

Evaluation of Climate Change on Drought Impulses in Thessaly, Greece

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Abstract: The impacts of various climate change scenarios on drought impulses were evaluated to provide a framework for sustainable water resources management in the region of Thessaly, Greece. Thessaly was divided into twelve hydrological sub-basins and monthly precipitation data from 50 stations were used for the estimation of sub-basin mean areal precipitation. The Canadian Centre for Climate Modeling Analysis General Circulation Model (CGCMa2) has been used to estimate the precipitation changes for the periods 2020-2050 and 2070-2100 and for three climate change scenarios (IS92a, SRES A2, SRES B2). The “delta” method was employed for the downscaling of precipitation. The Standardized Precipitation Index (SPI) computed at various time scales was used as an indicator of meteorological drought for present and future climate conditions. Comparison of the drought characteristics for the historical period (1960-1990) and the future periods indicated that the drought intensity, duration and severity increases for the three examined climate change scenarios. Furthermore, analysis of two historical drought periods has shown that frequent, extreme and spatially extended droughts would be expected in future.

Key words: climate change, downscaling, drought, Global Circulation Models, CGCMa2, Standardized Precipitation Index.

1. INTRODUCTION

The diversity and complexity of drought impacts and the low level of preparedness for future events is a point of global concern. The ongoing debate about climate change and its potential effects on the frequency and severity of extreme climatic events is adding further to the concerns of scientists and decision makers, because observed changes have shown that drought events are already on the rise. Research on how climate change will affect local and regional hydrological regimes has progressed as an international effort on many fronts. The results of this research have been summarized in the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2001; IPCC, 2007).

Global climate change is depicted on meteorological variables, mainly temperature and precipitation. Analysis of historical meteorological observations indicated that the 100-year linear trend (1906-2005) of $0.74 [0.56 \text{ to } 0.92]^{\circ}\text{C}$ (IPCC, 2007) is larger than the corresponding trend of $0.6 [0.4 \text{ to } 0.8]^{\circ}\text{C}$ (1901-2000) given in the Third Assessment Report (IPCC, 2001). However, the extent of climate change is not clearly evident everywhere, due in part to complexities arising from interactions between atmospheric processes, oceans, land surfaces, biota and polar ice masses. For example, studies in the Mediterranean region agreed that temperature exhibits a positive trend in west Mediterranean and a negative trend in the east Mediterranean over the 20th century (National Observatory of Athens, 2001). Since 1900, precipitation decreased by over 5% over much of the land bordering the Mediterranean Sea, with the exception of central North African coast (Tunisia and Libya). A general drying is evident over most of southeastern Mediterranean and Greece up to the first years of the last decade. However, increased precipitation has been observed during the recent years. A precipitation decrease has been well documented in the central-west Mediterranean over the last 50 years (National Observatory of Athens, 2001; IPCC, 2007).

Despite uncertainties in future climates, there is considerable evidence that there will be substantial impacts on the environment and human interests. The effects of climate change on hydrological, ecological and socioeconomic regimes have become a priority area, both for process research and for water management strategies. This is a three-step process basically consisting of:

(1) the development and use of general circulation models (GCMs) to provide future global climate scenarios under the effect of increasing greenhouse gases, (2) the development and use of downscaling techniques (both nested regional climate models, RCMs, and statistical methods) for “downscaling” the GCM output to the scales compatible with hydrological models, and (3) the development and use of hydrological, ecological and socioeconomic models to simulate the effects of climate change on hydrological regimes at various scales. General reviews of the methodology and progress in simulating hydrometeorological variables from GCM-derived climate change scenarios could be found in the bibliography (Leavesley, 1994; Xu 1999; Varis et al., 2004; Xu et al., 2005; Fowler et al., 2007).

Climate change will affect the hydrology of a region through changes in the timing, amount, and form of precipitation, evaporation and transpiration rates, and soil moisture, which in turn affect also the drought characteristics in a region. Droughts are long-term phenomena affecting large regions causing significant damages both in human lives and economic losses. Droughts are generally considered as periods with insufficient precipitation, soil moisture and water resources for sustaining and supplying the socio-economic activities of a region. A typical classification of droughts has been proposed by Dracup and his associates (1980) and it has been widely accepted (Wilhite and Glantz, 1985; American Meteorological Society, 2004). According to this classification, meteorological, hydrological, and agricultural droughts, are considered environmental droughts (Wilhite, 2000), and they are defined as periods with insufficient amounts of precipitation, river flow or groundwater, and soil moisture, respectively. The forth drought type is the social-economic drought, which is associated to the failure of water resources systems to meet the water demands.

The threat that droughts in a future climate pose to climate sensitive economic sectors has necessitated the assessment of the potential impacts of climate change at various scales to reduce their vulnerability. Few studies on climate change impacts on droughts have employed meteorological drought indices, which require considerably less input data when compared to weather, soil and land use information needed by meteorological, hydrologic, agrohydrologic and water management models as the tools for assessing drought responses (i.e. Kothavala, 1999; Blenkinsop and Fowler, 2007; Mavromatis, 2007). This study is a contribution towards meeting this challenge. It investigates the possible effects of climate change on droughts in Thessaly, Greece using meteorological drought indices. Thessaly region was divided into twelve basins or areas according to climatological and topographical characteristics. The Standardized Precipitation Index (SPI) was used for the identification and assessment of drought events. Historical time series of SPI were computed for various time scales using the areal average monthly precipitation of the twelve basins of Thessaly for the period from 1960 to 1990. The Canadian Centre for Climate Modeling Analysis General Circulation Model has been used to estimate precipitation changes for two future periods and three socioeconomic scenario forcings. The “delta” or “perturbation” method was employed for the downscaling of precipitation from the GCM predictor outputs. The future period SPI time series were calculated using the truncated time series of areal precipitation. Finally, the historical and the future SPI time series were analyzed to evaluate the effect of climate change on drought characteristics.

2. STUDY AREA AND DATABASE

Thessaly is located in central Greece and is a plain region surrounded by Mount Kisavos and Mount Pelion in the east, along the coast of the Aegean Sea, Mount Olympus in the north, the Pindus Mountain Range in the west, and the Othrys Mountain Range in the south. Thessaly's total area is about 13,700 km². The elevation ranges from sea level to more than 2,800 m, and the mean elevation of the region is about 500 m. Thessaly plain is surrounded by the mountains and has an area of about 4,000 km². It is one of the most productive agricultural regions of Greece. The main crops cultivated in the plain area are cotton, wheat and maize whereas apple, apricot, cherry, olive trees and grapes are cultivated at the foothills of the eastern mountains.

The climate at the western and central side of Thessaly is continental with cold winters and hot summers with large temperature difference. The coastal areas of Thessaly have a typical Mediterranean climate. Summers in Thessaly are usually very hot and dry, and in July and August temperatures can reach 40°C. Mean annual precipitation over the whole Thessaly region is about 700 mm and varies from about 400 mm at the central plain area to more than 1850 mm at the western mountain peaks. Generally, rainfall is minimal during the summer months.

Thessaly experienced severe, extreme and persistent droughts during the period from mid to late 1970s and the period from late 1980s to early 1990s. Especially, the hydrological years 1976-1977 and 1989-1990 are the first and second driest hydrological years in record, respectively. The driest January and February and the second driest March in record occurred during the hydrological year 1989-1990. The prolonged and significant decrease of monthly and annual precipitation adversely affected the natural vegetation and the agriculture of the region as well as on water resources.

Thessaly was divided into twelve basins or areas using a digital elevation model and hydro-meteorological information (Fig. 1). The digital elevation model was developed from digitized elevation contours with a contour interval of 100 m from topographical maps. Processed monthly precipitation data from 50 stations for the period October 1960 to September 1993 were available (Fig. 1). The mean areal precipitation of the sub-basins was estimated by the Thiessen polygon method modified by the precipitation gradient using the stations, which are within or in the vicinity of each sub-basin.

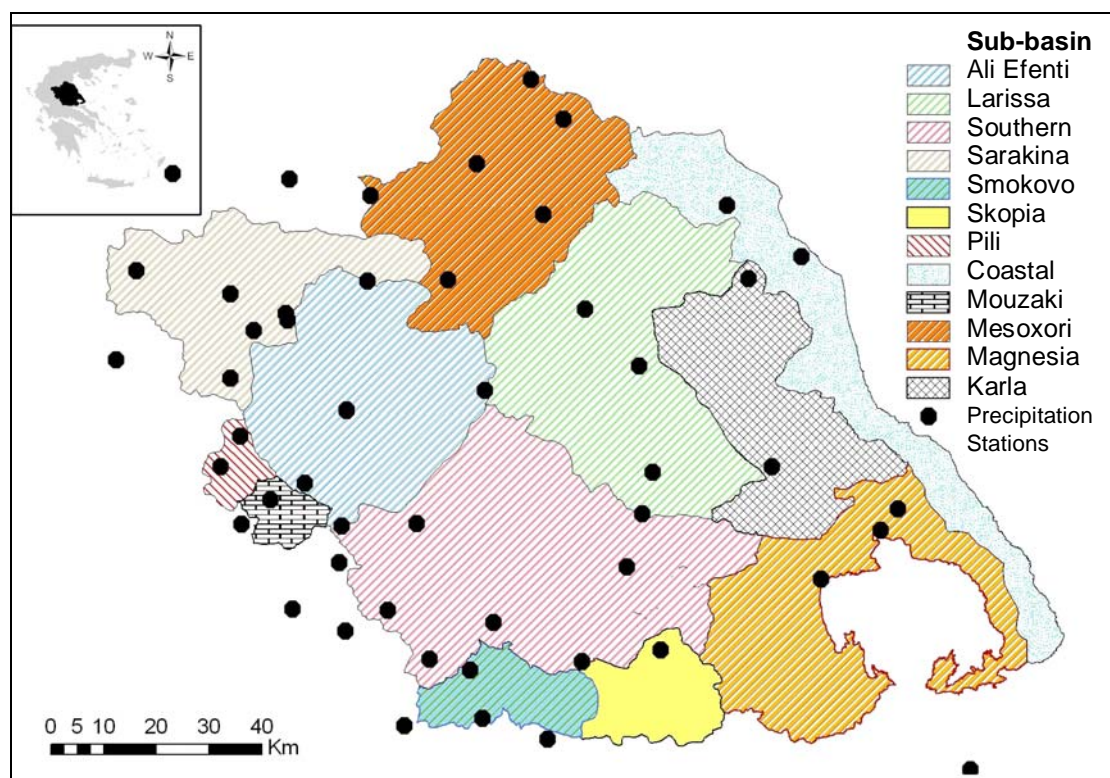


Figure 1. Sub-basins of Thessaly and location of precipitation stations.

3. METHODS

3.1 Standardized Precipitation Index

Many indices have been used for the identification of more than one type of drought (Tate and Gustard, 2000; Keyantash and Dracup, 2002) and their categorization may not be appropriate, although it is widely used. The Standardized Precipitation Index (SPI) quantifies the precipitation

deficit for multiple time scales and reflects the impact of drought on the availability of different types of water resources. For example, the moisture stored in the soil is highly affected by the short-term precipitation anomalies, whereas streamflow, groundwater and reservoir storage slowly respond to longer-term precipitation anomalies. Recent studies have used SPI as indicator of hydrological and water resources variables, like soil moisture, surface runoff and reservoir storage. (Loukas and Vasiliades, 2005; Vicente-Serrano and Lopez-Moreno, 2005).

The SPI has been developed by McKee and his associates (1993) for defining and monitoring droughts. It is used, among others, by the U.S. Colorado Climate Center, the U.S. Western Regional Climate Center, and the U.S. National Drought Mitigation Center to monitor drought in the United States (Redmond, 2000). The SPI can track drought on multiple time-scales. The U.S. National Drought Mitigation Center computes the SPI with five running time intervals, i.e. 1-, 3-, 6-, 9-, and 12-months, but the index is flexible with respect to the period chosen.

The SPI is computed by fitting a Gamma probability density function to a given frequency distribution of areal precipitation totals over a time scale. The alpha and beta parameters of the Gamma probability density function are estimated for each sub-basin or area, for each time scale of interest (1, 3, 6, 9, 12 months, etc.), and for each month of the year. The Gamma distribution is defined by its frequency or probability density function:

$$g(P) = \frac{1}{\beta^\alpha \Gamma(\alpha)} P^{\alpha-1} e^{-P/\beta} \quad \text{for } P > 0 \quad (1)$$

where α , β are the shape and scale parameters respectively, P is the precipitation amount and $\Gamma(\alpha)$ is the gamma function. Maximum likelihood solutions are used to optimally estimate α and β .

The Gamma distribution is not defined for $P = 0$ and a precipitation distribution may contain zeros. In this study a “naïve” method has been applied. According to this method the null precipitation is substituted with a small amount of precipitation, for example 0.1 mm. This substitution does not affect the distribution of precipitation and circumvent the problem. The error introduced by this method depend on the number of months with null precipitation ($P = 0$) and it is usually evident for the 1-month precipitation. In this study, the time series of monthly precipitation had only few cases of zero precipitation, observed during the summer months. For larger time scales (e.g. 3-month, 6-month, etc) the probability of null precipitation was zero.

The cumulative Gamma probability distribution, $G(P)$, after its computation, is transformed to the standard normal random variable z with mean equal to zero and variance of one, which is the value of the SPI. Wetter and drier climates can be represented in the same way by SPI, because it is a normalized index. Once standardized the strength of the anomaly is classified as set out in Table 1. This table also contains the corresponding probabilities of occurrence of each severity arising naturally from the Normal probability density function. Extreme values of SPI will, by definition, occur with the same frequency at all locations. Negative SPI values indicate droughts and positive SPI values denote wet weather conditions (Table 1). In this study, the areal averaged monthly precipitation accumulations were used for the estimation of the monthly SPI for each sub-basin or area for 1-, 3-, 6-, 9-, and 12-month time scales.

Table 1. Weather classification by SPI values and corresponding event probabilities

SPI value	Category	Probability (%)
2.00 or more	Extremely wet	2.3
1.50 to 1.99	Severely wet	4.4
1.00 to 1.49	Moderately wet	9.2
-0.99 to 0.99	Near normal	68.2
-1.49 to -1.00	Moderately dry	9.2
-1.99 to -1.50	Severely dry	4.4
-2 or less	Extremely dry	2.3

3.2 Climate Change Effects on Precipitation

Global Circulation Models (GCMs) have been used to study the effects of the increasing concentration of carbon dioxide and the other greenhouse gases on the Earth's climate. These models link atmospheric processes with ocean and land surface processes and can be used to provide projections of the changes in temperature, precipitation and other climate variables in response to changes in greenhouse gas emissions. The second generation of GCMs (Manabe and Stouffer, 1996; Johns et al., 1997; Boer et al., 2000; Hirst et al., 2000) is transient models assuming an increase of CO₂ equivalent concentration at a rate of 1% per annum from 1990 to 2100. In this study the outputs from the second-generation Canadian Centre for Climate Modeling and Analysis GCM (CGCMa2) (Flato and Boer, 2001) are used for the assessment of climate change impacts on monthly precipitation. The CGCMa2 is a spectral model with 10 atmospheric levels and has a resolution equivalent to 3.75° of latitude by 3.75° of longitude. The ocean component is based on the Geophysical Fluid Dynamics Laboratory MOM1.1 model and has a resolution of roughly 1.8° of latitude by 1.8° of longitude and 29 vertical levels.

IPCC has developed three sets of socio-economic scenarios. These emission scenarios were constructed to explore future global developments of society and environment. The first scenario is the IS92a published in the Second Assessment Report by IPCC (IPCC, 1992). According to this scenario, population rises to 11.3 billion by 2100 and the economic growth averages 2.3% per year from 1990 to 2100, with a mix of conventional and renewable energy resources being used. It represents a high emission scenario. The second scenario used is the SRES (Special Report on Emissions Scenarios) A2. SRES A2 scenario assumes a strong, but regionally oriented economic growth and fragmented technological change with an emphasis on human wealth. It represents an intermediate emissions scenario. The third scenario is the SRES B2 scenario which emphasizes the protection of the environment and social equity, but also relies on local solutions to economic, social, and environmental sustainability and represents a low emission scenario. All scenarios represent a world in which the differences between developed and developing countries remain strong. The three socio-economic scenarios used, namely IS92a, SRES A2 and SRES B2 have been widely adopted as standard scenarios for use in climate change impact studies (IPCC, 2001). Scenario runs were taken over two time periods: a) 2020-2050 and b) 2070-2100.

The commonly used approach in climate change studies is to combine the output of the GCMs with an impact model. This approach is quite realistic although there are inherent uncertainties about the details of regional climate changes. These uncertainties stem from a number of sources, namely from uncertainties in GCM outputs, downscaling of GCM outputs and specification of the climate change scenarios (Loukas et al., 2002). The major drawback of the current generation of GCMs is the limitation of their spatial resolution and the resolution of the output. Usually the output of GCMs is given for a much larger scale than the scale of even a large watershed. Interpolation techniques (McCabe and Wolock, 1999), statistical downscaling (Brandsma and Buishand, 1997; Wilby et al., 2002) and downscaling through coupling of GCM output and regional meteorological models (Leung and Wigmosta, 1999) are methods that have been used to overcome the spatial resolution limitation of the GCMs.

In this study, the simplest “delta” or “perturbation” downscaling method was used for the socio-economic scenarios IS92a, SRES A2, SRES B2. Differences between the control and future GCM simulations are applied to baseline observations by simply adding or scaling the mean climatic change factors. Therefore, it can be rapidly applied to several GCMs to produce a range of climate scenarios. This method assumes that GCMs more accurately simulate relative change than absolute values, i.e. assuming a constant bias through time and no consideration is made for changes in the variability of descriptors with climate change (Evans and Schreider, 2002; Diaz-Nieto and Wilby, 2005). However, it is widely used (Lettenmeier et al., 1999; Loukas et al., 2002; Morrison et al., 2002; Prudhomme et al., 2002) given the uncertainties in the variability of climate parameters under future climates, combined with the range of equally plausible estimates of climate variables from different GCMs.

4. APPLICATION AND RESULTS

Time series of SPI for various time scales were computed using the areal average monthly precipitation of the twelve sub-basins or areas of Thessaly for the available record length (i.e. 1960-1993). The historical period from October 1960 to September 1990 was considered as the base period in the analysis. The temporal and spatial characteristics of historical droughts were, then, analyzed. Secondly, the future climate areal monthly precipitation time series were estimated from the outputs of CGCMA2 for the three socio-economic scenarios using the “delta” downscaling technique. This procedure has been applied for two future periods a) October 2020-September 2050, and b) October 2070 to September 2100. Thirdly, the future climate time series of SPI for various time scales and sub-basins or areas of Thessaly were calculated and compared to the respective base period SPI time series. Finally, the effect of climate change on drought impulses was assessed from the changes in the number of negative monthly SPI values by severity classes.

4.1 Analysis of Historical SPI Time Series

SPI time series for various time scales have been estimated for the twelve sub-basins or areas of Thessaly. Figure 2 shows the SPI temporal evolution for Thessaly region at multiple time scales, using the spatially average precipitation.

The temporal evolution of 1-month SPI timeseries (Fig. 2a) showed that the region experienced frequent moderate and severe droughts (i.e. $SPI < -1$) for all months of the year. As time scale increases, the monthly SPI time series were smoothed and the deviations from the long-term accumulated precipitation were assessed. Analysis of the 3-month SPI and 6-month SPI time series indicated that the record minimum SPI observed in March 1990 and April 1990, respectively, (Figs. 2b and 2c). Visual inspection of 9-month and 12-month SPI time series (Figs. 2d and 2e) indicated that droughts were quite frequent during the 1970s and 1980s. However, two distinct severe dry periods were revealed, considering only the annual minimum spatially averaged SPI value. The first period occurred during the hydrological year 1976-1977 and is characterized as an extreme drought event. The second period was the period from the hydrological year 1987-1988 to 1989-90 and is characterized as a severe drought for the whole area of Thessaly. Especially, the annual precipitation of the year 1976-1977 is the smallest for the historical period (Oct. 1960-Sept. 1990). The drought occurred in 1976-1977 is the most severe drought ever experienced in Thessaly region. Probabilistic analysis of SPI for the total study area (Loukas and Vasiliades, 2004) indicated that the 9-month SPI for this drought event occurred in August 1977 ($SPI = -2.19$) and had a return period of 22 years, whereas the annual minimum 12-month SPI observed in November 1977 ($SPI = -2.35$) and had an estimated frequency of recurrence of 37 years.

The second historical drought event is a much more prolonged drought event than the drought event of 1976-1977 and lasted over five years (1987-1993); it is interrupted by the wet 1990-1991 hydrologic year. The minimum values of spatially averaged monthly SPI were observed during the hydrologic year 1989-1990 for the 9-month and 12-month time scales and it is characterized as a severe drought event. The minimum 9-month SPI was observed in April 1990 ($SPI = -2.16$) and the minimum 12-month SPI was estimated for March 1990 ($SPI = -2.00$) for the Thessaly region. This event had an estimated return period of 20 years for the 9-month time scale and of 18 years for the 12-month time scale, respectively (Loukas and Vasiliades, 2004). This prolonged drought event caused exploding water demands and subsequent impacts in Thessaly region, Greece, and Eastern Mediterranean, in general. The above findings are representative for most of the Thessaly sub-basins, except for the three eastern sub-basins (e.g. Karla, Coastal, and Magnesia). For these sub-basins the second drought event was not as extreme as for the other sub-basins. The reason is the different spatial distribution of precipitation for the two identified drought periods, i.e. 1976-1977 and 1987-1990 (Zaragotas et al., 2007).

The spatial variation of SPI was investigated, firstly, by comparing the number of months for which the SPI values for all time scales indicated moderate drought ($-1.49 \leq SPI \leq -1.00$), severe

drought ($-1.99 \leq SPI \leq -1.50$), and extreme drought ($SPI \leq -2.00$) for the twelve sub-basins. Table 2, which shows the results for the 12-month SPI, do not indicate a specific and clear spatial pattern of SPI severity. The Sarakina sub-basin (Fig. 1) is the sub-basin with the largest number of months, 69, with SPI value ≤ -1.00 . This indicates that about 17.5% of the time this sub-basin experienced drought. On the other hand, the Smokovo sub-basin experienced drought for 46 months out of 396 months or about 12% of the time. Of this total number of dry months, on average, 58% are moderately dry months, 26% are severely dry month, and 16% are extremely dry months (Table 2). The Mouzaki and Smokovo sub-basins exhibited the largest and smallest percentage of moderately dry months (71% and 46%, respectively). The Karla and the Coastal sub-basins had the largest and smallest percentage of severely dry months (37% and 17%, respectively). Coastal and Smokovo had the largest percentage of extremely dry months (24%), whereas Karla sub-basin had the smallest percentage in extreme monthly dry events of all Thessaly sub-basins (5%).

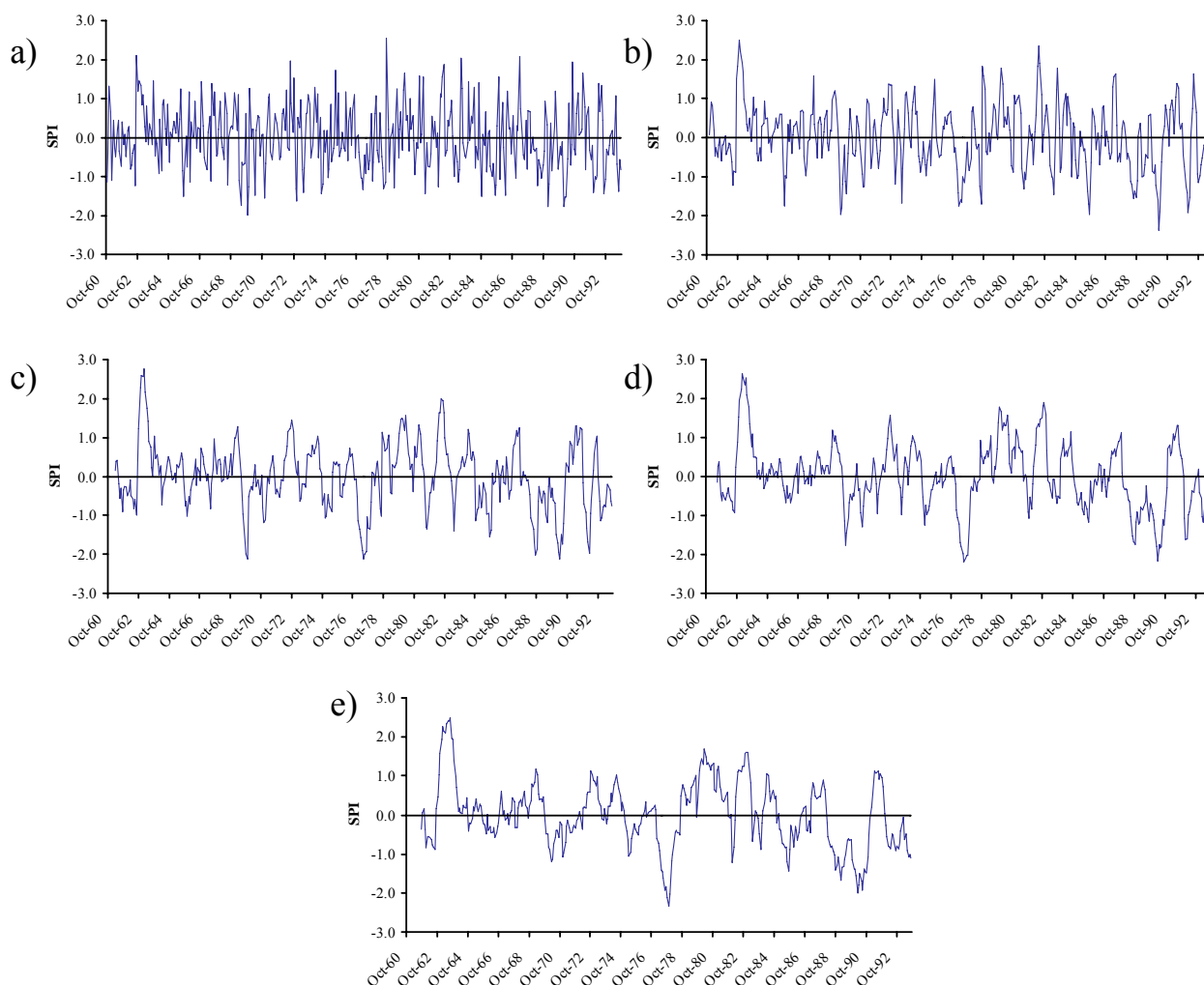


Figure 2. Historical average time series of SPI for a) 1-month, b) 3-month, c) 6-month, d) 9-month, and e) 12-month time scales for Thessaly region.

The results of the spatial analysis indicated that SPI values varied spatially with no consistent way and the spatial pattern was different for various drought events. This is clearly indicated in Figure 3 which shows the spatial variation of 12-month SPI values for November 1977, which is the driest month of the two identified historical extreme drought events (1976-1977 and 1987-1990). This figure indicates that the drought intensity in November 1977 was larger for the eastern and southern sub-basins, whereas the most drought-affected sub-basins for the driest month March 1990 (figure not shown due to paper length limitations) were lie in the central, northern and western part of the region. These results agreed with the results of previous study on the probabilistic

spatiotemporal analysis of droughts in Thessaly (Loukas and Vasiliades, 2004). Drought Severity-Areal Extent-Frequency analysis in the previous study (Loukas and Vasiliades, 2004) indicated that drought during these months affected the whole study area and the drought events had an estimated return period of 50-years.

Table 2. Numbers of dry months ($SPI \leq -1$) of 12-month SPI for various drought severity classes in Thessaly

Sub-basin	Moderately dry		Severely dry		Extremely dry		Total monthly number of droughts
	Cases	(%)	Cases	(%)	Cases	(%)	
Sarakina	36	52	22	32	11	16	69
Pili	30	52	15	26	13	22	58
Mouzaki	49	71	13	19	7	10	69
Southern	34	63	14	26	6	11	54
Smokovo	21	46	14	30	11	24	46
Skopia	38	61	13	21	11	18	62
Ali Efenti	34	58	17	29	8	14	59
Larissa	43	67	16	25	5	8	64
Karla	33	58	21	37	3	5	57
Mesoxori	32	52	16	26	14	23	62
Coastal	32	59	9	17	13	24	54
Magnesia	35	60	16	28	7	12	58

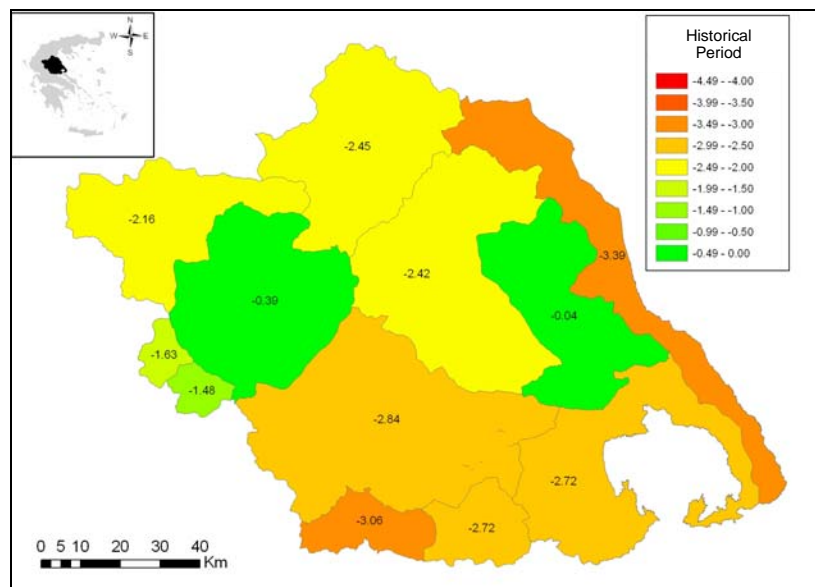


Figure 3. Spatial distribution of 12-month SPI for November 1977.

4.2 Climate Change Impacts on Droughts

In this study the “delta” method was employed for the downscaling of mean areal precipitation. The “delta” method achieves the precipitation downscaling by truncating the historical time series of precipitation by the monthly change of CGCMa2 grid precipitation between the historical base period 1960-1990 and the two future periods, 2020-2050 and 2070-2100. Application of the downscaling method for the three socio-economic scenarios, namely IS92a, SRES A2 and SRES B2, indicated that the scenario IS92a was the most severe, followed closely by SRES A2. The monthly precipitation was, in general, reduced for all months and sub-basins. The larger reduction was observed for the period 2070-2100 for all three socio-economic scenarios. Furthermore, methods, the “delta” method gave spatially homogenized results because the precipitation time

series for all the study sub-basins of Thessaly were truncated according to the same CGCMa2 grid precipitation change.

The truncated precipitation time series for the three socio-economic scenarios, and the twelve sub-basins were used for the estimation of SPI for the two future periods, 2020-2050 and 2070-2100. Figure 4 presents the 12-month SPI timeseries for Larissa sub-basin for the period 2070-2100. Similar future patterns are observed for the other sub-basins and SPI timescales.

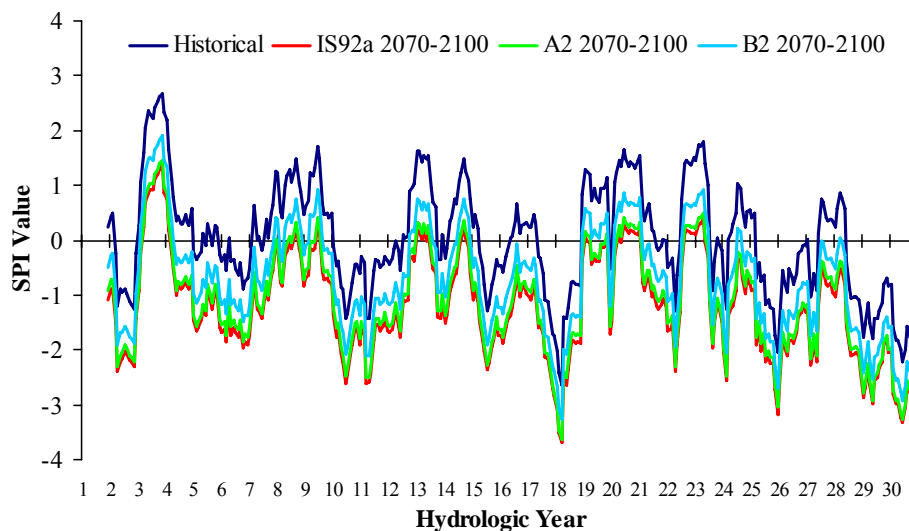


Figure 4. Present and future 12-month SPI timeseries for the period 2070-2100 and the three socio-economic scenarios, Larissa sub-basin.

The results indicated that the drought severity and duration would be increased in the future periods. Overall, the number of dry months ($SPI \leq -1.00$) will increase for all three scenarios and the two methods of downscaling. For example, Table 3 shows the number of months for the three scenarios and the two future periods for the Larisa sub-basin. The dry months are also categorized with the severity of drought according to the 12-month SPI value. These results indicated that the number of dry months increased for all three socio-economic scenarios, with the IS92a being the most severe and the SRES B2 being the most conservative scenario. The largest increase, compared to the base historical period, were observed for the extreme dry months ($SPI \leq -2.00$) for all scenarios and periods. Similar results have been found for the other sub-basins of Thessaly and SPI time scales.

Table 3. Numbers of dry months of 12-month SPI for various drought severity classes, climate scenarios and future periods - Larissa sub-basin.

Dry Months	1960-90		2020-50 IS92a		2070-00 IS92a		2020-50 A2		2070-00 A2		2020-50 B2		2070-00 B2	
	Number	% Change	Number	% Change	Number	% Change	Number	% Change	Number	% Change	Number	% Change	Number	% Change
Moderate	43	60.5	69	60.5	69	60.5	49	14	63	46.5	65	51.2	78	81.4
Severe	16	137.5	38	137.5	74	362.5	25	56.2	88	450	38	137.5	44	175
Extreme	5	180	14	180	51	920	11	120	63	1160	20	300	25	400
Total	64	89	121	89	194	203	85	32.8	214	234	123	92.2	147	129.6

Table 4 shows the total number of dry months with $SPI \leq 1$, for the twelve sub-basins and the three socio-economic scenarios. These results indicate that the number of dry months would increase in the future for all three scenarios and the twelve study sub-basins. Especially for the period 2070-2100 and the IS92a and SRES A2 scenarios, the vast majority of the sub-basins would experience drought for more than half of the time. The “delta” downscaling method gave spatially homogenized results, so that neighbouring sub-basins had similar number of dry months.

The above remark becomes clearer when the spatial variation of SPI is mapped for a specific drought event. Figure 5 shows the spatial variation of the 12-month SPI for November 2087.

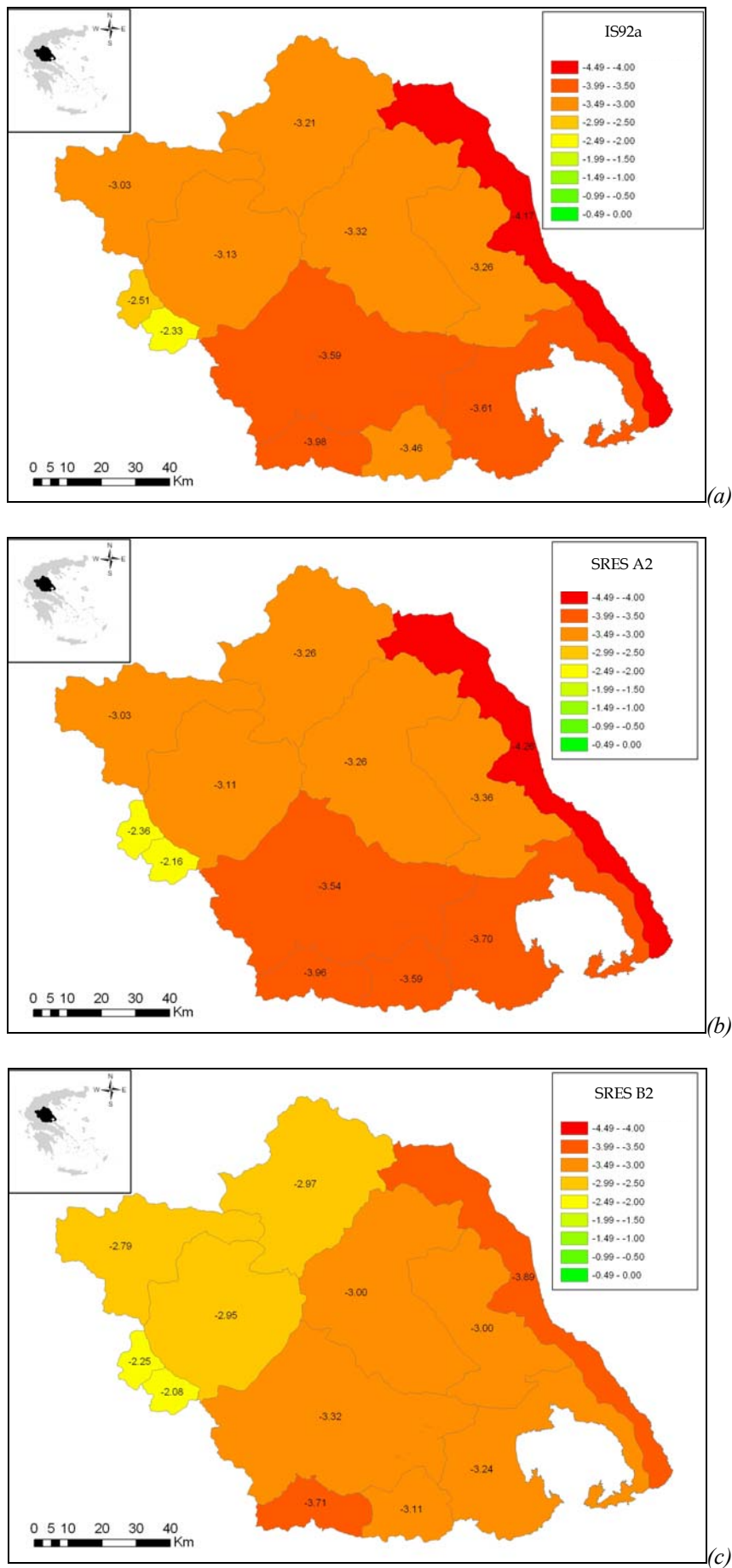


Figure 5. Spatial variation of 12-month SPI for November 2087 and the three scenarios: a) IS92a, b) SRES A2 and c) SRES B2.

November 2087 corresponds to November 1977 which was the month with the smallest 12-month SPI value in record. The spatial variation of SPI demonstrated that IS92a scenario produced the most severe droughts, while SRES B2 is the most conservative scenario. However, all scenarios indicated that the whole region of Thessaly would be under extreme drought ($SPI \leq -2.00$).

Table 4. Total numbers of dry months for climate scenarios and future periods for the twelve study sub-basins.

Sub-basin	Historical 1960-90	IS92a 2020-50	IS92a 2070-00	SRES A2 2020-50	SRES A2 2070-00	SRES B2 2020-50	SRES B2 2070-00
Sarakina	69	100	202	88	245	101	143
Pili	58	109	201	91	219	105	142
Mouzaki	69	107	203	90	218	112	149
Southern	54	109	200	81	230	119	146
Smokovo	46	112	219	73	256	120	167
Skopia	62	116	172	101	188	117	134
Ali Efenti	59	97	179	79	203	96	126
Larissa	64	121	194	85	214	123	147
Karla	57	111	187	81	215	110	142
Mesoxori	62	102	182	84	234	104	117
Coastal	54	100	175	77	211	97	121
Magnesia	58	118	190	88	224	119	142

5. CONCLUDING REMARKS

This study evaluated the impacts of climate change on drought impulses in Thessaly region, Greece. Thessaly region was divided into twelve sub-basins or areas and the historical (period 1960-1990) monthly areal precipitation time series for each sub-basin were estimated using the modified Thiessen method. The effect of future climate change was evaluated using the output of CGCMa2 global circulation model. Precipitation time series for two future periods, 2020-2050 and 2070-2100 and three socio-economic scenarios, namely IS92a, SRES A2, and SRES B2, were estimated using the “delta” downscaling technique. Based on these precipitation timeseries, the Standardized Precipitation Index was calculated at multiple time scales as an indicator of droughts for present and future climate conditions.

The results have been analyzed both spatially and temporally and have shown that Thessaly experienced frequent moderate and severe droughts during the period 1960-1990. The spatial distributions of historical droughts were quite different depending on the distribution of precipitation. Probable future climate change would result in a significant increase in dry conditions in Thessaly. This increase would be evident even in the period 2020-2050. However, the number, severity and duration of drought events would be largely increased in the period 2070-2100. The socio-economic scenarios IS92a and SRES A2 produced more extreme results than the scenario SRES B2, but even for this latter conservative scenario, drought events would be doubled and in some cases tripled by end of this century. Thus, it is mandatory to properly plan and manage the water resources of the region in order to mitigate possible future impacts of droughts in Thessaly.

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