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Hydrological drought analysis in Continental Temperate and Mediterranean environment during the period 1981-2017

Analisi della siccità idrologica in ambiente Temperato Continentale e ambiente Mediterraneo, nel periodo 1981-2017

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Abstract. A 37 year (1981-2017) study of the hydrological drought trend was conducted in two Italian regions, Piedmont and Sardinia, with different climatic features (Temperate Continental climate and Mediterranean climate, respectively). For this purpose, we have examined the daily data of 13 meteorological stations uniformly installed in the two areas, and the trends of the Standardised Precipitation Index (SPI) and Standardised Precipitation Evapotranspiration Index (SPEI) have been also evaluated. The similarities and differences between the indices of the two regions were then considered. In most stations of both zones, there is a statistically significant trend of increase in the SPI and decrease in the SPEI. Nevertheless, the trend of indices averaged over stations of the two indices is not significant in either of the two climatic zones considered.

Keywords. Hydrological drought, SPI, SPEI, climate indices.

Riassunto. Uno studio di 37 anni (1981-2017) sull'andamento della siccità idrologica è stato realizzato in Piemonte e in Sardegna, due regioni italiane che presentano diverse caratteristiche climatiche (rispettivamente clima Temperato Continentale e clima Mediterraneo). A tal fine, sono stati esaminati i dati giornalieri di 13 stazioni meteorologiche installate uniformemente nelle due aree, e sono stati altresì valutati gli andamenti dell'Indice di Precipitazione Standardizzata (SPI) e dell'Indice di Evapotraspirazione e Precipitazione Standardizzati (SPEI). Sono state quindi considerate le somiglianze e le differenze tra gli indici delle due regioni. Nella maggior parte delle stazioni di entrambe le zone, vi è una tendenza statisticamente significativa di aumento dello SPI e di diminuzione dello SPEI. Tuttavia, l'andamento dei valori medi sulle stazioni dei due indici non è significativo in nessuna delle due zone climatiche considerate.

Parole chiave. Siccità idrologica, SPI, SPEI, indici climatici.

INTRODUCTION

Drought is a natural hazard caused by a lower-than-average reduction of precipitation. When the phenomenon occurs for the duration of a season or for extended periods of time, it creates insufficient conditions to supply human and environmental demands (WMO, 2006). In contrast to aridity, which is defined as a permanent condition, drought is a temporary climate phenomenon that typically begins as a dry spell or a period of abnormally dry weather.

A drought can alternatively be broadly defined as a temporary, recurring reduction in the precipitation in an area, and is considered as one of the most important climate change impacts on natural and socio-economic systems. Few extreme events are as economically and ecologically disruptive as drought, which affects millions of people in the world each year (Dai, 2011). Its effects occur after long periods without precipitation, therefore it is difficult to objectively quantify its characteristics in terms of intensity, amplitude, duration and spatial extent (Bordi *et al.*, 2009; Vicente-Serrano *et al.*, 2010; Bevan *et al.*, 2014). In recent years, drought has become more intense and frequent, which has a negative impact on the socio-economic balance of the countries concerned. For example, in recent years the Californian government had to limit water use for irrigation and domestic use (Dettinger and Cayan, 2014); in 2012 an increase in food price was caused by a simultaneous drought in USA and Russia (Van Loon, 2015); in 2011, a mass migration in the Horn of Africa was caused by drought (Viste *et al.*, 2012); and in 2010, drought affected food production in large parts of China (Lu *et al.*, 2011).

Mountain regions and the Mediterranean basin, considered "hot spots" of climate change, are susceptible to drought situations and are heavily impacted by extreme events (Ronchi *et al.*, 2007; Capra and Scicolone, 2012). Over the past 30 years, the temperature in Piedmont increased by 0.7 °C (Fratianni *et al.*, 2015), and July of 2015 was the hottest month on record, while the period from July to October of 2017 was one of the driest in the last 60 years, with the main Piedmontese river Po always below the average flow. While no significant variation was recorded in the annual amount of precipitation, the seasonal distribution has changed with a decrease during the winter season of -1.5 mm year^{-1} in the north of Italy, and -7.7 mm year^{-1} in the central part (Fratianni and Acquaotta, 2017). Extreme drought years have been reported in Sardinia since 1981, with a greater frequency in the last decade, especially in the springtime, at the beginning of the vegetative season, and in the South of the island (Pulina, 2012). Temperature and extreme events are expected to increase at the end of the century, according to future climate projections. For example, for the near future (next 15-20 years), Perini *et al.* (2011) predicted a strong decrease in winter and spring precipitation in Northern and Southern Italy, and a reduction of summer rainfall in Southern Italy and in the Islands. While, by the 2100s, a general temperature increase of about 3 °C is expected in all seasons across the whole of Italy, peaks of 4 °C are projected for the Po Valley in winter and over the whole north-west region in summer (Bucchignani *et al.*, 2016), according to the RCP4.5 scenario, with increasingly frequent and long-lasting heat waves, which will extend to more than thirty days over the entire summer season (Collins *et al.*, 2013; Drumond *et al.*, 2017; González-Hidalgo *et al.*, 2018). On the contrary, the RCP8.5 scenario predicts a strongly significant precipitation reduction in spring and summer in the Alpine area with a negative anomaly from 0.1 to 0.4 mm day^{-1} (Bucchignani *et al.* 2016). In these future climate scenarios, drought events will become increasingly common, more intense and less predictable, especially in vulnerable environments such as Alps and Mediterranean.

Although numerous climatic and biological classifications have been proposed for aridity and drought conditions (e.g. De Martonne, 1926; Thornthwaite, 1948; Palmer, 1965; Agnew and Anderson, 1992; Pashiardis and Michaelides, 2008; Hannaford *et al.*, 2011; Nastos *et al.*, 2013; Beguéria *et al.*, 2014; Beguéria *et al.*, 2018), it is still difficult to define wetness limits precisely and delineate the boundary between different degrees or levels of aridity/drought or the opposite, humidity. In 2009, the World Meteorological Organization, recommended that the Standardised Precipitation Index, SPI (McKee *et al.*, 1993) be used around the world to characterize meteorological droughts. Cheval *et al.* (2014), analysed the spatial and temporal variability of meteorological drought in Romania by using SPI and distinguished winter and summer driving factors of the drought spells. SPI was also investigated in six regions of southern South America in order to observe the duration of dry sequences (Minetti *et al.*, 2010). Furthermore, SPI is a useful index to analyse and compare time series of monthly precipitation in the past with the ongoing time series (Rana *et al.*, 2016). Temperature, wind and relative humidity are also important factors to include in characterizing drought, and most recently, Vicente-Serrano *et al.* (2010) proposed a further index which combines precipitation, temperature and evapotranspiration, called Standardised Precipitation Evapotranspiration Index (SPEI). SPI and SPEI were both used to characterize the summer 2015, which ranks as the hottest and climatologically driest summer since 1950 over extended regions in eastern Europe (Ionita *et al.*, 2017).

The aims of this work are *i*) to analyse the hydrological drought conditions, which are related to the effect of the absence of precipitation on water resources, in two different Italian climatic regions: Temperate Continental climate in Piedmont region and Mediterranean climate in Sardinia region; *ii*) to compare the two above-mentioned standardised indices (SPI and SPEI) to delineate drought conditions between two different environments, and *iii*) to verify potential drought trends during a period of 37 years (1981-2017), in an ongoing climate change scenario.

MATERIALS AND METHODS

Study area

The study was conducted in two Italian regions, Piedmont and Sardinia (Fig. 1), with a marked climatic difference (Fig. 2).

Piedmont region is located in the continental area at the base of the Western Alps, between 44°02'N and 46°26'N and between 06°49'E and 08°32'E. Although the region is relatively small, it is characterised by a varied topography with a predominance of mountains. The Alps, where most peaks are over 2,500 m, mark the border with France to the West and Switzerland to the North. The hilly areas which border the western part of the Po Valley complete the physical boundaries of the region. The altitudinal gradient (from about 100 m to 4,000 m a.s.l.) strongly influences the regional climate, which experiences great variation in temperature and precipitation over a short distance (Nigrelli *et al.*, 2018). The climate is Continental Temperate, "*Cf*", according to Köppen's classification (Fratianni and Acquaotta, 2017). The average annual temperature varies between 11-12 °C in the lowlands area and it does not exceed 1 °C in mountainous areas above 2,400 m a.s.l. Annual precipitation rate varies from 500-700 mm in the plains to 2,000 mm in the interior Alpine valleys. The rainfall pattern is characterized by a classic bimodal trend, with two peaks in spring and autumn, and a minimum in winter (Bandini, 1931; Baronetti *et al.*, 2018).

Sardinia region is the second largest island in the Mediterranean Sea and is located between 38°53'N and

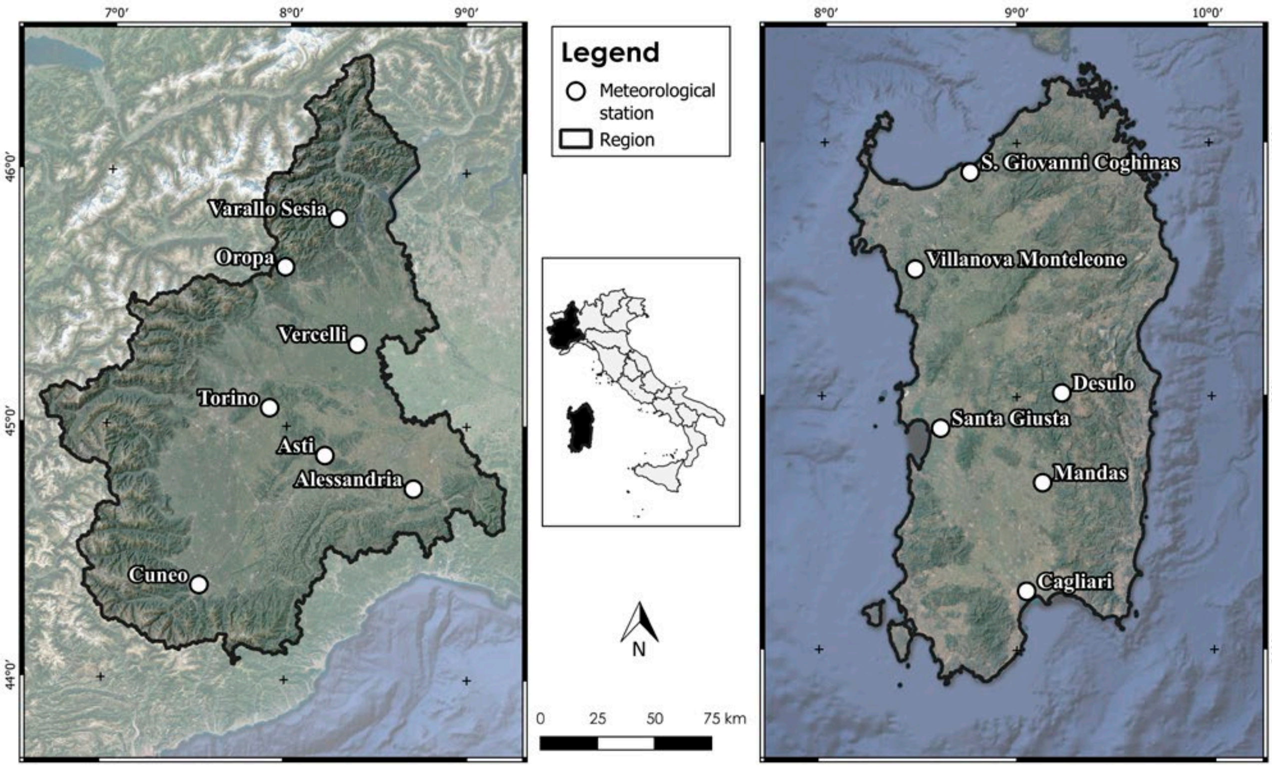

Fig. 1. Study area: Piedmont region on the left, Sardinia region on the right; white dots indicate positions of meteorological stations.

Fig. 1. Area di studio: Regione Piemonte a sinistra, Regione Sardegna a destra; i punti bianchi indicano le posizioni delle stazioni meteorologiche.

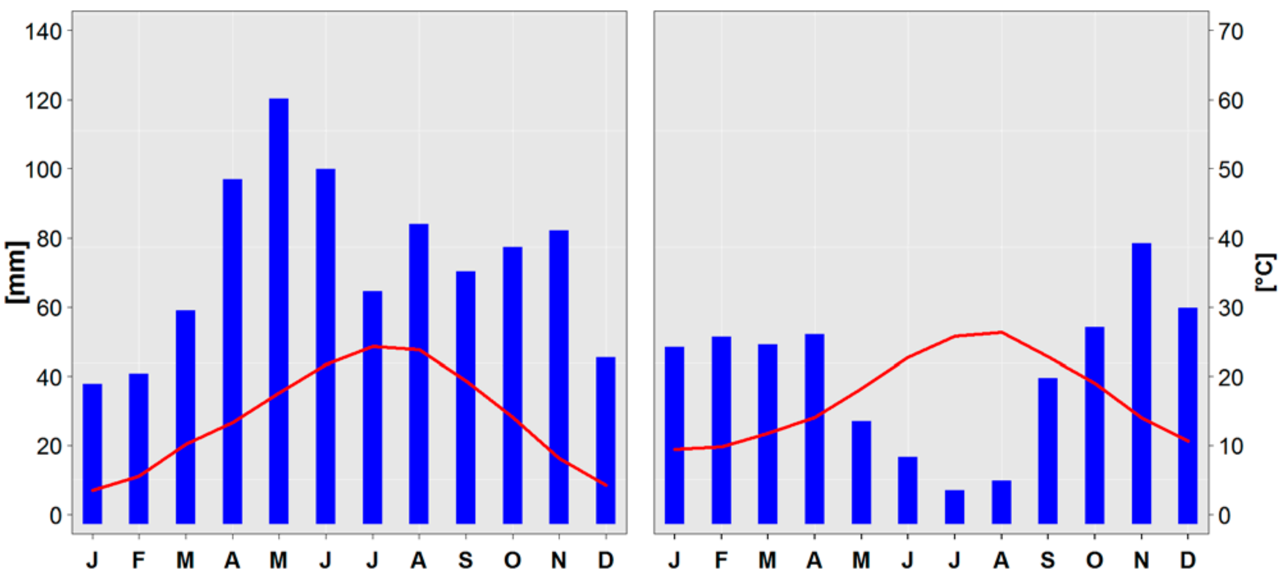

Fig. 2. Thermo-pluviometric diagram for Torino data series (on the left) and Cagliari/Elmas (on the right) during the period 1981-2017. Blue bars: precipitation amount; red lines: temperature.

Fig. 2. Diagramma termopluviometrico per le serie di Torino (a sinistra) e di Cagliari/Elmas (a destra), nel periodo 1981-2017. Barre azzurre: precipitazioni; linee rosse: temperatura

41°15'N and between 8°08'E and 9°48'E. The topography is mainly characterized by hills and plateaus, but also by flat areas in the West and mountainous areas in the East, with peaks higher than 1,300 m a.s.l. The average altitude is 334 m a.s.l. The climate is typically Mediterranean, "*Csa*", according to Köppen's classification, with mild and relatively rainy winters and hot, dry summers. Mean annual temperatures are strongly influenced by the distance from the sea and by the orography; the values range from 16-17 °C in the western plains (Campidano and Nurra) to 10-12 °C in the eastern highlands (Gennargentu, Limbara). The average annual precipitation is less than 500 mm in the lowlands area, while it exceeds 1,300 mm on the highest peaks. The maximum rainfall is normally recorded in December, with average values exceeding 200 mm in the mountainous areas (Pulina, 2015).

Meteorological data

Daily weather data in Piedmont region were collected from thermo-pluviometric stations of the Italian Hydrographic Mareographic Service (SIMN). Alessandria, Asti, Cuneo, Oropa, Torino, Varallo Sesia and Vercelli were the stations considered (Tab. 2). These are uniformly distributed in the region (Fig. 1) with an altitude range between 90 m and 1,180 m a.s.l. Meteorological stations above the limit of 1,200 m a.s.l. were excluded from the analysis in order to standardise the measurements with the Sardinian stations.

In the Sardinia region, daily temperature and precipitation data were obtained from the Hydrographic Sector of Sardinia Region (RAS) and Desulo, Mandas, San Giovanni Coghinas, Santa Giusta and Villanova Monteleone were the weather stations considered. These were supplemented by the addition of Cagliari/Elmas station from the Italian Air Force meteorological station network (Tab. 2). The altitude range of the stations (Fig. 1 and Tab. 2) is between 10 and 920 m a.s.l.. Their location is representative of the different geographical and topographical conditions of the island.

Daily precipitation (P) and maximum (T_x) and minimum (T_n) daily temperature data were considered for all stations during the period 1981-2010, which is the current climatological standard 30-year period (WMO, 2017).

An additional seven years (2011-2017) were collected for the stations of Torino and Cagliari/Elmas, in Piedmont and Sardinia region respectively, resulting in a total of 37 years of data. The two additional series of data (1981-2017), in the most representative stations of the two territories, were analysed in order to compare the most recent trends in two different areas. Fig. 2 shows the thermo-pluviometric diagrams of the two stations.

Method

A Quality Control (QC) analysis was conducted on the daily data series by using the R software *ClimPACT2* package (Alexander and Herold, 2016) to identify gaps, outliers and erroneous values (Acquaotta *et al.*, 2019). This algorithm detects incorrect values, such as P < 0 mm or $T_x < T_n$ and provides a series of graphical representations in the form of box diagrams in a monthly and annual scale, to evaluate discontinuities present in the series (Acquaotta *et al.*, 2016).

Outlier values are identified through the calculation of the estimated thresholds on the statistical characteristics of the series (Fortin *et al.*, 2016).

After the QC, on the T_x and T_n series, we carried out two homogenization tests, HOMER (Mestre *et al.*, 2013) and SLIDHOM (Mestre *et al.*, 2011) to identify and to correct the breaks or discontinuities (Acquaotta and Fratianni, 2014). HOMER was applied on monthly scale to identify the breaks, while the SPLIDHOM was carried out on the daily series to correct the inhomogeneities.

In order to characterize the hydrological drought in both regions, we used two derived indices: Standardised Precipitation Index - SPI (McKee *et al.*, 1993) and Standardised Precipitation Evapotranspiration Index - SPEI (Vicente-Serrano *et al.*, 2010). The two drought indices have been calculated for every meteorological station and subsequently represented as a single average value for each region.

SPI is an index based on monthly cumulative precipitation and classifies the accumulated precipitation of the month under consideration with respect to the long-term average monthly accumulated precipitation for the same month (or other time scales). SPI quantifies a deficit or surplus of rain over mean values, using a probabilistic approach for the precipitation event. The rainfall series is adapted to a gamma distribution, then transformed into a normal distribution having a null mean and a standard deviation equal to 1. SPI indicates the number of standard deviations by which a particular event exceeds from mean conditions.

SPEI is a multiscalar drought index designed to take into account both precipitation and potential evapotranspiration (PET). SPEI looks at long-term rainfall at different timescales and compares it with expected demand as indicated by potential evapotranspiration. The PET has been estimated with the Thornthwaite equations (Thornthwaite, 1948), a temperature-based method that uses only mean monthly temperature and latitude of the site to estimate potential evapotranspiration. The monthly average temperature and cumulative precipitation values were used to calculate SPEI.

Tab. 1. Classification of the wet and drought periods of SPI and SPEI, according to McKee et al. (1993) and Vicente-Serrano et al. (2010), respectively. SPI and SPEI indices are dimensionless.

Tab. 1. Categorizzazione dei periodi umido e di siccità di SPI e SPEI, rispettivamente secondo McKee et al. (1993) e Vicente-Serrano et al. (2010). Gli indici SPI e SPEI sono adimensionali.

Category	SPI and SPEI values (dimensionless)
Extremely wet	≥ 2.00
Severely wet	1.5 – 1.99
Moderately wet	1.00 – 1.49
Close to normal	-0.99 – 0.99
Moderately dry	-1.49 – -1.00
Severely dry	-1.99 – -1.50
Extremely dry	≤ -2.00

Classification of wet and dry periods based on SPI and SPEI indices as shown in Tab. 1.

On the annual scale (12-months) we calculated the trends of SPI and SPEI and then we compared the results with the annual trend of four climate indices, total annual P (prectot) for days with P ≥ 1.0 mm, total annual P from heavy rain days (r95p) with annual sum of daily P > 95th percentile, amount of hot days (T_X90p) percentage of days when T_X > 90th percentile, and amount of hot nights (T_N90p) percentage of days when T_N > 90th percentile (Tab. 2). The trend was computed by a linear least square and statistical significance was calculated at 95 % confidence level using F test, for both indices, in each station (Tab. 2) of the two regions (Fig. 3 and Fig. 4). A negative trend value means an increase of drought spells, and the statistical significance of the trend was verified by using the non-parametric test of Mann-Kendall (p value < 0.05) (Giaccone *et al.*, 2015).

Furthermore, the SPI and SPEI trends were calculated for the Torino and Cagliari/Elmas meteorological data on a timescale of 12 and 24 months, based on the period from 1981 to 2017.

RESULTS AND DISCUSSION

The Standardised Precipitation Index for the seven stations of Piedmont region showed no homogeneous trend (Tab. 2). The series of Cuneo, Torino and Vercelli stations showed a statistically significant upward trend. At these locations, increasing trends were observed in two climate indices of precipitation, prectot and r95p. Neither of the two indices were statistically significant according to the Mann-Kendall test. The trend was downward and statistically significant for Oropa site where the precipitation indices show decreasing trends and statistically significant for r95p. The series of Alessandria, Asti and Varallo Sesia stations, as well as the average SPI for those three stations showed no trend. Also, the trends of precipitation indices are not statistically significant, and the coefficients do not identify important variations. They range between 1.83 mm year^{-1} to 4.17 mm year^{-1} for prectot and between -4.87 mm year^{-1} to 0.94 mm year^{-1} for r95p (Tab. 2).

The period with the greatest number of consecutive wet months (SPI > 0) (Fig. 3) ranged from July 1992 to April 1997, a total of 58 months, while the period with the greatest number of consecutive dry months (SPI < 0) ranged from December 2004 to June 2008, 43 months. On average, wet periods alternated with dry periods of six months in this region.

On the other hand, the trend of SPEI is decreasing and is statistically significant in all the Piedmontese stations considered (Tab. 2). The maximum decrease (-0.004), is calculated for the Oropa station, followed by Asti and Cuneo (-0.003). The behaviour of this index is well correlated with the behaviour of temperature index, T_X90p. The trend of T_X90p is increasing and is statistically significant in most of the stations. The trends range between 0.67 % year^{-1}, calculated in Oropa, to 0.33 % year^{-1}, calculated in Alessandria (Tab. 2).

The average SPEI among stations shows a downward trend (-0.002), but not statistically significant. The longest wet period observed was between July 1992 and April 1997, 58 months, while the longest dry period lasted from November 2004 to November 2008, 49 months (Fig. 3).

Regarding Sardinia region, the SPI (Tab. 2) showed an increasing and statistically significant (0.002) trend only in 2 of the 6 stations considered (Santa Giusta and Desulo). The SPI calculated for the other stations and the average SPI for those stations showed no significant trend during the considered period. The trends on precipitation indices are not statistically significant in Santa Giusta e Desulo, with an increasing trend as for prectot while is decreasing for r95p. Also, in the other stations the trends are not statistically significant but for prectot the slopes are negative and near to zero, ranging between -0.99 mm year^{-1} to -0.47 mm year^{-1} (Tab. 2). The average SPI value over stations (Fig. 4) remained consistently above 0 for a maximum of 34 months, from April 1984 to January 1987 and for 30 consecutive months, from October 2003 to March 2006. Values were less

Tab. 2. Weather stations list analysed in Piedmont and Sardinia regions for the reference period 1981-2010, with their values of Elevation (Alt. m a.s.l.), coordinates (Lat N; Lon E), the calculated SPI and SPEI annual trends (year^{-1}) at 12 months, annual total wet-day (prectot), total annual P from heavy rain days (r95p), amount of hot days (T_X90p), and amount of hot nights (T_N90p) at 12- month time scale. Statistically significant trends with a *p value* ≤ 0.05 are indicated in bold.

Tab. 2. Elenco delle stazioni meteorologiche analizzate nelle regioni piemontesi e sarde per il periodo di riferimento 1981-2010, con i loro valori di quota (m s.l.m.), coordinate (Lat N; Lon E), i valori dei trend annuali di SPI e SPEI (anno^{-1}), precipitazioni totali (prectot) ed intense (r95p), numero di giorni di caldo (T_X90p), e numero di notti di caldo (T_N90p) su scale temporale di 12 mesi. I valori statisticamente significativi (p ≤ 0,05) sono evidenziati in grassetto.

	Station	Alt. m a.s.l.	Lat N	Lon E	SPI	SPEI	prectot	r95p	T_x90p	T_n90p
Piedmont Region	Alessandria	90	4955808	476651	0	**-0.002**	1.83	1.47	**0.33**	0.16
	Asti	117	4970569	437876	0	**-0.003**	3.41	0.94	**0.40**	**-0.32**
	Cuneo	575	4914085	382681	**0.002**	**-0.003**	3.98	4.05	0.62	0.10
	Oropa	1180	5053196	420664	**-0.003**	**-0.004**	-18.77	**-17.17**	**0.67**	0.14
	Torino	239	4991497	413680	**0.003**	**-0.001**	7.00	3.42	0.43	-0.11
	Varallo Sesia	453	5074366	443680	0	**-0.001**	1.40	-4.87	**0.55**	-0.04
	Vercelli	135	5019297	452240	**0.002**	**-0.002**	4.17	3.12	**0.58**	0.09
Sardinia Region	Cagliari	21	4342672	504315	0	0	-0.47	0.87	**0.20**	**0.24**
	Desulo	920	4429509	519699	**0.002**	**0.002**	4.71	-0.09	**-0.37**	-0.17
	Mandas	491	4390215	511294	0	0	-0.99	0.39	**0.22**	**0.26**
	S. Giovanni Coghinas	210	4526143	479570	0	**-0.003**	-0.95	-0.20	**0.36**	0.08
	Santa Giusta	10	4414049	466626	**0.002**	0	1.30	-0.16	**0.21**	0.01
	Villanova Monteleone	567	4483757	455470	0	**-0.002**	-0.88	-2.39	0.06	-0.05

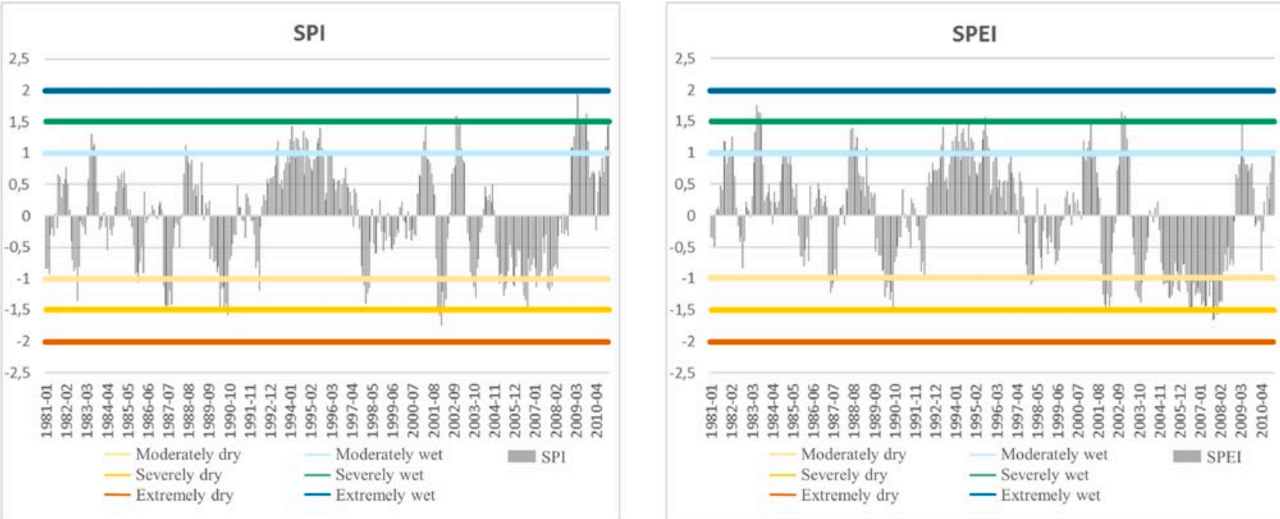

Fig. 3. Average of SPI (on the left) and SPEI (on the right) values for the stations of Piedmont region. The yellow/brown and blue/green coloured lines indicate the critical values of the indices in dry and wet conditions, respectively.

Fig. 3. Valori medi di SPI (a sinistra) e SPEI (a destra) per le stazioni della Regione Piemonte. Le linee colorate giallo/marrone e blu/verde indicano i valori critici degli indici in condizioni rispettivamente secche e umide.

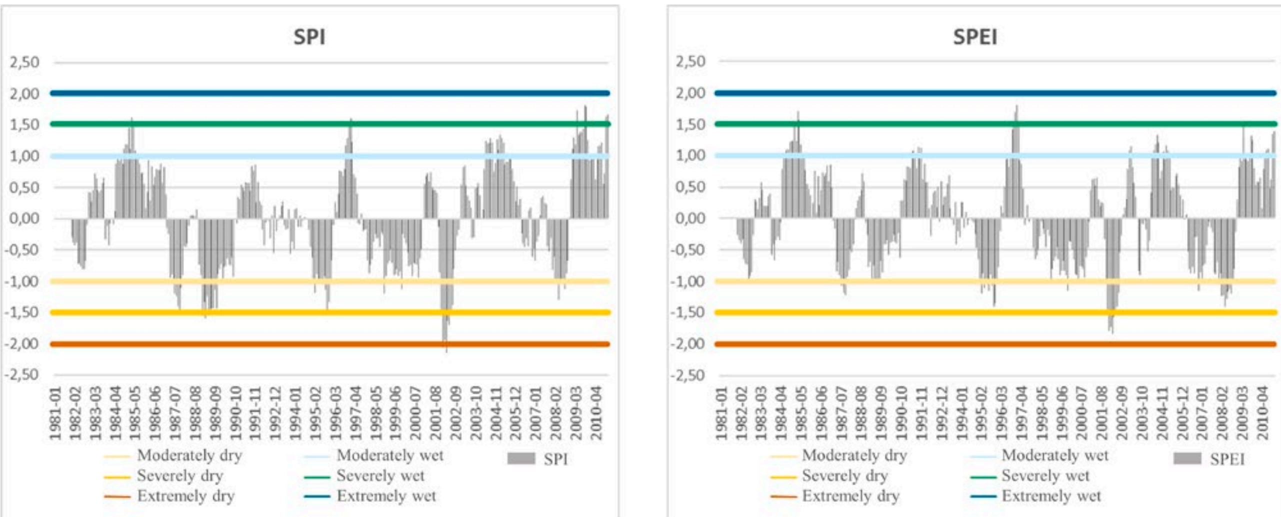

Fig. 4. Average of SPI (on the left) and SPEI (on the right) values for the stations in Sardinia region. The yellow/brown and blue/green coloured lines indicate the critical values of the indices in dry and wet conditions, respectively.

Fig. 4. Valori medi di SPI (a sinistra) e SPEI (a destra) per le stazioni della Regione Sardegna. Le linee colorate giallo/marrone e blu/verde indicano i valori critici degli indici in condizioni rispettivamente secche e umide.

than zero for a total of 40 months from September 1997 to December 2000, and for 25 consecutive months from November 1988 to November 1990. According to the classification of McKee *et al.* (1993), which evaluates the severity of drought, there were nine months considered "*Severely dry*", and two months "*Extremely dry*" (from January to March 2002), during the period 1981-2010.

The trend of SPEI (Tab. 2) is statistically significant in three of the six Sardinian stations considered. A positive trend was observed for Desulo station (0.002), and negative trend for the stations of Villanova Monteleone (-0.002) and San Giovanni Coghinas (-0.003). These behaviours are well correlated with the behaviour of temperature indices, in particular with maximum tem-

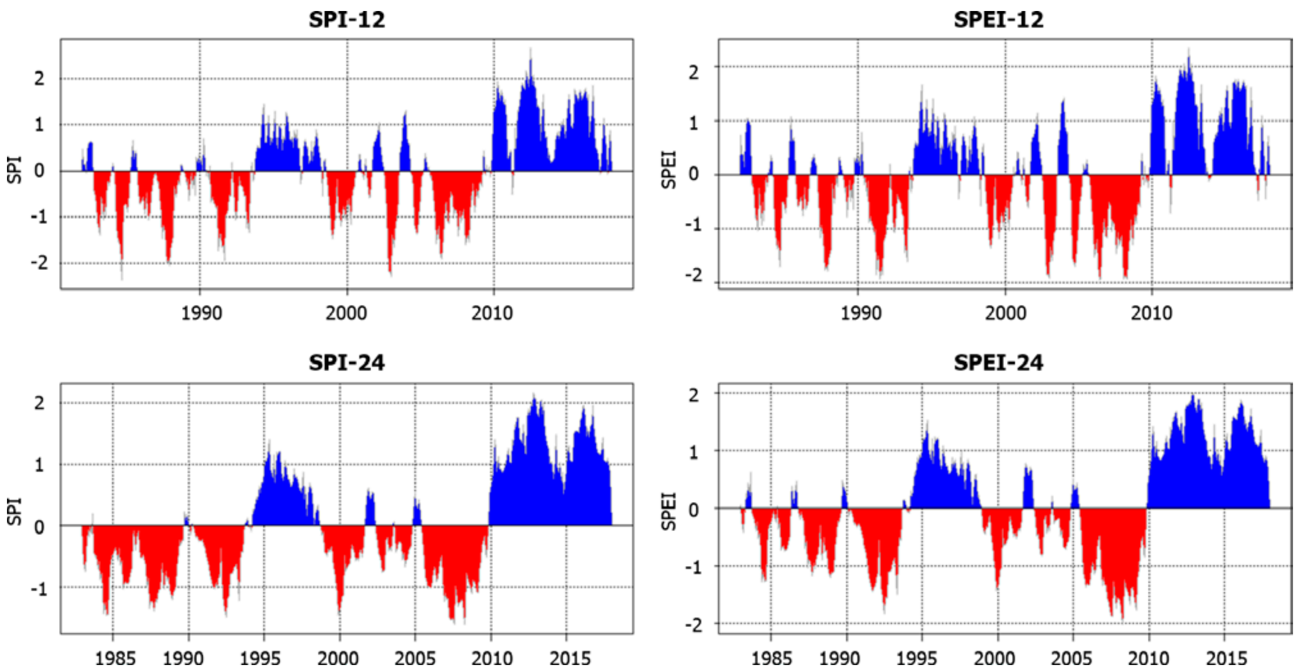

Fig. 5. SPI (on the left) and SPEI (on the right) values for the Torino station in Piedmont region, calculated on the period of 12, 24 months.
Fig. 5. Valori SPI (a sinistra) e SPEI (a destra) per la stazione di Torino in Piemonte, calcolati nel periodo di 12, 24 mesi.

perature, T_X90p. The T_X90p trend in Desulo is decreasing and statistically significant, -0.37 % year^{-1}, while in San Giovanni Coghinas and Villanova Monteleone the trends increase, but only in San Giovanni Coghinas the slope is statistically significant, 0.36 % year^{-1} (Tab. 2).

The average of SPEI shows a downward trend (< -0.001), but this is not statistically significant. The analysis of the trend of the average SPEI values (Fig. 4) showed the longest wet period was from May 1984 to January 1987 (33 months), and the longest dry period was from December 1997 to December 2000 (37 months in total).

Fig. 5 and Fig. 6 show the trend of the SPI and SPEI values calculated in the station of Torino and Cagliari/Elmas respectively, during the period 12 and 24 months.

In the last seven years in Torino, the SPI-24 and SPEI-24, as much as in the 12 months time scale, show a more humid trend with a remarkable increase of precipitation, which contrasts with the period 1981-2010 in the same region, in which dry events were prevalent. From 1993 to 1998 the second longest wet period was recorded, clearly highlighted by the 24 month graph (Fig. 5).

From a general point of view, the SPEI exhibits the difference between the dry and wet months better than the SPI. This is evident in the comparison between SPI-12 and SPEI-12. The wet episodes before 1990 are clearly shown in the SPEI-12 but are absent on the SPI-12 (Fig. 5).

In contrast to the trend experienced by Torino, the trend in Cagliari/Elmas is more regular with a clear alternation between drought and humid periods, as shown in the 24 month graphs (Fig. 6), with an exception during the period 2000-2006, during which the dry period lasted longer and no wet episodes were recorded. SPI-12 and SPI-24 recorded “*Moderately wet*” periods in the years between 2012 and 2015. SPI shows values greater than zero in the last two years in contrast to the SPEI, which shows smaller values for the same periods.

As described by Vicente-Serrano *et al.* (2010), the influence of PET on drought conditions is difficult to estimate. In this analysis it is possible to compare the extent of drought indicated by both SPI, which is a precipitation-based index in which PET is not included, and SPEI, in which PET is included, for the same time period. This comparison illustrates the different and sometimes contrasting outcomes regarding the evaluation of drought when PET is included in the analysis. For example, at the end of the time series in Cagliari/Elmas, SPI-12 and SPI-24 indicate a wet period while SPEI-12 and SPEI-24 indicate a continuation of drought condition (Fig. 6).

CONCLUSIONS

The trend analysis of hydrological drought in two different environments, Temperate Continental climate

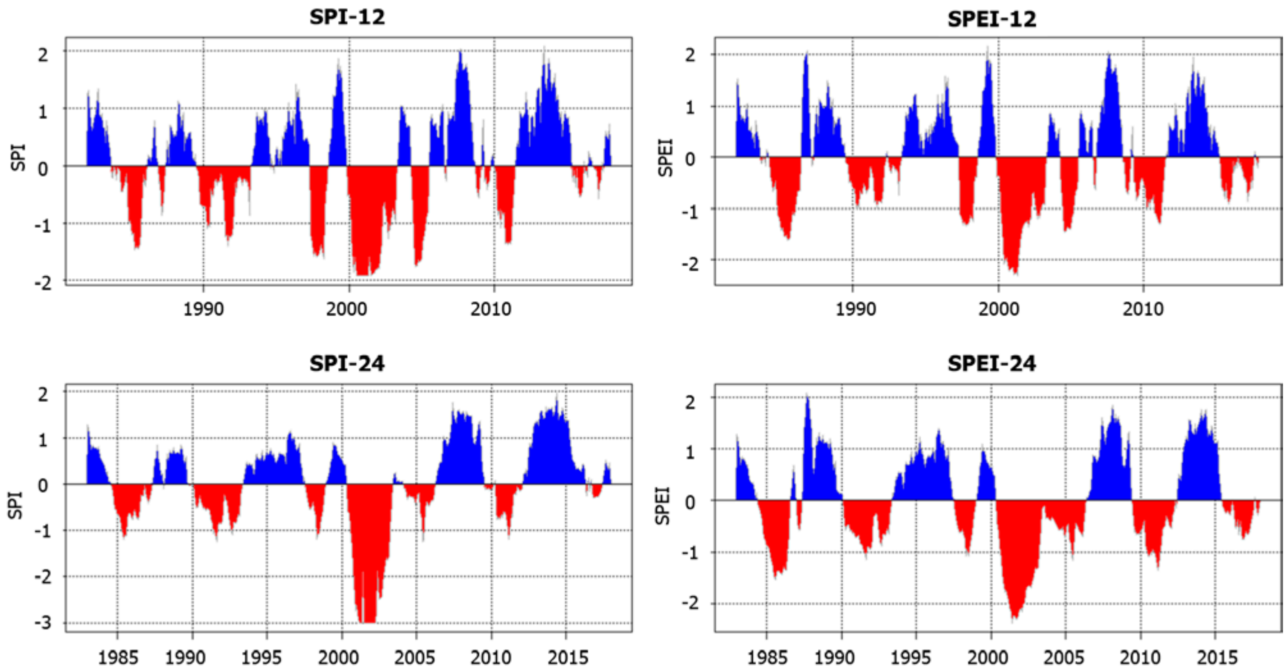

Fig. 6. SPI (on the left) and SPEI (on the right) values for the Cagliari/Elmas station in Sardinia region, calculated on the period of 12, 24 months.
Fig. 6. Valori SPI (a sinistra) e SPEI (a destra) per la stazione di Cagliari/Elmas in Sardegna, calcolati nel periodo di 12, 24 mesi.

and Mediterranean climate, was conducted using the thermo-rainfall series of seven stations in Piedmont region and six stations in Sardinia region, during the period 1981-2017. The Standardised Precipitation Index, SPI, and the Standardised Evapotranspiration Precipitation Index, SPEI, were calculated for each station, and average indices were also calculated for both regions.

Similarities and differences were detected between the two environments. Index trends were more defined in Piedmont region. In particular, the SPEI trend is significantly negative in all the stations considered, while the SPI trend is statistically significant with a positive correlation in three of the seven stations. Meanwhile, indices in Sardinia region showed a clear trend in only half of the stations considered. However, the trends of the average index values for all stations are not significant in either of the two climatic environments considered. Probably because of uncertainties in the SPEI drying trends might be overestimated due to the use of Thornthwaite PET estimation in this analysis. The use of this method is a limitation of the SPEI, as Thornthwaite PET is less physically realistic than other estimation techniques such as Hargreaves or Penman-Monteith equation.

On an annual level, no significant variations in precipitation quantity are recorded in either region, as confirmed by the Fratianni and Acquaotta (2017), and other studies did not show significant changes in annual precipitation in the Mediterranean basin (Coll *et al.*, 2017). On the contrary, in recent years the distribution of rainfall has changed due to the increase in extreme events.

According to Vicente-Serrano *et al.* (2010), both drought indices respond mainly to variability in precipitation, which is the main explanatory variable for drought. Nevertheless, trends of the drought indices in both regions are well correlated with the trends shown by the climate indices, in particular the temperature indices, such as the amount of hot days (T_X90p) and the amount of hot nights (T_N90p). A greater variation is calculated in Piedmont for both the precipitation pattern (prectot) and its manifestation as short but intense events (r95p). Meanwhile, the climate indices calculated in Sardinia for the rain series do not show significant change. However, there is a significant increase in temperatures classified as hot (T_X90p), in both regions. This trend impacts the performance of the SPEI, for which decreasing, and statistically significant trends were calculated in most cases.

The average duration of the wet period was longer in Piedmont region, where we calculated 58 consecutive months with SPI values greater than zero (from July 1992 to April 1997), compared to 34 consecutive months in Sardinia (from April 1984 to January 1987). The duration of dry periods was almost the same in both regions, 43 months with SPI values less than zero in Piedmont (from December 2004 to June 2008) and 40 consecutive months in Sardinia (from September 1997 to December 2000).

An increase in drought for most of the twenty-first century is predicted by future climate projections. Ecosystems and human activities could be profoundly impacted by the projected drying trends, while observed drying trends are having an effect on social-ecological systems, e.g. reduction in vineyard yield in Piedmont in 2017, accompanied by an increase in alpine wildfire. Concerted political and practical action to conserve water is necessary to minimize the impact of future drought, such as appropriate water management policies, and climate-smart agriculture practices.

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