

SATELLITE-BASED VARIABILITY OF DROUGHT CHARACTERISTICS

Nicolas R. DALEZIOS¹, Anna BLANTA¹, Efrosyni KANELLOU¹ & Nicos SPYROPOULOS²

- (1) Department of Agriculture, Ichthyology & Acquatic Environment, Laboratory of Agrometeorology, University of Thessaly, Volos, Greece, email: dalezios@uth.gr, amblanta@uth.gr, efi_kanel@yahoo.com,
(2) Department of Natural Resource Development and Agricultural Engineering, Agricultural University of Athens, Athens, Greece, email: nicosp@hol.gr

ABSTRACT

Drought indices are estimations of precipitation shortage and water supply deficit. A number of satellite drought-monitoring indices have been developed based on NOAA-AVHRR data exploiting the remote sensing potential at different time intervals. The estimation of drought based on the Reconnaissance Drought Index (RDI) enables the assessment of hydro-meteorological drought, since it uses hydro-meteorological parameters, such as precipitation and potential evapotranspiration. RDI is a fairly comprehensive index as it combines the simplicity of use and the successfully assessment and monitoring of the phenomenon. In this study, drought assessment is conceived through remotely sensed RDI in Thessaly, central Greece, which is a drought-prone agricultural region. Areal extent, onset and end time, duration and severity are analysed from monthly RDI images over the period 1981-2001. The results indicate mainly moderate to severe droughts with a duration of about 12 months. For the severe and extreme droughts the start usually coincides with the beginning of the hydrological year (October), whereas for moderate droughts the start is usually in spring (April), both lasting until the end of the hydrological year (September). There is also an increase in the areal extent of drought during each drought period with the maximum occurring usually in the summer.

1 INTRODUCTION

Drought is referred to as ‘‘non-event’’, since its basic cause is the lack of precipitation events in a region over a period of time and can be regarded as an extreme climatic phenomenon associated with water resources deficit. It is recognized that there is no universally accepted definition of drought, because there is a wide variety of sectors affected by drought, its diverse spatial and temporal distribution and the demand placed on water supply by human-used systems (Heim, 2002). Drought indicators are variables, which describe features of drought. Several indicators can also be synthesized into a single indicator on a quantitative scale, called a drought index. In

fact, the monitoring and assessment of drought conditions in a region is usually performed through drought indices. For drought assessment several studies have been carried out, which mainly estimate the precipitation shortage and the water supply deficit (Keyantash and Dracup, 2002). These studies have focused on the development of drought indices for drought identification and quantification. During the last decades, numerous drought indices based on several variables were developed (e.g., Heim, 2002; du Pissani et al., 1998). Although temperature or evapotranspiration are generally included in drought index calculation, precipitation is the most important parameter (Oladipo, 1985; Guttman, 1998; Keyantash and Dracup, 2002).

There are several commonly used drought indices based on ground (conventional) and/or remotely sensed data (Kanellou, 2010). Traditional drought quantification methods rely on conventional hydrometeorological data, which are limited in a region, often inaccurate and most significant unavailable in near real-time (Thenkabail et al., 2004). On the other hand, satellite-based data are consistently available and can be used to detect several features (Kanellou et al., 2006). Specifically, the growing number and effectiveness of pertinent earth observation satellite systems present a wide range of new capabilities, which can be used to assess and monitor the effects of drought. Over the last decades, remote sensing has gradually become an important tool for the detection of the spatial and temporal distribution and characteristics of drought at different scales.

There are also several drought features and characteristics that should be determined through monitoring and are very significant inputs in any drought preparedness and mitigation plan (Rossi, 2000; Dalezios et al., 1991). In particular, in order to assess and monitor drought episodes and to alleviate the impacts of droughts it is necessary to detect several drought features such as severity, duration, periodicity, areal extent, onset and end time and to link drought variability to climate and its variability (Piechota and Dracup, 1996; Loukas et al., 2002). It is clear that there is a need for proper quantification of drought impacts. Thus monitoring of drought development is of critical importance in economically and environmentally sensitive regions.

The objective of this paper consists of exploring the remote sensing potential in terms of data and methods in order to quantify drought and assess several drought features and characteristics. In this paper the Reconnaissance Drought Index (RDI) is used, which is a new index suitable for hydrometeorological drought estimation (Tsakiris and Vagelis, 2005). RDI is a physically-based general index, which can be used in a variety of climatic conditions. Moreover, RDI provides information for the water deficit in a region as it is based not only on precipitation, but also on potential evapotranspiration. In the computation of RDI the innovation consists of employing Blaney-Criddle method for potential evapotranspiration instead of Thornthwaite method, since it is more appropriate for the Mediterranean region with dry and hot summers (Blaney and Criddle, 1950). Furthermore, in this paper Blaney-Criddle method is based on Brightness Temperature (BT) and Land Surface Temperature (LST), which is derived from satellite data (Kanellou et al., 2009). Several drought features and characteristics are analyzed from monthly remotely sensed RDI images for the period 1981-2001 for Thessaly, Greece. Specifically, areal extent and severity during drought periods signify the spatiotemporal variability of droughts in Thessaly. The paper is organized as follows: in section 2 drought types and features are defined and presented; in section 3 the study area and database are described; in section 4 the remotely sensed

methodology for RDI estimation is presented along with the analyzed drought features and section 5 delineates the analysis and discussion of results.

2 DROUGHT TYPES AND FEATURES

If drought is considered as a phenomenon, it is certainly an atmospheric phenomenon. However, if drought is considered as a hazard, there is a tendency to classify drought types into three categories, namely meteorological or climatological, agricultural and hydrological drought and to include as a fourth class the socioeconomic impacts of drought (Keyantash and Dracup, 2002).

- Meteorological or climatological drought is generally characterized by a precipitation anomaly being lower than average for some time period and by prolonged and abnormal moisture deficiency.
- Agricultural drought is described in terms of crop failure and exists when soil moisture is depleted so that crop yield is reduced considerably.
- Hydrological drought is considered to be a period during which the actual water supply, either surface water or groundwater, is less than the minimum water supply necessary for normal operations in a particular region (watershed).
- Socioeconomic impacts of drought are defined in terms of loss from an average or expected return and can be measured by both social and economic indicators (McVicar and Jupp, 1998).

The Reconnaissance Drought Index (RDI) is a new index, which is used for hydrometeorological drought estimation (Tsakiris and Vangelis, 2005). RDI is a physically-based and general index and can be used in a variety of climatic conditions. This index can be calculated for any time period (1-, 3-, 6-, 9- and 12-months). Moreover, RDI provides information for the water deficit in an area as it is based not only on precipitation, but also on potential evapotranspiration. In order to assess and monitor drought, it is necessary to detect several drought features. Moreover, remote sensing data and methods can delineate the spatial and temporal variability of several drought features in quantitative terms. A description of some key drought follows (Kanellou, 2010).

Severity: severity or intensity of drought consists of the classification and escalation of the phenomenon from mild to moderate, severe and extreme. The severity is usually determined through drought indicators and indices, which include the above mentioned classes.

Duration: duration of a drought episode is the time interval from the start and end time usually in months. Since drought is a complex phenomenon and hazard the assessment of start and end time is a complicated issue.

Onset: the beginning of drought is determined by the appearance of drought episode. The beginning of droughts is assessed through indicators or indices reaching certain threshold value.

End time: end time of drought episode signifies the termination of drought based again on threshold values of indicators or indices.

Areal extent: areal extent of drought is considered the spatial coverage of the phenomenon as it is quantified in classes by indicators or indices. Areal extent varies in

time and remote sensing has contributed significantly in the delineation of this parameter.

3 STUDY AREA AND DATABASE

3.1 Study area

The region of Thessaly overtakes the central - Eastern department of continental Greece and overtakes a total areal extent of 14036 Km² (10.6% of total extent of country). The 36.0% of ground are in a plain, the 17.1% semi-mountain, while the 44.9% is mountainous. High mountains surround the plain of Thessaly, which constitutes the bigger plain of country that divided westwards to Eastern from the river Pinios that is the third bigger river of country. Pinios River is springing the western slopes of Pindos Mountains and outflows, after 216 km, in the Aegean Sea. Its main tributaries are Titarisios, Enipeas, Kalentzis and Litheos. Surface and groundwater resources are jointly used to cover rural, urban and industrial needs, whilst on the same time they are essential to the preservation of the wetland developed in the area. The main watershed in Thessaly water district is the Pinios basin which covers 9500 km². Thessaly is one of the thirteen hydrological districts of the country and it is located in Central Greece (Figure 1). Thessaly plain is a drought-prone area, which is also the main agricultural region of Greece.

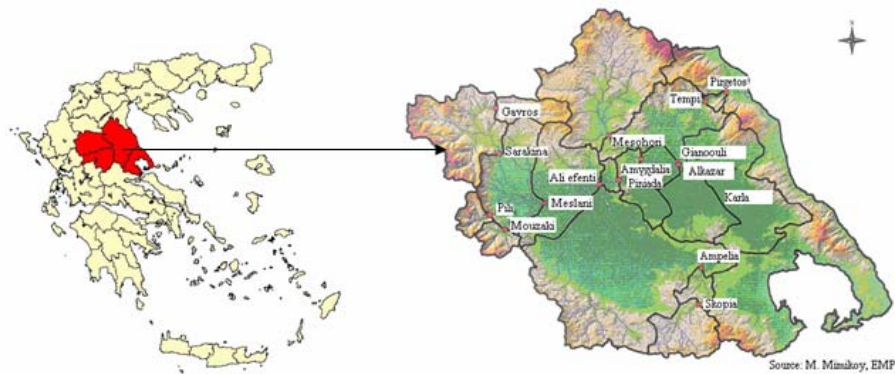


Figure1. Location and geographical map of Thessaly region.

At the western side of Thessaly the climate is continental; the winters are cold and the summers are hot and the temperature difference between the two seasons is large. At the eastern side of Thessaly the climate is typical Mediterranean. 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 700mm and it is distributed unevenly in space and time. The mean annual precipitation varies from about 400mm at the central plain area to more than 1850mm at the western mountain peaks.

3.2 Database

For the RDI estimation the following data is used:

- Daily precipitation of Thessaly water district in 50 x 50 km² spatial analysis derived by ground measurements provided by the Joint Research Center (JRC) of EC, Ispra, Italy.
- Crop coefficients maps extracted by Corine Hellas 2000 for each month of the year.
- Monthly maps of daytime sunshine duration for 39.39° Middle North Latitude of Thessaly.
- A time series of ten-day Brightness temperature (BT) images extracted from Channels 4 and 5 of NOAA/AVHRR for 20 consecutive hydrological years (October 1981 - September 2001) 8x8 km² provided by NOAA.
- A time series of ten-day NDVI extracted from Channels 1 and 2 of NOAA/AVHRR for 20 consecutive hydrological years (October 1981 - September 2001) 8x8 km² provided by NOAA.

4 METHODOLOGY

The methodology covers the estimation of RDI based on remote sensing data and techniques. Specifically the methodology follows the described steps, which include preprocessing of satellite data, calculation of air temperature, estimation of potential evapotranspiration with the use of satellite data, rain map extraction and remotely sensed estimation of RDI. A brief description follows.

4.1 Preprocessing of satellite data

Satellite data that are used come from 10-day NOAA/AVHRR images with spatial resolution 8*8 Km². The variables which are extracted from satellite data are Brightness Temperature (BT) and Normalized Difference Vegetation Index (NDVI) on monthly time step. Next step is the geometric correction of all images with the use of software Erdas Imagine.

4.2 Calculation of air temperature

Air temperature maps are derived from LST satellite images based on regression analysis between LST values and ground measurements of air temperature from the meteorological station of Larissa, which is located in the region. LST is calculated with the use of BT and NDVI images on a pixel basis (Kanellou, 2010). The derived empirical relationship between LST and air temperature (T_{air}) is given by:

$$T_{air} = 0.6143 - LST + 7.3674 \quad (R^2 \approx 0.82) \quad (1)$$

4.3 Estimation of potential evapotranspiration with the use of satellite data

The RDI uses precipitation and potential evapotranspiration. In this paper potential evapotranspiration is estimated with the use of Blaney-Criddle method. This method is selected as it is appropriate for subtropical climates with dry and hot summers such as Mediterranean region, since it has been applied in California, instead of Thornthwaite

method, which is more appropriate for climates with wet and hot summers (e.g. East U.S.A). Blaney and Criddle (1950) estimated the monthly potential evapotranspiration (ET_m) in mm, by the equation (2):

$$ET_m = k * [0.46T + 8.16] * p \quad (2)$$

where T is the mean monthly air temperature, p is the monthly daytime sunshine duration, which depends on the latitude of the area, and k is the crop coefficient, different for each cultivation, vegetation type and land use.

Maps of mean monthly crop coefficients for each vegetation type and land use in 500x 500 m² pixel size, as well as maps of daytime sunshine duration (p) for each monthly value for the Thessaly water district (39,39° North Latitude) are extracted in a GIS environment (ArcMap 9.1. software) (Kanellou *et al.*, 2006).

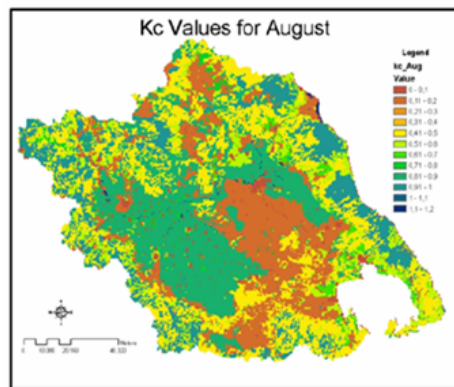


Figure 2. Crop coefficient map (August).

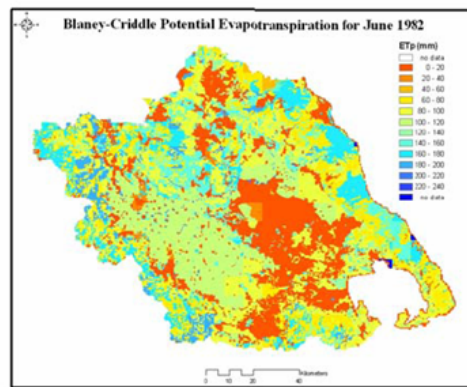


Figure 3. Blaney-Criddle ETp for June 1982.

The monthly crop coefficient and the maps of daytime sunshine duration are combined with the air temperature maps for the whole data set in order to extract Blaney-Criddle potential evapotranspiration for each month in the time series (1981-2001) using the software Erdas Imagine 8.7 version..

4.4 Rain map extraction

For the estimation of RDI it is required to estimate monthly areal precipitation. Rain maps over Thessaly on a monthly basis are provided by JRC, ISPRA. These data cover Greece from 1975 to 2005 per 50x50 km². From daily values of all time series the monthly cumulative rain of each hydrological year from 1975 to 2005 is calculated. Then rain maps are produced every month using linear interpolation.

4.5 Remotely sensed estimation of RDI

Estimation of RDI is achieved with the use of models in software Erdas Imagine, in which monthly temperature maps are used, crop coefficient (Kc) maps, sunlight maps (p), potential evapotranspiration Blaney- Criddle (ETp) maps and rain maps (P) are used. In this study, RDI is calculated on a monthly and annual basis.

The calculation of the index starts with the estimation of a_k coefficient (Tsakiris *et al.*, 2007), as it is given by the equation:

$$a_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j} \quad (3)$$

where P_j and PET_j are the precipitation and potential evapotranspiration, respectively, of the j -th month of the hydrological year. The hydrological year for the Mediterranean region starts in October, hence for October $k=1$.

RDI_n is the Normalised RDI, which is given by:

$$RDI_n(k) = \frac{a_k}{\overline{a_k}} - 1 \quad (4)$$

The Standardised RDI (RDI_{st}) is given by:

$$RDI_{st}(k) = \frac{y_k - \overline{y_k}}{\sigma_k} \quad (5)$$

where y_k is the $\ln a_k$, $\overline{y_k}$ is its arithmetic mean and σ_k is its standard deviation. The drought categories based on RDI are shown in Table I.

Table I. Drought categories based on RDI (Tsakiris and Vangelis, 2005).

Drought Categories	RDI Values
Extremely Wet	>2.00
Very Wet	1.50 to 1.99
Moderately Wet	1.00 to 1.49
Near Normal	-0.99 to 0.99
Moderately Dry	-1.00 to -1.49
Severely Dry	-1.50 to -1.99
Extremely Dry	<-2.00

5 RESULTS AND DISCUSSION

A time series of annual RDI for Larisa (1981-2001) is shown in figure 4. The results include sample monthly RDI maps of Thessaly during drought periods (Figure 5 and 6). The results also include figures and tables presenting several features of drought, such as severity, duration, start and end time, as well as areal extent. In particular, Table II presents the drought periods, their duration along with the start and end times based on

RDI monthly estimates. Similarly, Table III presents the areal extent of the monthly RDI values including all the drought classes in terms of number of pixels for the drought years. Moreover, Figure 7 shows the cumulative areal extent of the severe to extreme class (<-2.0) during drought years.

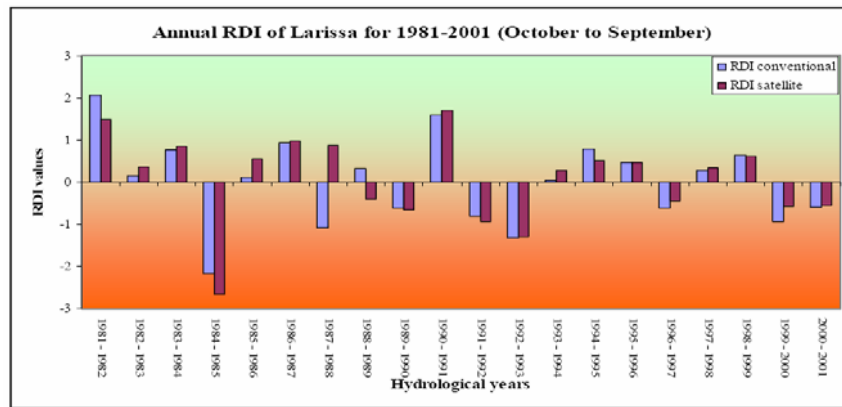


Figure 4. Annual RDI of Larissa for 1981-2001 (October to September).

Table II. Duration of drought episodes (in months in Thessaly)

Drought Years	Start	End	Duration
Oct 1984 - Oct 1985	Oct 1984	Oct 1985	13
Oct 1987 - Oct 1988	Oct 1987	Oct 1988	13
Sep 1989 - Oct 1990	Sep 1989	Oct 1990	13
Oct 1991 - Sep 1992	Oct 1991	Sep 1992	12
Oct 1992 - Oct 1993	Oct 1992	Oct 1993	13
Oct 1996 - Sep 1997	Oct 1996	Sep 1997	12
Oct 1999 - Sep 2000	Oct 1999	Sep 2000	12
Oct 2000 - Sep 2001	Oct 2000	Sep 2001	12

It is clear that remote sensing due to its increasing level of reliability and effectiveness presents new capabilities in assessing and monitoring the spatiotemporal variability of drought episodes. From Table III it is assessed that the total areal extent in Thessaly during drought years ranges in the same order of magnitude. Moreover, the cumulative areal extent (figure7) of extreme drought shows two distinct patterns with some drought years indicating high values of areal extent and the remaining indicating rather low values of areal extent. It is also characteristic in this figure 7 that in years of high areal extent drought starts during the first three months of the hydrological year, whereas in the years of low areal extent drought starts in spring (April). This finding also signifies the possibility for first-guess predictive drought assessment. It is well known that drought prediction and especially the start time is a very complicated issue.

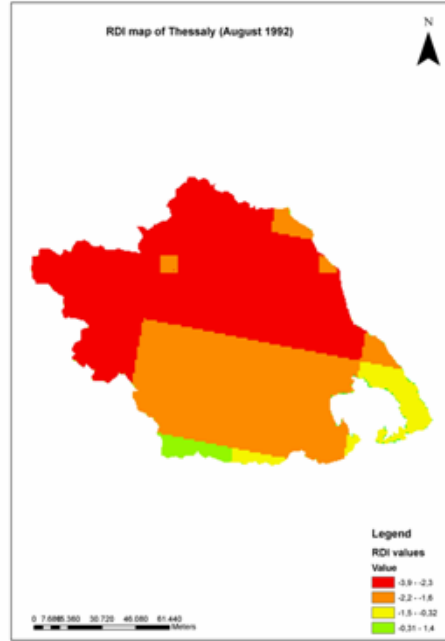
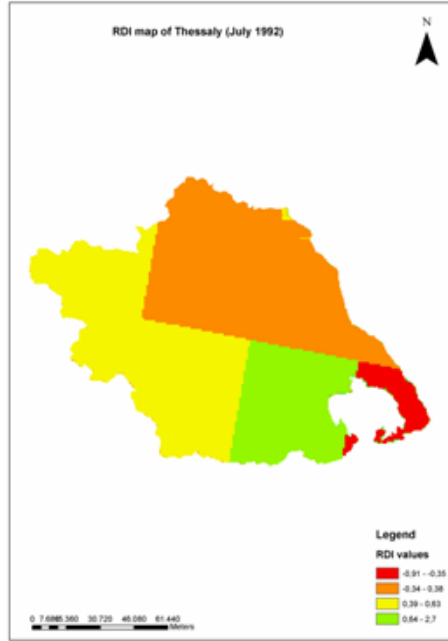


Figure 5. RDI map of Thessaly (July 1992). **Figure 6.** RDI map of Thessaly (August 1992).

Table III. Monthly Areal Extent of Drought years for the period 1981-2001. The values are in number of pixels (each pixel= 8x8 km²)

Years	1984-1985	1987-1988	1989-1990	1991-1992	1992-1993	1996-1997	1999-2000	2000-2001
Month								
Oct	207.704	0.039	75.214	81.906	111.175	2.589	25.984	16.675
Nov	84.984	0.234	167.91	163.812	128.343	207.769	8.398	207.691
Dec	95.527	66.21	23.019	205.765	203.183	45.351	74.156	205.273
Jan	82.093	86.312	207.714	207.648	199.039	72.425	199.3	40.957
Feb	2.441	0.238	207.789	207.496	45.347	199.359	22.148	164.46
Mar	0.265	0.218	207.789	203.925	199.718	201.363	207.417	207.617
Apr	167.148	127.707	159.589	0.222	206.437	0.41	203.73	4.847
May	125.921	196.152	2.089	12.472	0.105	207.753	185.269	14.039
Jun	205.144	59.792	161.484	8.48	114.875	16.73	12.289	133.984
Jul	128.741	60.468	40.132	8.386	201.535	146.554	171.257	0.089
Aug	114.992	130.746	0.25	203.839	191.9609	0.128	193.574	49.066
Sep	123.332	83.679	77.0234	204.066	81.285	203.824	75.566	199.304
Total	1338.27	811.8	1330.007	1508.023	1683.007	1304.261	1379.093	1244.007

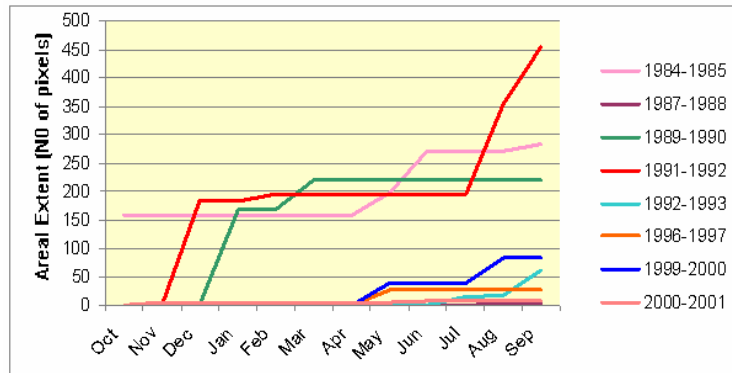


Figure 7: Cumulative Areal Extent (N of pixels 8X8 km²) of extreme drought (>2.0) during drought years based remotely sensed RDI.

6 CONCLUSIONS

In this paper, RDI is applied in Thessaly water district based on remote sensing and GIS techniques. RDI monitors the hydrometeorological drought and is estimated on annual and monthly basis. The data set covers a period of 20 hydrological years, from October 1981 to September 2001. The results show that, mostly, in central, northwestern and southeastern parts of Thessaly the drought episodes are very often. It is clear that remote sensing has indicated some new capabilities in assessing and monitoring the spatiotemporal variability of drought episodes. For the severe and extreme droughts the start usually coincides with the beginning of the hydrological year (October), whereas for moderate droughts the start is usually in spring (April), both lasting until the end of the hydrological year (September). There is also an increase in the areal extent of drought during each drought period with the maximum occurring usually in the summer. This finding also signifies the possibility for first-guess predictive drought assessment.

Acknowledgments. This research was funded by Pleiades, Smart and Hydrosense EC projects. The conventional meteorological data was provided by the National Meteorological Service of Greece. The precipitation maps were provided by the Joint Research Center (JRC) of EC, Ispra, Italy. The satellite data was provided by NOAA.

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