Assessing changes in drought and wetness episodes in drainage basins using the Standardized Precipitation Index

Álvaro Silva, M. Isabel P. de Lima, Fátima Espírito Santo and Vanda Pires

Beurteilung von Änderungen in der Abfolge von Trocken- und Feuchtperioden in Einzugsgebieten mit Hilfe des Standardisierten Niederschlagsindex (SPI)

1 Introduction

In recent years, more extreme precipitation events have been observed in many parts of the world, a behaviour that is often being associated with the increased moisture content of the atmosphere as a result of global warming; however, precipitation increases might be scattered because of the complex combination of different prominent factors (e.g. TRENBERTH, 1999). At the same time, drought episodes are also affecting many areas in the world. In fact, although changes in the water cycle are related to a large range of spatial and temporal scales, their local impact can differ with geographical location.

Changes in the precipitation and air temperature have been already reported for several regions worldwide (e.g. ALEXANDER et al., 2006), including Europe (e.g. KLEIN TANK & KÖNNEN, 2003) and, in particular, the Iberian Peninsula. For mainland Portugal, recent studies (e.g. RAMOS et al., 2011; DE LIMA et al., 2013a, 2013b; ESPÍRITO SANTO et al., 2014a, 2014b; DE LIMA et al., 2015) have investigated trends in time series of several precipitation and air temperature extremes indices (e.g. threshold, probability, duration indices; e.g. PETERSON et al., 2001; KLEIN TANK et al., 2009) calculated for many locations across the area. However, for assessing the extent of the areas affected by extreme conditions, at various time scales, and changes (in time and space) in hydrological variables – and their

Zusammenfassung

Die raum-zeitliche Variabilität des Niederschlags beeinträchtigt die Gesellschaft, die Umwelt und die Wirtschaft in unterschiedlicher Weise. Die vorliegende Studie verwendet die Methode des Standardisierten Niederschlagsindex (SPI) um außerordentliche Trocken- und Feuchtephasen zu identifizieren und deren räumliche Muster im Einzugsgebietsmaßstab für ausgewählte Gebiete Portugals besser zu verstehen. Der SPI kann für hydrologische Untersuchungen insbesondere bei fehlenden Niederschlagsmessungen sinnvoll eingesetzt werden. Der SPI weist für den Zentralbereich Portugals Änderungen der Ausdehnungen trockener und feuchter Extrema aus, die durch saisonale und lokale Faktoren bestimmt sind.

Schlagwörter: Niederschlagstrends, Dürre, Hochwasser, Standardisierter Niederschlagsindex.

Summary

The temporal and spatial variability of precipitation might affect in a different way the society, the environment and the economy at the local and regional scales, depending on specific conditions. This study focuses on using the Standardized Precipitation Index (SPI) to identifying abnormal dry and wet periods and to understanding its spatial patterns at the drainage basin scale, for selected basins in mainland Portugal (1941–2012); this index might be useful in hydrological studies, in particular in basins missing detailed information on precipitation. Overall, SPI shows changes in the extent of dry and wet extremes throughout various time scales that depend on the season and geographical location within mainland Portugal.

Key words: Precipitation trends, drought, flood, Standardized Precipitation Index.

impact on water balances and transport processes at the basin scale and for different time scales –other more convenient study approaches can be used; namely, simple and standardized ways to quantifying and expressing the spatio-temporal variability of the precipitation input, such as the Standardized Precipitation Index (SPI).

Thus, this study reports on using the SPI to examine the variability and trends in the recent temporal and spatial extent of abnormal precipitation in mainland Portugal, leading to severe and extreme dry and wet episodes, at the drainage basin scale. The SPI was calculated at short (3 and 6 months) and long (12 and 24 months) time scales, for the period 1941–2012. The results are detailed for the Portuguese part of the Douro, Tagus and Guadiana river basins, which are trans-boundary rivers (Fig. 1, left).

2 Study area and data

In mainland Portugal, latitude (ranging between approximately 36º 56′ and 42º 09' N), orography (altitude < 2000 m a.s.l.) and the effect of the Atlantic Ocean are the factors that dominate most the climate in the territory, characterized by large north-south and east-west precipitation gradients: mean annual precipitation varies from about 3000 mm in the north to roughly 500 mm in the south. Seasonality is very marked across the area, with autumn and winter precipitation contributing with around 70 % to annual precipitation, and summer precipitation with only roughly 6 %.

This study uses monthly precipitation data from 53 climatologic weather stations and rain-gauges (Fig. 1) from the networks of the Portuguese Sea and Atmosphere Institute (IPMA) and Portuguese Environment Agency (Agência Portuguesa do Ambiente, APA), for the period 1941–2012. The data were complete and showed no statistical evidence of non-homogeneity. The data were used to investigate precipitation anomalies over selected drainage basins in mainland Portugal. Here we focus on the Portuguese part of the Douro, Tagus and Guadiana river basins (Fig. 1). On average, the contribution of these basins to total precipitation in the country is 23 % (Douro), 25 % (Tagus) and 8 % (Guadiana).

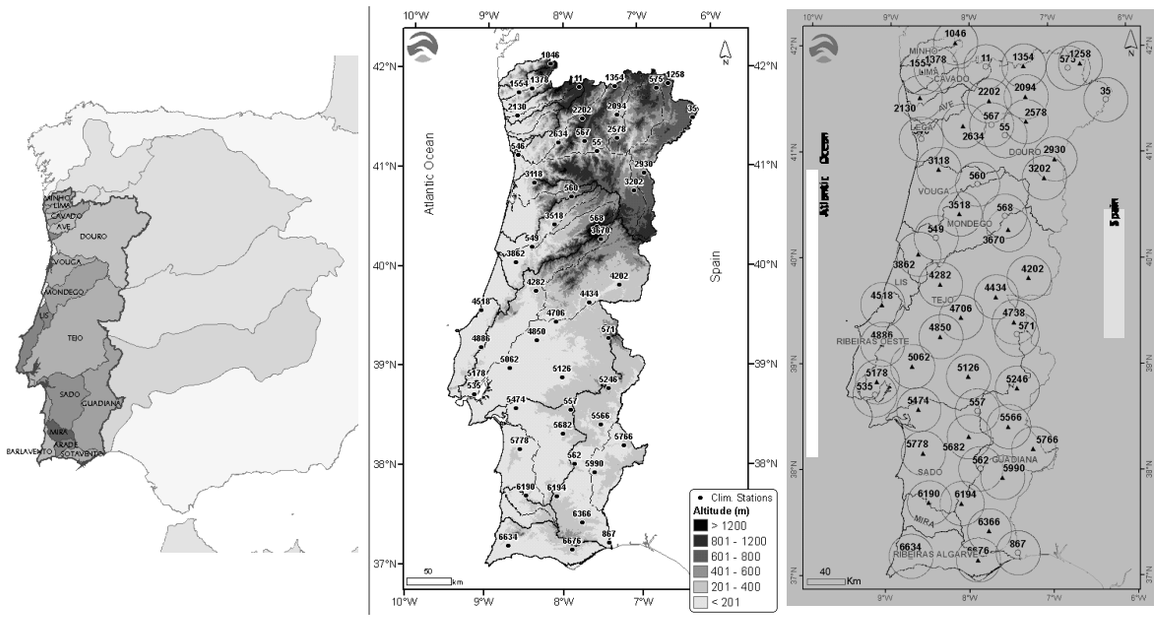

Figure 1: Left: Representation of the main river basins in mainland Portugal, highlighting the trans-boundary basins. Center: Relief map showing the location of the precipitation stations used for calculating the SPI, in mainland Portugal, including the main rivers (dash lines) and the limits of the main drainage basins (solid line). Right: The average density of the selected stations on the territory is 1 per 1700 km^2, circles centered on the stations

Abbildung 1: Links: Lage der Hauptflusseinzugsgebiete Portugals (grenzüberschreitende Gebiete sind hervorgehoben). Mitte: Reliefkarte Portugals mit Einzugsgebietsgrenzen und den verwendeten Niederschlagsstationen. Rechts: Mittlerer Abdeckungsgrad der Niederschlagsstationen (1 Station pro 1700 km^2 durch Kreise dargestellt)

3 Methods

The Standardized Precipitation Index (McKee et al., 1993, 1995) is a probability-based indicator that is used to investigate precipitation anomalies with respect to long-term normal conditions, based on the associated number of standard deviations. Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. In this method, precipitation is normalized using a probability distribution; in the calculations, the method described by Edwards & McKee (1997) was applied. Based on the SPI, wet and dry episodes can be classified as shown in Table 1.

Table 1: Classification of wet and dry events based on the SPI and corresponding probabilities (adapted from e.g. WMO, 2012)
Tabelle 1: Klassifizierung trockener und feuchter Ereignisse anhand des SPI mit den dazugehörigen Auftrittswahrscheinlichkeiten (angepasst aus WMO, 2012)

SPI value	Category	Probability (%)
≥ 2.00	Extremely wet	2.3
1.50 to 1.99	Very wet	4.4
1.00 to 1.49	Moderately wet	9.2
0 to 0.99	Mildly wet	34.1
0 to –0.99	Mildly dry	34.1
–1.00 to –1.49	Moderately dry	9.2
–1.50 to –1.99	Severely dry	4.4
≤ –2.00	Extremely dry	2.3

In relation to other indices, SPI has the advantage that it can be calculated for a variety of time scales (frequently, in the range from 3 to 24 months; e.g. SPI-3 is for 3 months) on which precipitation shortage/excess can affect different aspects of the hydrologic cycle and thus the environment, eco-systems, water availability for agriculture and human consumption, stream flow, reservoir storage, energy production and groundwater supplies, for example. The shortest scales quantify more superficial soil water (i.e. more related to agriculture) whereas the longest scales (12 or 24 months) indicate the state of the subsoil moisture and, thus, increases in soil wetness that can enhance flood events. Therefore, these time scales are related to the natural lags in the response (e.g. depletion and replenishment) of surface and ground water resources to the precipitation input. So, the combination of different SPI scales in the analysis might contribute to monitor the development and persistence of dry and wet hydro-meteorological situations.

Moreover, this normalized index is suitable for spatial representations (e.g. Wu et al., 2005; WMO, 2012). By applying an appropriate interpolation algorithm – the inverse distance weighting (e.g. Patel et al., 2007; Rhee et al., 2008) – to the SPI values, spatial grids (1 km resolution) were obtained for all the months and main time scales. These grids were used to obtain the SPI statistics for selected drainage basins, using an areal statistics function; the dry and wet episodes were thus classified (Table 1) and the areas affected were assessed.

Linear trends in the SPI time series were calculated by ordinary least squares fit; different levels of the statistical significance of the trends were evaluated using the Student's *t* test and the non-parametric Mann–Kendall test (e.g. Kendall et al., 1983), as suggested by Nicholls (2001).

4 Results and discussion

In mainland Portugal, annual precipitation shows large inter-annual variability and, overall, a downward trend during the 72 years investigated (1941–2012). During this period the largest negative anomalies in the Douro, Tagus and Guadiana river basins and throughout mainland Portugal occurred in the year 2004/2005, with an annual precipitation of about 431 mm, 379 mm, 228 mm and 411 mm, respectively. The wettest year was 1966/67 in the Tagus basin (1380 mm), 2000/2001 in the Douro basin (> 1500 mm) and 1995/1996 in the Guadiana basin (916 mm).

Analysis of the SPI shows a high frequency oscillation between negative and positive SPI values, particularly for long-term scales. Nevertheless, there is an overall downward trend in the SPI calculated for almost all time scales, which indicates a tendency for the occurrence of drier conditions in the region; the exception is SPI-3 for autumn (SON, see Fig. 2), which agrees with the increasing trend in autumn precipitation already reported by e.g. de Lima et al. (2010, 2013b) and Espírito Santo et al. (2014a). Note that trends in the data are not always statistical significant at the 5 % level, although they might have hydrological relevance.

Analysis of the SPI-3 (Fig. 2) and SPI-6 also shows that there are considerable differences between seasons and between the wet half-year (October-March) and the dry half-year (April to September). The extreme wet episodes seem to be more frequent in the winter months, which can be partly explained by the precipitation regime itself. The summer SPI-3 shows the lowest frequency of droughts among

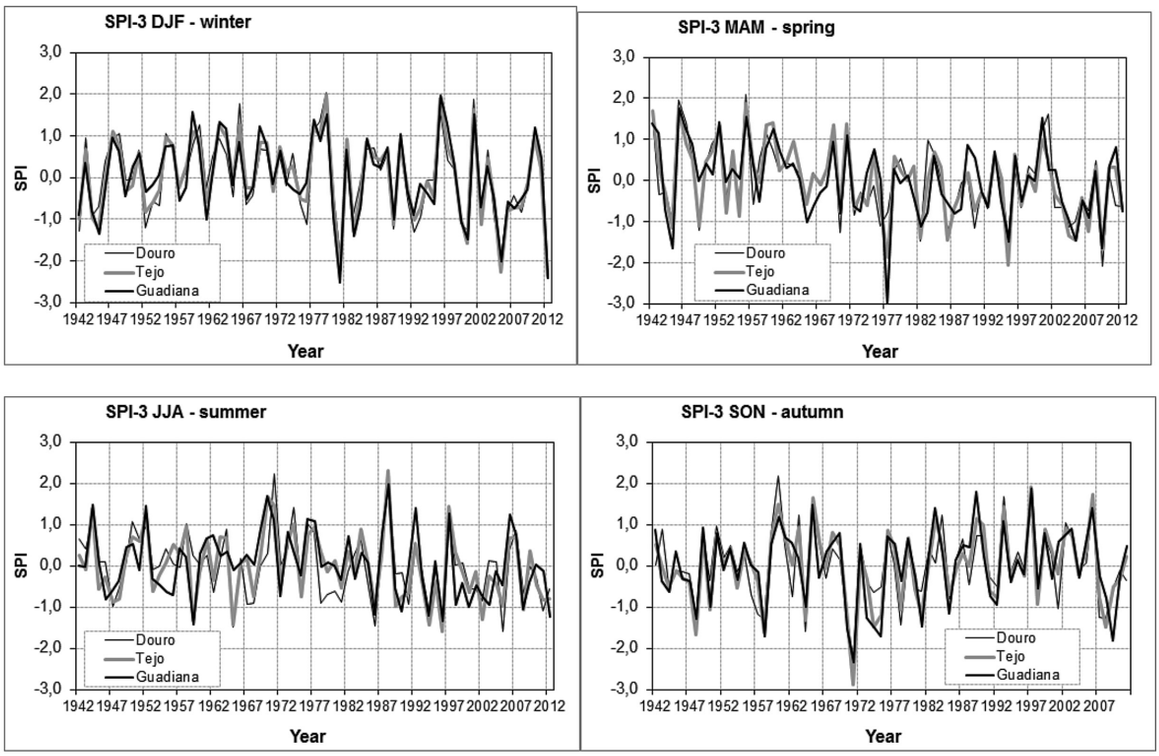

Figure 2: Time series of seasonal SPI-3 values in the Portuguese part of the Douro, Tagus and Guadiana river basins, for the period 1941–2012
Abbildung 2: Zeitlicher Verlauf der saisonalen SPI-3 Werte der Portugiesischen Einzugsgebiete von Douro, Tagus und Guadiana der Periode 1941–2012

all seasons and a frequency of wet episodes that are similar to fall; however, results depend on geographic location. For SPI-6, the 3 basins investigated showed similar results.

For longer time scales, both the SPI-12 and SPI-24 show that, in general, the most severe droughts were observed in the years 1944/1945, 1980/1981 and 2004/2005 (Fig. 3a). It is notable that the Guadiana river basin experienced the highest number of years classified as severe or extreme drought – six years in total. As for occurrences classified as severe to extreme wet, only the year 2000/2001 (Fig. 3b) is noteworthy, especially for the conditions in the Douro basin.

Trends in the area of the Portuguese part of the Douro, Tagus and Guadiana river basins observing moderate to extreme precipitation anomalies were evaluated using the SPI for scales of 6, 12 and 24 months. SPI-12 and SPI-24 (Table 2) reveal that there is an increasing trend in the area showing moderate to extreme drought; however, the only statistically significant result at the 5 % level is for SPI-24, for the Tagus basin: +3.89 percent area per decade. On the other hand, there is a decreasing trend in the area affected by moderate to extreme excess precipitation; the results for SPI-24 are statistically significant for the basins of the Douro and Guadiana rivers, respectively, -2.37 and -3.12 percent area per decade. For shorter time scales, the fraction of the territory experiencing severe and extreme dryness and

Table 2: Trends in the area of the Portuguese part of the Douro, Tagus and Guadiana river basins affected by moderate to extreme dryness and wetness in the period 1941–2012, shown by SPI-12 and SPI-24. Trends are in percentage of territory per decade (bold indicates statistical significance at 5 % level)
Tabelle 2: Trends (als Flächenanteil pro Dekade) für extreme Trockenheit und Feuchte für den Zeitraum 1941 bis 2012 anhand SPI-12 und SPI-24 Auswertungen. Fett gedruckte Werte sind am 5 %-Niveau statistisch signifikant

BASIN	Drought		Wet	
	SPI-12	SPI-24	SPI-12	SPI-24
Douro	3.60	4.21	-1.64	**-2.37**
Tagus	3.45	**3.89**	-1.19	-2.19
Guadiana	2.64	3.22	-1.40	**-3.12**

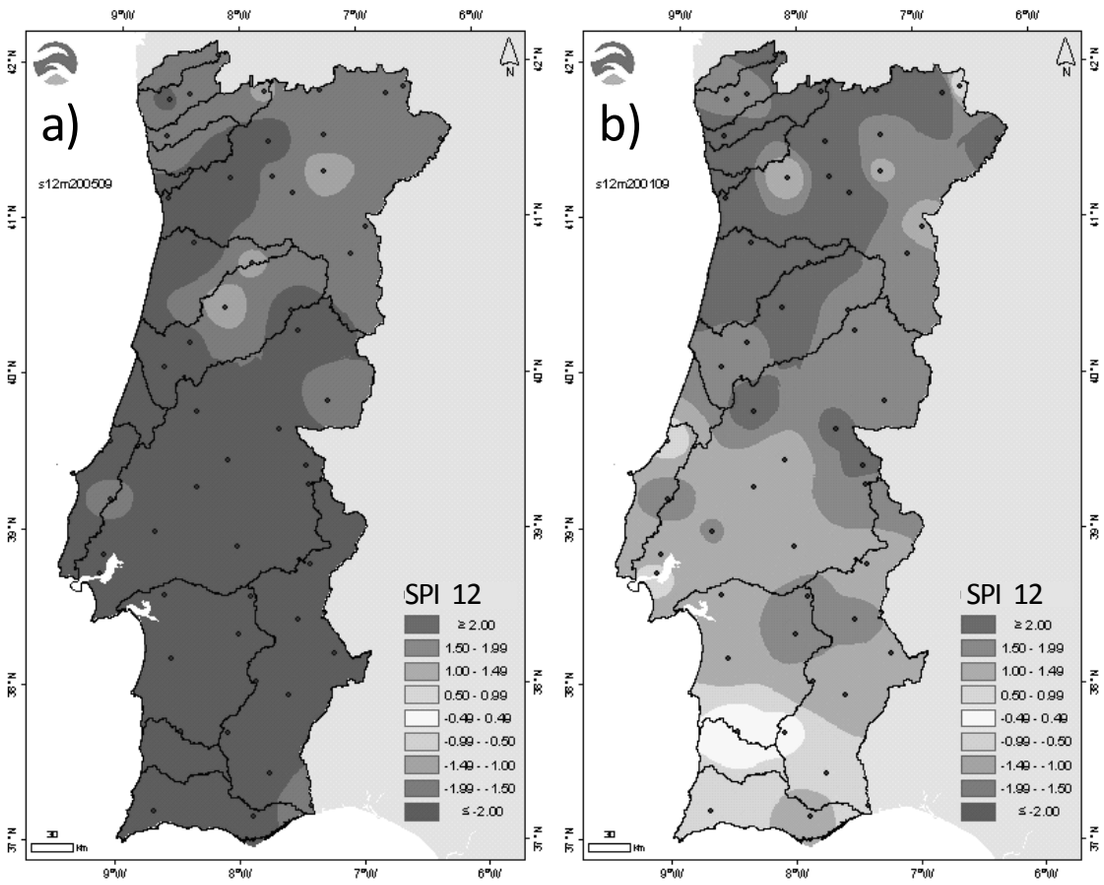

Figure 3: Spatial distribution of SPI-12 (October to September) in mainland Portugal for two extreme episodes: a) the extreme dry year 2004/2005, with SPI < 0; b) the extreme wet year 2000/2001, with SPI > 0. The main river basins are shown

Abbildung 3: Räumliche Verteilung von SPI-12 in Portugal für a) das extreme Trockjahr 2004/2005 mit SPI < 0; b) das extreme Feuchtjahr 2000/2001 mit SPI > 0. Die Haupteinzugsgebiete sind explizit dargestellt

wetness tends to increase or decrease, depending on the season and observation period.

5 Final remarks

For the different SPI time scales, the frequency and severity of wet/dry events have a marked north/south spatial variability for the 3 basins; this is directly related to the location of the Douro, Tagus and Guadiana river basins in mainland Portugal (respectively, north, centre and south).

However, overall results suggest that drought situations, in mainland Portugal, have become more frequent and intense, particularly in the last four decades. At the seasonal scale, the SPI-3 and SPI-6 values exhibit high frequency oscillation between dry and wet periods, and notable differences among seasons. In particular, a significant reduction in spring precipitation is confirmed: the SPI-3 shows a statistically significant (at the 5 % level) decreasing trend in spring, in the three main basins analyzed. Results also show an increase in autumn precipitation, namely a growing tendency in SPI-3.

For longer time scales, the annual SPI shows an increase in the area affected by moderate to extreme dryness that is larger than the decrease in the extent of wet episodes; for SPI-24, trends are higher than for SPI-12 and are significant for wet episodes in the Douro and Guadiana basins, and for dry episodes in the Tagus basin.

This study illustrates that SPI can be implemented at the drainage basin scale, which should be accompanied by a choice of the SPI time scale that is in accordance with the predominant basin's land uses; thus, it can play an important role in agricultural and hydrological assets, including when applied to small basins water management.

References

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., and 20 others (2006): Global observed changes in daily climate extremes of temperature and precipitation. Journal Geophysical Research Atmospheres, 111, D05109, doi: 10.1029/2005JD006290.

de Lima, M. I. P., Carvalho, S. C. P. & de Lima, J. L. M. P. (2010): Investigating annual and monthly trends in precipitation structure: an overview across Portugal. Natural Hazards and Earth System Sciences, 10: 2429–2440, doi: 10.5194/nhess-10-2429-2010.

de Lima, M. I. P., Espírito Santo, F., de Lima, J. L. M. P. & Ramos, A. M. (2013a): Recent precipitation variability over 67 years in mainland Portugal. Die Bodenkultur – Journal for Land Management, Food and Environment, 64(3–4): 21–26.

de Lima, M. I. P., Espírito Santo, F., Ramos, A. M. & de Lima, J. L. M. P. (2013b): Recent changes in daily precipitation and surface air temperature extremes in mainland Portugal, in the period 1941–2007. Atmospheric Research, 27: 195–209, doi: http://dx.doi.org/10.1016/j.atmosres.2012.10.001.

de Lima, M. I. P., Espírito Santo, F., Ramos, A. M. & Trigo, R. M. (2015): Trends and correlations in annual extreme precipitation indices for mainland Portugal, 1941–2007. Theoretical and Applied Climatology, 119(1–2): 55–75, doi: 10.1007/s00704-013-1079-6.

Edwards, D. C. & McKee, T. B. (1997): Characteristics of 20th century drought in the United States at multiple time scales. Climatology Report 97-2, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado.

Espírito Santo, F., Ramos, A. M., de Lima, M. I. P. & Trigo, R. M. (2014a): Seasonal changes in daily precipitation extremes in mainland Portugal from 1941 to 2007. Regional Environmental Change, 14(5): 1765-1788, doi: 10.1007/s10113-013-0515-6.

Espírito Santo, F., de Lima, M. I. P., Ramos, A. M. & Trigo, R. M. (2014b): Trends in seasonal surface air temperature in mainland Portugal, since 1941. International Journal of Climatology, 34(6): 1814–1837, doi: 10.1002/joc.3803.

Kendall, M. G., Stuart, A. & Ord, J. K. (1983): The Advanced Theory of Statistics. Vol. 3, Design and Analysis, and Time-Series. 4th ed. Griffin, 780 pp.

Klein Tank A. M. G. & Können, G. P. (2003): Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999. Journal of Climate, 16: 3665–3680.

Klein Tank A. M. G., Zwiers, F. W. & Zhang, X. (2009): Guideline on analysis of extremes in a changing climate in support of informed decisions for adaptation. Climate Data and Monitoring. WCDMP-No. 72, WMO-TD No. 1500, Geneve, Switzerland.

McKee, T. B., Doesken N. J. & Kleist, J. (1993): The relationship of drought frequency and duration to time scale. In: Proceedings of the Eighth Conference on Applied Climatology, Anaheim, California, 17–22 January 1993. Boston, American Meteorological Society, 179–184.

McKee, T. B., Doesken N. J. & Kleist, J. (1995): Drought monitoring with multiple timescales. In: Proceedings of the Ninth Conference on Applied Climatology, Dallas, Texas, 15–20 January 1995. Boston, American Meteorological Society, 233–236.

Nicholls, N. (2001): The insignificance of significance testing. Bulletin American Meteorological Society, 82: 981–986.

Patel, N. R., Chopra, P. & Dadhwal, V. K. (2007): Analyzing spatial patterns of meteorological drought using standardized precipitation index. Meteorological Applications, 14: 329–336, doi: 10.1002/met.33.

Peterson, T. C., Folland, C., Gruza, G., Hogg, W., Mokssit A. & Plummer N. (2001): Report on the Activities of the Working Group on Climate Change Detection and Related Rapporteurs 1998–2001. Report WCDMP-47, WMO-TD 1071, World Meteorological Organisation, Geneva, Switzerland. WMO-TD No. 1071, 146 pp.

Ramos, A., Trigo, R. M. & Santo, F. E. (2011): Evolution of extreme temperatures in Portugal: reporting on recent changes and future scenarios. Climate Research, 48: 177–192. doi:10.3354/cr00934

Rhee, J., Carbone, G. J. & Hussey, J. (2008): Drought index mapping at different spatial units. Journal of Hydrometeorology, 9(6): 1523–1534, doi: http://dx.doi.org/10.1175/ 2008JHM983.1

Trenberth, K. E. (1999): Conceptual framework for changes of extremes of the hydrological cycle with climate change. Climatic Change, 42: 327–339.

WMO – World Meteorological Organization (2012): Standardized Precipitation Index User Guide (M. Svoboda, M. Hayes and D. Wood). WMO-No. 1090, Geneva, Switzerland.

Wu, H., Hayes, M. J., Wilhite, D. & Svoboda, M. D. (2005): The effect of the length of record on the standardized precipitation index calculation. International Journal of Climatology, 25(4): 505–520, doi: 10.1002/joc.1142.

Address of authors

Álvaro Silva, IPMA, IP – The Portuguese Sea and Atmosphere Institute, Rua C ao Aeroporto, 1749-077 Lisboa, Portugal
alvaro.silva@ipma.pt
M. Isabel P. de Lima, IMAR – Institute of Marine Research; MARE – Marine and Environmental Sciences Centre; Department of Civil Engineering, Faculty of Science and Technology of the University of Coimbra, Rua Luís Reis Santos, Campus II – University of Coimbra, 3030-788 Coimbra, Portugal
iplima@uc.pt
Fátima Espírito Santo, IPMA, IP – The Portuguese Sea and Atmosphere Institute, Rua C ao Aeroporto, 1749-077 Lisboa, Portugal
fatima.coelho@ipma.pt
Vanda Pires, IPMA, IP – The Portuguese Sea and Atmosphere Institute, Rua C ao Aeroporto, 1749-077 Lisboa, Portugal
vanda.pires@ipma.pt

Address of corresponding author

M. Isabel P. de Lima, Institute of Marine Research (IMAR); Marine and Environmental Sciences Centre (MARE); Department of Civil Engineering, Faculty of Science and Technology of the University of Coimbra, Rua Luís Reis Santos, Campus II – University of Coimbra, 3030-788 Coimbra, Portugal
iplima@uc.pt