# Impact of the dry day definition on Mediterranean extreme dry spells analysis

Pauline Rivoire[1]
Yves Tramblay[1]
Luc Neppel[1]
Elke Hertig[2]
Sergio M. Vicente-Serrano[3]

[1] HSM (Univ. Montpellier, CNRS, IRD), Montpellier, France
[2] Institute of Geography, University of Augsburg, Germany
[3] Instituto Pirenaico de Ecologia (IPE-CSIC), Campus de Aula Dei, Zaragoza, Spain

**Revised manuscript, 31/05/2019**

## ABSTRACT

To define a dry day, the most common approach is to identify a fixed threshold below which precipitation is considered equivalent to zero. This fixed threshold is usually set to account for measurements errors and also for precipitation losses due to the atmospheric evaporation demand. Yet, this threshold could vary in time according to the seasonal cycle but also in the context of long-term trends such as the increase of temperature due to climate change. In this study, we compare extreme dry spells defined either with a fixed threshold for a dry day (1 mm) or with a time-varying threshold estimated from reference evapotranspiration ($ET_0$) for a large data base of 160 rain gauges covering large parts of the Mediterranean basin. Results indicated positives trends in $ET_0$ in particular during summer months (June, July and August). However, these trends do not imply longer dry spells since the daily precipitation intensities remains higher than the increase in the evaporative demand. Results also indicated a seasonal behavior: in winter the distribution of extreme dry spells is similar when considering a fixed threshold (1 mm) or a time-varying threshold defined with $ET_0$. However, during summer, the extreme dry spell durations estimated with a 1 mm threshold are strongly underestimated by comparison with extreme dry spells computed with $ET_0$. We stress the need to account for the atmospheric evaporative demand instead of using fixed thresholds to define a dry day when analyzing dry spells, in particular with respect to agricultural impacts.

**Keywords:**

Extremes, dry spell, Mediterranean, reference evapotranspiration, atmospheric evaporative demand

## 1. INTRODUCTION

The Mediterranean region is affected by severe droughts episodes, linked to the strong inter-annual variability of precipitation patterns (Mariotti and Dell'Aquila, 2012). These droughts can impact agricultural production (Páscoa et al., 2017), and water resources (Lorenzo-Lacruz et al., 2013), in particular when occurring during the (wet) winter season (Raymond et al., 2016). In addition, several studies indicate a tendency toward a warming and drying of the Mediterranean region that could intensify in the future according to climate projections (Hoerling et al. 2012, Hertig and Tramblay 2017, Naumann et al. 2018).

There are different methods to analyze droughts, by means of drought indices (Mishra and Singh, 2010, Mukherjee et al., 2018) but also by explicitly modelling the frequency/duration of dry spells (Vicente-Serrano and Beguería-Portugués, 2003). A dry spell is meteorologically defined as a sequence of consecutive dry days with no precipitation, or precipitation below a certain threshold. Although dry spells cannot be used to determine drought severity, as a consequence of the climatological differences, they are highly useful to assess spatial differences in the drought hazard probability (Lana et al., 2006), but also to determine possible trends associated to climate change (Raymond et al., 2016). Moreover, analyses based on dry spells have usually been used for agricultural management purposes in different regions of the world (Sivakumar, 1992, Lana et al., 2006, Mathugama and Peiris, 2011, Raymond et al., 2016).

Several authors analyzed long dry spells, considering different precipitation thresholds (1 to 10 mm/day), but fixed for the whole observation period (Vicente-Serrano and Beguería-Portugués, 2003, Lana et al., 2006, Serra et al., 2016, Raymond et al., 2016, 2017, Tramblay and Hertig, 2018). About the threshold considered for a "dry" day it is usual to use values higher than zero to account for measurements errors or very little amounts of rain that are not available for plants or water resources, due to interception or/and direct evaporation (Douguedroit, 1987, Raymond et al., 2016). In a climate change context it is also used to reduce the typical “drizzle effect” of dynamical models which results in too many low precipitation amounts compared to observations. The determination of this threshold, noted Daily Rainfall Threshold (DRT), can be a key issue to relate dry spells risk to impacts in different sectors. Douguedroit (1987) defined a threshold of 1 mm of precipitation in environments with a Mediterranean climate, because below this amount the rainfall is generally not absorbed by soils under conditions of high evapotranspiration. It is the most widely used daily rainfall threshold (Polade et al., 2014, Raymond et al., 2016, 2017), even though this arbitrary value has not been supported by any experimental study.

However, fixed thresholds are not representative of real ground conditions, since the evaporation varies throughout the year and for different locations. The atmospheric evaporative demand (AED) can strongly modulate the net precipitation that is available for the plants, affecting water stress levels by plants and crops (Allen et al., 2015; Anderegg et al., 2016; Lobell et al., 2015; Lobell and Field, 2007). It is expected that based on precipitation records, dry spells of similar duration could be characterized by different water stress as a function of the differences in the AED as suggested by drought indices using precipitation and the AED for calculations (Beguería et al., 2014, Manning et al., 2018). AED can be calculated using meteorological data from different approaches such the potential evaporation (McMahon et al., 2013) or the reference evapotranspiration ($ET_0$) (Allen et al. 1998) but it can be also measured by means of Evaporation Pans. In the Mediterranean region different studies have shown an increase in the AED in recent decades (Vicente-Serrano et al., 2014) that has increased drought severity (Vicente-Serrano et al., 2014a, Stagge et al., 2017). It is unclear how these trends could affect extreme dry spell severity.

The goal of the present study is to evaluate the influence of different daily precipitation thresholds to define a dry day on the estimation of seasonal extreme dry spell hazard in the Mediterranean. The novelty of the approach proposed herein, is to use the AED to identify dry days prior to the analysis of extreme dry spell risk. Two thresholds to define a dry day are compared: 1 mm/day, the threshold commonly used in most Mediterranean studies, and a daily precipitation threshold defined by the AED, thus seasonally and temporally variable. Two questions are addressed in the present work: (i) are there trends in extreme dry spell length in Mediterranean region and is the trend detection influenced by the way at which dry days are defined? (ii) since in most studies a distinction is made between winter and summer dry spells due to their different characteristics and impacts (Raymond et al. 2018, Tramblay and Hertig, 2018)- is there a different impact on the estimation of extreme dry spells in winter or summer according to different daily rainfall thresholds?

## 2. PRECIPITATION AND REFERENCE EVAPOTRANSPIRATION DATA

A network of 160 stations with long daily precipitation records in the Mediterranean region is considered (see Hertig and Tramblay, 2017, Tramblay and Hertig, 2018 for more details about this dataset). Since most stations have almost complete records between 1960 and 2000, it is the period considered in the present analysis to allow a comparison between stations. The years with more than 5% missing days have been discarded from subsequent analysis. A preliminary sensitivity analysis considering different missing day ratios has shown that it does not impact the results.

In addition to precipitation data, as a representative and spatially comparable metric of the AED, the reference evapotranspiration ($ET_0$) from the Climate Research Unit (CRU) dataset version 4.2 is considered (Harris et al., 2014). Several studies (McVicar et al., 2012a, 2012b, Todorovic et al., 2013, Vicente-Seranno et al., 2014b, Anabalón and Sharma, 2017) highlighted the need to consider a physically based $ET_0$ calculation, such as the FAO-PM, to account for possible changes in other variables than temperature in the AED and to have an accurate quantification of the climate change effect on drought (Trenberth et al., 2014). Reference evapotranspiration is defined as the rate of evapotranspiration, only influenced by the atmospheric conditions, from a clipped grass surface having 0.12 m height and bulk surface resistance equal to 70 s $m^{-1}$, an assumed surface albedo of 0.23 and no moisture stress. In the CRU dataset, the $ET_0$ is computed from a simplified version of the FAO Penman-Monteith (FAO-PM) equation (Allen et al. 1998) that uses data of air temperature, sunshine duration, vapor pressure deficit and a climatology for wind speed. The detail for the computation is given in Harris et al. (2014). By comparison, Potential Evapotranspiration (PET) is the evapotranspiration from a given crop surface, requiring the use of crop coefficients that can vary in time due to the development stage of the vegetation. The use of $ET_0$ allows the comparison between stations and does not require estimating local crop coefficients.

Two different definitions for a dry spell are used in the present work. The first one considers a dry spell as consecutive days with precipitation below 1 mm. For the second one, the $ET_0$ is considered as a threshold to define a dry day when $P-ET_0 <= 0$. In addition, to provide a measure of rainfall intensity we computed from daily precipitation the Simple Precipitation

Intensity Index (SDII), defined as the monthly sum of precipitation during wet days divided by the number of wet days in the month (expressed as mm/day). It is an interesting metric for the present dry spells analysis, since the SDII can provide a measure of rainfall intensity that can be compared with the threshold used to define a dry day during a dry spell.

## 3. METHODS

### 3.1 Statistical tests

To test the presence of trends in the different station time series, the non-parametric Mann-Kendall (Mann, 1945) test was used. Since the presence of autocorrelation in the data could lead to an increased number of type I errors (Serinaldi et al., 2018), we used the trend-free pre-whitening method introduced by Yue et al. (2002) and modified according to Serinaldi et al. (2006). In addition, since the tests are repeated on a large ensemble of stations (160), we also implemented the false discovery rate (FDR) method of Benjamini and Hochberg (1995) to distinguish between at-site and regionally significant trends (Wilks, 2018).

To compare the different extreme dry spells distributions, computed with different definitions of a dry day, the Anderson Darling test (Scholz andStephens, 1987, Viglione et al., 2007) is considered. The test verifies the hypothesis that two independent samples belong to the same population without specifying their common distribution function. The test statistic measures the distance between the empirical cumulative distribution functions and places more weight towards the tail of the distributions, hence making it adapted to the analysis of extreme values.

### 3.2 Distribution fitting

To compute the return levels for different extreme dry spell durations, there is the need to fit a distribution to the samples. No single distribution is commonly applied to extreme dry spell lengths and also we define differently dry spells than previously (Vicente-Serrano and Beguería-Portugués, 2003, Lana et al., 2006, Serra et al., 2016). Thus, the GEV, Gamma and Log normal distribution are first compared to represent extreme dry spells, using the maximum likelihood estimation method. A split-sample procedure has been implemented to validate the choice of the distribution. The same procedure as described in Zkhiri et al. (2017) or Renard et al., (2013) is retained, based on a bootstrap cross-validation. The relative average root mean square error (RRMSE) for the validation samples is used as an evaluation metric to select the best distribution. The best distribution retained is then used to compute extreme dry spell quantiles computed with different precipitation thresholds for a dry day.

### 3.3 Definition of the seasons

The Mediterranean regions are classified as Csa and Csb climate types in the Köppen classification (Peel et al., 2007), defined as climates with a precipitation deficit during summer months (when the sub-tropical high pressure belt moves northward and prevent moisture advection from westerlies). The Mediterranean climate is then characterized by two contrasted seasons: A summer (dry) season from around April to September and an extended winter season (wet) from October to March, with most of the precipitation occurring during this period. Yet the transitional months could vary depending on the location and one single definition of the Mediterranean seasons is probably not appropriate due to strong North/South and West/East variations on the beginning/finishing dates for the season of precipitation deficit. This has been highlighted be the recent study of Raymond et al. (2018). Reiser and Kutiel (2009) previously observed different lengths for the wet season, (on 40 stations) with less than 6 months in the south and up to 10 months in the North. Thus, in the present study we choose to define the season lengths for each station according to an objective criterion, being the precipitation deficit in summer (ie. the months when P-$ET_0$ = 0 are defined as the summer season). Then a clustering approach (Ward, 1963) is used to group stations with a similar seasonality. The optimal number of clusters is estimated with the gap statistic (Tibshirani et al. 2001) and silhouette plot (Kaufman and Rousseeuw, 1990).

## 4. RESULTS

### 4.1 Climatic trends

There are increasing trends in $ET_0$ in West/Central Mediterranean stations, mostly during summer months and to a lesser extent in March for the Iberian Peninsula (Figure 1). These monthly trends imply an increase of $ET_0$ at the annual scale for these stations (Spain, South France, Italy, East Algeria and Tunisia). When tested on the annual total $ET_0$, the trends are regionally significant at 67 stations, located in south France, Spain, Middle East, Tunisia and Algeria, Italy and the Adriatic. With both thresholds 1mm or $Et_0$ to define a dry days (named thereafter respectively S1 and $SET_0$), there is an increase in the frequency of dry days in February and March, centered on the stations in Spain, Portugal and South France (Figure 2 and Figure 3). The spatial patterns of detected trends are similar with the two thresholds but the increase is more pronounced, with more regionally significant trends, when using $ET_0$ as threshold for dry days. Yet, the increase in $ET_0$ during summer months does not imply an increase in the frequency of dry days during this season when considering $ET_0$ to define a dry day. On the contrary, in March the increase in $Et_0$ in the Western Mediterranean is accompanied by an increased frequency of dry days. The monthly $ET_0$ during winter months lies in the interval 0.5 to 2 mm for all stations, when for the summer daily $ET_0$ ranges between 3 mm and 7 mm/day.

Additionally, we tested the trends for the Simple Daily Intensity Index (SDII). The results indicate a decrease of SDII for a few stations, in particular in February in South France, but overall these trends are not regionally significant. An interesting feature is illustrated in Figures 4 and 5: the ratio between $ET_0$ and the SDII during June, July and August show a remarkable North/South difference: In the south the average precipitation amounts during summer stay below evapotranspiration during rainfall events. During the summer months there is also a large variability and the ration is often exceeding 1. This implies that, on average, precipitation events will not be able to end a succession of dry days and this characteristic favor very long dry spells during summer. On the opposite, in the north the average precipitation during an event stay above $ET_0$.

### 4.2 Seasonal comparison of extreme dry spells

As mentioned in the previous section and in section 3.3, there is a different seasonal behavior of dry spells between winter and summer months. In addition, several studies have shown that long dry spells during the winter season may have more severe consequences than those occurring during summer. This justifies a seasonal analysis of the extreme dry spells defined according to different dry day definitions.  Nevertheless, prior to a seasonal comparison, a classification of stations according to monthly net precipitation (P- $ET_0$) has been performed as explained in section 3.3. The classification shows a marked distinction between two clusters as shown in Figure 6, very similar to the spatial patterns of Figure 5, with northern stations (approximately north of 40°N) with a precipitation deficit from April to September and southern stations with a precipitation deficit from March to October.

Then for each season and each year, the maximum dry spell lengths have been extracted at the different stations according to two thresholds for a dry day: 1 mm and $ET_0$ (thereafter the extreme dry spells derived from the two thresholds are noted S1 and $SET_0$). Then, the Anderson-Darling test has been applied between summer and winter maxima. For S1, the test rejects the null hypothesis at the 5% significance level for 135 stations. The remaining 25 stations where the winter and summer distributions are found similar are located in northern Mediterranean countries such as France (including Perpignan, Nîmes, Orange), Spain (Huesca, Valencia, Soria, Vallalolid), Italy (Ferrara, Genoa), Croatia (Gospic, Zavizan). For $SET_0$, the test rejects the null hypothesis for 155 stations (except Mantova, Verona, Reijka, Milan, Mons). This indicates that the majority of stations the winter and summer distributions of extreme dry spell are different whatever the threshold considered for a dry day. Indeed, the extreme dry spells tends to be longer in summer than in winter for all stations and this feature accentuates with increased aridity. This result justifies the need to perform a seasonal analysis when considering extreme dry spells risk.

Finally, the same Anderson-Darling test has been applied for a given season between extreme dry spells computed with the threshold 1 mm (S1) and extreme dry spells computed with $ET_0$ ($SET_0$). As shown in Figure 7, there are strong differences in summer when extreme dry spells are computed with the dry day threshold 1 mm or $ET_0$. For most stations, the two distributions are significantly different at the 5% level. On the opposite, for winter it can be assumed that extreme dry spells computed with 1mm or the $ET_0$ are stemming from the same distribution. This is due to the fact that during winter the AED is low and close to the value 1mm.

**4.3 Return levels of extreme dry spells**

Prior to the fitting of statistical distributions, there is the need to verify the hypothesis of stationarity. Overall, there are not significant trends in extreme dry spells duration, neither for winter or summer, with the threshold 1 mm or $ET_0$ to define dry days. This finding is quite surprising since there is an increase of $ET_0$ in summer and one would expect an increase in dry spells when considering $ET_0$ as daily rainfall threshold. As elements of explanations, it was shown before that the increase of $ET_0$ is focused only in the months of June, July and August (see Figure 1). Furthermore, two extreme cases are exemplified here, Montpellier in the North (783mm/year on average) and Gafsa in the South (168mm/year). In Figure 8 the daily rainfall for a random year (1998) is plotted together with $Et_0$ at the beginning of the time period (1960), in 1998 and for the end of the time period (2000). In Gafsa or Montpellier, the increase of $ET_0$ in summer is not high enough to exceed daily events of intense precipitation (often thunderstorms). In the south, the $ET_0$ is already higher than most of precipitation events (e.g. Figure 5), except for a few high-intensity events above $ET_0$. Still, the increase in $ET_0$ does not impact the longest dry spells sequences as indicated by the trend analysis.

The GEV, Log Normal and Gamma distributions have been compared to fit extreme dry spells. The results are illustrated in Figure 9 for 10 stations located in different regions having long records and very little or no missing data over their full records. For both S1 and S $ET_0$, the Gamma distribution outperforms the GEV or Log-Normal since it provides lower mean RRMSE values in validation results on independent samples. Quantiles corresponding to a 20-year return period have been computed from a Gamma distribution for each station and each season, according to the two different thresholds for dry days. A relative difference between the two quantiles has been computed, taking the S1 quantile as reference, since it is up to now the most widely used approach to estimate dry spell durations. Results, shown in Figure 10, indicate a strong underestimation of extreme dry spells during summer when using the fixed threshold of 1 mm. This underestimation is on average -29%, but only 4% in winter. This result question the use of a fixed threshold of 1 mm during summer, since it is not representative of the real amount of water available on the ground due to evaporation. On the contrary, focusing on winter only with a fixed threshold 1 mm does not induce strong uncertainties due to the low AED during this season.

## 5. Discussion

The results obtained in the present work indicate the need to consider AED in particular during summer months to define a dry day, which is probably more realistic than with a fixed threshold of 1 mm. In more arid environments than the Mediterranean region, such as the Middle East and North Africa regions, it would mean that the analysis of dry spell could be strongly impacted whether the AED is taken into account or not. It implies that it necessary to re-define appropriate thresholds to define dry days according to different regions. By comparison with other drought indices, such as the SPI or SPEI that are averaged on a monthly basis for different time horizons (Mukherjee et al., 2018), the explicit consideration of extreme dry spells could be an interesting way of relating dry spells to impacts. Indeed, dry spell durations computed with dry day thresholds representative of real climate conditions could be directly related to plants phenology to study the drought impacts for different agricultural productions. This new definition of dry spells, considering a time varying threshold based on AED, is a departure from the classical viewpoint of a meteorological drought index since it tries to relate the atmospheric and ground conditions to assess the amount of water that is actually available for plants or water use. In that sense, it relates to the SPEI but tailored at the scale of individual dry spell events.

The results of the present study rely on the estimation of AED with reference evapotranspiration. Still more reliable than $ET_0$ estimates from temperature only, the FAO-PM equation may not be fully representative of the AED at the different locations considered. McMahon et al. (2013) provided a synthesis of the uncertainties related to the estimation of the AED: data limitations such as wind or humidity, which are not always available for all gauging stations, but also the fact that reference evapotranspiration rely on an hypothetical grass surface that may not be representative of the real land cover at the different stations during the different seasons of the year. Indeed, it is possible to derive the potential evapotranspiration from reference evapotranspiration using crop coefficients representative of the real ground conditions. These changes in land cover could modulate the AED between different locations. As an alternative, it could be possible to use actual evapotranspiration but since it cannot be measured (at least for large areas) this would require the use of land surface modelling. However, there are differences in actual evapotranspiration computed from different land surface models, due to different parametrization, climate forcing, and representation of the semi-arid surface processes (Quintana-Seguí et al., 2019). Finally, it must be stressed that the estimation of AED in the Mediterranean for a long term perspective and climate change impact studies, must face several sources of uncertainties, such as land cover changes, forest fires that could induce drastic changes in surface processes, water soil conditions influenced by human activity and irrigation, among others.

## 6. Conclusions

In this study, the extreme dry spells defined either with a fixed dry-day threshold (1 mm/day) or with a time-varying threshold estimated from reference evapotranspiration ($ET_0$) have been compared for a large data base of 160 rain gauges covering the whole Mediterranean basin. An increase in $ET_0$ is found for summer months (JJA) mainly in the central/western parts of the Mediterranean basin. The reported trends for summer are consistent with previous studies in Spain, driven by a decrease in relative humidity and an increase of maximum temperature (Vicente-Serrano et al., 2014a, 2014b). Also increases in the number of dry days are found for February and March at a large number of stations, either with 1mm or $ET_0$ to define a dry day. However, no trends are detected for extreme dry spell lengths when using both thresholds to define a dry day. The distributions of extreme dry spells have been found to be different for winter and summer, with much longer extreme dry spells during summer. Also, for many locations a stronger variability in winter extreme dry spells became apparent. These results highlight the need of a seasonal analysis to avoid the misestimating the extreme dry spells risk. Despite the climatic trends on precipitation and evapotranspiration, there are no significant trends in seasonal extreme dry spells risk in most areas. The frequency analysis of seasonal extreme dry spells reveals that using a fixed threshold set to 1 mm implies an underestimation of extreme dry spells risk by comparison to a time-varying threshold representing evapotranspiration during the extended summer season. The time-varying thresholds appear a more relevant choice representative of real atmospheric conditions, but this needs to be further confirmed by relating extreme dry spells computed with this new approach and drought impacts in different sectors (agriculture, vegetation, etc.). As a conclusion, we stress the need to account for the atmospheric water demand when analyzing dry spells in particular if the goal is to relate them with agricultural impacts.

## Acknowledgements

This work is a contribution to the HYdrological cycle in The Mediterranean EXperiment (HyMeX) program, through INSU-MISTRALS support for the studentship of Pauline Rivoire. The results have been obtained using the R packages: extRemes, MASS, kSamples, randtests, stats, zyp.

## References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M.: Crop evapotranspiration, guidelines for computing crop water requirements, Irrigation and drain, Paper No 56 FAO, Rome, Italy, 2008.

Allen, C. D., Breshears, D. D., McDowell, N. G.: On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene, Ecosphere, 6(8), doi:10.1890/ES15-00203.1, 2015.

Anderegg, W. R. L., Klein, T., Bartlett, M., Sack, L., Pellegrini, A. F. A., Choat, B., Jansen, S.: Meta-analysis reveals that hydraulic traits explain cross-species patterns of drought-induced tree mortality across the globe, Proc. Natl. Acad. Sci. U. S. A., 113(18), 5024–5029, doi:10.1073/pnas.1525678113, 2016.

Anabalón, A., Sharma, A.: On the divergence of potential and actual evapotranspiration trends: An assessment across alternate global datasets, Earth's Future, 5, 905-917. doi:10.1002/2016EF000499, 2017.

Beguería, S., Vicente-Serrano, S. M., Reig, F., Latorre, B.: Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring, Int. J. Climatol., 34, 3001–3023, 2014.

Benjamini, Y., Hochberg, Y.: Controlling the false discovery rate: A practical and powerful approach to multiple testing, J. Roy. Stat. Soc. B, 57, 289–300, 1995.

Douguedroit, A.: The variations of dry spells in marseilles from 1865 to 1984, J. Climatol., 7, 541–551, 1987.

Greve, P., Orlowsky, B., Mueller, B., Sheffield, J., Reichstein, M., Seneviratne, S. I.: Global assessment of trends in wetting and drying over land, Nat. Geosci., 7(10), 716–721, doi:10.1038/NGEO2247, 2014.

Harris, I., Jones, P., Osborn, T., Lister, D.: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, Int. J. Climatol., 34: 623-642. doi:10.1002/joc.3711, 2014.

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G. , Klok, E.J., Jones P.D., New, M.: A European daily high-resolution gridded dataset of surface temperature and precipitation, J. Geophys. Res (Atmospheres), 113, D20119, doi:10.1029/2008JD10201, 2008.

Hertig, E., Tramblay, Y.: Regional downscaling of Mediterranean droughts under past and future climatic conditions, Global and Planetary Change, 151, 36-48, 2017.

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X., Zhang, T., Pegion, P.: On the increased frequency of Mediterranean drought, J. Clim., 25, 2146–2161, 2012.

Kaufman L., Rousseeuw P.J.: Finding Groups in Data: An Introduction to Cluster Analysis, Hoboken, NJ: John Wiley & Sons, New York., 1990.

Lana, X., Martínez, M. D., Burgueño, A., Serra, C., Martín-Vide, J. and Gómez, L.: Distributions of long dry spells in the iberian peninsula, years 1951–1990, Int. J. Climatol., 26: 1999–2021. doi:10.1002/joc.1354, 2006.

Lobell, D. B. and Field, C. B.: Global scale climate–crop yield relationships and the impacts of recent warming, Environ. Res. Lett., 2(1), 014002, doi:10.1088/1748-9326/2/1/014002, 2007.

Lobell, D. B., Hammer, G. L., Chenu, K., Zheng, B., Mclean, G. and Chapman, S. C.: The shifting influence of drought and heat stress for crops in northeast Australia, Glob. Chang. Biol., 21(11), 4115–4127, doi:10.1111/gcb.13022, 2015.

Lorenzo-Lacruz, J., Vicente-Serrano, S. M., González-Hidalgo, J. C., López-Moreno, J. I. and Cortesi, N.: Hydrological drought response to meteorological drought in the Iberian Peninsula, Clim. Res., 58(2), doi:10.3354/cr01177, 2013.

Naumann, G., Alfieri, L., Wyser, K., Mentaschi, L., Betts, R. A., Carrao, H., et al.: Global changes in drought conditions under different levels of warming. Geophysical Research Letters, 45, 3285–3296. https://doi.org/10.1002/2017GL076521, 2018.

Mann, H. B.: Nonparametric tests against trend, Econometrica, 13, 245– 259, 1945.

Manning, C., Widmann, M., Bevacqua, E., Van Loon, A.F., Maraun, D., and Vrac, M.: Soil Moisture Drought in Europe: A Compound Event of Precipitation and Potential Evapotranspiration on Multiple Time Scales, J. Hydrometeor., 19, 1255–1271, 20180

Mariotti, A., Dell'Aquila, A.: Decadal climate variability in the Mediterranean region: roles of large-scale forcings and regional processes, Clim. Dyn. 38, 1129–1145, 2012.

McMahon, T. A., Peel, M. C., Lowe, L., Srikanthan, R., and McVicar, T. R.: Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis, Hydrol. Earth Syst. Sci., 17, 1331-1363, https://doi.org/10.5194/hess-17-1331-2013, 2013.

McVicar, T. R., Roderick, M. L., Donohue, R. J., Li, L.T., VanNiel, T. G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Ma-howald, N.M., Mescherskaya, A.V., Kruger, A.C., Rehman,S., Dinpashoh, Y.: Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation, J. Hydrol., 416–417, 182–205, 2012a.

McVicar, T.R., Roderick, M. L., Donohue, R.J., Van Niel, T.G.: Less bluster ahead? Overlooked ecohydrological implications of global trends of terrestrial near-surface wind speeds, Ecohydrology, 5, 381–388, 2012b.

Mishra, A.K., Singh, V.P.: A review of drought concepts. J. Hydrol. 391, 202–216, 2010.

Mathugama, S. C., Peiris, T. S. G.: Critical Evaluation of Dry Spell Research, Int. J. Basic Appl. Sci., 11, 153–160, 2011.

Mukherjee, S., Mishra, A. Trenberth, K. E.: Climate Change and Drought: a Perspective on Drought Indices, Curr. Clim. Chang. Reports, 4(2), 145–163, doi:10.1007/s40641-018-0098-x, 2018.

Páscoa, P., Gouveia, C. M., Russo, A. Trigo, R.M.: The role of drought on wheat yield interannual variability in the Iberian Peninsula from 1929 to 2012, Int. J. Biometeorol., 61(3), 439–451, doi:10.1007/s00484-016-1224-x, 2017.

Peel, M. C., Finlayson, B. L., McMahon, T.A.: Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633-1644, https://doi.org/10.5194/hess-11-1633-2007, 2007.

Quintana-Seguí, P., Barella-Ortiz, A., Regueiro-Sanfiz, S. and Miguez-Macho G.: The Utility of Land-Surface Model Simulations to Provide Drought Information in a Water Management Context Using Global and Local Forcing Datasets, Water Resources Management, https://doi.org/10.1007/s11269-018-2160-9, 2019.

Raymond, F., Ullmann, A., Camberlin, P., Drobinski, P., Chateau Smith C., 2016. Extreme dry spell detection and climatology over the Mediterranean Basin during the wet season, Geophys. Res. Lett., 43, 7196–7204, doi:10.1002/2016GL069758.

Raymond F., Ullmann A., Camberlin P., Oueslati B., Drobinsky P.: Atmospheric conditions and weather regimes associated with extreme winter dry spells over the Mediterranean basin, Climate Dynamics 50, 4437-4453. doi:10.1007/s00382-017-3884-6, 2018.

Reiser H., Kutiel H.: Rainfall uncertainty in the Mediterranean: definition of the daily rainfall threshold (DRT) and the rainy season length (RSL), Theor. Appl. Climatol. 97: 151–162, 2009.

Renard, B., Kochanek, K., Lang, M., Garavaglia, F., Paquet, E., Neppel, L., Najib, K., Carreau, J., Arnaud, P., Aubert, Y., Borchi, F., Soubeyroux, J.M., Jourdain S., Veysseire J.M., Sauquet E., Cipriani, T., Auffray, A.: Data-based comparison of frequency analysis methods: a general framework, Water Resour Res 49:825–843, 2013.

Serra C., Lana X., Burgueno A., Martinez M.D.: Partial duration series distributions of the European dry spell lengths for the second half of the twentieth century, Theorical and Applied Climatology 123, 63-81, 2016.

Scholz, F. W., Stephens, M. A.: K-Sample Anderson–Darling Tests, Journal of the American Statistical Association, 82:399, 918-924, 1987.

Serinaldi, F., Kilsby, C.: The importance of prewhitening in change point analysis under persistence, Stochastic Environmental Research and Risk Assessment, 30(2), 763-777, 2016.

Serinaldi, F., Kilsby, C.G., Lombardo, F.: Untenable non-stationarity: An assessment of the fitness for purpose of trend tests in hydrology, Adv. Water Resour., 111, 132–155, https://doi.org/10.1016/j.advwatres.2017.10.015, 2018.

Sivakumar, M.V.K.: Empirical analysis of dry spells for agricultural applications in West Africa. J Climate 5:532–540, 1992.

Stagge, J.H., Kingston, L. M. Tallaksen, Hannah, D.M.: Observed drought indices show increasing divergence across Europe. Sci. Rep., 7, 4045,https://doi.org/10.1038/s41598-017-14283-2, 2017.

Tibshirani, R., G. Walther, Hastie T.: Estimating the number of clusters in a data set via the gap statistic, Journal of the Royal Statistical Society: Series B., 63(2), 411–423, 2001.

Todorovic, M, Karic, B, Pereira, L.S.: Reference evapotranspiration estimate with limited weather data across a range of Mediterranean climates, J. Hydrol., 481, 166–176, 2013.

Tramblay, Y., Hertig, E.: Modelling extreme dry spells in the Mediterranean region in connection with atmospheric circulation. Atmospheric Research, 202, 40-48, 2018.

Trenberth, K. E., Dai, A., van der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R. and Sheffield, J.: Global warming and changes in drought, Nat. Clim. Chang., 4, 17, http://dx.doi.org/10.1038/nclimate2067, 2014.

Vicente-Serrano, S. M., Beguería-Portugués, S.: Estimating extreme dry-spell risk in the middle Ebro valley (northeastern Spain): a comparative analysis of partial duration series with a general Pareto distribution and annual maxima series with a Gumbel distribution, Int. J. Climatol., 23: 1103–1118, 2003.

Vicente-Serrano, S. M., C. Azorin-Molina, A. Sanchez-Lorenzo, J. Revuelto, E. Morán-Tejeda, J. I. López-Moreno, Espejo F.: Sensitivity of reference evapotranspiration to changes in meteorological parameters in Spain (1961–2011), Water Resour. Res., 50, 8458–8480, doi: 10.1002/2014WR015427, 2014a.

Vicente-Serrano, S.M., Azorin-Molina, C., Sanchez-Lorenzo, A., Revuelto, J., López-Moreno, J.I., González-Hidalgo, J.C., Espejo, F.: Reference evapotranspiration variability and trends in Spain, 1961–2011. Global and Planetary Change, 121, 26–40, 2014b.

Vicente-Serrano, S.M., Lopez-Moreno, J.I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J.M., Azorin-Molina, C., Tejeda-Moran, E., Revuelto, J., Trigo, R., Coelho, F., Espejo, F.: Evidence of increasing drought severity caused by temperature rise in Southern Europe. Environ. Res. Lett., 9 (4), 044001. http://dx.doi.org/10.1088/1748-9326/9/4/044001, 2014c.

Vicente-Serrano, S.M., Van der Schrier, G., Beguería, S., Azorin-Molina, C., Lopez-Moreno, J.I.: Contribution of precipitation and reference evapotranspiration to drought indices under different climates, J. Hydrol., 526, 42-54, 2015.

Vicente-Serrano, S.M., D.G. Miralles, F. Domínguez-Castro, C. Azorin-Molina, A. El Kenawy, T.R. McVicar, M. Tomás-Burguera, S. Beguería, M. Maneta, Peña-Gallardo, M.: Global Assessment of the Standardized Evapotranspiration Deficit Index (SEDI) for Drought Analysis and Monitoring, J. Climate, 31, 5371–5393, 2018.

Ward, J. H.: Hierarchical Grouping to Optimize an Objective Function, Journal of the American Statistical Association, 58 (301): 236–244, 1963.

Wilks, D.S.: The Stippling Shows Statistically Significant Grid Points: How Research Results are Routinely Overstated and Overinterpreted, and What to Do about It, Bulletin of the American Meteorological Society, 97(12), 2263-2273, 2016.

Zkhiri, W., Tramblay, Y., Hanich, L., Berjamy, B.: Regional flood frequency analysis in the high-atlas mountainous catchments of Morocco, Natural Hazards, 86(2), 953-967. http://dx.doi.org/10.1007/s11069-016-2723-0, 2017.

## INDEX OF FIGURES

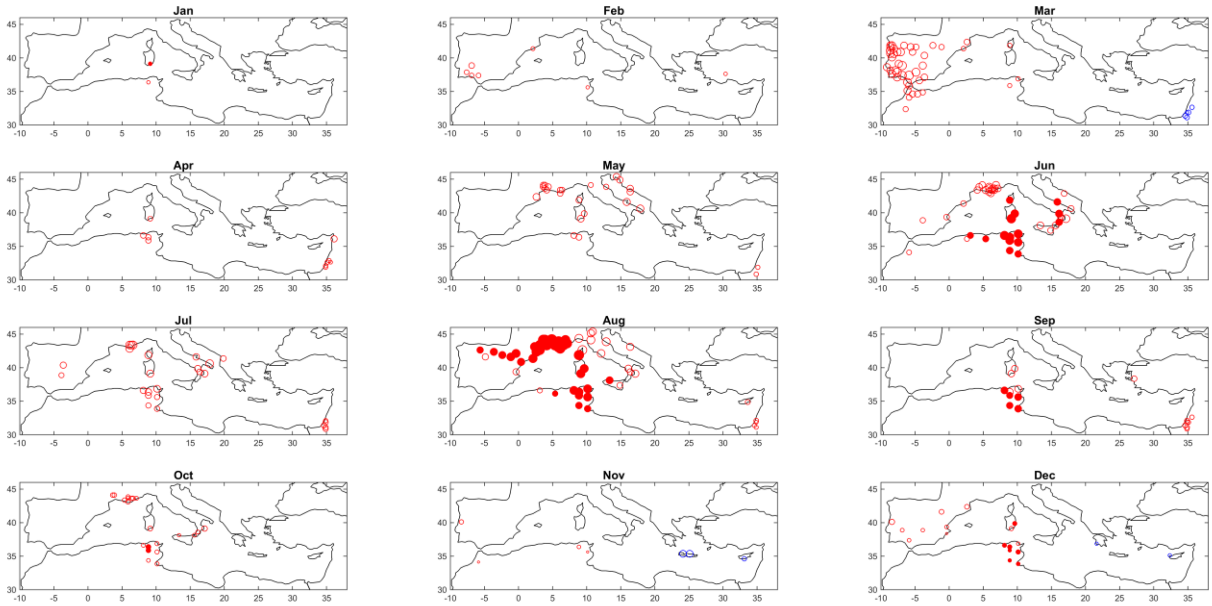


Figure 1: Significant trends (5% level) in monthly $ET_0$. The size of the circles indicate the magnitude of the trends (red = increasing, blue = decreasing) and the filled circles denote regional significant trends

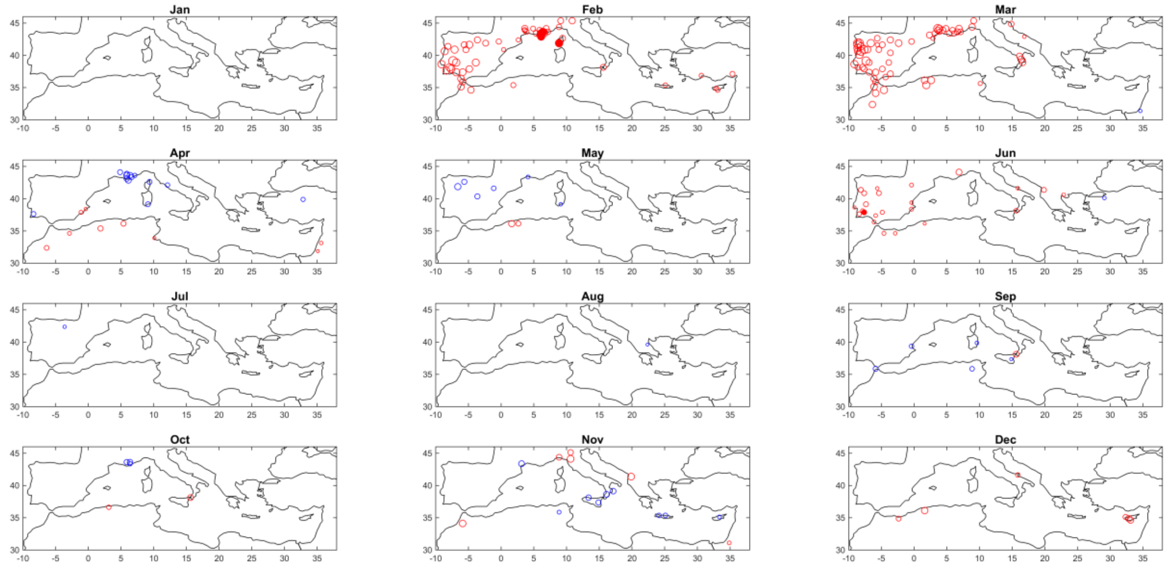


Figure 2: Significant trends (5% level) in the frequency of dry days when considering the 1mm threshold to define a dry day. Same as Fig.1 for the display

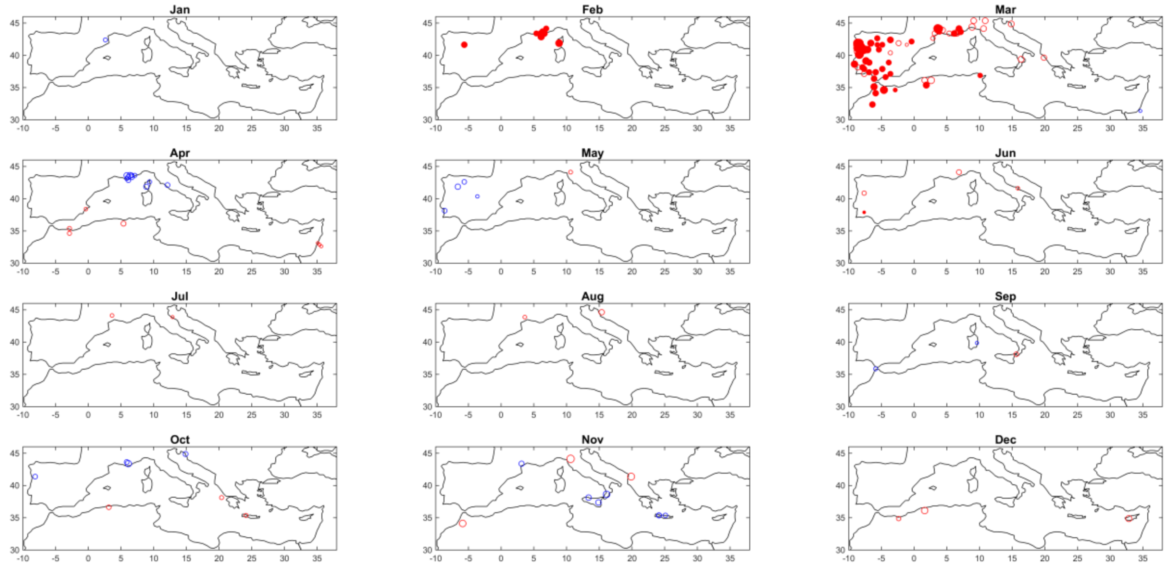


Figure 3: Significant trends (5% level) in the frequency of dry days, considering that P-$ET_0$ = 0 is a dry day. Same as Fig.1 for the display

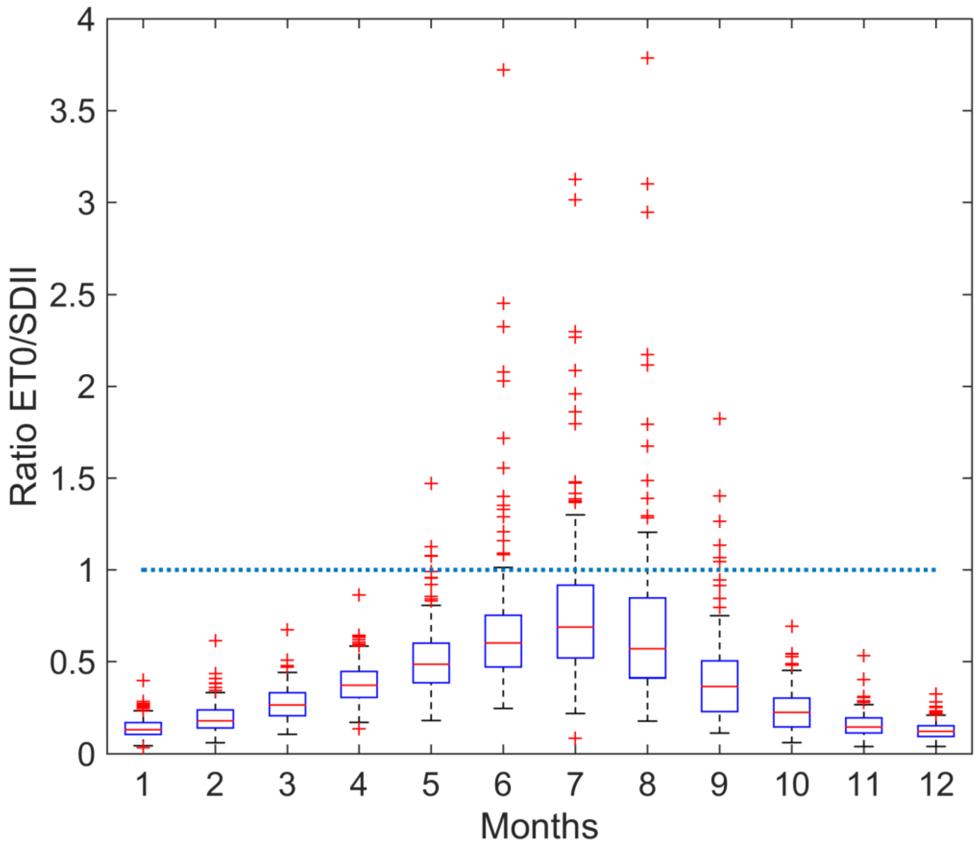


Figure 4: Boxplot of the monthly ratios between ET0 and SDII. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to +/- 1.5 interquartile range

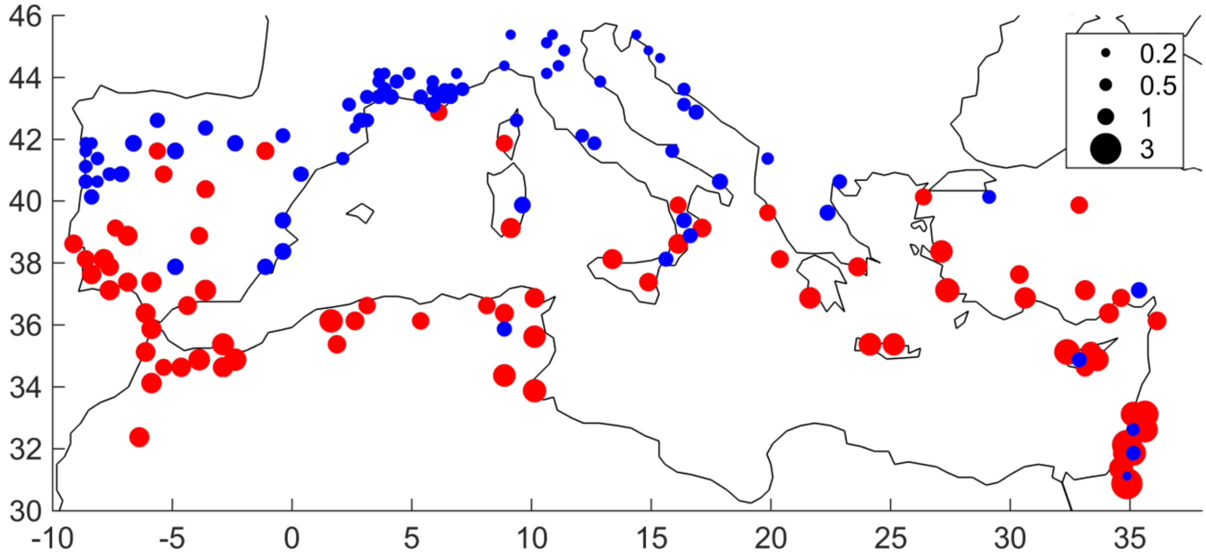


Figure 5: Ratio between ET0 and SDII for June, July, August. In blue the stations where the ratio is inferior to 1 (SDII>ET0), in red where the ratio superior to 1 (SDII<$ET_0$)

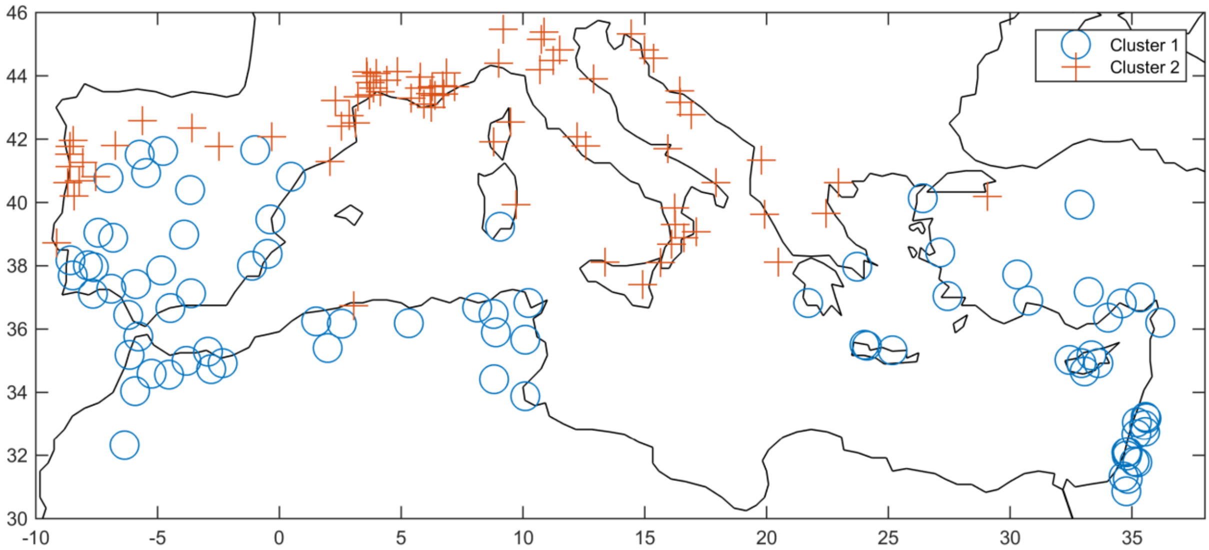


Figure 6: Clustering result of monthly net precipitation (P-ET$_0$)

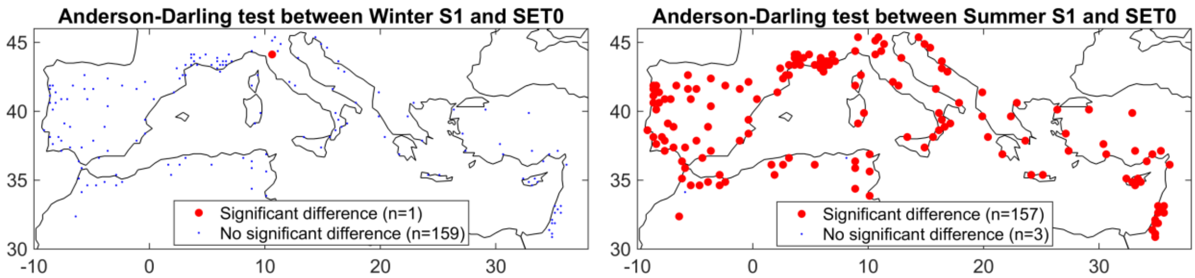


Figure 7: Anderson-Darling test results between winter extreme dry spells defined with S1 or SETP (left) and summer extreme dry spells defined with S1 or SET$_0$ (right)

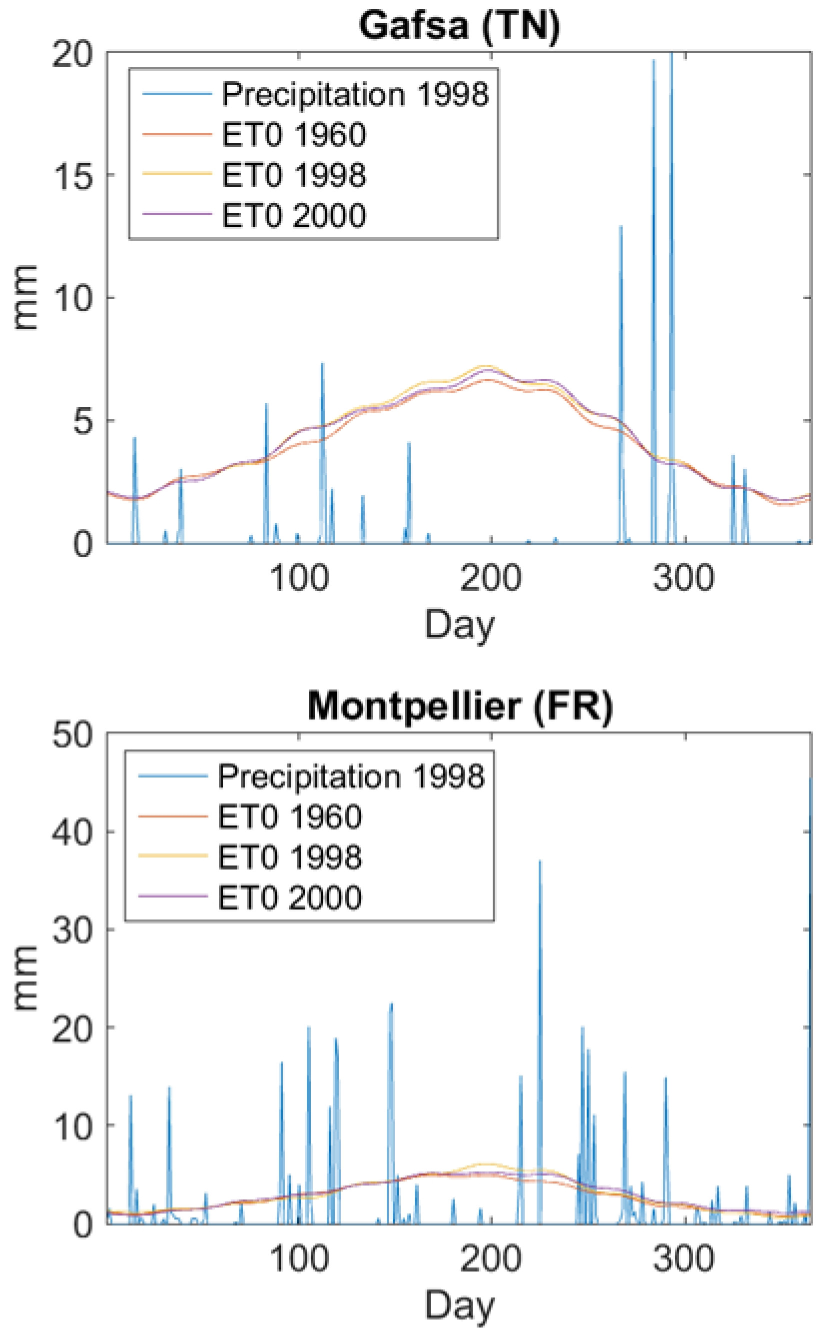


Figure 8: Daily precipitation for the year 1998 plotted with $ET_0$ in 1960, 1998 and 2000 for two stations, Gafsa in Tunisia and Montpellier in France

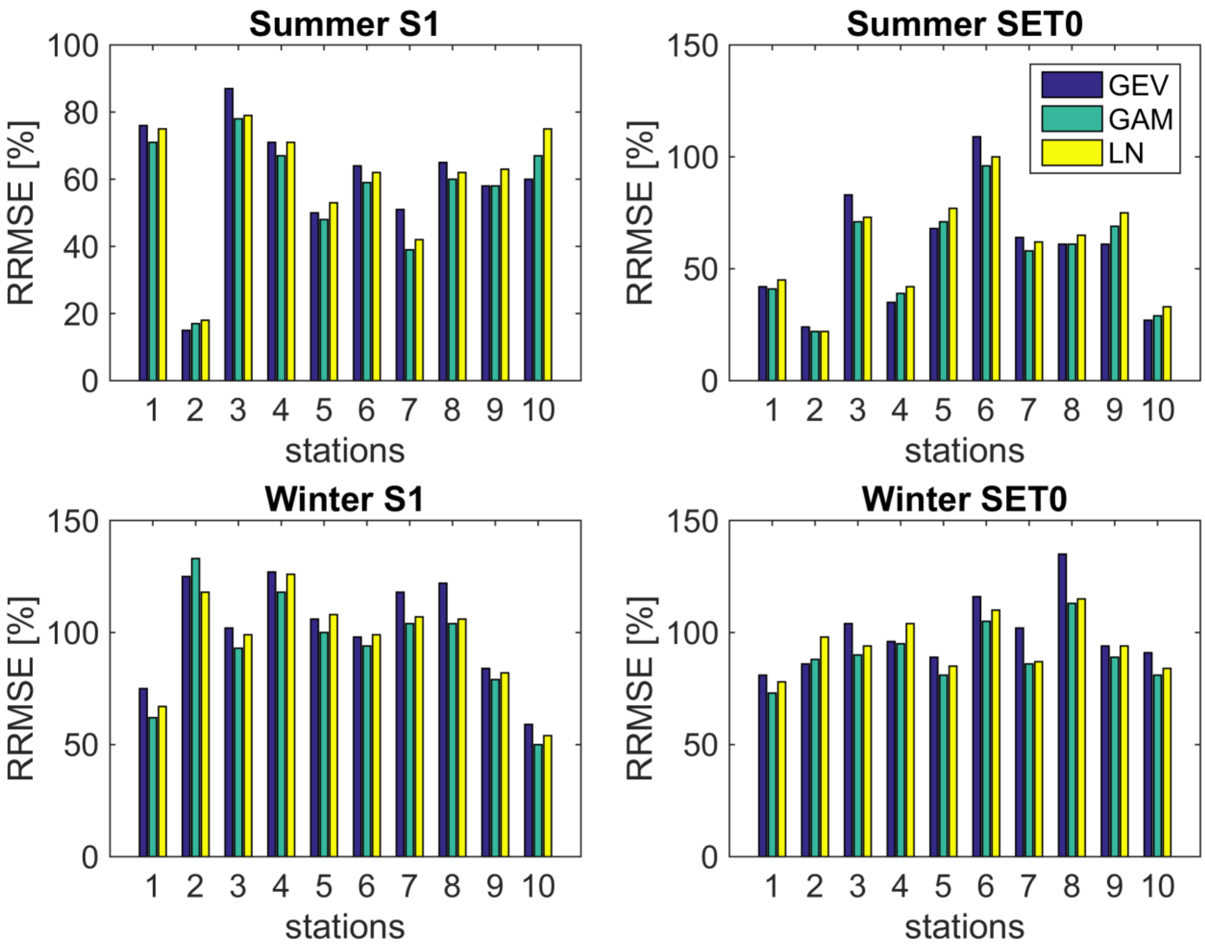


Figure 9: Validation results of the fitting of the GEV, Gamma (GAM) and Log-Normal (LN) distributions in terms of relative root mean square error (RRMSE) for 10 representative stations (stations numbers: 1-Athens (GR), 2-Tel Aviv (IS), 3-Mantova (IT), 4-Lisboa (PT), 5-Madrid (ES), 6-Montpellier (FR), 7-Roma (IT), 8-Beni Mellal (MA), 9-Tunis (TN), 10-Capo Bellavista (IT))

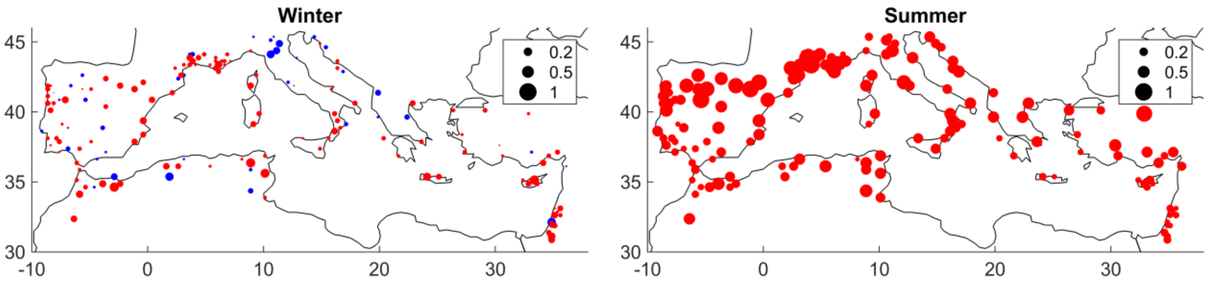


Figure 10: Relative difference of the 20-year quantile of extreme dry spell computed with $SET_0$ compared to S1. Red (blue) dots indicate that $SET_0$ 20-year quantiles are larger (smaller) than those obtained with S1. The larger the bubble, the largest is the difference between S1 and SET0 (in the legend, 1 = 100% overestimation)