European Water 47: 31-43, 2014.

Drought characterisation in Cyclades complex, Greece

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Abstract: The analysis of past drought episodes can enhance the understanding of drought characteristics in a specific region, lending support to the development of drought management plans. Such an analysis has been undertaken for three islands in the Cyclades complex, Greece, where drought planning is not performed even though drought conditions are experienced frequently. The Standardized Precipitation Index (SPI), the Reconnaissance Drought Index (RDI) and the Threshold Level method were used for past drought characterisation, and a trend analysis was carried out to assess any trends in precipitation and temperature that may have affected past drought frequency and severity. The analysis was performed for the 1970-2010 period, using historical precipitation and temperature data. The analysis indicates that mild drought conditions were most frequently experienced in the islands, which however resulted into significant impacts due to the water scarcity problems faced. The analysis results indicate that drought monitoring should be performed individually in each island, to account for local characteristics and trends. In addition, monitoring should not solely be based on indices using climate data but instead should reflect water sources and uses as well as drought vulnerability in each island.

Keywords: Drought hazard, SPI, RDI, Threshold analysis, Trend analysis, Cyclades.

1. INTRODUCTION

Drought is an extreme event associated with climate variability that can occur in any given region. In contrary to other extreme climate events, such as floods, the analysis of drought characteristics (i.e. severity, duration, probability, spatial extent) has been a challenging task, resulting in a large number of drought definitions and methods for drought hazard analysis.

Four types of drought are widely acknowledged (meteorological, agricultural, hydrological, and socioeconomic), distinguished according to the propagation of drought conditions in the hydrological cycle and its anticipated impacts. For each one, a series of indices or drought statistics has been developed (reviews can be found in different sources including Heim, 2002; Keyantash and Dracup, 2002; Tsakiris et al., 2007a), providing a measure of drought on the basis of one or more (climate, hydrological) parameters. These indices have been tested and validated in different regions and it is nowadays acknowledged that more than one is needed in order to adequately represent drought conditions (Heim, 2002; Steinemann et al., 2005; Quiring, 2009; Sun et al., 2011). Their selection should be based on the hydro-meteorological conditions in the study region, the type of drought examined, data availability, regional characteristics defining vulnerability to drought and their applicability for monitoring and early warning (Hisdal and Tallaksen, 2000; Fleig et al., 2006; MED WS&D WG, 2007).

In the Mediterranean region, the analysis of drought is of particular relevance as it is a rather frequently occurring event (the most recent being the 2007-2008 drought, European Environment Agency, 2012) with significant impacts on water resources availability and water-dependent activities. Hoerling et al. (2012) report that the "*ten driest winters out of twelve since 1902*" have occurred the last twenty years, whereas the estimated economic cost of the 1988-1991 drought was more than 2.1 billion € (EurAqua, 2004). Overall the economic cost of drought in the Mediterranean region over the past twenty years is estimated to be about five times greater than in the USA (CRED, 2005; Iglesias et al., 2007). Enhancing the understanding of drought conditions should therefore be a core component of water management and drought planning in any region and particularly in the Mediterranean basin, given: (i) the increasing severity of drought events in the last decades (Demuth and Stahl, 2001), which may be further exacerbated due to climate change (Christensen et al., 2007; Giorgi and Lionello, 2008), and (ii) the social, economic and environmental impacts of droughts, particularly in water scarce regions (EEA, 2001; Estrela and Vargas, 2011).

Greece, in the Northeastern Mediterranean region, is facing additional challenges due to its wide range of microclimates and regional characteristics that define vulnerability to drought (Karavitis et al., 2012). The Cyclades complex in Greece has one of the highest numbers of consecutive dry days per year in the country (Nastos and Zerefos, 2009). Tigkas (2008) used the Reconnaissance Drought Index (RDI) to characterise droughts in the 1955-2002 period and found that the drought frequency for the Cyclades is about 45%. However, a comprehensive drought analysis has not yet been undertaken for each island individually, with the exception of Naxos and Milos Islands. Tsakiris and Vangelis (2005) used the RDI index to analyse past drought events in Naxos Island, whereas Kanellou et al. (2008) compared the ability of three indices (deciles, RDI, PDSI) to describe drought conditions in the island. Dalezios et al. (2000) analysed the frequency of droughts and wet periods over Greece using data from twenty-eight meteorological stations, including the station operating in Milos Island.

This paper presents the results of drought hazard analysis in the Cycladic islands of Syros, Naxos and Milos. Different methods are applied to characterise drought events on the islands, in order to enhance understanding of drought conditions. In addition, results for Naxos and Milos Islands are compared to those from previous studies (Dalezios et al., 2000; Tsakiris and Vangelis, 2005; Kanellou et al., 2008) to assess options for drought monitoring, as part of an integrated drought management plan.

2. DATA AND METHODS

2.1 Study region

The Cyclades complex is located in the Southern Aegean Sea (Figure 1) and includes 24 inhabited islands. Syros Island (area 84km^2, total population of 21,507 inhabitants, census 2011) is located in the center of the Cyclades and its vulnerability to drought is related to the local climate conditions and its special characteristics (e.g. small catchment areas with limited options for exploiting surface run-off, water scarcity problems that are intensified during the summer peak season). Naxos Island (area 430km^2, total population of 17,930 inhabitants, census 2011) is experiencing frequent droughts that affect agricultural productivity and result into water shortages (Tsakiris and Vangelis, 2005). Milos Island (area 158km^2, total population of 4,997 inhabitants, census 2011) faced significant water shortage problems during past drought events, and the island was supplied with water from the mainland (water hauling).

All islands have a typical Mediterranean climate, with dry summers and low yearly precipitation (400 mm/yr on average, almost 86% of which occurs between October and March). Syros Island has the lowest precipitation height and presents a greater variation in values, as illustrated in Figure 2. July is the warmest month (average temperatures of 27^{o}C, 26^{o}C and 25^{o}C respectively for Syros, Milos, and Naxos Islands) and January is the coolest (on average 11^{o}C).

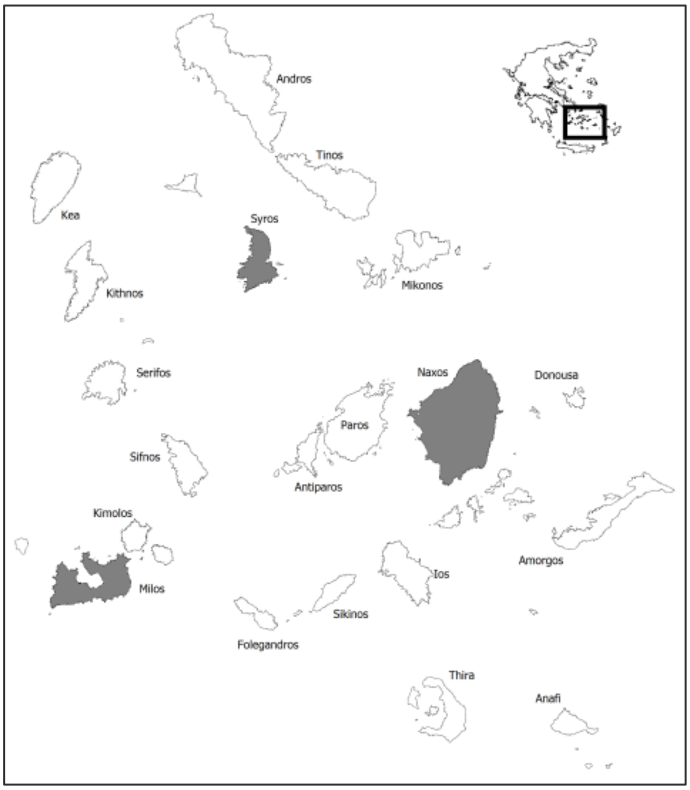


Figure 1. Map of Cyclades complex, Greece.

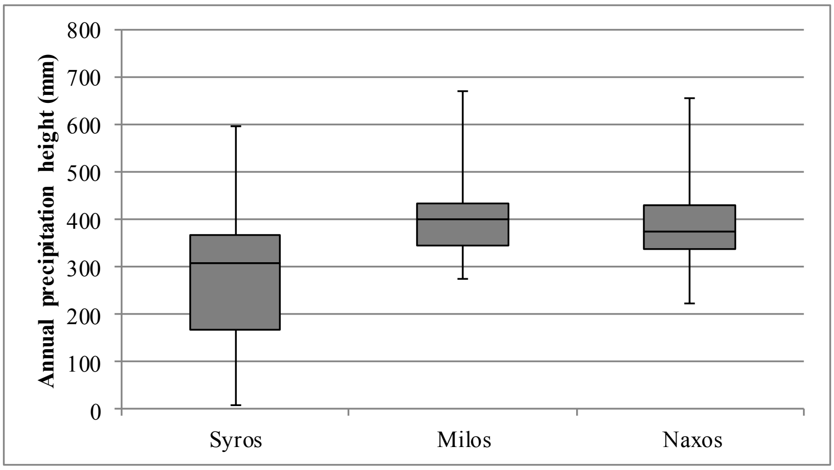


Figure 2. Annual precipitation height in the three islands for the 1970-2010 period.

2.2 Methods

Drought hazard analysis was performed for the 1970-2010 period, using monthly precipitation and temperature records provided by the Hellenic National Meteorological Service. Three methods were applied for characterising past drought events in terms of duration and severity: (i) Standardized Precipitation Index (SPI) and Reconnaissance Drought Index (RDI) estimation to define meteorological droughts; and (ii) Threshold level method to define droughts on the basis of precipitation deficits. In addition, Trend Analysis was performed to define trends and change points in the precipitation and temperature time series using: (i) the Mann-Kendal Test (S & Z statistics), (ii) Sen's slope (Q), and (iii) the percentage change relative to the mean (T).

2.2.1 Standardized Precipitation Index

The SPI (McKee et al., 1993) is commonly used for drought characterisation due to the simplicity of its computation (Hayes et al., 1999), its standardization that guarantees that the probability of occurrence of extreme drought events at any location and on any time scale will be consistent (Lloyd-Hughes and Saunders, 2002), and its calculation for different time scales (1-, 3-, 6-, 9-,12-month interval) that can support both short-term and long-term analysis of drought impacts. It was selected for analysing past drought events in the islands, as it has previously been used in several studies for monitoring drought conditions in Greece (e.g. Loukas et al., 2007; Livada and Assimakopoulos, 2007; Vasiliades et al., 2009; Chortaria et al., 2010; Karavitis et al., 2011; Karavitis et al., 2012) and is one of the indicators of the Combined Drought Indicator used in the European Drought Observatory (Niemeyer et al., 2009).

2.2.2 Reconnaissance Drought Index

The RDI (Tsakiris and Vangelis 2005, Tsakiris et al, 2007b) is typically applied in arid and semi-arid regions (Tsakiris et al., 2013). The index is calculated using data on cumulative precipitation (P) and potential evapotranspiration (PET) for any time period, ranging from one month to one (calendar or hydrological) year. The main advantages of the index are that it is physically sound and it can be linked to agricultural drought (Tsakiris et al, 2007b). The RDI has been already applied successfully for characterising drought events in Cycladic islands. For example, Kanellou et al. (2008) conclude in their analysis that the RDI index, Z-index and Deciles method identify the same drought events and with similar drought characteristics in Naxos, whereas Tsakiris and Vangelis (2005) show that the standarised RDI index provides similar results with SPI in the island.

2.2.3 Threshold Level method

The Threshold Level method is used for analysing hydrological droughts by defining the beginning, end, duration, water deficit and intensity (the ratio of deficit and duration) of a drought episode (Fleig et al., 2006; Van Loon et al., 2010). The method is based on the statistical method of run theory (Yevjevich, 1967), in which a drought event is identified when the river flow is below a given threshold (Hisdal et al., 2001), and can be applied in different time scales (daily, monthly or yearly). The selection of the suitable threshold is critical for the implementation of this method, as it should: (i) correspond to the water regime of a given region, and (ii) account for specific drought characteristics (e.g. multi-year droughts) (Hisdal and Tallaksen, 2000). Typically, the threshold is defined as the average value or a percentile of the flow and can be either fixed or variable over the year.

In our study the threshold method is applied for studying precipitation deficits (meteorological drought), as precipitation is one of the main factors related to drought conditions (Lloyd-Hughes and Saunders, 2002). Periods with precipitation deficiencies (i.e. below a given threshold) can be characterised as drought events.

2.2.4 Trend analysis

Trend analysis can be considered an alternative version of the change point detection, which is a method to determine whether a change has occurred in a given time series (Salarijazi et al., 2012). A non-parametric trend analysis of precipitation and temperature data has been undertaken in two steps: (a) the Mann-Kendall non parametric statistical test, and (b) Sen's slope non parametric procedure. In addition, the percentage change relative to the mean (T) has also been calculated.

- Man-Kendall non parametric test

The Man-Kendall test is a non-parametric procedure, which identifies any trend in a given time series without taking into account whether the trend is linear or not (Hisdal et al., 2001). This test is used widely due to the fact that the existence of missing values in the time series is acceptable (Wu et al., 2008). The Man Kendall test is based on S statistic, which is expressed by the following formula (Eq.1):

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \operatorname{sgn}(Y_j - Y_i) \tag{1}$$

where Y_j and Y_i are the data in defined positions in the time series, and N is the total number of data points. If S has a positive value then there is an upward trend, otherwise a downward trend is determined. The significance of the test, for a specified significance level, is calculated by using the test statistic Z, expressed mathematically by the following formulas (Eq.2):

$$Z = \begin{Bmatrix} (S-1)\Big/\sqrt{Var(S)}, S > 0 \\ 0, S = 0 \\ (S+1)\Big/\sqrt{Var(S)}, S < 0 \end{Bmatrix} \tag{2}$$

The null hypothesis (H_0) of no trend is tested by this method against the alternative hypothesis (H_A) of the existence of a trend (increasing or decreasing).

- Sen's slope method

The non-parametric procedure introduced by Sen (1968) is used for the estimation of the linear monotonic trends of climatic data, also providing information about the magnitude of the trend for a given significance level. The Sen's slope Q_s is the median slope of (Q), where Q is estimated by the following expression (Stahl et al., 2010):

$$Q = \frac{Y_j - Y_i}{j - i} \tag{3}$$

The variables Y_j and Y_i are data values at time points j and i respectively, where $j > i$.

- Percentage change to the mean

The percentage change to the mean (T), for each time series with (n) values, relative to the mean value (x_n), was calculated using the following equation (Stahl et al., 2012):

$$T = \frac{Q_s . n}{x_n} .100 \tag{4}$$

3. RESULTS

3.1 Drought indices

The SPI and RDI indices were calculated at different time scales (1 to 12 months) from 1970 to 2010 to analyse both short- and long-term effects of precipitation deficits. Results are in agreement with the previous study of Tigkas (2008) for the entire Cyclades complex, as according to the indices drought conditions are experienced nearly 40% of the time, with mild drought episodes (index values 0 to -0.99) being more frequent (Figures 3 and 4). Severe and extreme events (index values ≤ -1.5) are identified in Syros island only by the SPI-12 index, in line with the finding of Hayes et al. (1999) that at short time scales, the SPI cannot identify extreme drought events in water scarce regions (low seasonal precipitation total). Also, a difference in results is noted in the case of Syros Island when using the SPI and RDI indices, which can be attributed to the higher variance of precipitation in the island (Figure 2) compared to Milos and Naxos.

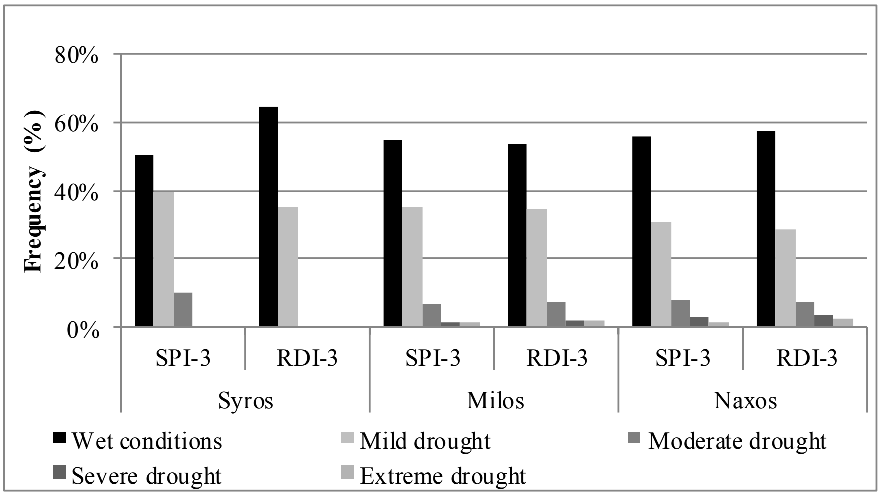


Figure 3. Frequency of drought events for the 1970-2010 period according to the SPI-3 and RDI -3 severity indices.

Even though the same drought periods were identified in the three islands (e.g.1989-1992, 2000-2001), spatial differences were also found. For example, in 2007 a state of emergency due to drought was declared for the entire Cyclades complex and all islands received an emergency fund to cope with water shortages. However, as shown in Figure 5, among the three study sites only Milos appears to have experienced drought conditions. This highlights the importance of individual drought characterisation, particularly when it is linked with the deployment of drought mitigation actions. Another finding that stresses the importance of local micro-climate conditions is the evolution of drought characteristics (Table 1), when dividing the time series in two periods: 1970-1990 & 1991-2010. Results for Milos Island follow a different pattern, as there is an increase in drought events, and particularly extreme ones, over the past 20 years.

Table 1. Frequency of wet and drought periods using the SPI-12 index.

	Syros		Milos		Naxos	
	1970-1990	1991-2010	1970-1990	1991-2010	1970-1990	1991-2010
Wet conditions	52.1	69.6	53.9	47.1	51.9	55.8
Mild drought	26.8	20.0	30.7	40.8	34.8	29.2
Moderate drought	7.7	2.1	11.2	5.0	6.6	7.5
Severe drought	10.8	6.3	3.3	2.1	2.5	3.8
Extreme drought	2.6	2.1	0.8	5.0	4.1	3.7

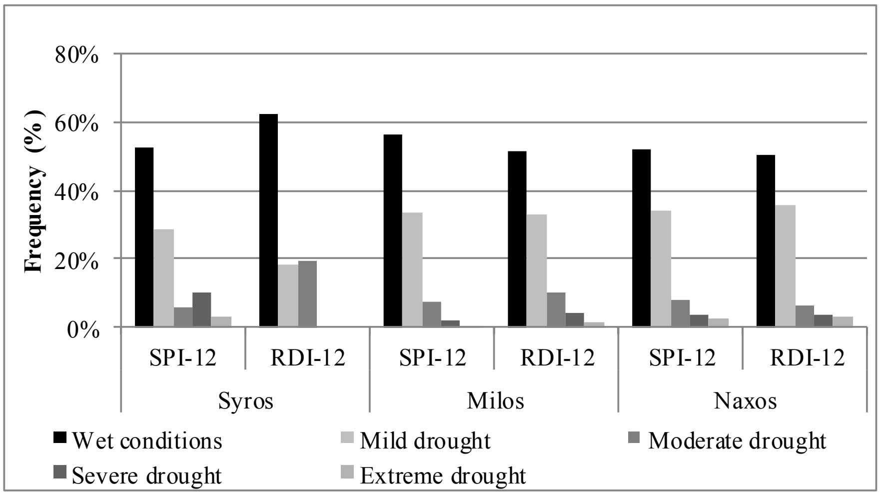


Figure 4. Frequency of drought events for the 1970-2010 period according to the SPI-12 and RDI-12 severity indices.

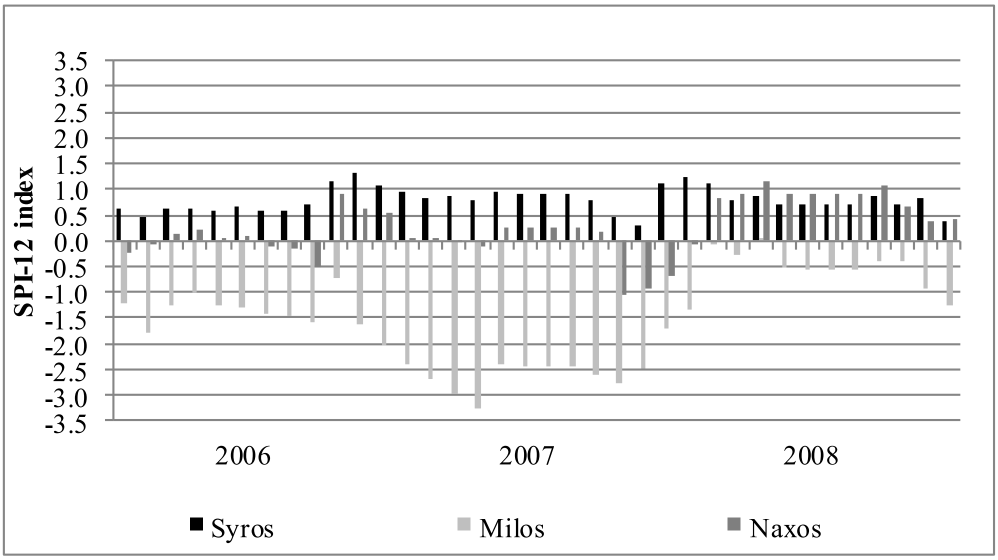


Figure 5. The SPI-12 severity index the 2006-2008 period.

3.2 Threshold level method

Two variable monthly thresholds have been used in this study, corresponding to: (i) the 50-percentile (Q_{50}) of monthly precipitation, and (ii) the monthly average precipitation (Q_{Av}). Typically the Q_{80} or Q_{90} percentiles are used in hydrological drought analyses. However, for the case of the semi-arid Cycladic islands, these percentiles are equal to zero and would result in the identification of drought conditions for all months in the dataset. The importance of the threshold selected for drought identification is indicated in Table 2, as drought duration (consecutive months below the threshold) is significantly increased when using the Q_{Av} as threshold.

The drought events identified were grouped in four ranges based on the number of consecutive months with precipitation below the threshold, in order to distinguish between short and long lasting droughts: 1-5 months, 6-12 months, 13-24 months, >24 months. The last two ranges were found only for Syros Island when using the Q_{Av} as threshold, corresponding to 4.2% and 1.4% of drought events respectively. The frequency of drought events of up to five consecutive months is 76% in Syros Island when using the Q_{Av} as threshold (85% for Q_{50}), 82% in Milos (99% for Q_{50}) and 75% in Naxos (97% for Q_{50}).

Table 2. Drought duration and intensity using the threshold method.

Island	Threshold	Total number of months below the threshold	Maximum number of consecutive months below the threshold	Average drought intensity (mm/month)	Recent years with the higher number of months in a year below the threshold
Syros	Q_{50}	152 (33%)	8	13.9	1996-97 (4)
	Q_{Av}	312 (68%)	37	12.9	1997 (11)
					1998-99 (8)
					2004 (8)
Milos	Q_{50}	180 (37%)	6	17.3	2004 (7)
					2007 (7)
					2008 (6)
	Q_{Av}	330 (67%)	11	19.7	2004 (11)
					2007 (10)
					2008 (9)
Naxos	Q_{50}	180 (37%)	8	14.2	2000 (6)
					2004 (7)
					2007 (6)
	Q_{Av}	329 (67%)	14	16.1	2000 (11)
					2001 (10)
					2006-2008 (9)

Most drought events have drought intensity below 10mm/month (Figures 6 and 7), whereas for short events, deficits higher than 30mm/month are almost as frequent as those of 10mm/month in Milos. This result (along with Tables 1 and 2) indicates that Milos experiences more intense drought conditions than the other two neighboring islands.

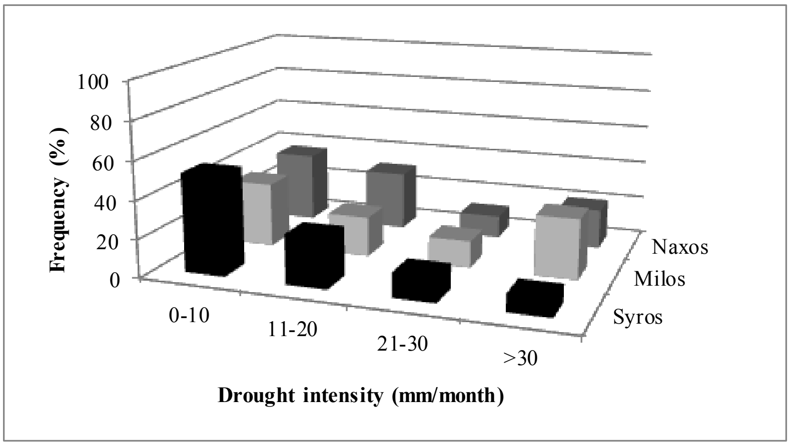


Figure 6. Frequency and drought intensity for events of 1 - 5 months duration (threshold equals average monthly values).

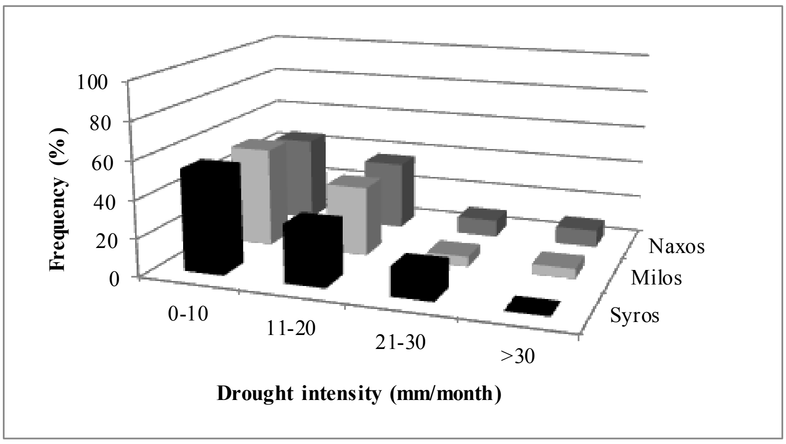


Figure 7. Frequency and drought intensity for events of 6 - 12 months duration (threshold equals average monthly values).

3.3 Results of trend analysis

The time series of annual precipitation for the three islands is presented in Figure 8. An increasing linear trend is observed for Syros Island, no trend is apparent for Milos Island, whereas a slightly decreasing trend is noted for Naxos Island. The hypothesis of no trend (the null hypothesis) or trend was tested at the 95% confidence level. An increasing trend in the precipitation series was confirmed only for Syros Island (Table 3, Table 4), which follows a seasonal pattern, with increasing trend for all months except for summer and an annual increase rate of 7.2 mm/year (Figure 9). However, overall results for the Cyclades complex indicate that no trend can be observed in the precipitation data series. If the same trend remains in the future (assuming no climate change effect on precipitation), drought conditions, especially mild droughts, will continue to be frequent.

Table 3. Trend analysis results for precipitation in Syros Island (significant trends highlighted bold).

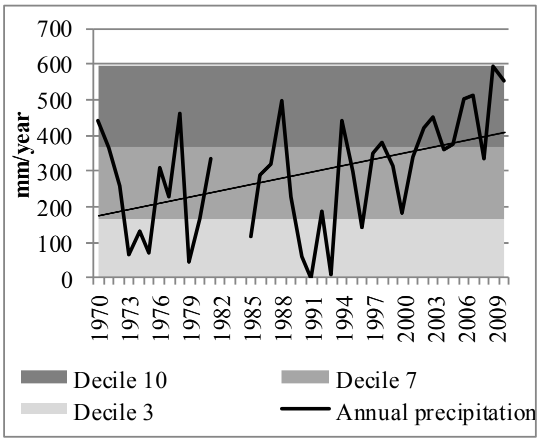
Variable	Z_{95}	Q_{95}	T	p-value	Hypothesis test
Annual	2.99	7.20	93.33	0.003	**Trend**
Jan	1.44	0.59	46.80	0.003	No Trend
Feb	0.69	0.26	19.61	0.150	No Trend
Mar	1.49	0.50	51.50	0.488	No Trend
Apr	1.32	0.16	36.51	0.135	No Trend
May	2.07	0.02	9.62	0.185	Trend
Jun	1.89	0.00	0.00	0.039	No Trend
Jul	2.23	0.00	0.00	0.059	Trend
Aug	2.91	0.00	0.00	0.026	**Trend**
Sep	2.38	0.00	0.00	0.004	**Trend**
Oct	2.33	0.35	49.97	0.017	**Trend**
Nov	2.08	0.69	77.32	0.020	**Trend**
Dec	2.93	1.80	120.57	0.038	**Trend**

Trends have been analysed also for the two time periods, 1970-1990 and 1991-2010. No trend in monthly and annual precipitation series has been estimated in the three islands. This result verifies that precipitation height was higher in Syros Island over the period 1991-2010 and this trend reflects the increase of the frequency of wet conditions in Syros Island, according to the drought indices, the past 20 years (Table 1).

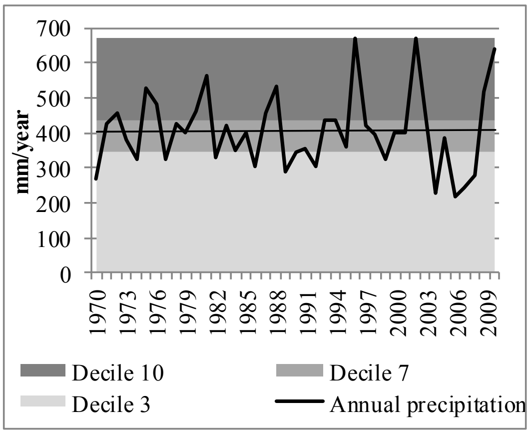
Table 4. Trend analysis results for precipitation in Milos and Naxos Islands.

Island	Milos					Naxos				
Variable	Z_{95}	Q_{95}	T	p-value	Hypothesis test	Z_{95}	Q_{95}	T	p-value	Hypothesis test
Annual	-0.33	-0.72	-7.27	0.745	No Trend	-0.84	-0.88	-9.83	0.400	No Trend
Jan	-0.22	-0.10	-5.94	0.822	No Trend	0.22	0.18	11.02	0.822	No Trend
Feb	0.42	0.28	21.52	0.678	No Trend	-0.62	-0.35	-25.94	0.537	No Trend
Mar	-0.06	-0.02	-1.99	0.955	No Trend	-1.25	-0.61	-54.77	0.212	No Trend
Apr	-0.47	-0.10	-20.01	0.637	No Trend	-1.12	-0.22	-51.95	0.261	No Trend
May	0.05	0.00	0.00	0.964	No Trend	0.79	0.07	26.44	0.431	No Trend
Jun	1.05	0.00	0.00	0.293	No Trend	-0.81	0.00	0.00	0.416	No Trend
Jul	0.00	0.00	0.00	1.000	No Trend	-1.10	0.00	0.00	0.271	No Trend
Aug	0.00	0.00	0.00	1.000	No Trend	-0.28	0.00	0.00	0.782	No Trend
Sep	0.20	0.00	0.00	0.843	No Trend	1.52	0.00	0.00	0.128	No Trend
Oct	-1.24	-0.43	-42.65	0.216	No Trend	-0.39	-0.10	-10.83	0.694	No Trend
Nov	0.00	-0.02	-1.18	1.000	No Trend	0.01	0.02	1.22	0.991	No Trend
Dec	0.91	0.52	24.48	0.363	No Trend	0.60	0.32	19.52	0.552	No Trend

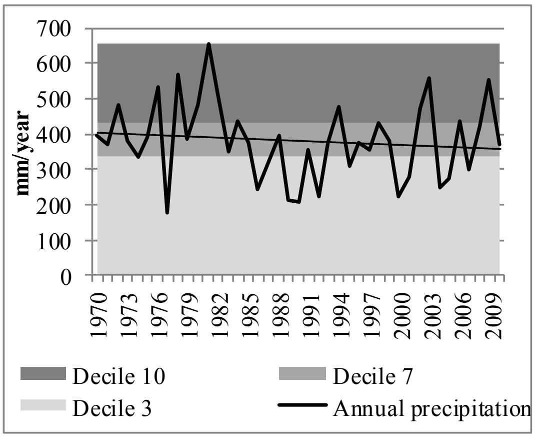
Concerning the temperature series, a significant increasing trend in the monthly average temperature was estimated for the summer months (Table 5), indicating that climate change may already be evident in the region. According to Wetherald and Manabe (2002) and IPCC (2007), warmer climates increase the risk of droughts. As temperature rises, the moisture content of soil is reduced and the risk of agricultural droughts is increased. Therefore, if the existing trend persists, particularly in Milos, the probability of agricultural drought may be increased in the future.



(a) Syros Island



(b) Milos Island



(c) Naxos Island

Figure 8. Precipitation time series in the three islands and its classification using deciles.

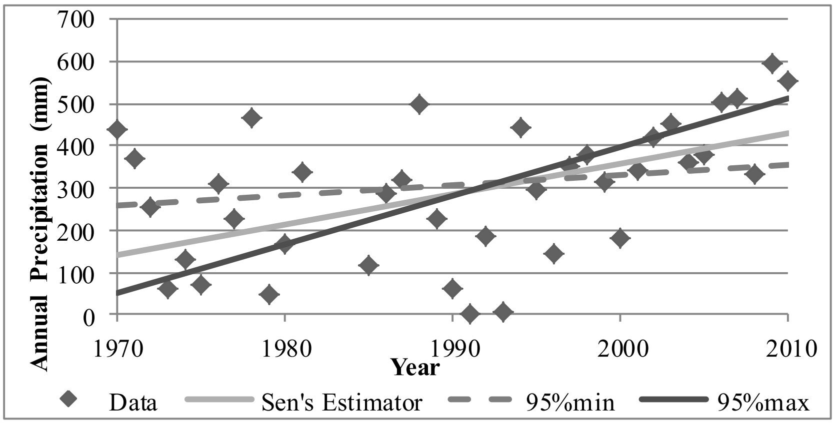


Figure 9. Sen's slope estimator for the annual precipitation in Syros Island for the time period 1970-2010, with 95% confidence level.

Table 5. Percentage change to the mean (T, %) for temperature.

Variable	T_{annual}	T_{Apr}	T_{Jun}	T_{Jul}	T_{Aug}	T_{Sep}	T_{Oct}	T_{Nov}
Syros	-	-9.2	-	-	4.1	-	-	-
Milos	5.9	-	5.5	11.9	11.8	9.7	9.7	8.1
Naxos	3.7	-	-	6.2	8.3	7.5	-	-

4. CONCLUDING REMARKS

This study aimed at analysing past drought characteristics and their temporal evolution in three Cycladic islands, in order to make proposals for drought monitoring in the region. Given that the available climate data are limited to precipitation and temperature records, drought characterisation was based on the SPI and RDI indices and the analysis of precipitation deficits. Results indicate that mild drought conditions were more frequently experienced in the islands, with Milos Island facing more frequent and extreme drought conditions, particularly during the period 1991-2010. For the other two islands, the severity of earlier drought events (e.g. 1973-1975, 1977, 1979-1980) was higher compared to that of events in the last twenty years.

The choice of drought indices for monitoring purposes should take into account the climate conditions, water sources and uses, and drought vulnerabilities in each island. The SPI index is more suitable as a meteorological indicator of drought compared to the threshold level method when only precipitation data are available, as the results from the threshold analysis are sensitive to the threshold selected. In addition, the analysis indicated that the ability of the SPI to describe drought events (in terms of duration and intensity) increases with the time scale of SPI estimation. Therefore, the SPI-12 index is proposed for the characterisation of drought, given data availability and the need for easy and simple tools for use by the local authorities, which lack the necessary technical capacity. The RDI index provides similar results with the SPI index. However, RDI can be further associated to agricultural drought, as evapotranspiration is used in its calculation making the index sensitive to climate variability. Therefore, RDI is preferred where drought analyses support agricultural applications.

However, drought monitoring should not be solely based on indicators or approaches using climate-related (e.g. precipitation, temperature) data. As groundwater is a major source of water in Cycladic islands, composite indices that include information about the available water reserves should be developed and tested, taking into account data availability limitations and the cost of establishing a new monitoring network. Further work on drought indices is thus required, incorporating more climate data (e.g. soil moisture) or water resources-related variables, to improve the reliability of information for drought monitoring and early warning in the region.

Temporal trends of significance in the precipitation time series were found only in Syros Island, whereas in the temperature time series an increasing trend was found for the summer months, particularly in Milos and Naxos Islands. Therefore, given no climate change effects, drought conditions may not differ significantly in the future and preparedness to drought can be improved through targeted actions, such as drought monitoring and developing water reserves.

ACKNOWLEDGMENTS

This study has been supported by the European Union-funded FP7 project DROUGHT-R&SPI "Fostering European Drought Research and Science-Policy Interfacing" (Grant agreement no.: 282769).

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