activity is a risk: any even brief period of deep frost in winter can kill the fragile active new tissues or at least damage them, paving the way for invasive pathogens. Higher temperatures during humid periods from fall to spring also favor dangerous fungi and insects such as the processionary caterpillar, which are gaining ground northward and upward in elevation, and unprecedented outbreaks have occurred in recent years. Reproduction processes are also being disturbed. As a consequence, forest dieback episodes have been multiplied by 3 to 4 in the last 30 years in the Mediterranean region (Allen et al. 2010, Fig. 3). Species at the lower limit of their distribution area are particularly threatened, such as Scots pine and silver fir. Repeated droughts also reduce the resilience of Mediterranean forest to wildfires, limiting its ability to regenerate.



Figure 3
Example of forest dieback episode in a Mediterranean environment.
Author: M. Vennetier.

production, a more direct measurement of the impact of drought on vegetation is needed. For this reason, in the last two decades scientists have proposed a number of new approaches for the estimation of drought conditions, based on the use of remotely sensed satellite data.

Optical sensors make it possible to study vegetation dynamics and its variations over time. Most studies are based on the use of the normalized difference vegetation index (NDVI), which is related to photosynthetic activity and whose good accuracy has been demonstrated for the quantification of green vegetation cover or vegetation abundance. The vegetation condition index (VCI) has also been tested at different sites, where it revealed its high potential for the detection and monitoring of drought, and showed a high correlation with agricultural production. The vegetation anomaly index (VAI) also showed a high correlation with precipitation levels over Tunisia.

Microwave remote sensing is also very useful as it measures soil moisture anomalies. The soil water index (SWI) product provided by the Advanced SCATterometer (ASCAT) or other moisture profiles retrieved from the SMOS (Soil Moisture and Ocean Salinity) Mission is essential for this type of discussion, as several studies have shown, including in Tunisia.

The combined use of these remote sensing indices, not only allows us to study drought in areas with few meteorological stations, but also to study how drought propagates to the soil (soil moisture) and to the vegetation and how it impacts agriculture and forestry, for example.

Future trends

Future droughts as seen by regional climate models

Regional climate models make it possible to downscale global climate simulations to regions of interest (e.g. the Mediterranean) in order to simulate finer scale physical processes. A simplest way to study drought using regional climate models is to analyze periods of consecutive dry days (dry spells). This was done using a group of European regional climate models (RCMs) (ENSEMBLES project). First, the annual mean dry spell length was studied in the last four decades of the 20th century (1961-2000). Then, the percentage change in the mean dry spell length from these RCMs, forced by different global climate models (GCMs), was analyzed in future conditions (2021-2050) under the A1B emissions scenario. The results showed that RCMs successfully reproduce the general characteristics of the observed dry spells. A north-south gradient of the mean dry spell length index along the Mediterranean basin was obtained in the baseline and historical periods, with the maximum length values located over the Sahara Desert (more than 200 days/year) and minimum over the mountain ranges in the northern part of the basin (with around 3-4

days/year). High values were also observed in the southern half of the Iberian Peninsula, on the western and southern coast of the Mediterranean Sea (over 15 days/year). When climate change projections are analyzed, an overall increase in the mean dry spell length appears over the Mediterranean basin for all the combinations of GCM/RCM pair simulations, with no clear spatial pattern, suggesting that droughts are more probable in the future. Nevertheless, some uncertainties in the magnitude of the increase emerge among them, ranging from less than 5 to more than 15 days/year, depending on the simulation.

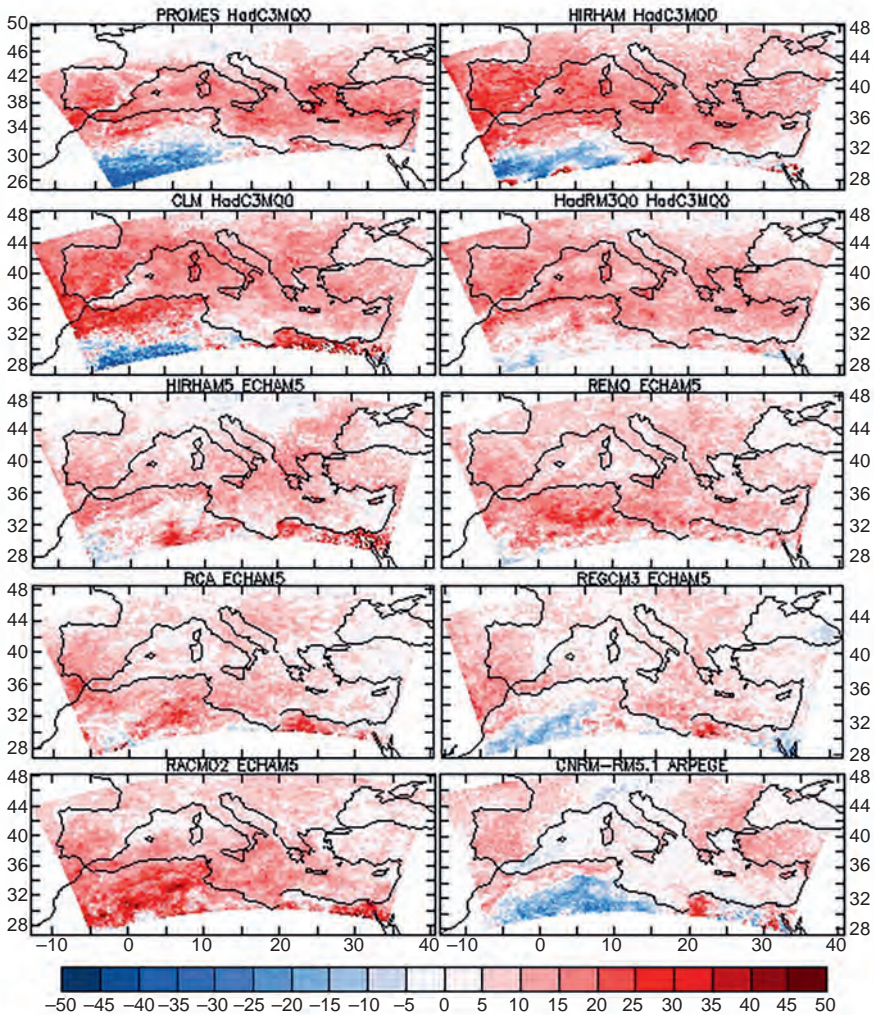


Figure 4

Percentage change (2050-2021) – (1951-1980) in the mean dry spell length under the A1B emissions scenario. RCM/GCM pairs are indicated above each figure.

Source: E. Sánchez.

Future Mediterranean river flows

Studying the impact of climate change on river flow is difficult due to the uncertainties involved. However, some clear signals emerge. For example, Quintana-Seguí et al. (2010, 2011) studied the impacts of climate change on mean and extreme river flows in French Mediterranean basins in the middle of the 21st century, using a regional climate model, statistical downscaling techniques, and a hydrological model. These studies showed that it is possible to draw general conclusions concerning the expected impacts on the whole region, but that it is very difficult to quantify changes at the basin scale, as most Mediterranean basins are rather small. The studies also showed that there might be significant changes in the seasonality of precipitation over the mountain ranges close to the sea (Cévennes), with increases in some seasons (e.g. winter, spring) and decreases in others (e.g. summer), rendering water management more difficult. In general, a decrease in annual mean precipitation is also possible, causing a decrease in the average discharge, which will be more marked in summer, thereby exacerbating the lack of the resource when it is most needed. Concerning low flow extremes (hydrological drought), low flows are expected to be up to -20% lower almost everywhere in the region. The study revealed a clear signal concerning the increase in the frequency of the low flows, which in the 20th century had a return period of 5 years.

Conclusions

Drought is a very complex phenomenon involving the atmosphere, soil, vegetation, rivers and underground waters, at different time and space scales. It can be estimated using different indices that make use of meteorological, remote sensing and *in situ* data, the standardized precipitation evapotranspiration index (SPEI) being a noteworthy index. Drought can also be understood and predicted using physical models. In the Mediterranean region, drought is a phenomenon that has major impacts on society. Mediterranean drought displays high spatial variability, thus, when it happens, it does not necessarily affect the Mediterranean region as a whole. Studying extreme drought is difficult, due to relatively short time series of records, as a result, past droughts that lasted longer periods need to be reconstructed to better prepare ourselves for future Mediterranean droughts. This has been done in France with promising results. In terms of processes, the Mediterranean has a marked north-south gradient, which could be modified by climate change. Work is ongoing to improve our understanding of drought events in semi-arid areas. The role of vegetation is very important in this respect, as Mediterranean vegetation is well adapted to drought conditions. Remote sensing allows us to study drought and vegetation even in areas where few measurements are available. Unfortunately, an increase in the occurrence of drought may have

negative impacts not only on agriculture, but also on our forests, with increased mortality of trees. In the future, it is expected that the increase in droughts in the Mediterranean region, which may make low river flows more frequent, together with a decrease in mean flow, may increase water scarcity in a densely populated region.

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