

Precipitation variability in Portugal from 1960 to 2011

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Abstract: This study analyses spatial variability and trends in annual and monthly precipitation (amount and concentration) based on data from 42 stations in mainland Portugal during the period 1960–2011. Relationships between certain geographic variables (elevation, latitude and longitude) and precipitation variability were also determined in order to check for specific dependencies and spatial patterns in precipitation distribution, concentration and changing trends. Trends and relationships have been analysed using both parametric and non-parametric tests.

The results showed that annual precipitation had decreased in all stations and that this trend is statistically significant for most of the time series (70% of the stations showed negative trends with at least a 0.1 significance level). The Annual Precipitation Concentration Index revealed an opposite behaviour pattern, suggesting that even though the annual trend for precipitation amount was negative overall, more than half of the udometric stations registered a more marked seasonality for precipitation during the period 1960–2011. However, only one station showed statistical significant time trend. Regarding the influence of geographical features, latitude is the most important variable, governing spatial distribution and variations in annual precipitation as well as its intra-annual changeability. These important changes in precipitation, involving both amount and concentration, may have severe consequences for ecosystems and societies.

Keywords: precipitation trend; precipitation concentration index; spatial patterns; geographical variables; Portugal

1 Introduction

Changes in the amount and intra-annual distribution of precipitation can have important environmental and economic effects. Changes in total annual and monthly precipitation, as well as in its concentration over time, are important factors which affect water availability by modifying river regimes and groundwater recharge (de Luis *et al.*, 2011; López-Moreno *et al.*, 2009; Paredes *et al.*, 2006), which may have a strong influence on water consumption and hydroelectric production (Paredes *et al.*, 2006). Variations in precipitation can also limit ecosystem productivity, affect soil erosion (Nunes *et al.*, 2011; Nunes *et al.*, 2014; Michiels

et al., 1992; Prats *et al.*, 2013) and forest fires (Carvalho *et al.*, 2008) and, in some areas, intensify the processes of land degradation and desertification (Nunes *et al.*, 2014).

In Portugal, as well as in the Mediterranean region in general, there is a complex pattern for spatial and seasonal variability in precipitation, aggravated by the inconstancy of rainfall from year to year and during the year. This inter-annual variability therefore makes it difficult to assess trends in precipitation distribution patterns and the impact of potential climate change (Ramos and Martínez-Casasnovas, 2006).

However, several authors have highlighted different aspects of this variability for specific areas in the Mediterranean basin and have quantified trends with indices. For example, Bartzokas *et al.* (2003) analysed the spatial distribution of precipitation amount and duration in Greece for each main rainfall period and showed the differences between northern, western and eastern areas. In their study of spatio-temporal variability in precipitation in Castile and León during the period 1945–1996, Labajo and Pioro (2001) identified a declining trend in annual precipitation, although this was not statistically significant. De Luis *et al.* (2009, 2010) also found decreases in yearly precipitation in most of the Mediterranean Iberian Peninsula when analysing the annual trends for the period 1951–2000. Nunes *et al.* (2014), analysing the period 1950–2008, detected decreases in annual precipitation accompanied by increases in precipitation concentration in southern Portugal, although no generalised, significant trends for these variables have been found. This trend also concurs with the results obtained by de Luis *et al.* (2011), which show that precipitation concentration has increased across most of the Spanish Iberian Peninsula.

It is accepted that precipitation variability results from various geographical variables such as latitude, longitude and topography. However, only a small number of studies have investigated the relationship between trends in precipitation variation and geographical variables (Nunes *et al.*, 2014).

This study therefore aims to analyse spatial variability and trends in annual and monthly precipitation (amount and concentration) in mainland Portugal during the period 1960–2011. Relationships between certain geographic variables (such as latitude, longitude and elevation) and annual and monthly precipitation distribution and trend were checked in order to identify specific dependencies and spatial patterns in precipitation distribution, concentration and changing trends.

In fact, the enormous importance of water availability for ecosystems and societies highlights the need to understand precipitation variability and trends, both in time and in space, as well as their link to the large-scale climate system, in order to understand how these changes can affect regional water supplies.

2 Study area

Mainland Portugal is located in the extreme southwest of continental Europe, in the Iberian Peninsula, between 42°00' and 37°00'N and 7°00' and 9°15'W Greenwich. The average annual precipitation varies from around 2000 mm to 500 mm in the north-west (between the Minho and Douro rivers) and south-eastern areas of the country, respectively. This pattern is reversed for the average annual temperature, with the highest values registered in the Alentejo (Central and Lower Alentejo) and Algarve regions, and the lowest in the northern-

most territories.

Despite this variability, the country as a whole reflects the seasonal pattern typical of a Mediterranean climate, characterised by cool, wet winters and hot, dry summers. With the exception of the northwest region, the entire territory has a reasonably long, dry season, lasting three to five months and increasing from north to south and from coastal to inland areas.

3 Material and methods

Yearly and monthly precipitation data for the period between 1960 and 2011, taken from 42 udometric stations spatially representative of Portuguese territory, was obtained from the National Institute of Water database (INAG–Instituto da Água/SNIRH–Sistema Nacional de Informação de Recursos Hídricos, <http://snirh.inag.pt>) (Figure 1 and Table 1). The udometric stations, which have a length of record of 52 years, are located between 39°62' and 37°15'N and 7°00' and 9°12'W Greenwich, and the altimetric gradient varies from 2 m to 1018 m (asl).

As these 42 rain gauges are used for monitoring precipitation on a national scale, the data were complied with important quality criteria, namely: (i) a limited number of gaps in the monthly time series, generally less than 1% of the total observation record longevity, (ii) the fact of being spatially representative of the distribution irregularity for precipitation in mainland Portugal, and (iii) normality and homogeneity requirements.

However, when some data was missing from the time series, the following procedure was adopted. A linear correlation was first established for the time series in order to choose the nearest udometric station with a time series whose precipitation characteristics most closely resembled those of the station with the missing data. Spatial regression was then used to estimate the missing values (Peterson and Easterling, 1994) or correct anomalous precipitation values. Afterwards, using non-parametric tests, the Shapiro-Wilk test and the

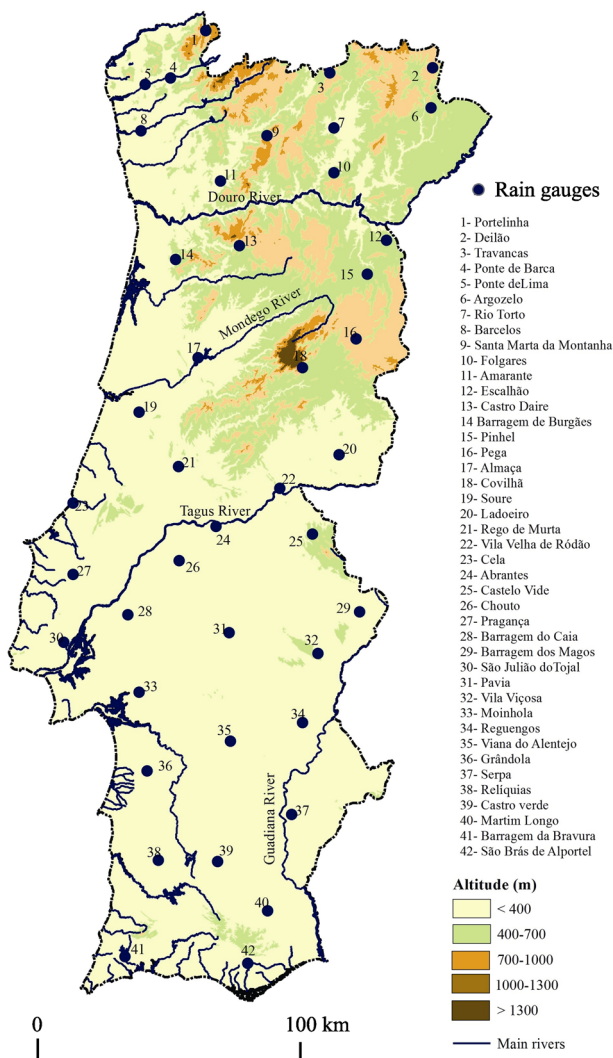


Figure 1 Location of the gauging stations used in this study

Table 1 Characteristics of gauging stations used in this study (Length of record =52 yr)

Rain gauges*	Altitude (asl m)	Latitude North	Longitude W Greenwich	Mean rainfall (mm)	St. deviation (mm)
(1) Portelinha	1018	42°05'	8°17'	1975	525
(2) Deilão	892	41°85'	6°59'	784	211
(3) Travancas	884	41°83'	7°31'	941	263
(4) Ponte da Barca	39	41°80'	8°42'	1599	406
(5) Ponte de Lima	18	41°77'	8°60'	1566	403
(6) Argozelo	685	41°64'	6°60'	756	197
(7) Rio Torto	322	41°54'	7°28'	537	149
(8) Barcelos	36	41°53'	8°62'	1511	390
(9) S.M.Montanha	866	41°50'	7°75'	1709	448
(10) Folgares	739	41°30'	7°28'	623	165
(11) Amarante	146	41°26'	8°07'	1215	330
(12) Escalhão	615	40°95'	6°92'	546	127
(13) Castro Daire	697	40°92'	7°94'	1577	456
(14) B.Burgães	306	40°85'	8°38'	1733	452
(15) Pinhel	606	40°77'	7°06'	597	165
(16) Pega	770	40°43'	7°14'	773	231
(17) Almaça	116	40°34'	8°23'	1056	308
(18) Covilhã	719	40°28'	7°51'	1615	506
(19) Soure	18	40°05'	8°63'	851	238
(20) Ladoeiro	215	39°83'	7°27'	577	168
(21) R. Murta	241	39°77'	8°36'	987	297
(22) V.V.Ródão	84	39°65'	7°67'	739	217
(23) Cela	2	39°57'	9°07'	769	197
(24) Abrantes	105	39°45'	8°10'	679	199
(25) Castelo Vide	552	39°41'	7°45'	823	236
(26) Chouto	126	39°27'	8°35'	725	210
(27) Pragança	183	39°20'	9°06'	912	260
(28) B. Caia	217	39°00'	7°14'	489	155
(29) B. Magos	43	38°99'	8°69'	640	187
(30) Pavia	189	38°90'	8°01'	590	170
(31) S.J. Tojal	6	38°84'	9°12'	736	217
(32) Vila Viçosa	417	38°78'	7°42'	709	212
(33) Moinhola	41	38°58'	8°62'	681	175
(34) Reguengos	218	38°42'	7°53'	527	165
(35) V. Alentejo	314	38°33'	8°01'	676	187
(36) Grândola	95	38°17'	8°55'	651	180
(37) Serpa	209	37°94'	7°60'	509	174
(38) Relíquias	232	37°70'	8°48'	640	207
(39) Castro Verde	217	37°70'	8°09'	524	157
(40) Martim Longo	294	37°44'	7°77'	515	190
(41) B. Bravura	64	37°20'	8°70'	693	229
(42) S.B. Alportel	334	37°16'	7°90'	865	291
Mean				896	254

* Rain gauges stations are listed in accordance with their latitude, towards North to South.

Kolmogorov-Smirnov test (Lima *et al.*, 2010), the data was statistically tested for normality. The Standard Normal Homogeneity Test was selected to check the time series homogeneity (Alexandersson and Moberg, 1997; Lima *et al.*, 2010).

A statistical analysis of the precipitation was carried out for all the rain gauges in order to identify any trends in annual and monthly amounts, using IBM SPSS 20.0 software. Two different methods were used to detect whether there was a trend in the precipitation series. The *Spearman* test (R_s), which is a rank-based distribution-free method, was used to identify trends and determine the significance. Statistical significance was assessed on four levels: statistically significant at 0.01 level (representing a very strong trend); statistically significant at 0.05 level (representing a strong trend); statistically significant at 0.1 level (representing a moderate trend); not statistically significant at 0.1 level, interpreted here as having 'nil' significance. As non-parametric tests detect a trend but do not quantify it, linear regression was used to determine the magnitude of the trend on an annual scale.

Oliver (1980) proposes a Precipitation Concentration Index (PCI) which has been used by several researchers in different regions of the world (Apaydin *et al.*, 2006; de Luis *et al.*, 2010; Elagib, 2011). A modified version of the Precipitation Concentration Index (PCI) (de Luis *et al.*, 2010, 2011; Elagib, 2011; Nunes *et al.*, 2014) was used to estimate annual and monthly rainfall heterogeneity. Using the PCI, data related to the long-term variability in rainfall amount was obtained and calculated using the next equation on an annual scale:

$$PCI = \frac{\sum_{i=1}^{12} p_i^2}{\left(\sum_{i=1}^{12} p_i \right)^2} \cdot 100$$

where p_i is the monthly precipitation in month i .

According to Oliver's classification, PCI values of less than 10 indicate regular precipitation distribution (low precipitation concentration), values between 11 and 15 represent moderate precipitation concentration, values from 16 to 20 indicate irregular distribution, and values above 20 represent strong irregularity, i.e. high precipitation concentration, in precipitation distribution.

Relationships between precipitation variation trends (amount and concentration) and certain geographical features, such as altitude, latitude and longitude, have been analysed using parametric and non-parametric tests.

4 Results

4.1 Yearly and monthly precipitation: spatial patterns and trends for amount and concentration

The mean annual rainfall values for the 42 time series distributed over Portuguese territory varied from 489 mm and 1975 mm y^{-1} (Table 1), with an average standard deviation of around 254 mm. In general the mean annual precipitation decreased from north to south and from the coastal region to inland Portugal, although this behaviour was more evident in the north and centre of the country. Thus, the highest values were found in the north-west region, with values between 1500 and 2000 mm yr^{-1} . In the north-east the mean annual precipitation

values were significantly lower by around one half or one third in comparison to the values recorded in the north-western area. As example Ponte de Lima and Deilão, both located at the same latitude but the first close to the Atlantic coast and the second in inland of the country, nearby the border with Spain, recorded in average respectively 1600 yr^{-1} and 780 mm yr^{-1} .

In the area south of the River Tagus, the Alentejo and Algarve regions recorded the lowest average annual precipitation values of approximately $500\text{--}600 \text{ mm yr}^{-1}$. The highest values were recorded in the mountainous areas of the Alentejo (the São Mamede mountain ridge) and Algarve (Monchique and Caldeirão) and in the stations nearest the coast. Conversely, the lowest average amounts were found in the south-eastern Alentejo, particularly on the left bank of the River Guadiana (Figure 2a).

According to the PCI classification, 12 of the rain gauges ($\pm 30\%$) registered moderate annual precipitation concentration, while in 30 of the stations it was categorised as the seasonal variation type, i.e. revealing irregular distribution in intra-annual precipitation. The highest values were found in the southern and southeastern parts of Portugal and the lowest values in the north-western region (Figure 2b). The correlations found between annual amount and precipitation concentration were negative and statistically significant ($r = -0.453$; significant at 0.001 level), suggesting that the stations with the lowest annual precipitation depth have the greatest intra-annual precipitation concentration.

Figure 3 maps the degree of significance of the trend detected for total annual precipitation according to the *Spearman* coefficient and the magnitude of change in relation to mean annual rainfall (in mm yr^{-1}). Based on an analysis of Figure 3a), annual precipitation has decreased in all of the 42 udometric stations in mainland Portugal, and this trend is statistically significant for most of the time series (more than 70% of the rain gauges showed negative trends with at least a 0.1 significance level). A great percentage of stations (43%) showing, however, a very strong negative trend (significant at 0.01 level), indicating that several areas of the Portuguese territory has been suffering an important precipitation decrease, and the central and northern areas seem to be more affected. The linear trends further confirm that the magnitude of the decrease in cumulative rainfall, over the studied period, is more pronounced in the northern and central areas of the country, highlighting the northwest mainland Portugal, where in all of the rain gauges the decline exceeds 8 mm yr^{-1} (Figure 3b). In those stations (Portelinha, Ponte de Lima, Ponte da Barca, Barcelos and Amarante) the estimated decrease corresponds to about 30% of the annual value.

The annual rainfall series with trends that are not statistically significant were found mainly in the area to south river Tagus, particularly in the eastern Alentejo and Algarve region.

Various trends were revealed in each of the 12 subseries of individual months from January to December (Tables 2–4). March experienced a homogenous negative trend in precipitation whilst in February and June only one station (Martim Longo) denoted a positive tendency but without statistical significance. In these months, the decline in precipitation was statistically significant in around 80%, 60% and 50% of the stations respectively in February, June and March, when the *Spearman* coefficient was applied. In January and November more than 90% of the time series also showed a negative trend. However this reduction was just statistically significant at 0.1 level for January in 45% of the rain gauges (Tables 2 and 4).

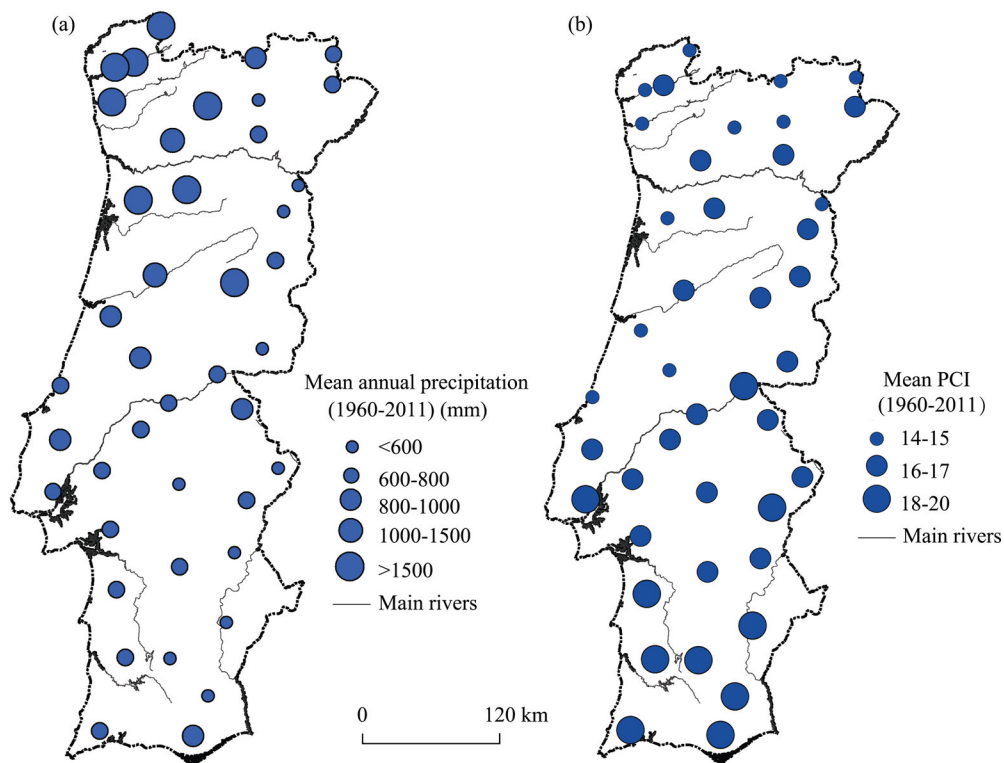


Figure 2 Spatial distribution of mean annual precipitation (a) and mean annual precipitation concentration index (PCI) (b), in mainland Portugal for the period 1960–2011

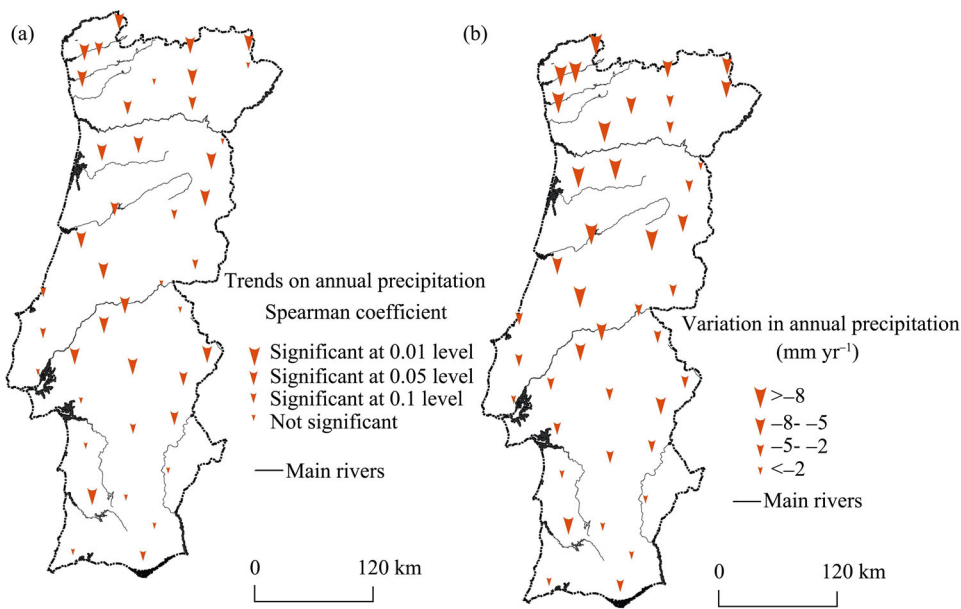


Figure 3 Trends on annual precipitation: *Spearman* coefficient (a); magnitude of change in mm per year (mm yr⁻¹) (b)

Table 2 Monthly precipitation trends (1960–2011)

Rain gauges	Months											
	J	F	M	A	M	J	J	A	S	O	N	D
(1) Portelinha	−0.284**	−0.314**	−0.255*	−0.052	−0.089	−0.116	0.134	0.079	−0.190	0.110	−0.105	−0.061
(2) Deilão	−0.204	−0.300**	−0.197	−0.016	−0.074	−0.270*	−0.207	0.047	−0.154	−0.001	−0.113	0.035
(3) Travancas	−0.302**	−0.305**	−0.211	−0.089	−0.153	−0.240*	−0.113	0.010	−0.246*	0.050	−0.180	−0.018
(4) P. Barca	−0.232*	−0.385***	−0.236*	−0.026	−0.085	−0.100	0.184	0.112	−0.241*	0.042	−0.049	−0.031
(5) P.Lima	−0.258*	−0.357***	−0.239*	−0.099	−0.184	−0.050	0.169	0.138	−0.296**	−0.043	−0.053	−0.092
(6) Argozelo	−0.223	−0.285*	−0.094	0.124	−0.094	−0.053	0.054	0.105	−0.036	0.090	−0.027	0.067
(7) Rio Torto	−0.136	−0.378**	−0.191	−0.096	0.097	−0.240	−0.122	0.204	−0.116	0.088	−0.155	−0.021
(8) Barcelos	−0.259*	−0.341**	−0.230	−0.043	−0.140	−0.120	0.309**	−0.025	−0.303**	0.126	−0.054	−0.132
(9) S.M.Montanha	−0.044	−0.265*	−0.228	0.053	−0.004	−0.164	0.167	0.124	−0.172	0.026	−0.086	0.032
(10) Folgares	−0.187	−0.310**	−0.228	−0.067	−0.107	−0.311**	−0.054	0.217	−0.134	0.138	−0.115	0.069
(11) Amarante	−0.153	−0.345**	−0.296**	−0.029	−0.066	−0.215	−0.042	0.115	−0.181	−0.010	−0.079	0.022
(12) Escalhão	−0.115	−0.233*	−0.200	0.008	−0.017	−0.200	−0.060	0.190	−0.075	0.173	−0.114	0.081
(13) Castro Daire	−0.245*	−0.343**	−0.300*	−0.040	−0.186	−0.308**	0.130	0.170	−0.132	0.138	−0.120	−0.006
(14) B.Burgães	−0.274*	−0.393***	−0.326**	−0.107	−0.189	−0.145	0.266*	0.134	−0.220	0.056	−0.008	−0.023
(15) Pinhel	−0.177	−0.257*	−0.293**	−0.028	−0.007	−0.262*	−0.020	0.158	−0.110	0.099	−0.183	0.012
(16) Pega	−0.169	−0.275*	−0.197	−0.197	0.010	−0.286**	−0.054	0.231	0.006	0.128	−0.202	−0.030
(17) Almaça	−0.208	−0.258*	−0.325**	−0.092	−0.214	−0.260*	0.102	0.155	−0.066	0.102	−0.146	−0.020
(18) Covilhã	−0.242*	−0.345**	−0.146	0.061	−0.131	−0.288**	−0.086	0.210	−0.018	0.136	−0.092	0.020
(19) Soure	−0.325**	−0.302**	−0.253*	−0.053	−0.137	−0.280**	0.073	0.164	−0.196	0.043	−0.157	−0.152
(20) Ladoeiro	−0.192	−0.250*	−0.293**	−0.027	−0.095	−0.437***	−0.027	0.037	0.008	0.177	−0.081	−0.033
(21) R. Murta	−0.321**	−0.343**	−0.355***	−0.082	−0.244	−0.338**	0.037	0.234*	−0.204	0.095	−0.242*	−0.097
(22) V.V.Ródão	−0.100	−0.211	−0.189	0.161	0.070	−0.345**	0.097	0.293**	0.019	0.203	−0.067	0.016
(23) Cela	−0.322**	−0.262*	−0.271*	0.026	−0.133	−0.248*	0.280**	0.230	−0.096	0.050	−0.177	−0.110
(24) Abrantes	−0.268*	−0.252*	−0.306**	−0.035	−0.103	−0.314**	0.231*	0.166	−0.126	0.099	−0.160	0.030
(25) Castelo Vide	−0.129	−0.216	−0.248*	0.025	−0.085	−0.349**	0.066	0.197	−0.184	0.191	−0.113	0.038
(26) Chouto	−0.311**	−0.324**	−0.227	−0.084	−0.060	−0.326**	−0.078	0.021	−0.068	0.043	−0.141	−0.159
(27) Pragança	−0.321**	−0.383***	−0.259*	0.041	−0.064	−0.123	0.384***	0.450***	0.113	0.127	−0.070	−0.075
(28) B. Caia	0.022	−0.158	−0.100	−0.235	−0.263	−0.225	−0.118	−0.048	−0.411***	0.200	0.335**	−0.031
(29) B.Magos	−0.250*	−0.339**	−0.271*	0.022	−0.188	−0.280**	0.168	0.113	0.025	0.099	−0.216	−0.120
(30) Pavia	0.133	−0.146	−0.063	−0.172	−0.325**	−0.336**	−0.078	−0.155	−0.456***	−0.006	0.260*	−0.127
(31) S.J. Tojal	−0.090	−0.194	−0.203	0.051	0.022	−0.050	0.335**	0.194	0.141	0.186	−0.081	−0.005
(32) Vila Viçosa	−0.228	−0.302**	−0.372**	0.021	0.055	−0.287**	0.198	0.292**	0.024	0.050	−0.116	−0.159
(33) Moinhola	−0.200	−0.252*	−0.206	−0.022	0.026	−0.136	0.299**	0.226	0.002	0.170	−0.058	−0.077
(34) Reguengos	−0.299**	−0.281**	−0.285**	0.103	−0.050	−0.312**	0.387***	0.299**	−0.046	0.056	−0.214	−0.085
(35) V. Alentejo	−0.129	−0.175	−0.171	0.146	0.094	−0.203	0.228	0.188	0.014	0.164	−0.105	−0.083
(36) Grândola	−0.122	−0.238*	−0.196	0.117	0.071	−0.167	0.416***	0.236*	0.292**	0.137	−0.098	0.063
(37) Serpa	−0.169	−0.223	−0.131	0.114	0.018	−0.457***	0.287**	0.238*	0.208	0.135	−0.075	−0.008
(38) Relíquias	−0.299**	−0.281**	−0.285**	0.103	−0.050	−0.312**	0.387***	0.299**	0.010	−0.119	−0.175	−0.059
(39) Castro Verde	−0.192	−0.258*	−0.228	0.063	−0.066	−0.524***	0.248*	0.366***	0.168	0.084	−0.062	0.040
(40) M. Longo	0.205	0.047	−0.479***	0.368**	0.186	0.214	0.082	−0.007	0.152	−0.193	−0.210	−0.149
(41) B. Bravura	−0.239*	−0.195	−0.223	0.084	−0.056	−0.040	0.539***	0.241*	0.190	0.079	0.019	0.150
(42) S.B. Alportel	−0.281**	−0.331**	−0.232*	0.053	0.032	−0.305**	0.428***	0.161	0.217	0.094	−0.085	0.090

Negative trend

Positive trend

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*** Significant at 0.01 level; ** Significant at 0.05 level; *Significant at 0.1 level.

Table 3 Monthly and annual PCI trends (1960–2011)

Rain gauges	Months												
	J	F	M	A	M	J	J	A	S	O	N	D	Year
(1) Portelinha	-0.133	-0.197	-0.130	0.087	0.099	0.002	0.236*	0.163	-0.061	0.245*	0.048	0.103	-0.068
(2) Deilão	-0.068	-0.195	-0.083	0.108	0.057	-0.173	-0.044	0.097	-0.103	0.128	0.014	0.188	0.142
(3) Travancas	-0.094	-0.206	-0.045	0.064	-0.010	-0.126	-0.046	0.131	-0.133	0.185	-0.023	0.179	0.146
(4) P. Barca	-0.044	-0.339**	-0.080	0.112	0.044	0.025	0.258*	0.195	-0.193	0.129	0.072	0.131	0.056
(5) P.Lima	-0.028	-0.256*	-0.092	0.075	-0.072	0.099	0.279**	0.216	-0.150	0.072	0.091	0.137	-0.049
(6) Argozelo	-0.175	-0.246*	-0.043	0.173	0.001	-0.006	0.089	0.119	0.011	0.161	0.076	0.151	-0.130
(7) Rio Torto	0.002	-0.310**	-0.075	0.028	0.199	-0.115	-0.040	0.302**	-0.010	0.248*	-0.036	0.123	-0.065
(8) Barcelos	-0.001	-0.238*	-0.057	0.133	-0.002	0.012	0.351**	0.054	-0.219	0.192	0.080	0.065	0.095
(9) S.M.Montanha	0.054	-0.209	-0.106	0.157	0.103	-0.085	0.197	0.172	-0.131	0.030	0.001	0.141	-0.023
(10) Folgares	-0.046	-0.273*	-0.151	0.041	0.029	-0.222	0.050	0.264*	-0.047	0.236*	-0.017	0.169	0.074
(11) Amarante	-0.046	-0.310**	-0.195	0.142	0.089	-0.093	0.021	0.241*	-0.107	0.098	0.038	0.192	0.069
(12) Escalhão	-0.040	-0.203	-0.077	0.038	0.053	-0.170	-0.030	0.221	-0.028	0.252*	-0.022	0.137	0.096
(13) Castro Daire	-0.048	-0.258*	-0.209	0.069	-0.039	-0.177	0.186	0.273**	-0.013	0.248*	0.024	0.189	-0.025
(14) B.Burgães	-0.163	-0.317**	-0.202	0.079	-0.037	-0.047	0.348**	0.229	-0.068	0.212	0.142	0.195	-0.116
(15) Pinhel	-0.023	-0.186	-0.190	0.087	0.166	-0.151	0.040	0.183	-0.019	0.207	-0.129	0.127	0.105
(16) Pega	-0.072	-0.192	-0.065	-0.020	0.091	-0.160	-0.005	0.267**	0.154	0.313**	-0.122	0.089	-0.056
(17) Almaça	-0.129	-0.175	-0.171	0.146	0.094	-0.203	0.228	0.219	0.042	0.248*	0.011	0.060	0.010
(18) Covilhã	-0.215	-0.307**	-0.031	0.211	-0.021	-0.275**	-0.059	0.242*	0.082	0.231*	-0.030	0.147	-0.008
(19) Soure	-0.129	-0.177	-0.152	0.111	0.048	-0.216	0.139	0.222	-0.028	0.207	0.003	0.015	0.022
(20) Ladoeiro	-0.131	-0.114	-0.211	0.067	-0.029	-0.397***	-0.020	0.077	0.125	0.281**	0.028	0.072	0.249
(21) R. Murta	-0.154	-0.186	-0.207	0.134	-0.089	-0.231*	0.103	0.308**	-0.016	0.258*	-0.051	0.203	0.140
(22) V.V.Ródão	-0.100	-0.211	-0.189	0.161	0.070	-0.345**	0.097	0.293**	0.019	0.273*	0.015	0.088	0.105
(23) Cela	-0.210	-0.131	-0.183	0.186	-0.048	-0.168	0.321**	0.288**	0.010	0.175	0.021	0.013	-0.044
(24) Abrantes	-0.147	-0.095	-0.221	0.083	0.058	-0.226	0.238*	0.210	-0.025	0.188	-0.016	0.191	-0.065
(25) Castelo Vide	-0.014	-0.137	-0.176	0.091	-0.019	-0.325**	0.091	0.244*	-0.137	0.245*	-0.002	0.155	0.110
(26) Chouto	-0.155	-0.134	-0.074	0.078	0.106	-0.220	-0.026	0.109	0.077	0.185	0.008	-0.040	0.110
(27) Pragança	-0.278**	-0.293**	-0.152	0.158	0.035	-0.084	0.410***	0.475***	0.220	0.220	0.039	0.081	-0.174
(28) B. Caia	0.199	-0.001	0.030	-0.048	-0.142	-0.098	0.041	0.061	-0.329**	0.232*	0.360***	0.044	0.048
(29) B.Magos	-0.159	-0.180	-0.110	0.209	-0.082	-0.224	0.204	0.179	0.151	0.249*	-0.104	0.024	0.099
(30) Pavia	0.256*	0.029	0.065	0.021	-0.167	-0.201	0.047	-0.068	-0.372***	0.013	0.307**	-0.004	0.216
(31) S.J. Tojal	-0.130	-0.148	-0.128	0.168	0.057	-0.427***	0.291**	0.237**	0.251*	0.194	-0.060	0.032	-0.021
(32) Vila Viçosa	-0.131	-0.201	-0.243*	0.180	0.125	-0.233*	0.216	0.324**	0.120	0.185	-0.016	-0.043	0.083
(33) Moinhola	-0.126	-0.124	-0.123	0.041	0.095	-0.109	0.310*	0.256*	0.075	0.228	-0.011	-0.005	-0.059
(34) Reguengos	-0.065	-0.171	-0.242*	0.226	0.184	-0.277**	0.053	0.162	0.036	0.150	-0.102	0.065	0.107
(35) V. Alentejo	-0.129	-0.175	-0.171	0.146	0.094	-0.203	0.228	0.219	0.042	0.248*	0.011	0.060	0.010
(36) Grândola	-0.096	-0.187	-0.181	0.167	0.110	-0.170	0.427**	0.255*	0.296*	0.180	-0.081	0.110	-0.154
(37) Serpa	-0.100	-0.162	-0.161	0.108	0.071	-0.035	0.333*	0.203	0.168	0.259*	-0.071	0.067	-0.183
(38) Relíquias	-0.161	-0.179	-0.129	0.254*	0.097	-0.268*	0.419**	0.337**	0.106	0.009	-0.049	0.093	0.020
(39) Castro Verde	-0.164	-0.184	-0.177	0.127	0.014	-0.518***	0.251	0.377***	0.195	0.134	-0.002	0.151	-0.018
(40) M. Longo	0.200	0.069	-0.508***	0.352**	0.182	0.188	0.117	-0.025	0.158	-0.230	-0.283**	-0.148	-0.034
(41) B. Bravura	-0.248*	-0.209	-0.158	0.083	0.010	-0.003	0.555***	0.249*	0.216	0.097	0.054	0.207	-0.159
(42) S.B. Alportel	-0.263*	-0.233*	-0.148	0.101	0.103	-0.288**	0.452***	0.180	0.258*	0.158	-0.019	0.151	-0.135

Negative trend

**

*

Positive trend

**

*

*** Significant at 0.01 level; ** Significant at 0.05 level; *Significant at 0.1 level.

Table 4 Synthesis of monthly precipitation and PCI trends (%)

Precipitation (1960–2011)								
Negative trend					Positive trend			
	ns	0.1	0.05	0.01	ns	0.1	0.05	0.01
J	47.6	21.4	23.8		7.2			
F	19.0	28.6	40.5	9.5	2.4			
M	50.0	23.8	21.4	4.8				
A	52.4				45.2		2.4	
M	71.4		2.4		26.2			
J	40.5	11.9	38.1	7.1	2.4			
J	31.0				35.7	7.0	11.9	14.4
A	9.5				66.7	9.5	9.5	4.8
S	47.6	4.8	4.8	4.8	35.7		2.4	
O	14.3				85.7			
N	90.4	2.4			2.4		4.8	
D	64.3				35.7			

Precipitation (1960–2011)								
Negative trend					Positive trend			
	ns	0.1	0.05	0.01	ns	0.1	0.05	0.01
J	81.0	4.8	2.4		9.4	2.4		
F	66.6	14.2	14.4		4.8			
M	88.0	4.8		2.4	4.8			
A	4.8				90.5	2.4	2.4	
M	31.0				69.0			
J	62.0	7.1	11.9	7.1	11.9			
J	19.0				45.2	11.9	16.7	7.1
A	4.8				52.4	16.7	21.4	4.8
S	42.9		2.4	2.4	45.2	7.1		
O	2.4				59.5	33.3	4.8	
N	47.6			2.4	45.2		2.4	2.4
D	11.9				88.1			

ns: Without statistical significance; Significant at 0.1, 0.05 and 0.01 level.

In May and September, a negative trend predominated in 74% and 62% of the time series, whilst an opposite precipitation trend was revealed for April and December: around half of the stations presented a negative trend and the other half a positive trend. In spatial terms, the trend towards an increase occurred mainly in the southernmost region of Portugal, whereas the decreasing trend coincided with the centre and north of the country.

Conversely, positive trends were found for August (90%), October (86%) and July (70%). Nevertheless, in October none featured at the 0.1 significance level. In the other months, around 35% of stations, in July, and 25%, in August, showed positive statistically significant tendencies.

With regard to the Precipitation Concentration Index (PCI), i.e. the intra-annual distribu-

tion of precipitation, 22 stations presented positive trends and 20 stations negative trends (Tables 3 and 4). Only one station (Ladoeiro) had a positive statistically significant trend. Although no definite trend pattern was evident, this opposite behaviour suggests some patterns not previously identified. In fact, even though the annual trend in precipitation amount was negative overall, more than half of the udometric stations registered a more marked seasonality in precipitation during the period 1960–2011.

Negative trends dominated the monthly series for January (88%), February (95%), March (95%) and June (88%). The overall decline in PCI in the winter months correlated with the decrease in average precipitation for this season. Conversely, an increase in precipitation concentration can be observed in April (95% of the time series), July (81%), August (95%), October (98%) and December (88%). This trend is statistically significant for about half of the rain stations in July (36%) and August (43%). However, despite the general trend towards a greater concentration in October, only 40% of the stations are statistically significant. An opposite trend was observed in the precipitation concentration time series for May, September and November: around 70% of the stations revealed a positive trend in May whereas in September and November half indicated a positive trend and the other half a negative trend. In spatial terms, a more homogeneous positive trend occurred in the southernmost region of mainland Portugal (Table 3).

4.2 Influence of geographical features on precipitation and concentration

Figure 4 provides scatter plots of annual precipitation and concentration versus altitude, latitude and longitude. Latitude emerges as the most important of the three variables governing the geographical distribution of mean annual precipitation, followed by altitude. With regard to the spatial distribution of PCI in mainland Portugal, latitude is also the most powerful influence, explaining approximately 72% of the variance observed in the intra-annual distribution of precipitation.

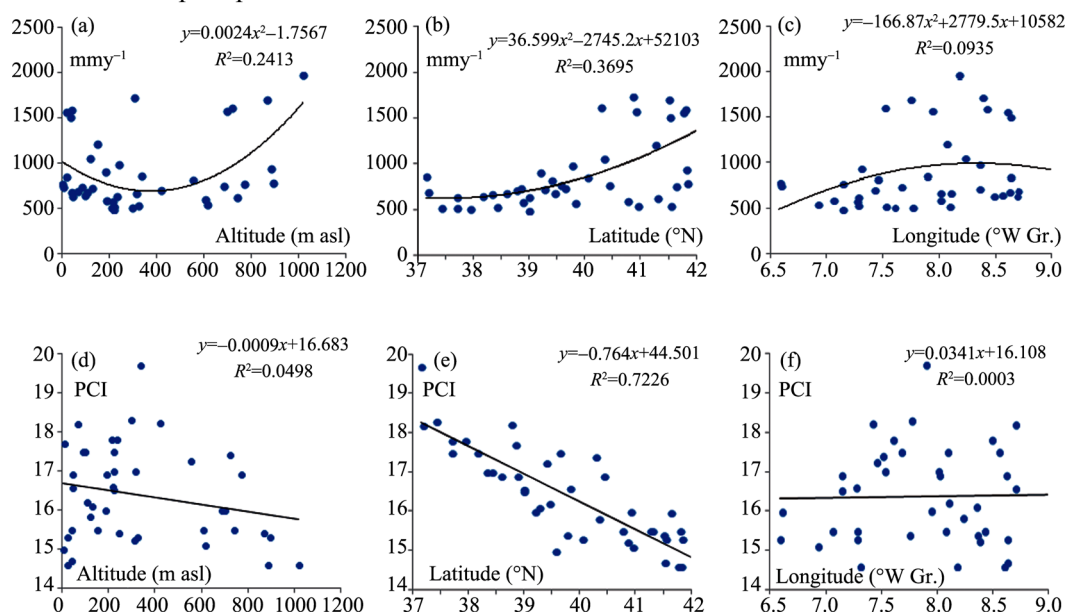


Figure 4 Correlations between altitude, latitude and longitude and mean annual precipitation and concentration (PCI).

Correlations between the annual trends for precipitation amount and concentration and geographical features are shown in Figure 5 and Table 5. According to the results obtained, latitude is the main factor influencing the spatial variation in the annual trends recorded for precipitation during the studied period, whilst longitude has a more significant correlation with the spatial trend observed in PCI. Both correlations are negative, meaning that the udometric stations with more marked decreasing trends in yearly precipitation are mainly located in the highest latitude, i.e. the northernmost regions of Portugal. On the other hand, the trend towards greater irregularity in intra-annual precipitation distribution was found mainly in the stations further away from influence of the Atlantic Ocean, in the lowest longitudes.

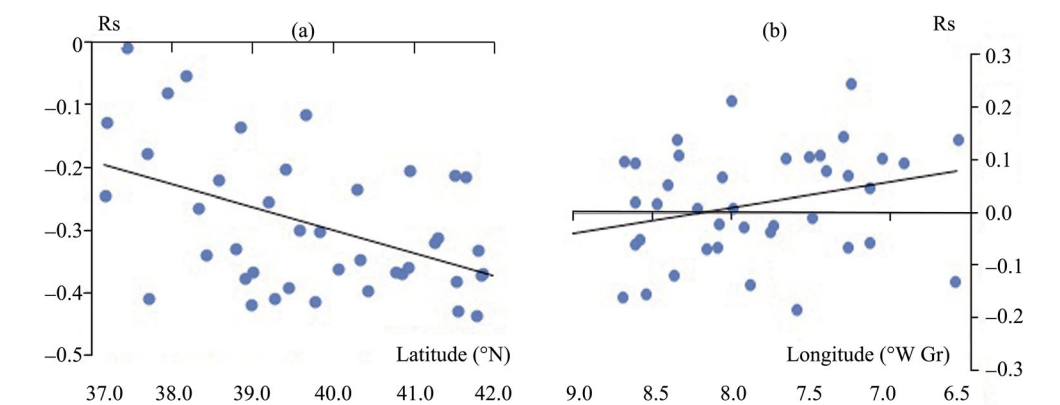


Figure 5 Spearman correlation (Rs) between trends in annual precipitation and latitude (a) and PCI trends and longitude (b)

Table 5 Correlation between precipitation trends (PT) and PCI trends and the geographical features

PT	J	F	M	A	M	J	J	A	S	O	N	D	Year
Altitude	0.144	−0.078	0.087	−0.049	0.089	−0.149	−0.478*	−0.09	−0.091	0.042	−0.240	0.347*	−0.054
Latitude	−0.128	−0.490	0.079	−0.512**	−0.405**	0.276*	−0.492**	−0.405**	−0.696**	−0.100	0.009	0.090	−0.422**
Longitude	−0.457**	−0.153	−0.263	0.067	−0.154	0.300	0.696**	0.191	0.099	−0.170	0.118	−0.356*	−0.049
PCI	J	F	M	A	M	J	J	A	S	O	N	D	Year
Altitude	0.130	−0.249	0.105	−0.189	0.172	−0.020	−0.501**	−0.072	−0.138	0.135	−0.202	0.397**	0.097
Latitude	0.315*	−0.534**	0.342*	−0.305*	−0.191	0.376*	−0.441**	−0.187	−0.678*	0.123*	0.330*	0.367*	0.194
Longitude	−0.379*	0.048	−0.112	0.301	−0.157	0.099	0.727**	0.247	0.203	−0.221	0.171	−0.204	−0.305**

** Significant at 0.01 level; * Significant at 0.05 level

An analysis of the correlation between long-term trends in precipitation on a monthly level and the three geographical features (Table 5) reveals strong negative relationships between latitude and the precipitation trend for February, April, May, July, August and September. The influence of longitude on the monthly precipitation trend is statistically significant for two months: January, with negative indications, and July, with positive indications.

With regard to monthly trends in precipitation concentration (Table 5), an opposite inter-correlation was obtained for the influence of latitude: a negative correlation was found

for February, April, July and September and a positive coefficient for January, March, June, November and December. The relationship between altitude and monthly trends in precipitation concentration is only significant for July and December. A positive inter-correlation between longitude and the July PCI trend was observed, whereas the January PCI reveals a negative relationship with this variable.

5 Discussion

Annual precipitation in mainland Portugal can be described as highly irregular, both in spatial and temporal terms. Great irregularity can also be observed in inter and intra-annual distribution. During the period analysed (1960–2011), a general pattern of a decrease in the annual precipitation amount was recorded in mainland Portugal, based on a stations analysis. In fact, the majority of the udometric stations showed a consistent negative trend, which was more pronounced in the central and northernmost regions of the country. The results obtained for monthly trends reveal an overall decrease in precipitation quantity in November, January, February, March and June, together with a general increase in July, August and October. The aforementioned negative trends in precipitation affected the late autumn period and the whole of the winter, i.e. the wettest period of the year. These results concur with the findings of other researchers working on a regional level, who have reported a decline in precipitation across the Mediterranean basin, particularly during the wet season (Buffoni *et al.*, 1998, 1999; de Luis *et al.*, 2009; Esteban-Parra *et al.*, 1998; González-Hidalgo *et al.*, 2010; Kadioğlu *et al.*, 1999; Paredes *et al.*, 2006; Philandras *et al.*, 2011; Piervitali *et al.*, 1998; Tomozeiu *et al.*, 2002; Xoplaki *et al.*, 2000; Xoplaki *et al.*, 2004).

A significant decrease in precipitation during the wet period can have severe consequences on the hydrological cycle and water supply, both for ecosystems and societies. In fact, a change in precipitation quantity results in changes in runoff and affects the groundwater recharge rates which, in turn, have an impact on the water supply. In terms of agricultural demand, both rainfed crops and irrigated cultures may face a soil-moisture deficit associated with lower precipitation. Changes in runoff also have a significant effect on the output of hydropower generation.

Concerning the influence of geographical features, latitude is the most important variable governing spatial distribution and variations in annual precipitation, as well as its intra-annual changeability, specifically in February and between April and September. In fact, several studies have shown that precipitation in the Mediterranean basin is influenced by large-scale atmospheric circulation (Brunetti *et al.*, 2002; Corte-Real *et al.*, 1995; López-Bustins *et al.*, 2008; López-Moreno *et al.*, 2011; Rodríguez-Puebla *et al.*, 2001; Trigo and Palutikof, 2001; Vicente-Serrano *et al.*, 2010), and also by local or regional characteristics, such as elevation and topography (Acero *et al.*, 2011; Hidalgo-Muñoz *et al.*, 2011; Lionello, 2012).

North Atlantic Oscillation (NAO) is one of the dominant atmospheric patterns in the temporal evolution of precipitation (Xoplaki *et al.*, 2004; Mariotti and Dell'Aquila, 2012; López-Moreno *et al.*, 2011; Angulo-Martínez and Beguería, 2012) and its relevance for surface climate variability is well known in relation to many regions in the western Mediterranean area, such as Portugal (Corte-Real *et al.*, 1998; Trigo and Da Camara, 2000). Accord-

ing to Mariotti and Dell'Aquila (2012), the NAO index reveals a positive long-term trend, in particular since the 1970s. Since the negative phase of these indices is associated with frontal conditions that trigger rainfall in the Mediterranean basin, the more frequent occurrence of positive phases after 1970 may explain the drying trends reported for several regions, as well as for Portuguese territory as a whole (Trigo *et al.*, 2000; Trigo and da Camara, 2000). Positive phases in the NAO index represent an increase of the Atlantic meridional sea level pressure gradient, which contributes to strength zonal flows (López-Moreno *et al.*, 2011).

Such strengthening is responsible for the increased moist and warm advections to north-east Europe, producing warm and humid conditions over Scandinavia and part of northern Russia, but losing progressively such effect toward southern and eastern Europe. This causes warm and wet winters in northern Europe and drier than normal winters in the south. Mariotti *et al.* (2002) consider, however, that the impact of the NAO on precipitation shows a decreasing influence in the southern and eastern sectors of the Mediterranean basin.

On the other hand, the analyses of the effects of the NAO on precipitation confirm the major influence of the winter NAO on precipitation in the Mediterranean mountain areas, particularly in the mountains of the Iberian Peninsula (López-Moreno *et al.*, 2011). These findings coincide with our results, in which the large negative trends were found particularly in the northern highlands.

On an annual scale, the precipitation concentration in Portugal can be described as irregular in the south and moderately irregular in the central and north-western areas. A more complex behaviour pattern was found for the Precipitation Concentration Index (PCI): around half of the stations indicated a trend towards greater irregularity in intra-annual precipitation distribution, whilst the other half revealed a trend towards lower irregularity. Only one station showed significant time trends when using the *Spearman* rank correlation coefficient.

The results obtained for monthly trends seem to be more homogenous: a negative trend was observed between January and March, and a positive trend was recorded for most stations during summer and, in particular, autumn (especially in October). This positive trend in PCI may have important consequences, specifically in terms of the potential of precipitation to cause soil erosion (Nunes *et al.*, 2014). According to González-Hidalgo (1996), precipitation concentration is one important factor which leads to erosivity. Stormy precipitation, chiefly at the end of summer and the beginning of autumn, can encourage sediment yield transport and strongly affect the sustainability of Mediterranean ecosystems, particularly if they are affected by other disturbances such as forest fires (Albaladejo 1995; Pérez-Trejo 1994) or if extensive areas are cultivated with rainfed cereals (Roxo and Casimiro, 2004; Nunes *et al.*, 2010, 2011).

The changes in annual and monthly PCI appear to be related to local factors affecting precipitation concentration trends (de Luis *et al.*, 2011). In fact, although the intra-annual distribution of precipitation is greatly influenced by latitude, the annual trends observed for the PCI were more significantly determined by longitude.

6 Conclusions

The analysis of correlations among spatial patterns of annual and monthly precipitation and concentration trends and some geographical features were performed. Main findings include

the following:

(1) A decrease in annual precipitation amounts is the general tendency observed in mainland Portugal, since the 1960s. The degree of decrease in precipitation is more significant in the highest latitudes, i.e. in the central and northern areas of the country, particularly in the wettest region.

(2) At monthly level, significant negative trends could be confirmed during winter months for almost all the stations, while July, August and October increases in precipitation prevailing, although only few stations showed statistically significant trends.

(3) Concerning to intra-annual variability, evaluated by PCI, only one station showed significant time trends when the *Spearman* rank correlation coefficient was applied. However, the positive tendency observed in more than half of the udometric stations suggested a more marked seasonality for precipitation during the analysed period. April, July, August and October showed a general trend towards a greater concentration.

The aforementioned changes in precipitation (amount and intra-annual distribution) may have a strong influence on natural processes such as runoff and soil erosion, modifying fluvial regimes, groundwater recharge and water availability, or in biomass productivity and forest fires spread. Even though past precipitation trends are not indicative of future trends, the results obtained from this study may be very important for the Portuguese Water Planning Agency, since the implications of the changes described may have important economic and environmental effects that could be greater than climatic change itself.

Acknowledgements

This paper was financed by the Department of Geography at the University of Coimbra and by the CEGOT (Centre for Studies in Geography and Spatial Planning), that beneficiates from the Foundation for Science and Technology (FCT) Pluriannual Financial Support Programme.

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