The analysis of the Standardized Precipitation Index in the Mediterranean area: large-scale patterns

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Abstract
Problems related to the identification and monitoring of drought are investigated. In particular, drought conditions in Italy are examined using the Standardized Precipitation Index (SPI) on different time scales for August 2000. Historical reconstruction of drought events is also shown for particular locations of Italy for the last fifty years. These preliminary applications show interesting results and demonstrate that the index considered is a tool that should be used operationally as part of a national drought watch system in Italy to monitor drought conditions objectively. An example of a monthly bulletin of drought for Italy is also shown.

Key words *climate variability – drought – monitoring*

1. Introduction

Drought is a normal feature of climate. It occurs in regions that may have quite different climatic regimes. As opposed to aridity, which is a permanent feature of climate, drought usually affects both wet and dry regions, and it is one of the most damaging climate-related hazards to impact societies. The response and the mitigation to its occurrence involve a careful planning of water resources and the design of a contingency plan to address and reduce the impacts when an early warning is issued. Thereby, it appears of a great importance to develop measures of drought intensity.

A step in defining drought is the updated knowledge of its strength over an area and how it is related to other areas.

In this paper we will discuss an application of the Standardized Precipitation Index (SPI) to identify large-scale drought conditions in Italy. Our analysis is simply based on the knowledge of the large-scale precipitation field, while its extension to a regional scale is presented in Bordi *et al.* (2001).

The methodology here described follows that generally used by many other drought watch centres. Nevertheless, to the best of our knowledge, the present effort is the first proposed for the Italian region.

The paper is organised as follows. In Section 2 we will describe some definitions of drought and its intensity through the indices mostly adopted in the international literature. As an example, in Section 3 we present the computation of the SPI for Italy. Section 4 shows the temporal behaviours of drought in particular locations of Italy for the last fifty years, while Section 5 presents a proposal for a monthly bulletin. In the final section we summarise the results and outline few conclusions.

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2. Defining drought

Drought is a recurrent feature of climate occurring in all climatic zones, although its impact may differ from one region to another. It originates from a deficiency of precipitation over an extended period of time and should be considered relative to some long-term average, as a negative imbalance between precipitation and evapotranspiration in a particular area. Drought is related to rainfall intensity, the number of rainfall events, delays to the start of the rainy season and the occurrence of principal seasons, while climatic factors such as high wind, high temperature or low relative humidity can amplify its intensity. Drought may be also defined in terms of agricultural, hydrological and socio-economic impacts. Factors in defining a dry period, in fact, may include land degradation, soil water deficits, reduced ground water and power production.

Over the years several indices have been developed and adopted to measure drought or wet spells intensity. Generally, they are based on the deviation of precipitation for a given period from historically established norms. Among these indicators, those that have been mostly used are: Percent of Normal, Deciles, SPI, Palmer Drought Severity Index (PDSI), Crop Moisture Index (CMI) and Surface Water Supply Index (SWSI).

The Percent of Normal index is calculated by dividing actual precipitation by normal precipitation, which is typically considered (according to World Meteorological Organisation recommendation) to be a 30-year mean, and multiplying by 100. This index can be computed for different time scales ranging from a single month to a particular season, or to a couple of years. The normal condition of precipitation for a specific area is considered to be 100%, while values less than 100% mean a dry condition. One of the major disadvantages in using this index is that the precipitation distribution on the time scale considered, is far from normal (this means, among other things, that the average precipitation is often not the same as the median precipitation). This makes it difficult to compare values of the index for different locations or time scales.

Gibbs and Maher (1967) proposed to arrange monthly precipitation data into deciles avoiding some of the limitations related to the percent of the normal approach. The technique in based on the division of the distribution of occurrence over a long-term precipitation record into tenths of the distribution. Deciles are then grouped into five classifications as shown in table I.

By definition, the fifth decile is the median and it is the precipitation amount not exceeded by 50% of the occurrences over the period of record.

This index can be calculated for several time scales and a long climatological record is needed to calculate the deciles accurately.

The SPI was developed by McKee *et al.* (1993) to quantify the precipitation deficit for multiple time scales (1, 3, 6, 12, 24, 48 months). This versatility allows the SPI to monitor short-term water supplies, such as soil moisture, important for agricultural production, and long-term water resources such as ground water supplies, steam-flow and reservoir levels.

The SPI computation is based on the long-term precipitation record for the desired time scale. The long-term record is fitted to a gamma probability distribution that is then transformed into a normal distribution, which, by definition, has zero mean and unit variance. Hence the SPI indicates the number of standard deviations that a particular event deviates from normal conditions. Moreover, since the SPI is normalised, wetter and drier climates can be monitored in the same way and a comparison between different locations can be made. The classification of dry and wet events resulting from the SPI calculation is shown in table II.

A drought event occurs if the SPI value is -1 or less and the event ends when the index becomes positive. It must be noted that not only the precipitation deficiency at a specific time scale, but also the consecutive occurrences of deficiencies define drought severity. Given the advantages of the index standardisation, the SPI has been largely used operationally to monitor climatic conditions across different locations, particularly in the United States.

Another index, widely used in the study of dry and wet spells, is the Palmer Drought Sever-

Table I. Deciles classification.

Decile	Percentage	Class
Deciles 1-2	Lowest 20%	Much below normal
Deciles 3-4	Next lowest 20%	Below normal
Deciles 5-6	Middle 20%	Near normal
Deciles 7-8	Next highest 20%	Above normal
Deciles 9-10	Highest 20%	Much above normal

Table II. SPI values classification.

SPI value	Class
> 2	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
– 0.99 to 0.99	Near normal
– 1 to – 1.49	Moderately dry
– 1.5 to – 1.99	Severely dry
< – 2	Extremely dry

Table III. PDSI values classification.

PDSI value	Class
> 4	Extremely wet
3 to 3.99	Very wet
2 to 2.99	Moderately wet
1 to 1.99	Slightly wet
0.5 to 0.99	Incipient wet spell
0.49 to – 0.49	Near normal
– 0.5 to – 0.99	Incipient dry spell
– 1 to – 1.99	Mild drought
– 2 to – 2.99	Moderate drought
– 3 to – 3.99	Severe drought
< – 4	Extreme drought

ity Index. The PDSI, originally proposed by Palmer (1965), is a measure of meteorological drought. It differs from the other indices, which are based on precipitation data only, because it takes into account temperature, evapotranspiration, runoff and soil water conditions also.

The index computation needs the knowledge of precipitation and temperature monthly means as well as the temperature long-term mean (usually calculated over 30-year period) and the soil water capacity (*i.e.* AWC, Available Water Capacity). The PDSI is based on the water balance equation for a two-layer soil model and varies roughly between – 4 and + 4. Each defined range of values corresponds to a particular class of events as listed in table III.

Initially, several local coefficients are computed to define local hydrological normal related to the temperature and precipitation data averaged over some calibration period. Then, the precipitation anomaly, with respect to climatically appropriate conditions for existing precipitation, and the moisture anomaly index are computed. The anomaly index is obtained using a weighting factor determined by Palmer from the calibration period of data referring to nine climatic divisions of the United States. The PDSI for a particular month is based partly on the anomaly index for that month and partly on the value for the earlier month. Moreover, Palmer developed the index to include the duration of a drought or wet spell. This because, for example, a series of months with near-normal precipitation following a serious drought event does not mean that the drought is over. Therefore, Palmer developed criteria for determining when a drought or a wet spell begins and ends, which adjust the PDSI accordingly.

Applications of PDSI to monitor drought events on different locations may have limitations (Alley, 1984; Karl and Knight, 1985). In particular, we mention the sensitivity to the soil water capacity (which needs the knowledge of soil local properties), the estimation of potential evapotranspiration using the Thornthwaite method (which is a popular technique, but is an approximation), or the use of constants to evaluate the weighting factor that are arbitrarily based on Palmer's study of Central Iowa and Western Kansas. The last limitation leaves open the question of a correct application of the PDSI to regions characterised by climatic conditions very different from those studied by Palmer.

The Crop Moisture Index was developed by Palmer (1968) to monitor week to week crop conditions using a procedure within the calculation of the PDSI. It is based on the mean temperature and total precipitation for each week. Since it is designed to monitor short-term moisture conditions, the CMI may provide misleading information about long-term conditions.

Finally, we recall the Surface Water Supply Index, which was developed by Shafer and Dezman (1982) to complement the Palmer index. The index takes into account topographic variations and snow accumulation, so the inputs for its computation are snowpack, stream-flow, precipitation and reservoir storage. Since there is a dependence on season, the winter months are calculated excluding the stream-flow, while the summer months exclude the snowpack. Moreover, the SWSI computation is unique to each basin or region. Therefore, it is difficult to make a comparison of its values among different regions (Doesken *et al.*, 1991).

3. SPI methodology and applications

In the following section we will show some applications of the SPI, which allow to monitor different time scales and do not have many of the limitations associated with the PDSI.

The method of SPI computation may be found in Guttman (1999). Nevertheless, to make the paper self-contained, in the following we will summarise the main steps needed for its computation.

The SPI computation for a specific time scale and location requires a long-term monthly precipitation record with 30 years or more of data. The probability distribution function is determined from the long-term record by fitting a gamma function to the data. The gamma distribution is defined as

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \text{for} \quad x > 0 \qquad (3.1)$$

where $\alpha > 0$ is a shape parameter, $\beta > 0$ is a scale parameter, x is the precipitation amount and $\Gamma(\alpha)$ is the gamma function.

The parameters of the gamma probability density function may be estimated from the data sample by means of a maximum likelihood method for each station, for each time scale of interest and for each month of the year. Thus, we obtain

$$\tilde{\alpha} = \frac{1}{4A}\left(1+\sqrt{1+\frac{4A}{3}}\right), \quad \tilde{\beta} = \frac{\bar{x}}{\tilde{\alpha}}, \qquad (3.2)$$

where

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}. \qquad (3.3)$$

Here n is the number of observations in which some precipitation has occurred. In addition $\bar{x}$, given a particular month, is the mean of the cumulative precipitation computed over all the same months in the record.

The resulting parameters are then used to find the cumulative probability of precipitation for the given month and time scale for the station considered. The cumulative probability, letting $t = x/\tilde{\beta}$, becomes the incomplete gamma function

$$G(x) = \int_0^x g(x)dx = \frac{1}{\Gamma(\tilde{\alpha})}\int_0^x t^{\tilde{\alpha}-1} e^{-t} dt. \qquad (3.4)$$

Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes

$$H(x) = q + (1 - q)G(x) \qquad (3.5)$$

where q is the probability of zero precipitation.

$H(x)$ is then transformed into a normal variable Z by means of the following approximation (Abramowitz and Stegun, 1965):

$$Z = SPI = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad \text{for} \quad 0 < H(x) \le 0.5$$

$$Z = SPI = +\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right) \quad \text{for} \quad 0.5 < H(x) < 1 \tag{3.6}$$

where

$$t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)} \quad \text{for} \quad 0 < H(x) \le 0.5$$

$$t = \sqrt{\ln\left(\frac{1}{(1.0 - H(x))^2}\right)} \quad \text{for} \quad 0.5 < H(x) < 1.0 \tag{3.7}$$

and c_0, c_1, c_2, d_1, d_2, d_3 are the following constants:

$$c_0 = 2.515517 \qquad d_1 = 1.432788$$
$$c_1 = 0.802853 \qquad d_2 = 0.189269 \tag{3.8}$$
$$c_2 = 0.010328 \qquad d_3 = 0.001308.$$

Hence, the SPI represents a Z-score variable and is normalised. At a given time, the SPI may be computed for different time scales, say one month or longer, just computing the cumulative probability at a given location for the time scale selected. Usually, 3, 6, 12 and 24-month time scales are considered to give information about drought and its impacts on different segments of the hydrological cycle for the area in question.

As an example of the SPI application, we computed the index for the Italian region (*i.e.* 7.6°E-19°E, 35.1°N-48.4°N). The data used for computations are provided by NOAA/CIRES Climate Diagnostics Centre and refer to the NCEP/NCAR reanalysis of meteorological fields from 1948 to present. The precipitation rate, which is the input for the SPI algorithm, is a gridded field of about 1.9° × 1.9° grid spacing.

In figs. 1a-d the SPI fields for the month of August 2000 and for 3, 6, 12 and 24-month time scales respectively are shown.

Figures show that on a 3-month time scale all the Italian regions are characterised by near normal conditions, while Puglia and Calabria are in moderately dry conditions. On a 6-month time scale the northern side of Italy features a moderately dry or near normal condition, while southern regions are affected by severe or extreme droughts. On longer time scales (12 and 24-month) the central regions are in normal or moderately wet conditions, while Sardegna and Sicilia are affected by a severe drought. This means that Sicilia and Sardegna are probably affected by hydrological drought with a consequent loss of water resources.

4. Historical reconstruction of drought

The historical reconstruction of drought in particular sites of Italy will be presented. In particular, our attention will focus on regions directly affected by drought during recent years, such as Sicilia, Puglia, Sardegna, East Alpi, and on central regions that have been less affected by dry events, such as the Marche.

The temporal behaviour of the monthly SPI on 24-month time scale are shown for the regions above in figs. 2, 3, 4, 5, 6 respectively. Computations cover the period spanning from January 1950 to August 2000 and refer to the nearest grid-points to the selected regions.

Historical reconstructions for these locations show a general trend of the SPI toward negative values starting from the last half of seventies, with different slopes in each region (on the Marche, for example).

At this stage of our analysis, the physical causes of this trend remain unclear. Nevertheless, two different interpretations may be offered: either in the last thirty years all regions considered have been affected by a linear decrease in precipitation, or the trend is only the descending part of a periodic behaviour, which we did not sample because the shortness of the

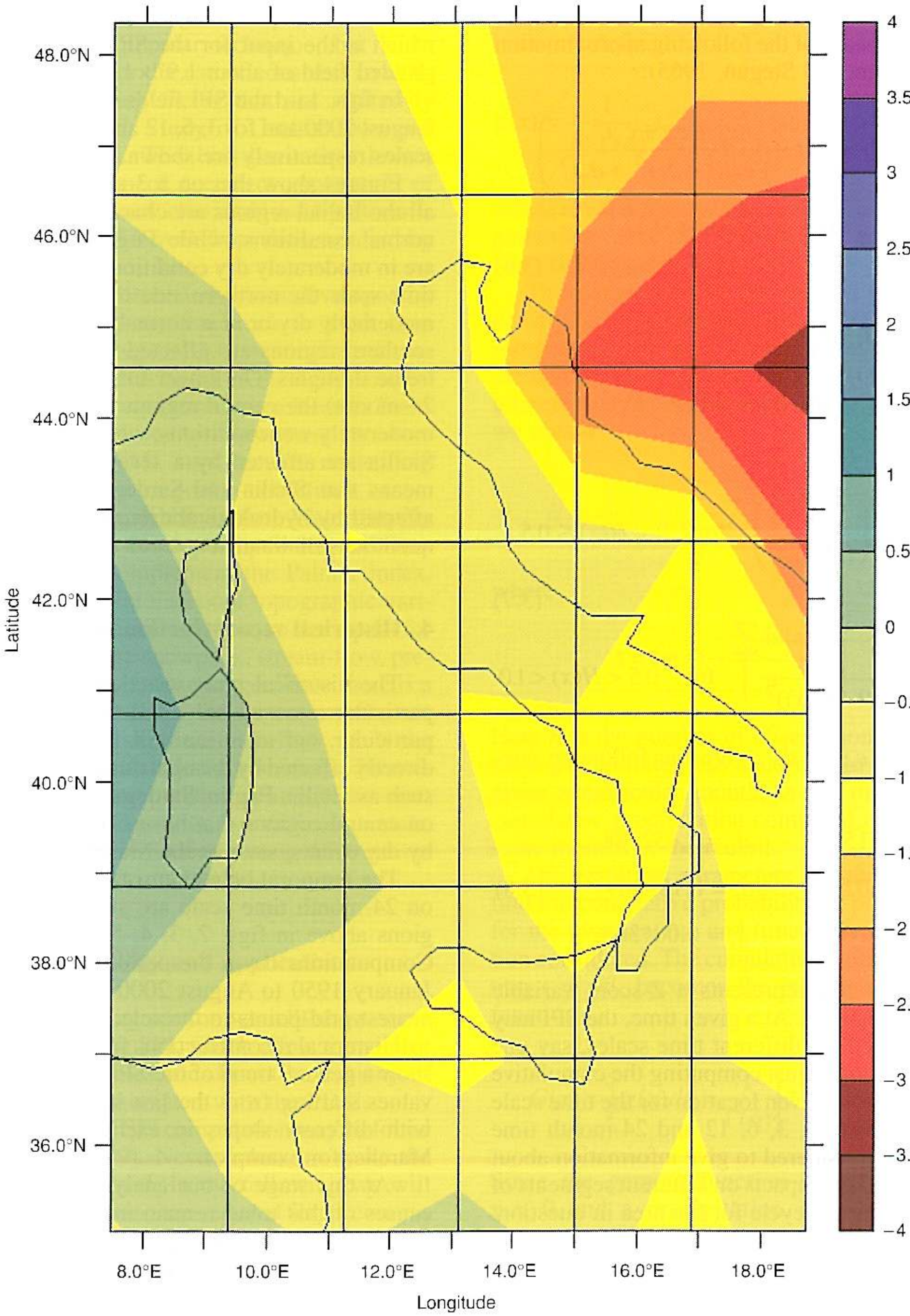

Fig. 1a. The SPI for Italy on 3-month time scale. Computation refers to August 2000 and the data used for the analysis are NCEP/NCAR precipitation rates. For the classification of SPI values see table II.

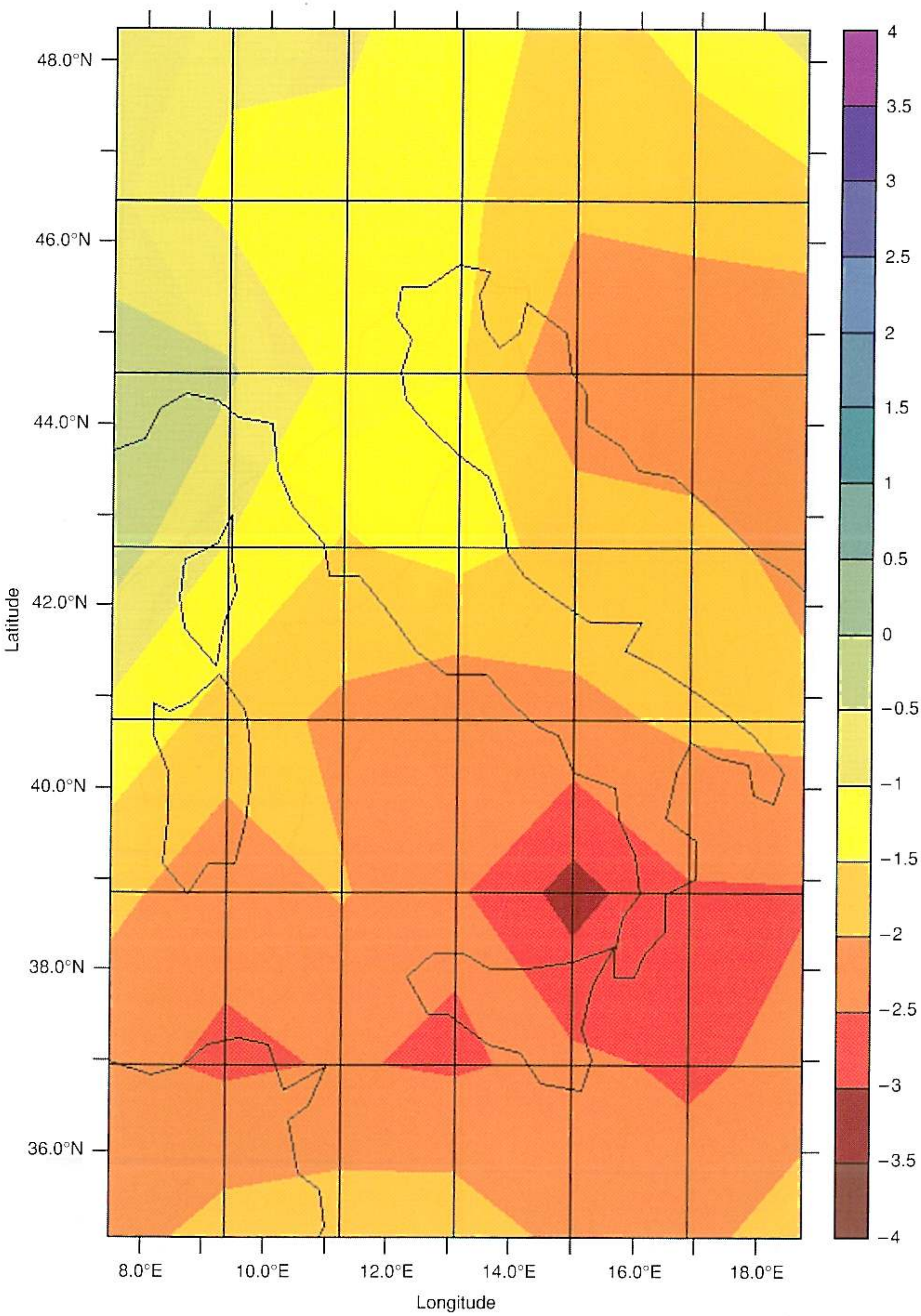

Fig. 1b. The SPI for Italy on 6-month time scale. Computation refers to August 2000 and the data used for the analysis are NCEP/NCAR precipitation rates. For the classification of SPI values see table II.

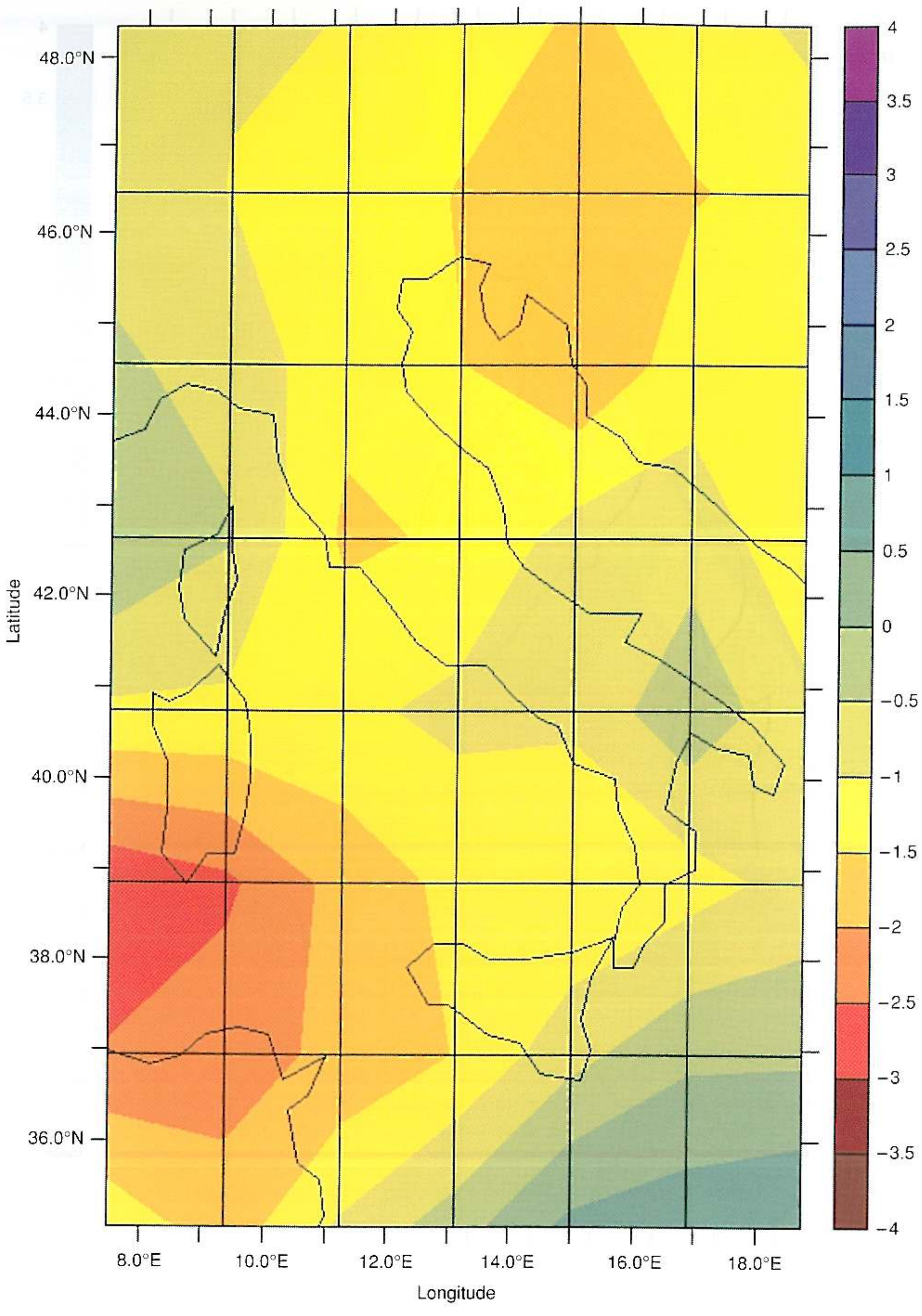

Fig. 1c. The SPI for Italy on 12-month time scale. Computation refers to August 2000 and the data used for the analysis are NCEP/NCAR precipitation rates. For the classification of SPI values see table II.

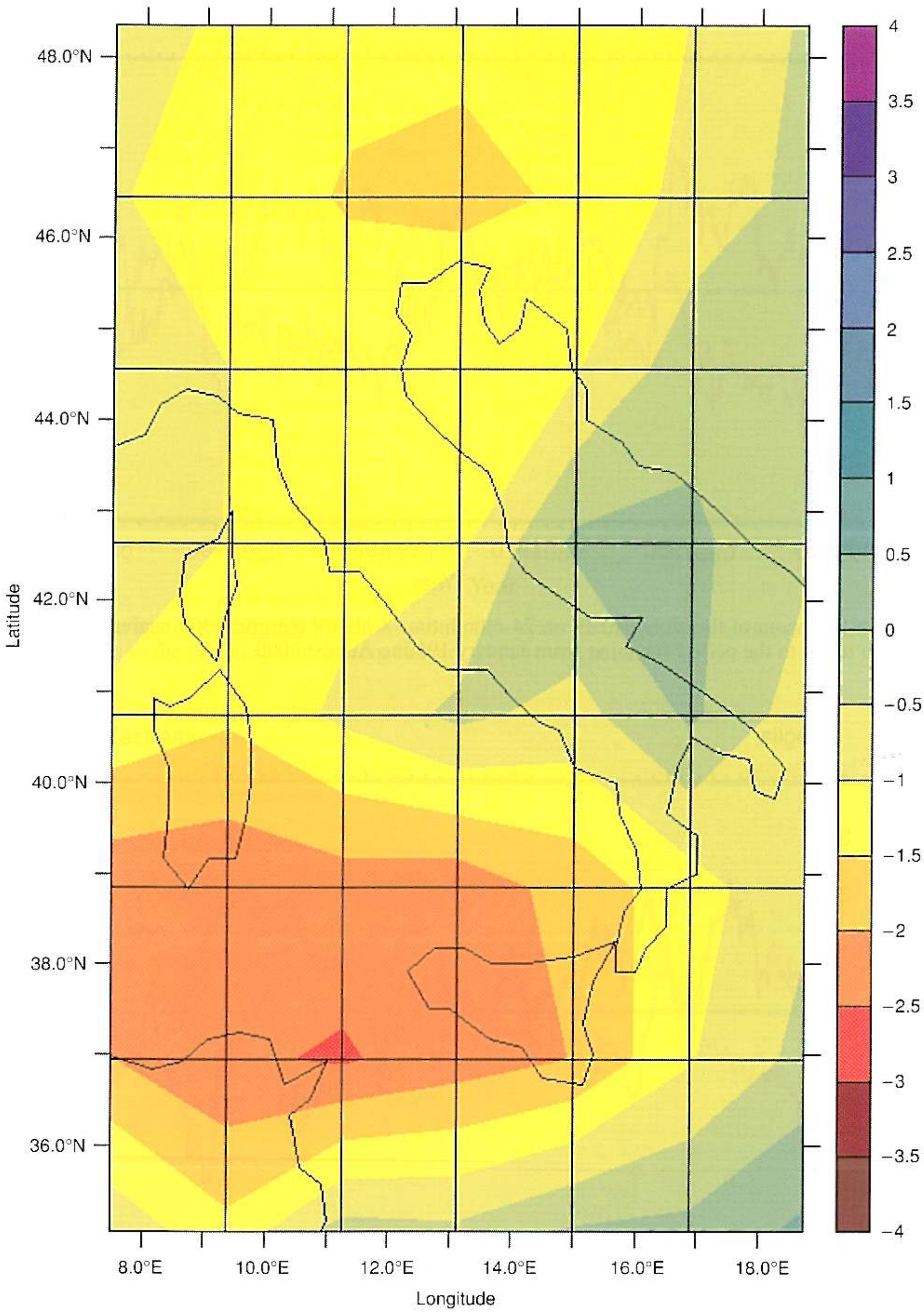

Fig. 1d. The SPI for Italy on 24-month time scale. Computation refers to August 2000 and the data used for the analysis are NCEP/NCAR precipitation rates. For the classification of SPI values see table II.

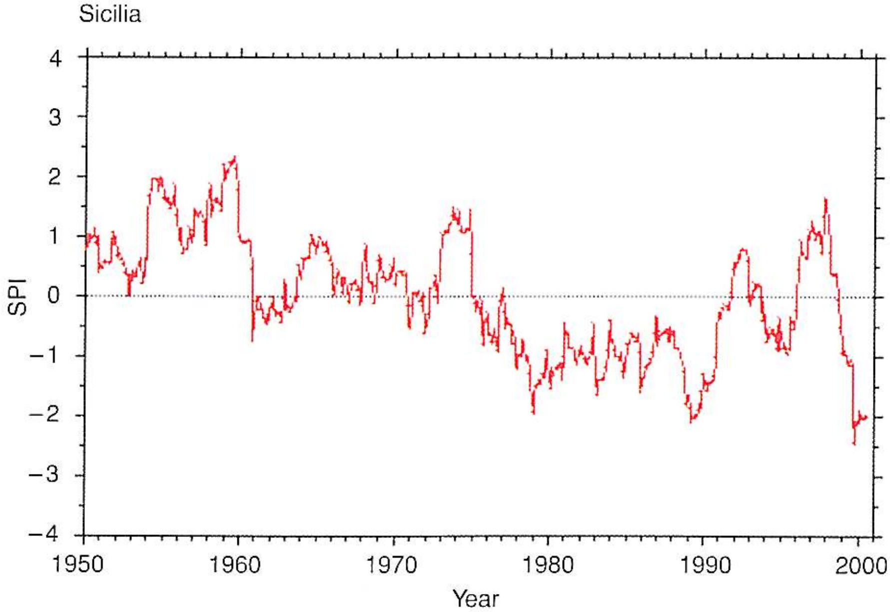

Fig. 2. Time-behaviour of the monthly SPI on 24-month time scale for the grid-point nearest to Sicilia region. Computation refers to the period spanning from January 1950 to August 2000.

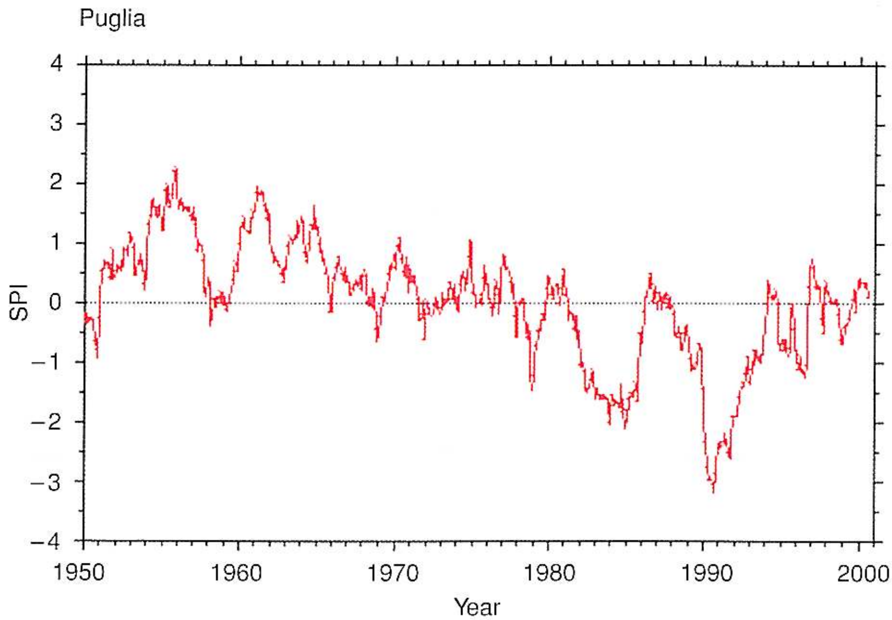

Fig. 3. Time-behaviour of the monthly SPI on 24-month time scale for the grid-point nearest to Puglia region. Computation refers to the period spanning from January 1950 to August 2000.

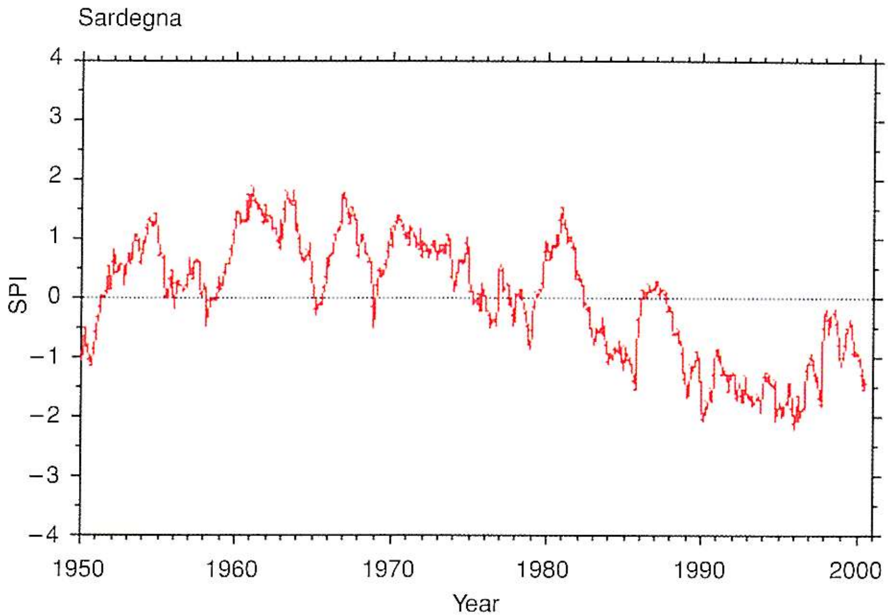

Fig. 4. Time-behaviour of the monthly SPI on 24-month time scale for the grid-point nearest to Sardegna region. Computation refers to the period spanning from January 1950 to August 2000.

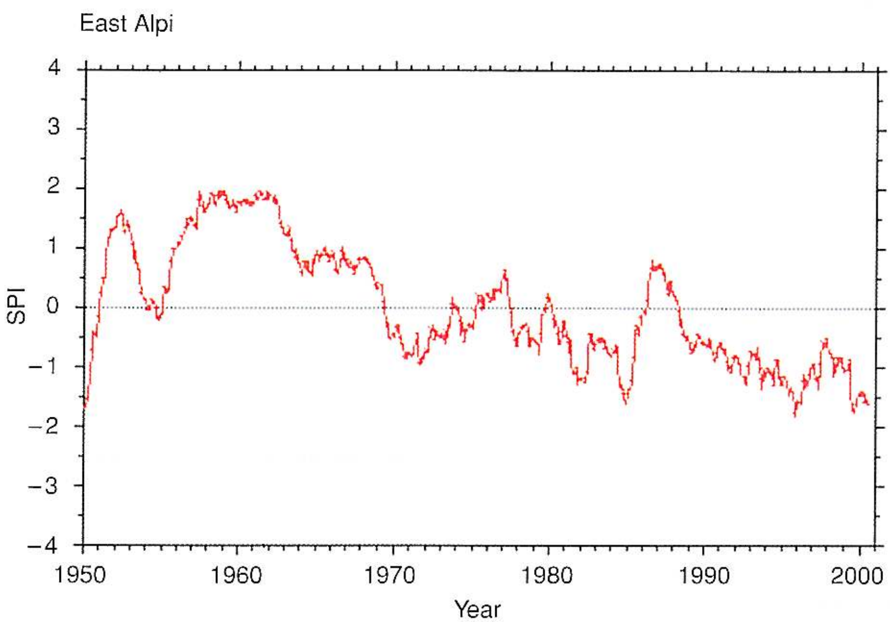

Fig. 5. Time-behaviour of the monthly SPI on 24-month time scale for the grid-point nearest to East Alpi region. Computation refers to the period spanning from January 1950 to August 2000.

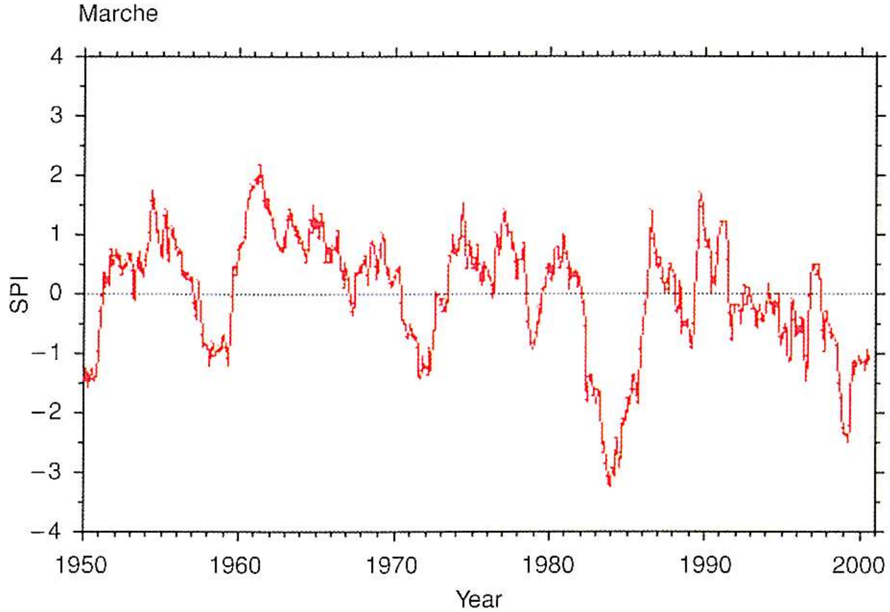

Fig. 6. Time-behaviour of the monthly SPI on 24-month time scale for the grid-point nearest to Marche region. Computation refers to the period spanning from January 1950 to August 2000.

time series considered. Probably, the last interpretation is the most reliable, since there are different almost periodic phenomena that can influence precipitation field over the globe on these time scales, such as NAO (North Atlantic Oscillation) (Wallace and Gutzler, 1981; Hurrell, 1995; Eshel and Farrell, 2000), ENSO (El Niño-Southern Oscillation) (Walker, 1924; Dai *et al.*, 1997) and so on.

5. A proposal for a drought bulletin

A proposal for a monthly bulletin to monitor drought in Italy is presented. This project is under study for a future operational service by the DSTN (Department of Italian National Technical Services). Since, among the indices discussed above, not one is the best to assess drought in all circumstances, we have selected few of them to describe the Italian climatic condition. Namely the Percent of Normal, the SPI, Deciles and Palmer index.

The bulletin should be monthly and the results of the main indices computation should be shown on a web site with comments and descriptions of the methodology adopted. The bulletin should consist of the following sections:

a) Drought monitor.
b) Meteorological conditions.
c) Large-scale analysis.
d) Regional analysis.
e) Forecast.
f) Archive.

Section (a) will present information on drought definition, its meteorological aspects and its impacts, the definition of the indices adopted and a description of the data used for calculations. Section (b) will contain the anomaly maps for the current month of the surface temperature, the sea level pressure and the precipitation rate. Section (c) will show results for the selected indices for the Italian region with comments on the current conditions, while section (d) will offer a regional analysis of drought as deduced from rain-gauge observations. Section (e) will be dedicated to forecasting drought conditions for future months. Finally, section (f) should provide an archive of the indices maps for each month analysed until five years earlier.

A prototype web page has been developed following the outlines described above for the Italian region and it is available at the URL http://romatm13.phys.uniroma1.it/siccita/index.html.

6. Summary and conclusions

The problem of drought identification and its meteorological aspects are investigated. The possibility of assessing and monitoring drought events on different time scales using the SPI computation is evaluated. Drought conditions in Italy are shown as an example of the index application.

The analysis is based on a large-scale (*i.e.* low spatial resolution) precipitation field from the NCEP/NCAR reanalysis data set. However, the methodology adopted can be easily extended to a finer scale down to the single rain-gauge element, provided that a homogeneous local precipitation record is available. Moreover, temporal behaviours of the 24-month time scale SPI in some locations of Italy reveal a trend that need further investigations to be clearly understood.

Future efforts will be made to study whether the trend found is related to some multi-decadal variability of the climatic system and to apply the SPI algorithm to a higher spatial resolution data set down to the station data.

Finally, the SPI applications confirm that the most important characteristics of the index are its flexibility to monitor different time scales and its standardisation. These characteristics make the SPI a useful tool to assess short or long-term drought conditions and should be used successfully as part of an operational drought bulletin.

Acknowledgements

The authors are grateful to Prof. M. Benedini, Eng. G. Monacelli, Prof. G. Rossi and Prof. P. Versace for their contributions to the early stage of this work. We thank the Italian Department of National Technical Services and ASI for financial supports under the EU program INTERREG IIC and ASI-ARS99-62ASTRO respectively.

Data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their website at the URL http://www.cdc.noaa.gov.

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(received January 8, 2001;
accepted December 10, 2001)