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## TRENDS OF CHANGE IN PRECIPITATION AND IN DROUGHT SUSCEPTIBILITY AS ASSESSED BY THE STANDARDIZED PRECIPITATION INDEX (SPI) IN NORTHEAST PORTUGAL

13

### TENDÊNCIAS DE MUDANÇA NA PRECIPITAÇÃO E NA SUSCEPTIBILIDADE À SECA AVALIADA PELO ÍNDICE DE PRECIPITAÇÃO NORMALIZADA (SPI) NO NORDESTE DE PORTUGAL

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#### ABSTRACT

Much of NE Portugal is an area of arid zones with moderate to severe susceptibility to desertification and drought. A single and coupled trend analysis of precipitation and SPI drought index was performed in six weather stations in NE Portugal (representative of the regional climate domains), over a seventy-year time series (1931-2000). Precipitation over the study period decreased at most stations, with a more pronounced trend in the wetter areas, whereas in the semiarid areas an increase in precipitation was found. As well as the frequency of months with severe and extreme drought, the frequency of dry and wet months increased when the SPI timescale increased (1 to 6 months) and when a more recent computation period is considered (1931-1960 to 1971-2000). The results highlight a tendency for precipitation extremes to occur in NE Portugal. The general development of trends in precipitation and drought reported in this study confirm a progressive severity in the susceptibility to desertification affecting NE Portugal.

**Keywords:** Climate variability, time trends, drought and desertification, precipitation extremes.

#### RESUMO

As zonas áridas ocupam boa parte do NE Portugal, região de moderada a severa suscetibilidade à desertificação e seca. A análise de tendência da precipitação, isolada e combinada, e do índice de seca SPI foi realizada em seis estações meteorológicas no NE Portugal (representativas dos climas regionais), no período 1931-2000. A precipitação diminuiu na maioria das estações, de modo mais pronunciado nas áreas mais húmidas, enquanto nas do semiárido se verificou um aumento na precipitação. Tal como no caso da frequência de meses com seca severa e extrema, a frequência de meses secos e húmidos aumentou com o aumento da escala de tempo do SPI (de 1 a 6 meses) e considerando o período de cálculo mais recente (de 1931-1960 a 1971-2000). Os resultados evidenciam uma tendência para o aumento da ocorrência de extremos de precipitação. Estas tendências de mudança na precipitação e seca confirmam um aumento da severidade na suscetibilidade à desertificação que afeta o NE Portugal.

**Palavras-chave:** Variabilidade climática, tendências temporais, seca e desertificação, precipitações extremas.

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## Introduction

Changes in global climate are being reported and future climate scenarios keep alerting to relevant changes in mean air temperature and rainfall amounts and distribution patterns (IPCC, 2014). Uncertainties persist in what regards projections of future climate precipitation amounts but such projections consistently point out future increase in precipitation variability. As so, actual precipitation extremes are expected to increase in frequency in the future and future extremes are expected to increase in magnitude as compared to the actual ones. As a consequence, droughts and flood events are expected to occur more frequently and with higher magnitude than in present time, prospecting potentially damaging impacts of climate change. Variability of weather conditions increased in recent years, and if this trend persists in the near future, higher frequency and severity of extreme events are expected, namely an extension of drought periods. Apart from the global scale evidence, for mainland Portugal the scenario of widened precipitation extremes also applies (SIAM2, 2006; Costa *et al.*, 2012; APA, 2015; EEA, 2021; Fraga *et al.*, 2017; Fraga *et al.*, 2021).

As a present evidence of the global temperature rise projections (IPCC, 2014), southern Europe has experienced an increase of drought frequency and severity (Vicente-Serrano *et al.*, 2014; Gudmunsson and Seneviratne, 2015), more pronounced in the Mediterranean regions (Hoerling *et al.*, 2012; Spinoni *et al.*, 2017; Spinoni *et al.*, 2019; Giorgi and Lionello, 2008). Understanding drought phenomena, their monitoring, identification and prediction, help mitigating drought effects around the world, and particularly in arid environments and in the Mediterranean drylands.

As a complex phenomenon, there is not a universal concept to define drought. In general terms, drought is understood as a natural phenomenon associated with water scarcity due to natural precipitation variability, to which has to be added an insufficient supply by water provision human-made structures (Wilhite, 1992). Each drought event should be defined according not only to the climatic characteristics of the area but also to the impacts that it causes (Wilhite, 1992; Wilhite *et al.*, 2007). In this sense, droughts are commonly classified in four types, according to its duration and related impacts: meteorological, hydrological, agricultural and socioeconomic drought (Wilhite and Glantz, 1985; Wilhite, 1992).

Many drought indexes have been developed worldwide, for a particular or large-scale climatic region, using different data sources. Most drought indexes are based on meteorological parameters, e.g. precipitation, temperature, evapotranspiration, while others include also soil moisture. Studies using remote sources, single or combined with ground data sources, visibly progressed

in the last decade (Nicolai-Shaw *et al.*, 2017; Wei *et al.*, 2021). On the thematic of drought and desertification, review works describing and comparing the existing drought indicators have also been published in the last decade (Cherlet *et al.*, 2018; Fernandes e Heinemann, 2009; Svoboda and Fuchs, 2017; Zargar *et al.*, 2011).

To characterize meteorological droughts around the world, the Lincoln Declaration on Drought Indices, approved in 2009 by experts of the United States National Drought Mitigation Center (NDMC), the World Meteorological Organization (WMO), the United States National Oceanic and Atmospheric Administration (NOAA), the School of Natural Resources of the University of Nebraska, the United States Department of Agriculture (USDA) and the United Nations Convention to Combat Desertification (UNCCD), recommended the use of Standardized Precipitation Index (SPI) by each National Meteorological and Hydrological Services (WMO, 2012, p. 1; Hayes *et al.*, 2011, p. 488).

The SPI was developed by McKee *et al.* (1993). It requires only precipitation as input data, and it was designed to detect precipitation deficit at multiple timescales (1 to 48-month), an advantage that recommended its wide application. In fact, once SPI is a normalized or standardized index, it has wide applicability and may allow comparison between distinct climate regions around the world (Svoboda and Fuchs, 2017). As pointed out by several studies, SPI's representation of actual drought conditions is more consistent for short-medium timescales than for the larger ones (Vicente-Serrano e López-Moreno, 2005; Tirivarombo *et al.*, 2018). SPI was used in several contexts within the drought and desertification thematic, approaches covering drought forecasting (Mishra and Desai, 2005; Cancelliere *et al.*, 2007) drought monitoring (Tirivarombo *et al.*, 2018), and drought prediction, in this case using Markov Chains to predict SPI Drought Class transition (Steinemann, 2003; Paulo *et al.*, 2005; Paulo and Pereira, 2007; Avilés *et al.*, 2016). As well, SPI was applied in the hydrological context, for example to investigate reservoir effect on catchment response as represented by the streamflow series (Serra, 2014).

Drought characterization by IPMA (Instituto Português do Mar e da Atmosfera) uses PDSI - Palmer Drought Severity Index, developed by Palmer in 1965, which is based on precipitation and temperature data, although IPMA is also applying SPI in internal research projects, following WMO recommendations. Some studies using SPI and PDSI have been conducted in Southern Portugal, as in the Alentejo (Paulo and Pereira, 2006), Algarve and Baixo Alentejo regions (Pulido-Calvo *et al.*, 2020). However, no specific study applying SPI is reported for the Northeast (NE) region of Portugal. For example, Paulo *et al.* (2016) carried out an analysis using SPI in several locations across Portugal, but none was located

in the NE region. Some approaches assessing the spatial variability of precipitation and drought events in Portugal are reported in literature, commonly using one type of cluster analysis to define homogeneous regions in what regards the studied parameters (Santos, *et al.*, 2010; Moreira *et al.*, 2015).

Much of Trás-os-Montes mountain region, NE Portugal, are drylands enduring soil degradation processes, therefore facing medium to high susceptibility to desertification and drought (Figueiredo *et al.*, 2015b). The Intermunicipal Plans for Adaptation to Climate Change of Terra Quente Transmontana and Terra Fria Transmontana (PIAAC\_TQT, 2018; PIAAC\_TFT, 2018) identified the main climate vulnerabilities to which the NE territory is susceptible, which include excessive precipitation events, heat waves and droughts, while minor expression was assigned to strong winds, cold waves, frosts and fog. Some of these vulnerabilities play also an essential role on wildfire occurrence, a hazard with potential and actual negative impacts on natural resources in this region, which increased frequency has been reported (Cavalli, *et al.*, 2019; Figueiredo *et al.*, 2014). Due to this critical scenario, typical of the Mediterranean mountains, it is important to monitor drought and study changes in climate patterns, supported in long term data series. In this line, the present study aimed at analyzing temporal change trends in precipitation and drought events over 70 years in the last century in the northeast (NE) Portugal. Moreover, an analysis was carried out on the extension of drought periods in the region, using SPI generated by long term precipitation series of representative weather stations.

### Methodology

The natural susceptibility of the study area, NE Portugal, increased by past and present human activities, has been already reported in literature. The Soil Map of Northeast of Portugal indicates that 60% of the territory (1.309 million ha) corresponds to degraded soils (Agroconsultores and Coba, 1991). Major soils that cover this surface are Leptosols (72%), with incipient profile development (Figueiredo, 2013). They are shallow, acid, present high stoniness and low organic matter content, limiting soil water storage, therefore conditioning land use options.

An analysis on Soil Degradation Risks and Status conducted by Figueiredo *et al.* (2015b) reveals that in 38% of the area soils depict a degradation status, which is qualified as extreme in 12%, very severe in 10% and severe in 16% of the area. Soils under severe risk of soil degradation, yet not degraded, occupy 9% of the territory, while the remaining areas present a minimum to moderate soil degradation risk. A large part of the degraded soils is concentrated in desertification susceptibility areas, defined according to the aridity index (Figueiredo *et al.*, 2015b).

The aridity index (AI) corresponds to the ratio between annual Precipitation and potential evapotranspiration, with four classes of AI observed in NE territory: Semiarid ( $0.2 < AI < 0.5$ ), dry-subhumid ( $0.5 < AI < 0.65$ ), wet sub-humid ( $0.65 < AI < 1$ ) and humid ( $AI > 1$ ) (PANCD, 2011). These climate classes are used for desertification susceptibility purposes, the semiarid corresponding to severe susceptibility and the dry sub-humid to moderate susceptibility. According to Köppen Climate Classification, NE Portugal fits in the Csa and Csb climates, both Mediterranean with dry, hot summer (Csa) in the south, and mild dry summer (Csb) in the north and extreme northeast of the region (Köppen, 1936; IPMA, 2021). Agroconsultores and Coba (1991) apply a regional climatic classification based on mean annual temperature and mean annual precipitation, following Gonçalves's works (Gonçalves, 1985a, 1985b), which divided the NE territory, known as Trás-os-Montes, in *Terra Fria (Cold Land)*, *Terra Quente (Warm Land)* and *Terra de Transição (Transition Land)*. These two classifications fairly match with that based on AI and so they may also be used to roughly identify areas with severe susceptibility to desertification in NE Portugal. In fact, most of the semiarid and dry sub-humid areas fall in Gonçalves Terra Quente climate classes (Royer, 2019).

The analysis was carried out on six selected weather stations considered representative of the climatic domains of the study area, NE Portugal (fig. 1, TABLE I). These weather stations are part of the meteorological monitoring network of SNIRH - *Sistema Nacional de Informação de Recursos Hídricos* - available online at <https://snirh.apambiente.pt/index.php?idMain=2&idItem=1>. Double mass analysis (Linsley *et al.*, 1982; Arian and Kahya, 2019) showed no break in the cumulative plot of paired weather stations monthly precipitation series for the study periods defined, and the correlation between all paired series ranged from 0.995 to 0.999, with a median of 0.999, therefore indicating the homogeneity of the data series analyzed in this study. The precipitation change trends over time were carried out with annual mean values of two reference periods: the decades and the thirty-year climatological normal. Moreover, an interannual analysis was performed by selecting two key months: the months with the highest and lowest precipitation of the hydrological year (October to September). In both cases, the temporal evolution of the coefficient of variation (standard deviation / average) of the precipitation series was also assessed, together with the influence of terrain variables on precipitation temporal trends derived for each weather station.

SPI computation requires precipitation monthly series as input data. For each station, the climatological normal periods with complete data series were identified and SPI was computed for each one of the thirty-year

periods indicated in TABLE I. In some stations, the last climatological normal period (1971-2000) was not available for SPI computation, due either to weather station deactivation or to gaps in the series. Gaps in the 2001-2010 decade also recommended not to include the 1981-2010 normal in the analysis.

Data treatment software used in this study included Excel, to organise input datasets, and SPIGenerator software v. 4.0 (made available by the National Drought Mitigation Center (NDMC) at <https://drought.unl.edu/>

[droughtmonitoring/SPI/SPIProgram.aspx](https://droughtmonitoring/SPI/SPIProgram.aspx)), to obtain the SPI monthly series. SPI adjusts data from a historical rainfall series through a gamma probability distribution, which is then transformed into a Standardized Gaussian distribution. Since it is based on the precipitation probability distribution and this is a standardized distribution, SPI can equally represent drier and wetter climate zones. Thus, comparisons between different locations worldwide can be established. According to WMO (2012), SPI central class corresponds to normal

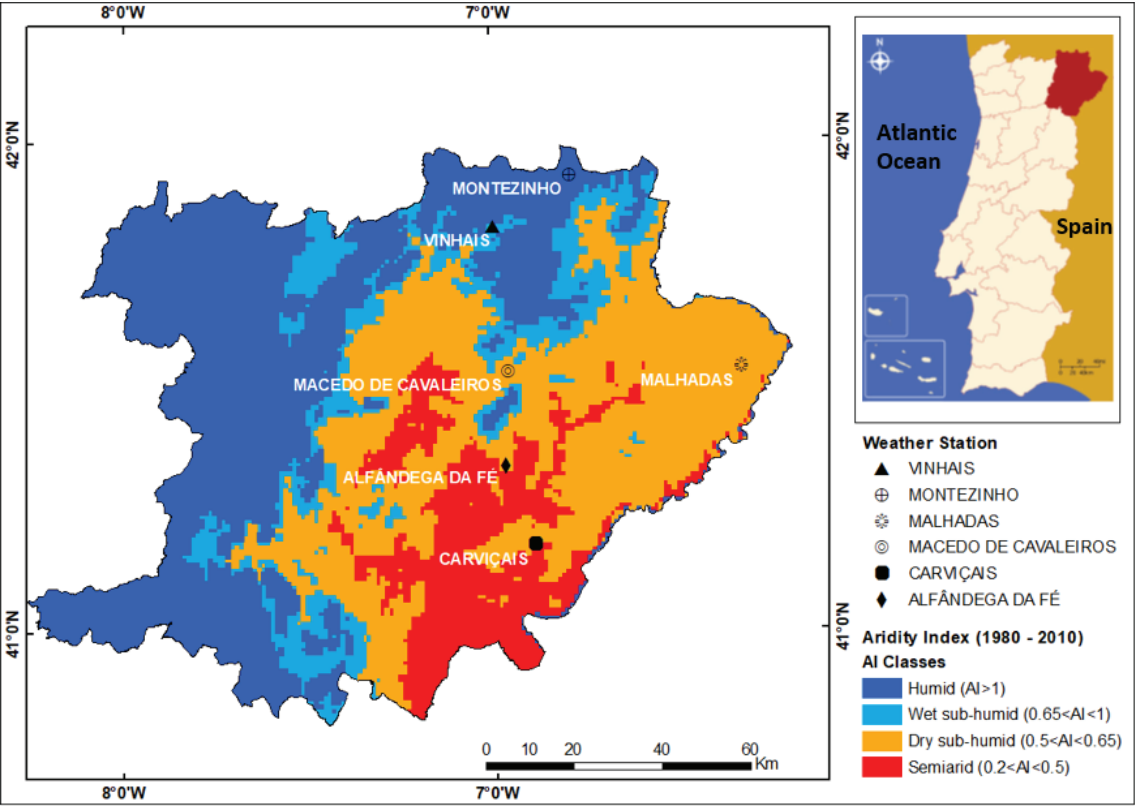


Fig. 1 - Location of the weather stations in the NE Portugal climate regions defined according to Aridity Index (1980-2010) classes (Data Source: SNIG and SNIRH. Coordinate system: ETRS89/PT-TM06).

Fig. 1 - Localização das estações meteorológicas nos domínios climáticos do NE de Portugal definidos de acordo com as classes do Índice de Aridez (1980 -2010) (Fonte de dados: SNIG e SNIRH. Sistema de coordenadas: ETRS89/PT-TM06).

TABLE I - Characteristics of the selected weather stations in NE Portugal.

TABELA I - Características das estações meteorológicas selecionadas no NE de Portugal.

Weather Station	Elevation (m)	Lat (°N), Long (°W)	AI Class	Available monthly precipitation data (climatological normal)
Alfândega da Fé	558	41.34, -6.966	Semi-arid	1931-1960, 1951-1980 and 1971-2000
Carviçais	611	41.179, -6.89	Semi-arid	1931-1960, 1951-1980 and 1971-2000
Macedo de Cavaleiros	551	41.532973, -6.958648	Dry subhumid	1931-1960, 1951-1980 and 1971-2000
Malhadas	780	41.537429, -6.326417	Dry subhumid	1931-1960 and 1951-1980
Vinhais	636	41.827975, -6.993837	Wet subhumid	1931-1960, 1951-1980 and 1971-2000
Montezinho	1159	41.932, -6.785	Humid	1931-1960 and 1951-1980

average precipitation, while negative SPI values indicate lower than median precipitation and positive values indicate higher than median precipitation (TABLE II). The SPI timescale corresponds to the number of months chosen for accumulating the monthly precipitation, e.g., to obtain the SPI-3 of March, rainfall from January to March is summed up. The SPI timescales represent the longer-term precipitation anomalies, intended to help assessing drought severity. McKee *et al.* (1993) suggest input precipitation series with at least 30 years records, once more extended input data series provides more reliable SPI values.

The methodology applied on drought temporal trend analysis is presented in a scheme (fig. 2). Firstly, monthly SPI values were calculated for each climatological normal (30 years) and then classified according to TABLE II. The timescales calculated in this study were SPI 1, SPI 3 and SPI 6 month. After this step, the periods overlapping two consecutive climatological normal periods were analysed, the SPI class frequencies issued from each one of the two overlapped normal periods being compared. Overlapped periods correspond to the 1951-1960 and 1971-1980 decades, summing a total of 120 months each period. For each one of these decades, the three selected SPI timescales were correlated by linear regression.

TABLE II - Classes of Standardized Precipitation Index (SPI) according to McKee *et al.*, 1993.

TABELA II - Classes do Índice de Precipitação Padronizada (SPI) segundo McKee *et al.*, 1993.

SPI value	Legend	SPI Classes	Aggregated classes
> 2.0		Extremely wet	Wet months
1.5 a 1.99		Very wet	
1.0 a 1.49		Moderately wet	
-0.99 a 0.99		Near normal	Normal months
-1.0 a -1.49		Moderately dry	Dry months
-1.5 a -1.99		Severely dry	
4< -2.0		Extremely dry	

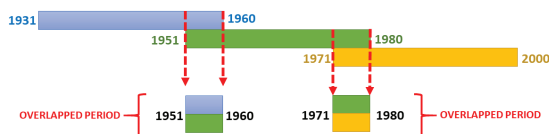


Fig. 2 - Scheme of the analysis of overlapped periods, using the SPI class frequencies as metrics.

Fig. 2 - Esquema da análise de períodos coincidentes usando como métrica as frequências das classes de SPI.

## Results and Discussion

### Change trends in precipitation

Mean annual precipitation in the selected weather stations for the whole study period (1931-2000), which shows the strong altitudinal influence in precipitation

distribution in NE Portugal (fig. 3). For the selected stations, mean annual precipitation is positively correlated with elevation ( $r^2 = 0.63$ ) and latitude ( $r^2 = 0.72$ ). The correlation between those variables is often reported. For the NE region, Figueiredo *et al.* (1990) obtained determination coefficients ( $r^2$ ) of 0.513 between annual precipitation and elevation, and of 0.430 between annual precipitation and latitude. Besides, mapping exercises of the regional climates distribution was very much supported on the altitudinal gradients of temperature and precipitation observed throughout this region (Gonçalves, 1985a; Agroconsultores and Coba, 1991). The effect of longitude on precipitation reflects continentality, a factor that may explain mean annual precipitation at Malhadas as compared with that at Vinhais (respectively below and above the expected from the altitudinal gradient). Malhadas is the most eastern inland station, under the continental influence of the Iberian Meseta, whereas Vinhais is the most western one, still receiving the Atlantic influence (Gonçalves *et al.*, 2016).

To explore the precipitation temporal pattern of evolution in each station throughout the whole study period, annual precipitation averages for three periods of climatological normal (1931-1960, 1951-1980, 1971-2000) and their overlapped decades: 1951-1960 and 1971-1980 are presented (fig. 4).

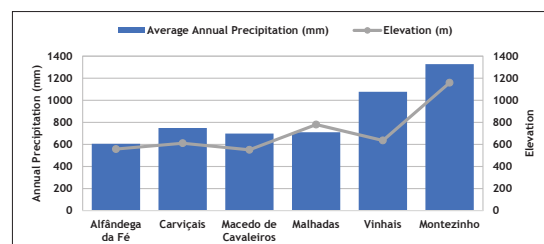


Fig. 3 - Mean Annual Precipitation of the study period (1931-2000) for each station and its respective elevation.

Fig. 3 - Precipitação média anual do período de estudo (1931-2000) para cada estação e sua respectiva altitude.

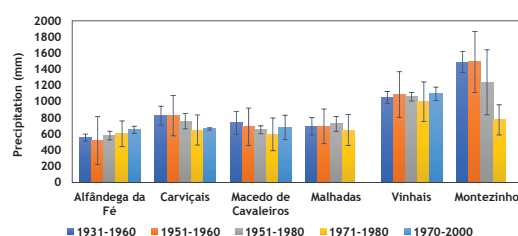


Fig. 4 - Annual precipitation (mean and standard deviation) in the climatological normal and overlapped decades for the selected NE weather stations.

Fig. 4 - Precipitação anual (média e desvio padrão) nas normais climatológicas e nas décadas de sobreposição para as estações meteorológicas selecionadas no Nordeste de Portugal.

The NE Portugal presents sharp climatic contrasts, well represented in fig. 3, and fig. 4 depicts annual rainfall



evolution during the study period. The highest mean annual precipitation is found in Montezinho, falling in the Humid climatic domain, followed by Vinhais, representing the wet sub-humid. In Montezinho, rainfall decreased over time, while in Vinhais no consistent change trend is noticed, positive or negative. The semiarid conditions are represented by Alfândega da Fé and Carviçais, which depict opposite change trends along study period, Alfândega da Fé with a slight increase in mean annual precipitation and Carviçais with a decrease. In Macedo de Cavaleiros the mean annual precipitation steadily decreased since 1931-1960, rising up in the last climatological normal period (1971-2000). The standard deviation is higher in the overlapped decades, as well as the coefficients of variation, once they represent just a 10 years series, while the climatological normal periods represents a 30 years period. Considering the coefficients of variation (CV) just for the three climatological normal periods, Carviçais, Alfândega da Fé and Malhadas presented a decrease in the CV from the latest to the most recent thirty-year period, while for the remaining stations the CV rose over time.

The months with the highest and the lowest precipitation of each hydrological year (October from September) were selected to analyze the temporal change trends that occurred along the study period in the wettest and the driest seasons, respectively. As expected in a Mediterranean domain, the wettest month was January (more frequently) or December, and the driest was August. The evolution of the mean monthly precipitation (fig. 5 and fig.6) for each station are subject to analysis, considering the same periods identified in fig.4.

Except for Alfândega da Fé and Malhadas, January average precipitation was lower in more recent years as compared to the first climatological normal period (fig. 5). While in most stations no consistent change trend was observed over time, Montezinho had a steady decrease in average precipitation along the study period. Largest decreases from the first to last computation period were 47 mm in Montezinho and 30 mm in Carviçais. Macedo de Cavaleiros presents a roughly continuous decrease along the study period. On the contrary, January mean rainfall in Alfândega da Fé increased, a trend roughly followed also in Malhadas.

Only the stations located in humid and wet sub-humid domains present mean rainfall above 20 mm in August (fig. 6). Except for Alfândega da Fé, the mean August precipitation decreased over time; although a slight increase is observed in the last climatological normal period of the 20<sup>th</sup> century. It is noteworthy the substantial decrease in August' mean rainfall in Montezinho along the study period, which ends in 1980 in this station as well as in that of Malhadas. All stations, except Alfândega da Fé, present an increase in the CV of the August precipitation

series along the century. For January, the CV has an opposite temporal change trend, depicting a reduction in all six stations.

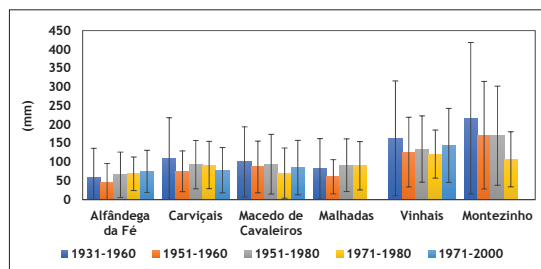


Fig. 5 - Mean monthly precipitation for January for the climatological normal and overlapped decades.

Fig. 5 - Precipitação média mensal do mês de Janeiro para as normais climatológicas e as décadas de sobreposição.

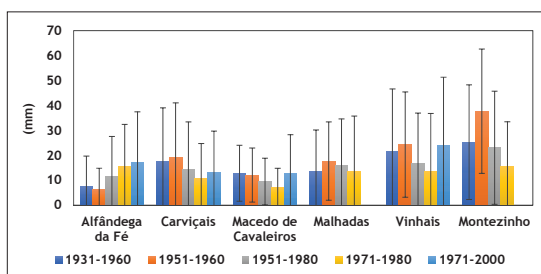


Fig. 6 - Mean monthly precipitation in August for the climatological normal and overlapped decades.

Fig. 6 - Precipitação média mensal do mês de agosto para as normais climatológicas e as décadas de sobreposição.

This overview reveals a tendency to both extremes, above-normal precipitation and scarce precipitation periods. For wet regions, in Terra Fria Transmontana, represented by Montezinho and Vinhais in this study, the reduction of the precipitation seems to be most expressive. For drylands, a contradictory behaviour between representative stations was detected. According to the precipitation anomaly analyzed in the Intermunicipal Climate Change Adaptation Plan for Terra Quente Transmontana (PIAAC\_TQT, 2018), it is expected an increase of mean annual precipitation values for Alfândega da Fé and Macedo de Cavaleiros, especially on the highlands, namely on Serra de Bornes (1200 m elevation). This rise in precipitation represents an increase in intense rainfall episodes (PIAAC\_TQT, 2018, p. 67). This same report reveals an increase in the projected annual precipitation as compared to the actual amounts, although a decrease in the mean number of days with precipitation higher than 1 mm for spring, autumn and summer is also projected. The combined projections suggest an increase in extreme rainfall events, i.e. more erosive rains will be expected (PIAAC\_TFT, 2018). It should be emphasized that the uncertainty associated with the predictions of precipitation anomalies is substantially higher than of temperature, as highlighted in those studies (PIAAC\_TFT, 2018; PIAAC\_TQT, 2018).

According to Costa *et al.* (2012), NE Portugal may be an exception in the national territory, since the future projections of regional climate models reveal an overall drying trend across Portugal, while a precipitation increase is projected over NE Portugal, concentrated in winter. Moreover, as also projected, an increase is expected in the numbers of extreme precipitation events and its contribution to the seasonal totals in winter and spring. As such contributions compensate the decrease in the drier seasons mean precipitation, in the future regional climate higher than actual annual precipitations are therefore expected (Costa *et al.*, 2012).

### *SPI change trends*

As mentioned before, SPI identifies the wet and dry months of a long-term monthly precipitation series, following the classification presented in TABLE II. The frequency of wet, normal and dry months were analyzed in all selected weather stations, according to the methodological approach presented in fig. 2. As an example with Vinhais, Malhadas and Montezinho data, the number of months of the 10-year series (120 months) classified as wet, normal or dry according to the SPI classes are presented (fig. 7). The 10-year series correspond to the overlapped years of two consecutive climatological normal periods. Moreover, each graph of fig. 7 depicts paired columns for each SPI timescale (1 month, 3 months and 6 months), which represent the SPI frequency class distribution when computed with the precedent and with the sequent thirty-year long data series, overlapped in the mentioned decade.

Montezinho depicts a decrease in the number of months classified as dry, when comparing an earlier with a more recent 30-year computation period, and when comparing a shorter with a longer SPI timescale. This matches the trend observed for August precipitation shown in fig. 6. Carviçais has a similar SPI class frequency distribution, in this case with a more clear increase in wet months at the expenses of the normal and dry months' frequencies. Malhadas shows a different SPI class distribution, with a decrease in the number of normal months at the expenses of the extreme classes, when comparing SPI timescales and computation period, earlier or more recent. However, while the number of wet months decreases, the opposite is found in the number of dry months. For Vinhais, Alfândega da Fé and Macedo de Cavaleiros, the number of both dry and wet months increased as a result of the two effects being analyzed: towards a more recent SPI 30-year period and towards a longer timescale. This same pattern of SPI class frequency distribution is exacerbated when considering the second and more recent overlapped period (1971-1980) (fig. 7). In summary, there is a general and noticeable tendency towards the increase in SPI extreme classes throughout the 70-years study period.

Furthermore, the SPI for the two overlapped periods were confronted by linear regression considering the same SPI timescale and the respective climatological normal. Regression functions obtained relate 120 paired sets of monthly SPI data in each overlapped decade, the ones issued from the earlier 30-year period (x) and the other issued from the more recent one (y). For most of the selected stations, the slopes of the regression line and the determination coefficients obtained in each case (TABLE III) tend to increase as the timescale increases, for the same overlapped decade. In other words, the SPI data distribution of each series is changed from the earlier to the more recent overlapped decade, and the regression parameters change so as to fit the more frequent extremes in more recent periods.

Focusing the analysis on the dry months, three stations were selected as example (fig. 8), where the earlier aggregated SPI classes are now presented as defined in TABLE II. As drought severity depends on duration, intensity and geographical extent of a specific event (Wilhite and Glantz, 1985), at longer timescales the SPI responds more slowly to short term precipitation changes because the precipitation of the following month has less impact in the index. Hence, drought conditions assessed by SPI6 tend to persist with higher severity (McKee *et al.*, 1993), summing up a larger number of months as compared to shorter timescales. In this study, this can be observed in both overlapped decades for Vinhais and Alfândega da Fé. Actually, Vinhais stands as a good example to show the SPI trend towards the extremes from earlier to more recent times, as in the more recent precipitation series more months are classified in the dry classes. It is important to remind that Vinhais falls in the wet sub-humid climatic domain. For the semiarid Alfândega da Fé, the same pattern was found, however, more pronounced in the first overlapped decade (1951-1960) since for the overlapped decade 1971-1980 fewer months are included in SPI dry classes. This may be explained by the increase in rainfall amounts recorded in Alfândega da Fé, as discussed in the previous subsection (PIAAC\_TQT, 2018). However, the opposite pattern is observed for Macedo de Cavaleiros, where the more recent overlapped period includes much more severe drought episodes than the earlier overlapped period (fig. 8). In this context, Kovacs *et al.* (2014) stress that increases in rainfall amounts alone do not necessarily lead to less severe hydrological drought conditions and higher soil moisture because of the rise in actual evapotranspiration. In fact, the extremely dry periods for Macedo de Cavaleiros station are more frequent in the more recent overlapped decade (1971-2000).

### *Precipitation variability and drought in NE Portugal*

A drought episode reflects a below-average rainfall expected for a region. Thus, to illustrate the relation between the precipitation amounts and SPI values



Fig. 7 - SPI aggregated class frequency for overlapped decades of the precipitation series of Alfândega da Fé, Carviçais, Macedo de Cavaleiros, Malhadas, Vinhais and Montezinho (number of months in columns, in a total of 120 months).

Fig. 7 - Frequência de classes agregadas de SPI para as décadas coincidentes das séries de precipitação de Alfândega da Fé, Carviçais, Macedo de Cavaleiros, Malhadas, Vinhais e Montezinho (número de meses nas colunas, num total de 120 meses).



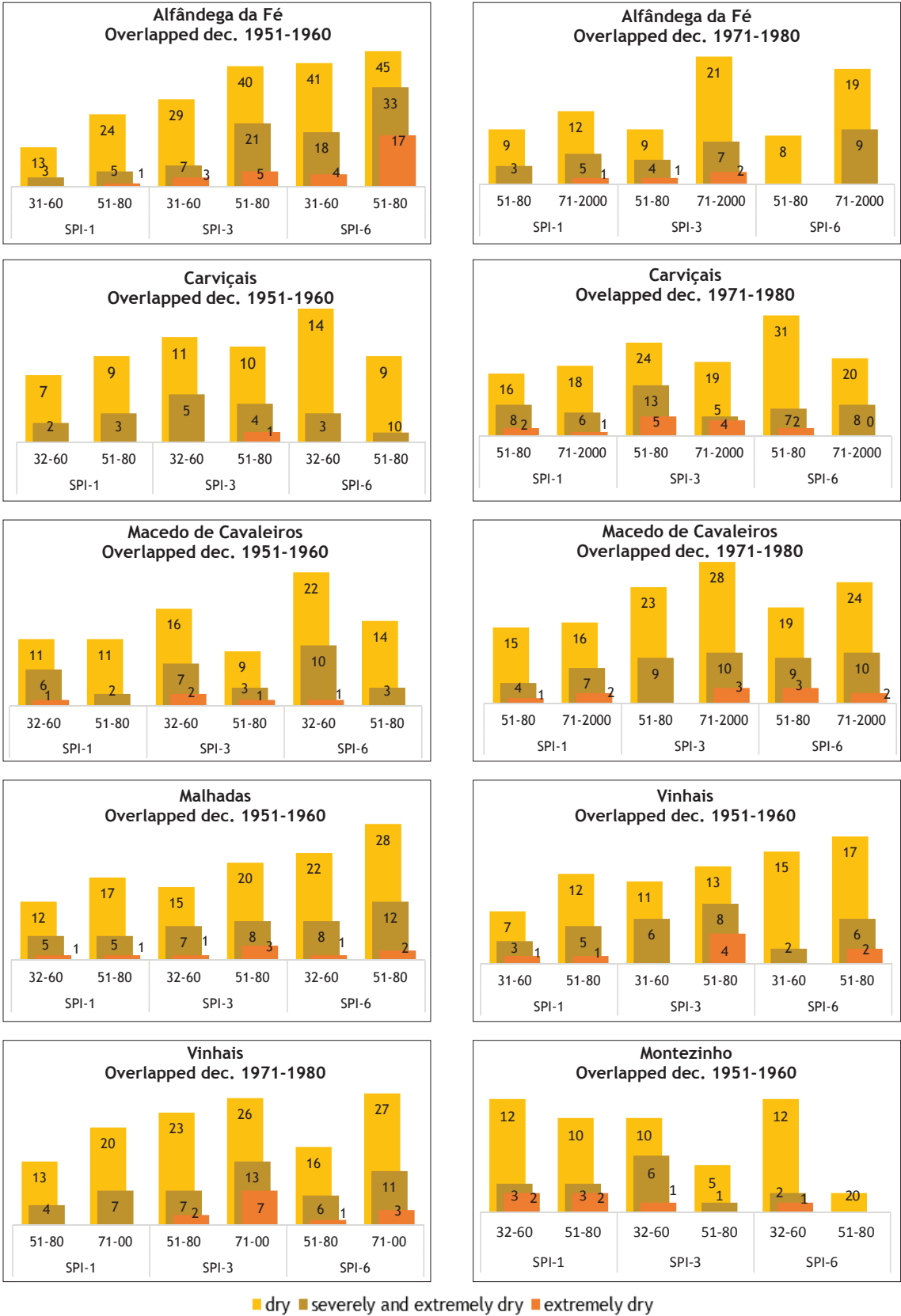


Fig. 8 - SPI class frequency of dry months in the overlapped decades at the Alfândega da Fé, Carviçais, Macedo de Cavaleiros, Malhadas, Vinhais and Montezinho (number of months in columns, in a total of 120 months).

Fig. 8 - Frequência de classes de SPI nos meses secos das décadas coincidentes nas estações Alfândega da Fé, Carviçais, Macedo de Cavaleiros, Malhadas, Vinhais e Montezinho (número de meses nas colunas, num total de 120 meses).

TABLE III - Regression parameters for the SPI series of the overlapped periods for the studied stations.

TABELA III - Parâmetros de regressão das séries de SPI para os períodos de sobreposição das estações estudadas.

Weather station	Parameter	Overlapped decade 1951-1960			Overlapped decade 1971-1980		
		SPI 1	SPI 3	SPI 6	SPI 1	SPI 3	SPI 6
Alfândega da Fé	$r^2$	0.895	0.933	0.920	0.832	0.835	0.777
	b	0.995	1.110	1.135	0.975	1.014	1.113
Carviçais	$r^2$	0.920	0.921	0.881	0.851	0.868	0.845
	b	0.998	1.032	1.000	0.934	0.924	0.974
Macedo de Cavaleiros	$r^2$	0.834	0.827	0.840	0.869	0.859	0.831
	b	0.892	0.874	0.920	0.917	0.927	0.852
Malhadas	$r^2$	0.915	0.924	0.882	-	-	-
	b	0.961	0.980	0.989	-	-	-
Vinhais	$r^2$	0.873	0.956	0.933	0.874	0.888	0.889
	b	1.009	1.084	1.108	0.970	1.028	1.116
Montezinho	$r^2$	0.921	0.813	0.709	-	-	-
	b	1.011	0.940	0.908	-	-	-

obtained for each station, the precipitation threshold to wet, normal and dry SPI categories are presented (fig. 9), considering the two overlapped periods as indicated before. As expected, Montezinho presents the highest mean monthly precipitation required to reach a certain SPI class, as compared to the other stations, 206 mm for wet and 59 mm for dry periods. On the contrary, the lowest rainfall threshold are found in Alfândega da Fé, 81 mm and 14 mm for wet and dry months, respectively. Rainfalls required to qualify a month as ‘normal’ are around 50 mm for most stations, the higher values being found in stations located in the wet sub-humid and humid climatic domains. Moving from 1951-1960 to 1971-1980 overlapped decades, the precipitation amount required to assign a month to a certain SPI class is slightly reduced for at least one of the extreme classes. For Vinhais, Carviçais and Macedo de Cavaleiros, the mean monthly precipitation threshold decreases from the earlier to the more recent overlapped decade, either for wet or for dry SPI classes. In southern weather stations in Portugal, Paulo *et al.* (2016) also observed this trend, since the precipitation thresholds for a given drought class in a more recent SPI computation period were lower than the threshold in the precedent period. Although those evidences are not statistically significant, they might be one more element confirming the actual trend towards precipitation extremes, which is a persistently outlined scenario in climate change projections.

The analysis presented above alerts to a potential increase in desertification susceptibility in NE Portugal. Not just the semiarid regions have been increasing severity in desertification susceptibility, but also other wetter areas evolved to dry subhumid (PANCD, 2011; Figueiredo *et al.*, 2015a). That is precisely the case of Macedo de Cavaleiros station, when comparing the AI index computed for the 1960-1990 and 2000-2010 periods: In the first period, it is classified as humid and in the second period as dry sub-humid according to

the aridity index based climate classification (PANCD, 2011). The same change in AI class occurred in Malhadas (wet subhumid to dry subhumid), Vinhais (humid to wet subhumid) and Carviçais (wet subhumid to semiarid) (PANCD, 2011). Seemingly, an annual precipitation decrease through time could justify the decrease in AI, but this was not consistently observed in the whole region, as described above when analyzing precipitation trends. The main outcome of this analysis was a trend towards the extremes in precipitation and SPI. The contribution of evapotranspiration changes to the AI trend could be related to the more widely reported positive change trend in temperature. However, this line was not explored in the present research.

In any case, the relationships being explored are complex and the interpretation of research results is not always straightforward, for which may also contribute topoclimatic effects, especially relevant in mountain areas as NE Portugal. The study by Paulo *et al.* (2012) may be taken as an example to this respect. These authors compared four drought indices in 27 weather stations across Portugal and did not found a significant relationship between the aridity index and the climate change trend observed in their work. Also, Paulo *et al.* (2016) did not detect a typical pattern of drought aggravation in their study across Portugal; however, they pointed out the need for revisiting and updating the definition of ‘normal’ conditions that are a key reference for detecting relevant or significant changes. This is not only because of precipitation changes through time, as part of its inherent variability, but also because more data are available as data series grow in extent.

Differences in drought variability patterns suggest splitting Continental Portugal in two sub-regions (Martins, *et al.*, 2012; Moreira *et al.*, 2015; Santos, *et al.*, 2010). Analyzing the spatial drought variability based on SPI and applying principal component analysis,

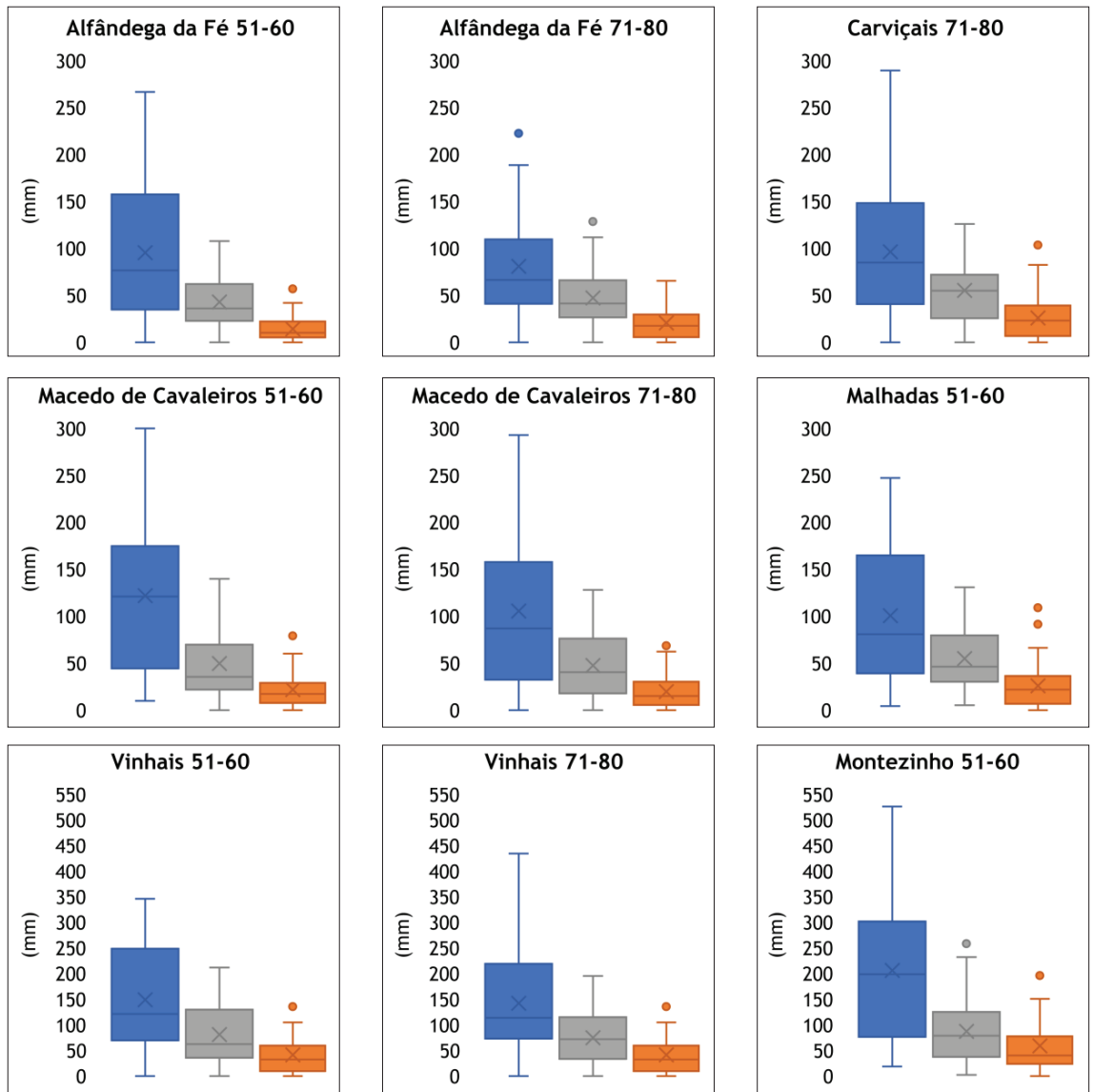


Fig. 9 - Monthly precipitation distribution for months classified as wet, normal, and dry according to SPI (boxplots presenting average, quartiles, extreme percentiles and outliers).

Fig. 9 - Distribuição da precipitação mensal para os meses classificados pelo SPI como húmidos, normais e secos (média, quatis, percentis extremos e valores aberrantes apresentados em boxplot).

Razieri *et al.* (2015) indicate a slight increase in the drought variability complexity for longer than shorter SPI timescales in Centre-Eastern Portugal, a third sub-region to be considered apart from the other two. The trend analysis across Portugal performed by Moreira *et al.* (2012) and by Martins *et al.* (2012) detected no evidence of either increase or decrease in drought severity and occurrence, considering the two sub-regions North-Western and Southern Portugal. However, in Moreira *et al.* 2012, no weather stations located in the NE Portugal were included in the analysis. In a recent study of precipitation extremes trends' projections, Santos *et al.* (2019) concluded that the maximum number of consecutive dry

days for the Trás-os-Montes regions tends to increase, in addition to the maximum number of consecutive wet days (Santos *et al.*, 2019).

Along the present study, change trends occurring in NE Portugal, concerning precipitation and drought, were identified and discussed, using a point approach based on weather stations representative of the different climatic domains prevailing in the region. This is understood as a contribution to address prospected challenges in regional water resources management in a changing environment and to consider in regional plans of adaptation to climate change as PIAAC\_TQT (2018), PIAAC\_TFT (2018) and Instituto da Água (2001).

## Conclusion

A single and coupled trend analysis of precipitation and SPI drought index was performed in six weather stations in NE Portugal, along a seventy-year time series. This included three climatological normal periods (1931-1960, 1951-1980 and 1971-2000), with two overlapped decades (1951-1960 and 1971-1980). The selected weather stations are representative of the climatic domains found in the region, ranging from semiarid to humid.

Precipitation over the last century study period tends to decrease in most weather stations. This trend is more pronounced in stations located in wetter areas. On the contrary, one station located in the semiarid shows an increase in mean annual precipitation and for the months with related highest and lowest precipitation (January and August, respectively), which is in agreement with future climate projections for the region (PIAAC\_TQT, 2018; Costa *et al.*, 2012). The decrease in mean rainfall amounts observed in stations located in wet subhumid and dry subhumid areas matches with reported changes in the aridity index in the same areas.

SPI was computed for some stations in the NE Portugal and allowed to assess drought frequency and severity across the study area. SPI class frequency analysis in the overlapped periods enabled to detect temporal changes in the proportion of dry, normal and humid classes. As SPI timescale increases (1 to 6 months) and a more recent climatological normal is taken as input data (1931-1960 to 1971-2000), the frequencies of dry and wet months in the overlapped periods increased, at the expenses of the frequency of normal months. Frequencies of months with severe and extreme drought during the overlapped periods increased as well, more visibly for the SPI 3-month timescale and for stations located in dry sub-humid and semiarid climatic domains. Globally, results highlight a tendency towards the occurrence of precipitation extremes in NE Portugal. Both extremes conditions, wet and dry, are damaging in frequency. These statistically driven findings agree with currently reported climate change projections, yet with a larger uncertainty when comparing precipitation with temperature.

Climate change projections are likely to have impacts on water resources availability, therefore, pointing out the need for tuned management of natural water bodies or reservoirs (Andrade *et al.*, 2011). Water scarcity (or excess) is a critical limitation to crop productivity and the agricultural product in Portugal, affecting crops as vines and olives, among others cultivated in NE Portugal (Yang *et al.*, 2020). Moreover, changes in precipitation temporal variability and seasonal distribution also have consequences to wildfire hazard (Costa *et al.*, 2012).

The general change trends in precipitation and drought reported in the study confirm a progressive severity in the susceptibility to desertification actually affecting NE Portugal.

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