General comments: In this paper, meteorological droughts affecting the Miño-Limia-Sil Hydrographic Demarcation during the period of 1980–2017 are identified and assessed using the one month SPEI index (and, in some cases, some other temporal scales). In this way, the problems associated with droughts, their origin and their impacts are analyzed at a regional level. It is shown that the driest/wettest conditions occur under some particular Circulation Weather Types. In addition, some teleconnection patterns seem to favor more/less frequent dry conditions with different temporal scales. Finally, soil moisture and river stream flows are also related to drier or wetter conditions in previous months. My general impression is that many of the presented results are not new, since most of the results shown in this document are in agreement with those presented in previous papers on droughts in the northwest of the Iberian Peninsula. Probably, the most original aspect of this paper is that it shows that the methods previously used in the NW Iberian Peninsula can be used successfully in a much smaller region, such as MLSHD. Anyhow, I think that this paper is acceptable for publication with some revisions and clarification.

Specific comments: In general, the indices used in the paper are described very diffusely and only some random information about them is provided to the reader (of course, references are provided on how those indices are defined. But further explanations would help to better understand what is presented in the paper). I think more information has to be provided on how those indices are calculated and what they represent. For example, why doesn't the 'materials and methods' section include a brief definition of SPEI and SSI and the way they are computed? Equations 1 and 2 define Eto (E1) and Rn2(S), but the text does not include the definition of some of the indices most frequently used in the paper (SPEI, SSI, severity...) or, for example, the way in which the statistical sifnificance of the wavelet coherence is calculated. Some information about the data is missing as well. Are the Miño and Limia rivers discharge series affected by reservoirs or by any other human regulation activity? This information should be included in the description of the data and considered in the discussion of the results. In the conclusions section, it is explained that the classification of the CWTs is daily. I think this information should be included in the description of the data.

We appreciate your advices to improve the manuscript. The methodology section was improved in order to provide a better description of the indices utilized, the calculation of drought indicators, the computation of WTs and the Wavelet coherence significance.

The Atlantic Multidecadal Oscillation is known to be characterized by a period that varies from approximately 40 to 80 years (even if a band of 20-30 years is accepted, the period studied in this paper does not even include two complete cycles of such C2 NHESSD Interactive comment Printer-friendly version Discussion paper an AMO oscillation). Therefore, it is very difficult to assess the impact of AMO with a study period of less than 40 years. If the maximum coherence period between AMO and SPEI1 is 6 years (figure 11) then it is not addequate to describe it as multidecadal coherent oscillation. My opinion is that the analysis of the impact of the AMO is too noisy (and not multidecadal enough) and that it should not be included in this paper.

We acknowledge your advice! We agree and consequently the AMO analysis and discussion was removed from the text.

Other suggestions, corrections and typos:

Abstract: Is it acceptable to define acronyms in the abstract? If so, MLSHD is defined for the first time in the abstract and it is not needed to re-define it in the Introduction (P3-L6)

The acronyms were deleted from the abstract.

Abstract-line 19: 'The results showed that atmospheric circulation from the southwest, west, and northwest were directly related to dry and wet conditions': To both dry and wet conditions?

Than you. This sentence was modified:

"The results showed that atmospheric circulation from the south-east/west, east/west, and north-east/west were directly related to dry/wet conditions in the Miño-Limia-Sil Hydrographic Demarcation during the entire climatological year"

Abstract-line 22: 'the major teleconnection atmospheric patterns': change to "the major atmospheric teleconnection patterns"

Changed

Page 3-Line 15: Delete '(Figure 1)': the MLSHD and figure 1 are already referenced a few lines before.

Deleted

P4-L15: define the variables in ec. 1

You are right They are now defined in the manuscript

P4-L17: SPEI is said to be a multiscale index, but it is not clear what is the advantage of this multiscale character. In fact, most of the paper deals only with SPEI1.

Yes, we mostly utilized the SPEI1 to identify meteorological droughts, which we believe are the best related with different WTs. Besides the meteorological drought can be perceived as the initial cause of other types of drought. The multiscalar advantage permit to assess whether this accumulated dry/wet conditions impact other steps of the hydrological cycle; in this case the soil moisture content and the runoff. The explanation was improved in the manuscript.

P4-L21: 1954-2014: 61 years, thus about six decades, not five.

Changed

P5-L13: ERA-Interim reanalysis for the period 1979-2017. If not, the period 1980-2017 cannot be set for all the analysis in this study (P6-L13).

Thank you, it was corrected. But the correct study period is 1980-2017 in order to fit a temporal scale with complete data of all variables (in this case the river discharge was complete from 1980 to 2017).

P5-L18 to L23: a better explanation of what 'pure' or hybrid' WTs are (and about the implications of WTs being 'pure' or 'hybrid') would be appreciated. A mathematical definition based on poorly defined parameters is not enough. Any mention to those 16 'hybrid' circulations could be removed from the main text since they are not mentioned in any other section of the paper.

The description of the methodology referred to the weather type computation was modified in order to provide further details. The difference between pure and hybrid types was introduced into the text as well as a description of how both types are considered in the percentage contribution.

"According to the methodology developed by Trigo and Da Camara (2000), 10 different "pure" WTs can be identified, namely Northeastern (NE), Eastern (E), Southeastern (SE), Northwestern (NW), Western (W), Southwestern (SW), North (N), South (S), Anticyclonic (A), and Cyclonic (C). Pure directional WTs (NE, E, SE, NW, W, SW, N, S) were those showing |Z| < F with the direction defined by tan-1 (WF/SF) (180° added if WF is positive).If |Z| > 2F, then the circulation would be considered C (if Z > 0) or A (if Z < 0). As not all the circulation patterns could be associated with a pure (directional/cyclonic/anticyclonic) type, 16 hybrid circulations were defined as a combination of A and C circulation with directional WTs. In this case, F < |Z| < 2F.

The methodology here described is able to daily identify the weather pattern (from the 26 listed before) presented over the area of study. From this daily information, and in order to study the WTs influence on monthly SPEI series, the monthly frequency of occurrence for every pure WTs is computed for the period 1979-2017. In the frequency computation, the 26 WTs are regrouped in the 10 "pure" ones. This procedure was realized following the same approach applied in Trigo and DaCamara (2000) in which the hybrid types were included into the corresponding pure WTs with a weight of 0.5, being the 10 final number of WTs analysed in this study."

P7-L12: '...occurred between December and February...': ?

It was changed for "from December to February"

P8-L6: '...the length of these episodes increased after 2003': Not the length, it is the frequency of long episodes what is higher. Long episodes can be found in 1988-1993 & 1980-1983, but after 2003 they are more frequent.

Thank you. It has been corrected on the text.

P8-L16-20: the trends described in these lines are far from being statistically significant (p values of 0.26, 0.52 and 0.26!!). Thus, it is difficult for me to understand why authors make so much emphasys in these trends.

The paragraph was modified according to the reviewer comment and this result was removed from the abstract as it not represents a relevant conclusion.

P9-L4: What do the numbers included as 'severity' in table 3 mean? How are these 'severity' values calculated? Same comment is applicable in table 2 and P8-L18. The definition of 'severity' and how it is calculated should be included in section 2.

In section 2 as added the explanation:

- *The duration is computed as the sum of all months from the onset with negative values, the peak is the month in which the episodes reach the highest value of SPEI1, and the severity is calculated as the sum of all SPEI values (in absolute values) during the episode.*

P11-L1: Pressure values in figure 4 are very small and difficult to read. The caption of this figure could include that reddish (blueish) isolines represent high (low) pressure values.

The figure and caption was changed to solve this!

P11-L18: Figure 5 caption: what do 'X's in the figure mean? I guess they represent not significant correlations, but it should be stated in the caption. What does the size of the circles in this figure mean? Is it just proportional to the value of the correlation? That information should be in the caption.

The information was included in the caption:

"The x's in the figure represent not statistical significant correlations at p < 0.05. The size for the circles is proportional to the correlation values"

P11-L22: moNths. The 'N' is missing

Thank you. It has been corrected

P12-L8-10: The description of what is shown in figure 7 included in the main text does not coincide with the caption of the figure. The caption seems to be wrong. Please, revise it.

The caption was wrong and it has been modified:

''Monthly percentage of occurrence for every WT associated with moderate, severe and extreme dry conditions. The red bars represent the number of times that each month was affected by each drought category''

P13-L3: Figure 7: Why are percentages negative? What WT is the one with a positive paper percentage? Its color is not included in the WT color table. Please, revise the caption and the main text and include this information.

The negative sing is a mistake in the figure, it was deleted. The original positive value (red bars) does not represent any weather type, just the number of times that each month was under different drought categories. It has been clarified in the text and in the caption.

P13-L10: Both the main text and the caption of Figure 8 should explain what the authors mean when they talk about the onset, the peak and the termination of the drought episodes. I guess the "onset" is the month in which the episode begins, the "peak" is the month in which the episodes reach the highest value of SPEI1 and the 'termination' is the month after the month in which the episode ends. But these ideas are not clear in the main text or in the caption.

*The description of onset, termination, and peak and other important terms were now introduced and best explained into the text accordingly with your suggestion. And yes, in this table the **onset** and the **end** represent the first and last month of the episode and the **peak** is the highest SPEI1 value reached in the episode.*

P19-Figure 10 caption: Correlations shown in figure 10a are obtained from monthly series? What are the 'X's in figure 10b? Confidence level?

Monthly time series were used to obtain correlations in Figure 10. The x's represent not significant correlation with 95% confidence level. This information was included in the caption.

Figures 10 and 11 Captions: SPEI1 is enough, delete '...the 1-mo Standarised Precipitation-Evapotranspiration Index...' (idem in figure 11 caption)

Changed

P19-L25 to P20-L2: The interpretation of figure 11 is already included in the figure caption. It could be deleted from the main text.

It was deleted form the text.

P21-L19: Should it be '...increased with the TEMPORAL SCALE OF SPEI...'

Changed

P21-L20: 'Figure 12b and c...' should be a new paragraph

Changed

P21-L31: '...basin features and water REGULATION...' this point is very important in the interpretation of the results. Nowhere in the paper it is said wether the streams were regulated or natural. I guess they are regulated and, thus, it is difficult to obtain clear interpretations from them.

We understand your concern and we confirmed that on the Spanish part of the MLSHD exist more than 2000 dams (according to the Hydrographic Confederation: https://www.chminosil.es/es/). In the Portuguese part are also several dams and hydroelectric stations. For this reason, we removed the analysis of the SSI. Although, Añel et al., (2014) found the dams in the Miño-Sil river basin had no influence on the natural river flows over the period 1978-2012 and based on this report we performed the initial study with the SSI. (http://catedranaturgy.webs4.uvigo.es/content/Workingpaper.pdf)

In order to avoid this the same analysis was performed but utilizing datasets of runoff at a resolution of ~ 4 km to compute the Standardised Runoff Index (SRI). An explanation of this index was added in section 2.

P22-L13-14: I do not understand very well what authors mean with their sentence 'The results revealed the frequency of the WTs prone...' Please, revise.

The sentence was changed

P23-L3-8: As I already said, I do not think any conclusion can be obtained about the influence of AMO.

After considering your concern, we agree, and the analysis of the AMO was removed from the manuscript.

P23-L10-14: Conclusions about soil moisture are sound, but results about river flows are much more duvious since those flows are most probably regulated.

We agree. The resolution of 0.25 is not adequate. We were thinking in using an interpolated moisture data from Terraclimate. However, we decided to focus on the runoff because soil moisture is almost similar to the SPEI, in fact the information of drought index like the SPEI and SPI is commonly representing soil moisture conditions.

Review of the manuscript nhess-2019-314, entitled "Meteorological drought in the Miño-Limia- Sil hydrographic demarcation: The role of atmospheric drivers", submitted by Rogert Sorí et al. for possible publication in Natural Hazards and Earth System Sciences. Recommendation Sorí et al. assessed drought characteristics in the Miño-Limia-Sil basin (NW Iberia) from 1980 to 2017 using the Standardized Precipitation Evapotranspiration Index (SPEI). The temporal variability of drought metrics was linked to changes in the dominant weather types and atmospheric circulation patterns in the region. Weather types in the study domain were classified using an automated version of the standard Lamb weather types' scheme. The study is interesting from the climatological point of view and falls within the scope of NHESS. The level of innovation of this work is fair/reasonable. Albeit with the availability of several studies, which assessed drought characteristics in the IP (most of them are referenced herein), this study applied well-established/existing methods in a standard fashion for a cross-boundary basin in the IP. The manuscript is generally well-written. However, the manuscript cannot be accepted for publication in its current version. Some methodological issues should be clarified. The structure of the manuscript should be refined. My major and specific comments are listed below:

I. Major comments

I want to point out one smaller aspect that deals with the general readability of the text. The readability is sometimes hampered by the use of various abbreviations (e.g. P, Y, M, MSRB, LRB, MLSHD, NWIP, VIMF, etc). If the reader is not very familiar with the terms and abbreviations, it is hard to follow. I would suggest using only those abbreviations that are reoccurring and central for the topic and trying to avoid others. This would strongly improve readability.

Following your advice some of the abbreviations were removed such as "y", "mo", NWIP, MSRB, LRB?

In the methods section, the authors need to clarify the final number of weather types retained in their work. Have they applied any regrouping/reclassification of hybrid types? What are the stopping criteria of their classification scheme? What statistical significance criteria are applied? How robust and reproducible are the results? What guided the reduction and grouping? Can you illustrate what the types represent, via typical flow or MSLP patterns? Also, a map illustrating the 16 points used for weather type classification should be included.

The total number of types was included in the study but, as suggested by the reviewer a regrouping of the hybrid types was realized in order to obtain the monthly percentage for every weather types. This and other issues addressed by the reviewer where added into the text to explain better the WTs computation process. The MSLP associated with every WTs is presented in Figure 4 and the points used in the computation are represented in Figure 1 (right panel). Transcription is presented below:

"The methodology here described is able to daily identify the weather pattern (from the 26 listed before) presented over the area of study. From this daily information, and in order to study the WTs influence on monthly SPEI series, the monthly frequency of occurrence for every pure WTs is computed for the period 1979-2017. In the frequency computation, the 26 WTs are regrouped in the 10 "pure" ones. This procedure was done following the same approach applied in Trigo and DaCamara (2000) in which the hybrid types count equally as a half occurrence to each of their pure types, being the 10 final number of WTs analysed in this study."

Regarding stopping criteria and statistically significance, it has been applied in other studies a 'stopping rule' to determine, for example, at what point to stop adding predictors (WTs) to obtain *the relative (%) contribution to total monthly Iberian rainfall by each WT. However, is not our case. However, as in other previous studies we distributed the few cases (<2%) with unclassified situations among the 26 classes. The unclassified situations occur when the module of the total shear vorticity (Z) is less than the standard deviation of Z/2 and simultaneously the total flow (F) is less than the square root of the sum of squared westerly and southerly flows.*

The types represent the MSLP. We considered the circulation associated to each WT to explain the role of directional flows. Several studies explain how to obtain the WT through the methodology here utilized, so, the results are perfectly reproducible.

I am wondering why the authors have not used some Mediterranean specific indices, such the WeMO and MO. Also, I am wondering why the authors did not consider SST as a driver of drought variability in their domain. This can be implemented using El Niño 3.4 index (SST anomalies in the central Pacific), El Niño 1 + 2 index (SST anomalies in the eastern Pacific) or SST anomalies in the tropical Atlantic. I am aware that the manuscript focuses mainly on specific atmospheric drivers, but at least in the discussion, the authors need to highlight the possible role of SST warming in drought reinforcement. See, for example: https://doi.org/10.1175/JCLI-D-11-00296.1

Thank you for your recommendation. These Index were also investigated and no significant correlation was obtained for any of El Niño Index (r values from 0.05 to 0.25 with the SPEI6 and TNA (r < 0.07). This information is included in the manuscript. The Index BEST already introduce information of SST of the region 3.4 and also takes into account the SOI (the pressure difference between Tahiti and Darwin), to give a better representation of the phenomenon. It has been argued in the manuscript.

The analysis for the WeMO index was incorporated and removed the AMO.

The authors should discuss their results in the context of some earlier studies whose results contradict the findings of the current study (particularly with respect to the significant role of NAO in drought variability in Europe in general and the IP in particular). See for example: https://doi.org/10.1007/s10584-007-9285-9. 10.1007/978-94-007-1372-7_3

We improve the discussion considering this advice. The link seems to be wrong.

The authors focused mainly on the temporal variability of drought and its connections with WTs and climate teleconnections. However, I have not seen any attempt to show the varying spatial response of drought to these drivers. The reasonable spatial resolution (0.1º) of E-OBS allows for a reliable assessment of the spatial variability of drought in response to the different atmospheric configurations. The authors indicate in the abstract "We concluded that regional patterns of land-use change and moisture recycling are important to consider in explaining runoff change, integrating land and water management, and informing water governance". I think decision-makers and water resources planners in any catchment seek for detailed information on the spatial variability of droughts so that they can adopt integrated policies and strategies for managing their catchment, taking into consideration the different conditions at both upstream and downstream.

To assess this, we decided to perform an EOF analysis for those months of the MLSHD when the average SPEI was ≤ - 0.84. In this analysis the PCA of the first EOF were correlated with each series of the WTs for the same chosen months. The first 6 EOF explain more than the 95% of the total *explained variance, and the two first around the 80%. Figures (EOF & PCA) has been added to the manuscript.*

In the Introduction, the authors lack the opportunity to comprehensively provide evidence on the hydrological, environmental and socioeconomic importance of MLSHD in the IP. A short description of the study domain, highlighting its main physiological, climatic and hydrological settings is needed. Section 3.1 is misplaced in the results section and should be forwarded to a new subsection called "study area".

Thank you for your advice. The Introduction has been improved by adding new information about its hydrological, environmental and socioeconomic characteristic of importance. The section 3.1 was also moved to the Introduction section in order to provide a more compressive information about the climate of the region.

A justification of the selection of the (-0.84) as a threshold for defining drought events is needed.

We improved this in section 2 as follows:

We avoid considering that any precipitation below the mean constitutes a drought. Therefore, the classification of drought categories according to SPI values proposed by Agnew (2000) (Table 1) was utilised in this study. Other authors have also employed this classification for investigating drought in the IP (e.g. Vicente-Serrano et al., 2006; Páscoa et al., 2017). This classification despite to be pre-established is built by probability classes rather than magnitudes of the SPI, and is therefore suggested as a more rational approach, with a most noticeable effect at the demarcation of mild and moderate droughts (Agnew, 2000). Then a drought episode was considered to occur (onset) when the SPEI at the temporal scale of 1 month fell below zero, reached a value of at least -0.84, and later returned to positive values. The threshold of -0.84 corresponds to 5% probabilities, whereby drought is only expected 2 years in 10, which reduce the incidence of mild meteorological droughts.

In the methodology, the authors should clarify how the different drought metrics were computed? How were the trend and its statistical significance assessed? Have they accounted for the possible presence of serial correlation in the series?

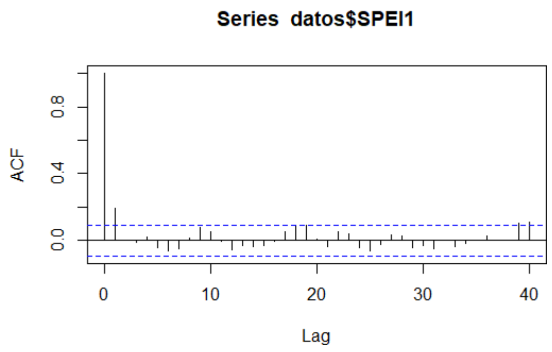
It is now clarified:

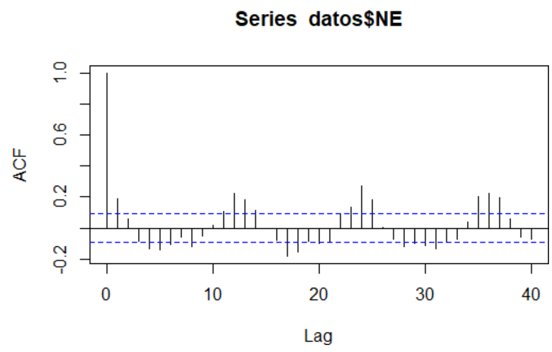
- *The duration is computed as the sum of all months from the onset with negative values, the peak is the month in which the episodes reach the highest value of SPEI1, and the severity is calculated as the sum of all SPEI values (in absolute values) during the episode.*

Besides, the whole section 2 was improved.
In the case of the trend we just made a regression and the significance is calculated using the Wald test with t-distribution of the test statistic, and the trend is considered significant when $p < 0.05$. In this new version the results were similar after utilize the Mann Kendall test and the Sen´s slope.

At first we didn't consider the presence of serial correlation in the series. I order to assess the possible autocorrelation of the series was utilised the function of autocorrelation (ACF) in the R program. For the SPEI1 the autocorrelogram show, as expected, non-significant values. However, for some WTs (e.g. NE) (see right panel below) it seems that exist a clear seasonality and several values are significant, confirming the autocorrelation. To solve this concern we applied the Mann-Kendall Test of Prewhitened Time Series Data in Presence of Serial Correlation Using the von Storch (1995)

Approach. A detailed description of this method was added to section 2. (next figures are just an example and won't be included into the manuscript).





The authors should clarify the rationale behind constraining their study from 1980, while EOBS dataset extends back to the 1950s (probably not for all climate variables).

Despite the EOBS data is available from 1950s other variables (such as Era-Interim data used for WTs computations) is from 1979 and at first moment the river discharge data were from 1980. Thus, we decided to reduce the study to the period 1980-2017.

I would recommend adding a new figure, in which the authors compare the accumulated SPEI values corresponding to each WT.

Initially we thank to made a new figure is compound by 10 new figures (10 episodes) showing the SPEI1 and each WT anomaly, or accumulating the anomalies of each WT, but we could made the figure you suggest above.

Prior to calculating correlation, it is important to detrend the series of the frequency of WT.

The series of WTs and SPEI were de-trended and the correlation was computed again. In this case the spatial correlation was also made.

In the discussion, the authors should refer to the role of zonal and meridional circulation in drought characteristics (in the context of the directional WTs).

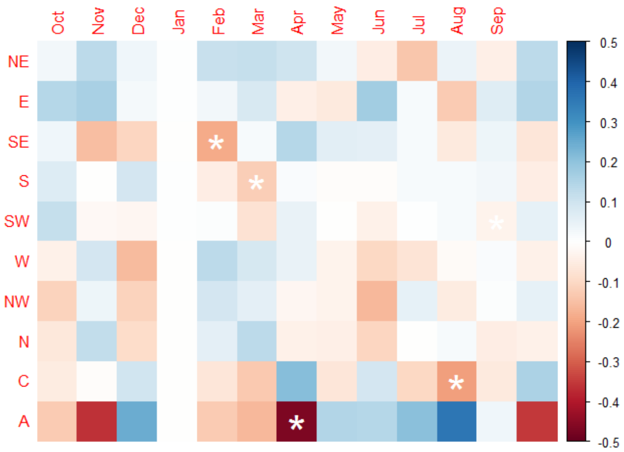
We improved the discussion considering this advice.

It is recommended to add a table, which summarizes trends of the 10 main WTs over the study period, their statistical significance and compares those with the trends observed for the different drought metrics (e.g. drought, severity, and occurrence).

We calculated the trend for each WT and also for individual months. We applied the Mann-Kendall Test of Prewhitened Time Series Data in Presence of Serial Correlation Using the von Storch (1995) Approach. As all p values are greater than 0.05, trends are not statistically significant.

	NE	**E**	**SE**	**S**	**SW**	**W**	**NW**	**N**	**C**	**A**
Z-value	1.04	1.43	-0.29	4.11	0.64	-0.37	-0.22	-0.18	-0.16	-0.70
Slope	0.002	0.004	-0.00	0.000	0.000	-0.0002	-0.0002	-0.0001	-0.0003	-0.004
p-values	0.29	0.15	0.77	0.96	0.52	0.70	0.81	0.85	0.86	0.48

Also, no statistically significant trends appear in almost every WTs and months. Significant trends only appear for SE in February, S in March, SW in September, C in August and A in April. Moreover, in most of the cases the trend show low values. We did not added the table above into the manuscript, but commented the results.



HS method for calculating PET is a temperature-based method, which is more suitable for arid and semi-arid regions (not humid regions like the study domain). Have the authors tested the performance/accuracy of this method in their region? Several studies reported a less performance of temperature-based methods in assessing PET in humid climates.

We agree about your concern. The limitation to computed the Eto thought the Penman Monthie method lies on the lack of several variables at high resolution for a long study period. To support our choice, the next paragraph was added to the manuscript.

By this method we do not consider that relative humidity and wind speed are also important factors that determine the vapour density above the soil surface and the aerodynamic resistance for vapor transport, permitting more realistic Eto values and consequently drought assessment (Bittelli et al., 2008; Vicente-Serrano et al., 2010; WMO, 2012; Davarzani et al., 2014). However, even though the Penman-Monteith offers a more accurate estimation of reference Eto than the Hargreaves formula (Tomas-Burguera et al., 2017), results of Vicente-Serrano et al., 2014 showed that Eto in Spain *estimated by the Hagreaves-Samani method for the period 1961 – 2011, had the closest agreement with the Eto obtained by the Peaman Monthie method in terms of temporal evolution and magnitude respect other eleven methods. These authors also found high correlations between Eto obtained by both methods in the northwest IP.*

Vicente-Serrano et al., (2014). Reference evapotranspiration variability and trends in Spain, 1961–2011. Global and Planetary Change, Volume 121, October 2014, Pages 26-40. https://doi.org/10.1016/j.gloplacha.2014.06.005

Given the limited area of the study domain, the spatial resolution of SMroot data seems to be coarse (0.25◦ × 0.25◦) to provide a reliable assessment of the response of soil moisture to precipitation deficit. Also, in humid climates like those of the study area, the response of soil moisture to accumulated precipitation deficit is more pronounced at longer time scales (not 1- month time scale). The persistence of negative soil moisture anomalies is expected to be higher when there is a cumulative long-term decrease in the amount of precipitation. This aspect should be discussed thoroughly.

In order to perform a better analysis, the figure and explanation for this section was removed. We considered your concern regarding the low resolution of the SMroot, which is representative for around 10 grid points. A similar analysis was performed but utilizing the soil moisture from the high-resolution (~ 4km) global dataset of monthly climate and climatic water balance "Terraclimate". We also utilized the Standardized Soil Moisture Index (SSMI) (Hao and AghaKouchak, 2013)

Describe all symbols given in Eq. 1.

Symbols are now described:

we used the method proposed by Hargreaves and Samani (1985) based on temperature data to estimate the Eto according to Equation 2:

$$Eto=0.408*Ch*Ra*(\sqrt{(Tx-Tn)})+(Tm+17.8) \quad (2)$$

Where Ch = 0.0023; Ra is the extraterrestrial radiation (derived from the latitude and the month of the year), and Tx, Tn and Tm the maximum, minimum and mean temperature respectively.

Which index exactly of the NAO, as well as ENSO, was used? Please, be more specific. There are different indices for quantifying each of them.

We added this and more information.

To obtain the Northern Hemisphere teleconnection indices utilized in the study the Climate Prediction Center (CPC) utilise the Rotated Principal Component Analysis (RPCA) method used by Barnston and Livezey (1987) but utilizing monthly mean standardized 500-mb height anomalies obtained from the CDAS in the analysis region 20°N-90°N. This procedure isolates the primary teleconnection patterns for all months and obtain the index time series.

Barnston and Livezey (1987, Mon. Wea. Rev., 115, 1083-1126)

Section 2.5 should be placed earlier in the materials and methods section (before the description of drought calculation).

The section was moved

The role of aerodynamic components in drought evolution should be discussed, given that these influences are not considered in HS method.

The next paragraph was added to section 2 in order to expose this topic, and along the manuscript are discussed other issues:

By this method (HS) we do not considered that relative humidity and wind speed are also important factors that determine the vapour density above the soil surface and the aerodynamic resistance for vapor transport, permitting to obtain more realistic Eto values and consequently drought assessment (Bittelli et al., 2008; Vicente-Serrano et al., 2010; WMO, 2012; Davarzani et al., 2014). However, some studies have shown similar Eto estimations by means of the Penman-Monteith and Hargreaves methods in Spain (López-Urrea et al. 2006; Gavilán et al. 2008; Vanderlinden et al. 2008; López-Moreno et al. 2009), although the Penman-Monteith offers a more accurate estimation of reference Eto than the Hargreaves formula (Tomas-Burguera et al., 2017).

II. Minor comments

Title: It is recommended to indicate the location of the study domain (i.e. NW Iberia), as the majority of the NHESS readers are not familiar with the study basin. Also, it is important to include "hydrological droughts" in the title.

The title was changed as follow: ''Hydrometeorological droughts in the Miño-Limia-Sil hydrographic demarcation (NW Iberian Peninsula): The role of atmospheric drivers''

In order to emphasize more on the hydrological issue, two figures showing the temporal evolution of the Standardized Soil Moisture Index (SSMI) (Haoand AghaKouchak, 2013) and the Standardized Runoff Index (SRI)(Shukla and Wood, 2008) were added. A detailed explanation of both index was added in section 2.

P1 - L14 and other parts of the ms: "period of" <> "period".

Thank you. It has been changed along the text

L16 and other parts of the ms: "mo" <> "month".

It was changed along the text

L17: For a study that covers 38 years, the use of the term "historically" is misleading; please, define the confidence interval at which the significance was assessed.

The historically term was removed from the text and the confidence level was provided (95%).

L18: "different" <> "the different".

Changed

L19: Based on which scheme this classification was made? The abstract should stand alone based on this basic information.

It was included

- *... a daily weather type classification based on standard Lamb scheme was utilised for the entire Iberian Peninsula.*

L20: “were directly related to dry and wet conditions” This statement is vague, with no clear phrasing. It does not make a clear conclusion on whether these weather types are favoring for above-normal or below-normal precipitation.

This sentence was removed and rewritten as follow:

Frequency and correlation analysis show that weather types conditioning an atmospheric circulation from the south-east/west, east/ west, north-east/west and the pure anticyclonic/cyclonic are associated to dry/wet conditions in the Miño-Limia-Sil Hydrographic Demarcation.

L25: Please, define the rainy season.

It was now defined: (October – May)

L27 and other parts of the ms: “1 y” <> “1 year”.

It was changed along the text

It is unclear how meteorological droughts assessed at 1-month time scale can be linked with land use changes (which almost occur at a coarse temporal scale”.

You are right, it was our mistake because at the same time were writing of a similar manuscript with a different scope. The sentence was removed.

P2 - L5: Please, give some examples of these thermodynamic factors (e.g. wind speed, air pressure).

In this case we modified the paragraph. Besides, in section 2 are explained the role of humidity and wind on the modulation of the Evapotranspiration and consequently the occurrence of dry conditions.

- *This phenomenon is usually considered a prolonged dry period in the natural climate cycle that can occur anywhere in the world. It is initially caused by a lack of rainfall as well as for thermodynamics processes that affect content of water on the soil, which are induced by the wind speed, temperature, relative humidity and solar and long-wave radiation (WMO & GWP, 2016; Vicente-Serrrano et al., 2010; Sereviratne, 2012; Miralles et al., 2019).*

- L15: Delete “e.g.” –

It was deleted

L19: “the precipitation” <> “precipitation”.

Changed

L25: “land” Do you mean air temperature? LST has a different conception and is mostly assessed using remote sensing products (e.g. MODIS, AVHRR), which are only available for the most recent decades.

The reviewer is right, it was clarified

L28: The study of Vicente-Serrano et al. (2011) does not provide any assessment of future projections of precipitation.

You are right. The reference was removed and added the correct.

Spinoni, J., Vogt, J.V., Naumann, G., Barbosa, P. and Dosio, A. (2018), Will drought events become more frequent and severe in Europe?. Int. J. Climatol, 38: 1718-1736. doi:10.1002/joc.5291

P3 - L8: "a homogeneous region in terms of the total P variance over the IP". This statement should be elaborated thoroughly.

This argument has been better discussed in the analysis of EOF of the SPEI.

P4 - L25: "A drought episode was considered to occur when the SPEI at the temporal scale of 1 mo fell below zero, reached a value of at least -0.84, and later returned to positive values". This definition should be made simpler.

The episode characterization was rewritten.

A drought episode occurs everytime the SPEI1 is continuously negative and reaches the value of −0.84 or less.

P5 - L1: "Results" <> "Results aepisond discussion".

Changed

L9: Language and style should be revised.

Thank you. We improved it.

L12: "modulate" <> "impact".

Changed

It is unclear why the classification of weather types is only restricted to the period 1989-2017.

This period is not correct, we apologize. The correct is 1980-2017. I was corrected in the text. This period was selected based on the available ERA Interim reanalysis data together with the rest of datasets in the moment we began to do this research (in particular the river discharge availability).

L15: Please, define this spatial window.

It was defined

For classifying weather types, the authors should clarify how SF, WF, ZS, ZW, F, and Z were computed?

The complete section was improved and the formulas were added:

$$SF = 1.305[0.25(p_5 + 2 \times p_9 + p_{13}) - 0.25(p_4 + 2 \times p_8 + p_{12})]$$

$$WF = [0.5(p_{12} + p_{13}) - 0.5(p_4 + p_5)]$$

$$ZS = 0.85 \times [0.25(p_6 + 2 \times p_{10} + p_{14}) - 0.25(p_5 + 2 \times p_9 + p_{13}) - 0.25 \times (p_4 + 2 \times p_8 + p_{12})$$

$+0.25(p_3 + 2 \times p_7 + p_{11})]$

$ZW = 1.12 \times [0.5 \times (p_{15} + p_{16}) - 0.5 \times (p_8 + p_9)] - 0.91 \times [0.5 \times (p_8 + p_9) - 0.5 \times (p_1 + p_2)]$

$F = (SF^2 + WF^2)^{1/2}$

$Z = ZS + ZW$

P6 - L20: “from daily values” <> “aggregated from daily values”.

Modified

L21: The name of the station “Albufeira Do Alto” does not fit with that labeled in Figure 1.

This Figure has been modified.

P7 - L5: “the annual cycle” <> “the year”; “western” <> “the western”.

Changed

L20: What is the difference between “extensive” and “intense”? Do you refer to drought duration and severity?

Yes, it was clarified into the text.

P8 - L30: “for in” <> “for”.

This expression does not appear in P8, it was changed in P18.

The acronyms “WTs” and “CWTs” are used interchangeably er in the text. - P23 (L10): “the soil” <> “soil”.

It was now corrected and only WTs is now used in the text

P23 (L10): “the moisture” <> “moisture”.

Changed

This work emphasized that drought did not respond linearly to most of the dominant circulation patterns in this region (apart from SCAN, AO) at 1-month timescale (Figure 10a). This finding should be discussed thoroughly in the text and linked with available literature.

We agree and the explanation was improved.

Tables

Table 1: There is a refinement of the drought categories of Agnew (mild drought is masked with another category).

Modified!

Table 2: Trends in SPEI values should be expressed in z-units/year.

Done

Figures

Figure 1: In the legend and caption, “rivers” <> “streams”. The negative symbol corresponding to the longitudes should be deleted, given that the direction “W” is already included. It is important to include a distribution of the meteorological stations whose data were used for SPEI calculation.

This figure was totally modified in order to follow your suggestions but also for representing the grid points utilized to compute the WTs.

Figure 3: how were drought episodes defined? Have you applied n consecutive months with SPEI <-0.84?

Yes. The explanation was improved in section 2. An episode was defined as the consecutive negative SPEI1 that reach at least the values of -0.84 or less.

Figure 4: I would recommend using the anomalies (not the actual values) of SLP corresponding to the different WTs. This will facilitate defining the positive and negative centers of action that control air advection at the surface.

Ok. Anomalies were calculated and will be added to the manuscript.

Figure 5: The use of the symbol “x” should be described. The use of the legend in a vertical form is confusing, given that all WTs at the top of the panel show a negative correlation (shown in blue). I would recommend reversing the legend so that negative values of correlation are shown at the top, while negative correlations are illustrated below. Why the authors did not use a portrait diagram showing the interpolated surface of the correlation coefficient, with some contour lines to show the significance of the correlation? This will facilitate the readability of the figure.

Dear reviewer. This figure in the new manuscript submitted is Figure 8. We apologize because we submitted the ancient figure without reverse the colorbar. We will add the new one with reversed colorbar.

The X values indicate those correlations no statistically significant at $p < 0.05$. We reversed the legend. We considered to contour the correlations following your instructions, but, the function contour automatically interpolates and in this analysis the correlations are made for different WTs, so, in order to show the more precisely, we prefer to keep this format of circles.

A new figure showing the spatial correlations of the SPEI with each WT was made. This is NOT the last version of this figure, we will show just the demarcation, change the color and limits of the color bar and add a line for indicate the statistically significant values.

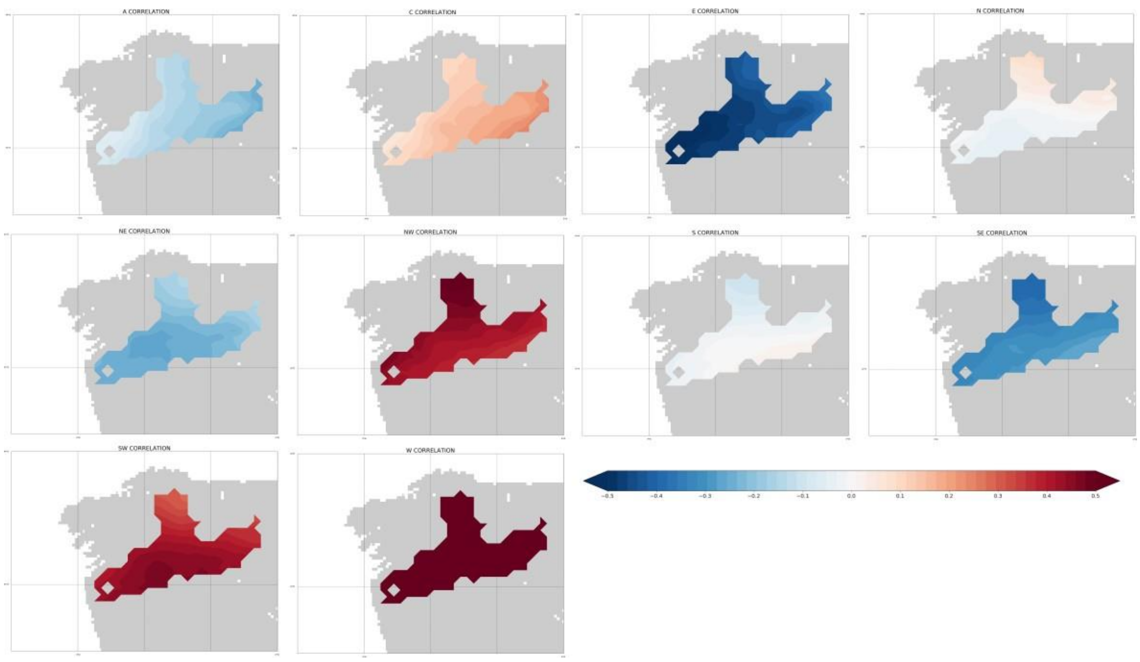


Figure 6: I would recommend plotting the events at the xaxis, while the stacked bars show the contribution of each WT to such events. This will deliver the message clearer.

Dear reviewer, we try to change this figure following your advice. However, we also made the figure accumulating the SPEI and showing the respective WT. So we consider this figure (in the new paper submitted is the Figure 12, could be a good choice to summarize the new figure we accumulating the SPEI. However, if you still think it worth to remove it and add 10 new figures we can do it.

Figure 7: why the percentages are given in negative? To which WT refers the "red" color? I would recommend adding a column to the three drought categories, which refers to wet conditions (i.e. SPEI values >0). This contrast can show interesting results about the role of each WT during dry vs. wet conditions

~~This figure was improved following your suggestions.~~ The red color don´t refer to any WT; it indicates the number of months under each drought category. ~~The same figure was added for the wet conditions.~~

Dear reviewer. It was expected from previous results described in the paper that WTs imposing circulation from the west are associated with wet conditions. So, we considered this as a little redundant, but if you still consider it should be added we will add, ok!

Hydrometeorological ~~D~~d~~d~~roughts in the Miño-Limia-Sil hydrographic demarcation (NW Iberian Peninsula): The role of atmospheric drivers

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Abstract. Drought is one of the main natural hazards because of its environmental, economic, and social impacts. Therefore, ~~its study,~~ monitoring and prediction for small regions, countries, or whole continents are challenging. In this work, the meteorological droughts affecting the Miño-Limia-Sil Hydrographic Demarcation ~~(MLSHD)~~ in the northwestern Iberian Peninsula during the period ~~of~~ 1980–2017 were identified. For this purpose, and to assess the combined effects of temperature and precipitation on drought conditions, the Standardised Precipitation-Evapotranspiration Index ~~(SPEI)~~ was utilised. Some of the most severe episodes occurred during June 2016 – January 2017, September 2011 – March 2012, December 2014 – August 2015. ~~During the study period there was no statistically significant trends in the series of SPEI at the temporal scale of 1 month (SPEI1); however, as well as for the number of drought episodes and their severity have been increasing historicallyin the period of study, but this metric was not statistically significant taking into account 95% confident level.~~ An Empirical Orthogonal Function analysis for the Standardised Precipitation-Evapotranspiration Index series revealed the that the spatial variability of the SPEI shows a great homogeneity in the region, and consequently the drought phenomenon behaves in the same way. Particular emphasis was given to investigating atmospheric circulation as a driver of different drought conditions. To this aim, a daily weather type classification based on Lamb weather type (LWT) classification (Lamb, 1972) ~~standard Lamb scheme~~ was utilised for the entire Iberian Peninsula. The results showed that atmospheric circulation from the southwest, west, and northwest are directly related to wet conditions in the Miño-Limia-Sil Hydrographic Demarcation~~MLSHD~~ during the entire climatological year. Contrastingly, weather types imposing atmospheric circulation from the northeast, east, and southeast are best associated to dry conditions. ~~and pure anticyclonic circulation were negatively correlated with the SPEI1~~. Anomalies of the integrated vertical flow of humidity and their divergence for the onset, peak, and

termination of the ten most severe drought episodes also confirmed these results. In this sense, the major atmospheric teleconnection ~~atmospheric~~ patterns related to dry/wet conditions were the Arctic Oscillation, Scandinavian Pattern, and North Atlantic Oscillation. Hydrological conditions investigated thorugh the Standardised Runoff Index were closely related to dry/wet conditons according to the Standardised Precipitation-Evapotranspiration Index at shorther temporal scales, specially during the rainy season. In these months hydrological droughts appears to be strongly influenced by accumulated drought conditions during previous 24 months.

~~Dry and wet conditions according to the Standardised Precipitation-Evapotranspiration IndexSPEI at shorter temporal scales were closely related to the soil moisture in the root zone, and also strongly influenced the streamflow of the Miño and Limia rivers, especially during the rainy season~~ (~~Octo~~December ~~–~~to ~~February~~May). ~~However, a direct relationship between soil moisture and streamflow was also observed when dry/wet conditions accumulated for more than 1 year.~~ ~~We concluded that regional patterns of land-use change and moisture recycling are important to consider in explaining runoff change, integrating land and water management, and informing water governance.~~

1. Introduction

Drought is ~~considered a~~ one of the most dangerous natural phenomena ~~major natural hazard~~ in many regions worldwide, as it affects a wide range of environmental, economic, and~~,~~ social~~, and~~ ~~environmental~~ sectors (Wilhite, 2000; McMichael et al., 2011; Stankeet et al., 2013; Gerber and Mirzabaev, 2017; Liberato et al. 2017; Guerreiro et al., 2018). This phenomenon is usually considered a prolonged dry period in the natural water cycle that can occur anywhere in the world. It is initially caused by a lack of rainfall as well as for thermodynamics processes (e.g. radiative and turbulent fluxes and water phase transitions (Wehrli et al., 2018;) ~~that affect the soil moisture content, which are~~ induced by the wind speed, temperature, relative humidity and solar and long-wave radiation (WMO & GWP, 2016; Vicente-Serrano et al., 2010; Sereviratne, 2012; Miralles et al., 2019). ~~This phenomenon is usually considered a prolonged dry period in the natural climate cycle; it is initially caused by a lack of rainfall as well as thermodynamics factors, and can occur anywhere in the world (WMO & GWP, 2016; Vicente-Serrano et al., 2010).~~ Drought propagation is also due to natural and human drivers through multiples feedbacks (Van Loon et al., 2016). The Iberian Peninsula (IP) in the Euro-Atlantic and Mediterranean regions is a drought-prone area (Páscoa et al., 2017) that has been affected by well known record-breaking droughts in 2004-2005 (García-Herrera et al., 2007), 2011-2012 (Trigo et al., 2013), and 2015-2016 (García-Herrera et al., 2019). ~~The Iberian Peninsula (IP) in the Euro-Atlantic and Mediterranean regions is a drought-prone area (Páscoa et al., 2017), where t~~Temperature increase has been responsible of greater drought severity and larger surface area affected in the IP from 1980s to 2010 (respect 1906-2010) due to the increase in atmospheric evaporative demand (Coll et al., 2017). -Concerning the existence of the trends in droughts ~~that has presented~~ a significant tendency towards dryness during 1901–1937 and 1975–2012 (Páscoa et al., 2017). ~~- also but~~ Over a shorter study period (1974–2010), Gómez-Gesteira et al. (2011) found a significant increasing trend in land atmospheric and sea surface temperatures of 0.5 °C and 0.24 °C per decade, respectively, but annual P did not show any trend in the north western IP. The high confidence level that global warming is likely to reach 1.5 °C above preindustrial levels in a short period (between 2030 and 2052) if it continues to increase at the current rate is a nowadays concern (IPCC, 2018). In this sense, the IP is considered one of the European regions that is most likely to suffer an increase in drought severity during the 21st century (Vicente-Serrano et al., 2011Spinioni et al., 2018). However, Trenberth et al. (2014) argued that increased heating from global warming may not cause droughts, but it is expected that when droughts occur they are likely to occur more quickly and be more intense.

In particular, the climate of the Euro-Atlantic sector is characterised by considerable variability over a wide range of time scales (Visbeck et al., 2001; Sousa et al., 2016; Abrantes et al., 2017).

Drought processes involve interactions amongst ocean processes (ocean teleconnections), land-based processes (water balance, runoff), and several atmospheric processes (Spinioni et al., 2017). Therefore, to investigate droughts and their impact on the availability of water resources in the IP have been used multiple methods and analysis such as the implementation of weather types classifications (WTs) (Cortesi et al., 2014; Ramos et al., 2014), identification of blocking events (Sousa et al., 2016), and assessments of climatic teleconnection patterns like the North Atlantic Oscillation (NAO) (Muñoz-Díaz and Rodrigo, 2004; Trigo et al., 2004; deCastro et al., 2006), which is considered a dominant mode of climate variability for Europe (Visbeck et al., 2001), the Arctic Oscillation (AO) (deCastro et al., 2006), El Niño Southern Oscillation (ENSO) (Vicente-Serrano, 2005), and the Scandinavian Pattern (SCAND) (deCastro et al., 2006). The impacts of drought have been widely investigated in the IP, and range from affecting the productivity of rainfed crops (Peña-Gallardo et al., 2019), forests (Gouveia et al., 2009; Barbeta and Peñuelas, 2016; Vidal-Macua et al., 2017; Peña-Gallardo et al., 2018), and even the human mortality in Galicia, northwestern Spain (Salvador et al., 2019). Terrestrial ecosystems often vary significantly in their responses to drought (Knapp et al., 2015). Moreover, IP is characterised by different climate types, from a humid Atlantic climate in the northwest and north to semi-arid Mediterranean conditions in the east and southeast (e.g. Parracho et al., 2016), and strong seasonal variability (Serrano et al., 1999). Therefore, regional-scale studies have the advantage of better characterising the phenomenon of drought and its impacts, thereby supporting the reduction of the vulnerability and losses induced by drought.

The north western IP is a hydrologically important region where water resources of the Miño-Sil and Limia river basins represent an important source of benefits for inhabitants of Galicia and the northern provinces of Portugal. Both basins make up the Miño-Limia-Sil Hydrographic Demarcation (MLSHD), a region of environmental shared resources for Spain and Portugal. The water resources in the MLSHD are crucial to develop agriculture and livestock. Indeed, in the Spanish part of the MLSHD, the water demands of agrarian use represent 73.2% of the total water demand (Vargas and Paneque, 2019). The rivers Miño and Sil river also make this region one of the main producing regions of electricity in Spain, producing 2.5 million megawatts every hour (MLSHD, 2017). To the best of our knowledge there are not any published drought studies considering the MLSHD as a whole. Therefore, in this study our aim is to investigate the occurrence of meteorological droughts and its propagation across the hydrological cycle in the MLSHD, and also, to evaluate the role of atmospheric circulation and the large-scale teleconnection patterns in the occurrence and magnitude of droughts. We focus on meteorological droughts attempting to explain the primary causes of other types of droughts. The accuracy of drought forecasting is a challenge for hidroclimate sciences. Therefore, investigating drought characteristics and generating mechanisms is essential to take actions such as monitoring and early warnings, which contribute to efficient water management and reduction of the vulnerability of ecosystems and the society. We expect that our results will contribute to increase the hydroclimate knowledge of the MLSHD, support early warning, and strength drought management plans for the MLSHD.

1.1 Study area

The MLSHD extends from approximately 41°N to 44°N and from 6.5°W to 9°W, and covers an area of approximately 20 000 km^2 in the NWIP (Figure 1), including the territories of Galicia (Spain) and northern Portugal. There are 191 municipalities of which 181 belong to the Spanish territory, and 10 to the Portuguese territory, with a total population of 1 084 636 people (by 2015) (Mora-Aliseda et al., 2015). It is considered a management unit where the terrestrial area is composed by the Miño-Sil and Limia river basins and the transitional, subterranean, and coastal waters associated with said basins (CHMLS, 2017). It is characterised by the presence of landscape diversity; diversity that is based on a complex relief structure and the Atlantic bioclimatic characters. The basins have a pronounced mountainous character with an average elevation of about 683 m above sea level (Book…). The coastline, valleys and mountains give it a wide variety of landscapes that are well differentiated both internally and with respect to other peninsular territories. In terms of annual mean flow, the Miño-Sil river basin is the fourth largest basin in the Iberian Peninsula and because of that is important for hydropower generation [Lorenzo-Lacruz et al., 2012, Añel etal., 2013].

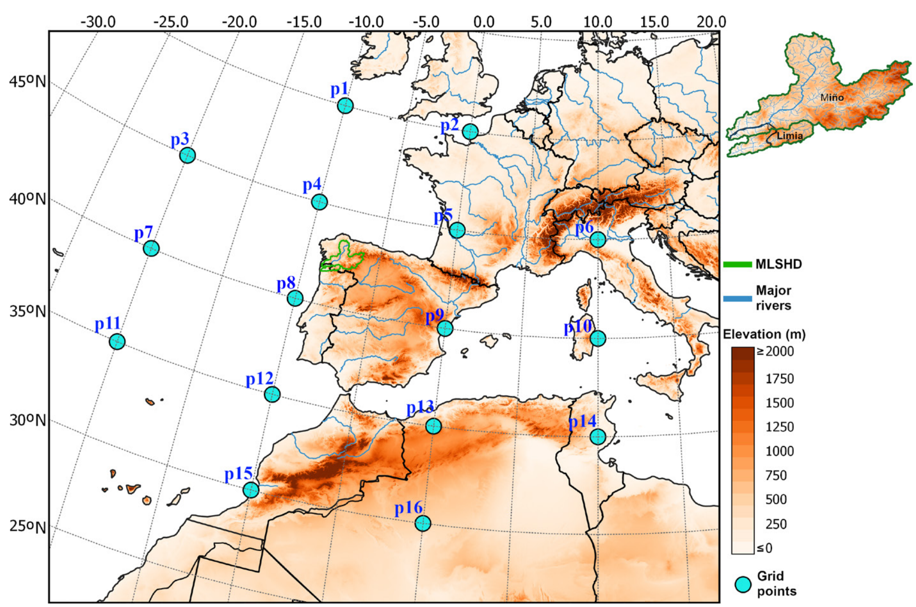


Figure 1. Geographic location and boundaries (green line) of the Miño-Sil and Limia River Basins which conform to the Miño-Limia-Sil Hydrographic Demarcation (MLSHD). The rivers are represented by blue lines and shaded reddish colours represent the elevation (in meters above sea level) from the HydroSHEDS project (Lehner et al., 2011). Light blue circles denote the location of the 16 points used to retreive daily MSLP values for the circulation weather types (WTs) computation.

Figure 1. Geographic location and boundaries (greenblack lines) of the Miño-Sil River Basin (MSRB) (1) and Limia River Basin (LRB) (2), which conform to the Miño-Limia-Sil Hydrographic Demarcation (MLSHD). The rivers are represented by blue lines, and shaded reddish colours (green to red) represent the elevation (in meters above sea level) from the HydroSHEDS project (Lehner et al., 2011). Light blue circles denote the location of the

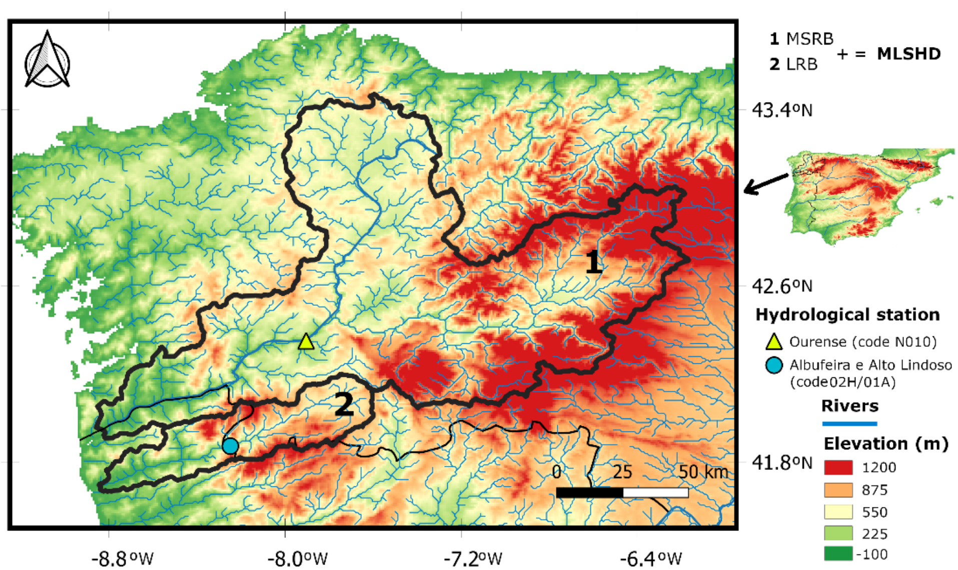


Figure 1. Geographic location and boundaries (black lines) of the Miño-Sil River Basin (MSRB) (1) and Limia River Basin (LRB) (2), which conform to the Miño-Limia-Sil Hydrographic Demarcation (MLSHD). The rivers are represented by blue lines, and shaded colours (green to red) represent the elevation (in meters above sea level) from the HydroSHEDS project (Lehner et al., 2011).

Its climate is characterized by mild winters, cool summers, humid air, abundant cloudiness and frequent rainfall in all seasons. The annual cycle of P, Tmax, and Tmin along the hydrological year (October of year n to September of year n+1) in the MLSHD using the E-OBS gridded dataset (Cornes et al., 2018). is shown in Figure 2. P presents a very high temporal variability across the year, and is greater than 100 mm from October to February. During winter, the large-scale circulation is mainly driven by the position and intensity of the Iceland Low, and western Iberia is affected by westerly winds that bring humid air and generate P (Trigo et al., 2004). The movement of the sub-tropical anticyclone to the south leaves the region open to the influence of the frontal systems from the west, which are responsible for most of the P. Synoptic-scale baroclinic perturbations from the Atlantic Ocean are responsible for most of the P between October and May (DeCastro et al., 2006). After February, P is lower and reaches the minimum value (P < 30 mm) in July. Summer is predominantly influenced by high pressures ~~of the eastern sub-tropical cyclone~~, which determine air subsidence and consequently atmospheric stability (PGRH, 2016). The annual cycle of Tx and Tn revealed a cycle opposite to that of P. Minimum monthly values of Tx (< 9 °C) and Tn (2 °C) occur from December to February, while the maximum values occurr in July and August (> 24 °C). Both the Miño and the Sil are remarkably regular rivers, although they have a maximum flow in winter (January and February) and a minimum in summer (August and September).

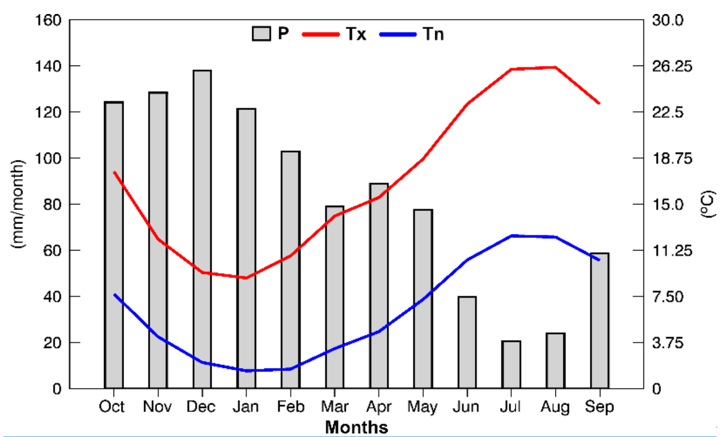


Figure 2. Annual cycle of precipitation (grey bars) and maximum (red line) and minimum (blue line) temperature in the Miño-Limia-Sil Hydrographic Demarcation from 1980–2017.

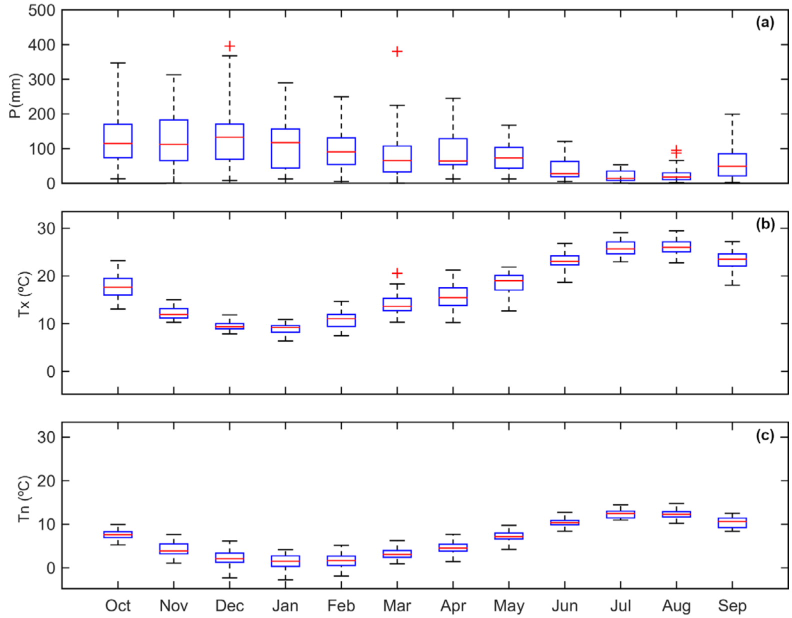


Figure 2. Annual cycle for the hydrological year spanning October of year n to September of year n+1, for the period 1980-2017, of monthly precipitation (a), maximum (b) and minimum (c) temperature in the Miño-Limia-Sil Hydrographic Demarcation, using the E-OBS gridded dataset. Boxes delineate median, upper and lower quartiles, with the whiskers representing the lowest and highest monthly value still within 1.5 of the interquartile range. +: outliers, i.e. values beyond the ends of the whiskers.

2. Materials and methods

2.1 Datasets

Monthly gridded data of P and maximum and minimum temperature (Tx and Tn, respectively) were obtained from daily values of the E-OBS gridded dataset (Cornes et al., 2018) with a resolution of 0.1° in longitude and latitude for the period1980–2017. This period was set for all the analyses in this study. These series were also utilised to compute the SPEI in the MLSHD. For the WTs computation, daily values of SLP were utilised from the ERA-Interim reanalysis datasets (Dee et al., 2011) with a resolution of 1° for the region between 25°N–70°N and 45°E–45°W, which is observed at Figure 1. The eastwards and northwards vertically integrated moisture flux from ERA-Interim was utilised to compute the Vertical Integral Moisture Flux (VIMF) anomalies and its divergence anomalies. Monthly values of runoff with a resolution of ~4-km monthly were freely downloaded from portal TerraClimate (Abatzoglou et al., 2018), available at http://www.climatologylab.org/terraclimate.html. TerraClimate uses climatically aided interpolation, combining high-spatial resolution climatological normals from the WorldClim dataset, with coarser spatial resolution, but time-varying data from CRU Ts4.0 and the Japanese 55-year Reanalysis (JRA55).

To identify the influence of short and large-scale modes of climate variability on the hidroclimate of the study region various datasets of teleconnection patterns are used. These are, the bivariate ENSO time series (BEST) (Smith and Sardeshmukh, 2000), (available at https://www.esrl.noaa.gov/psd/people/cathy.smith/best/) Western Mediterranean Oscillation (WeMO) (available at https://crudata.uea.ac.uk/cru/data/moi/), the North Atlantic Oscilation (NAO), Arctic Oscilation (AO), East Atlantic (EA), Scandinavia pattern (SCAND) (https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml). The BEST index time series is based on the combination of the atmospheric component of the ENSO phenomenon (the Southern Oscillation Index or "SOI") and an oceanic component (average Nino 3.4 Sea Surface temperature). WeMO index is based in the difference between the standardized atmospheric pressure recorded at Padua (45.40◦N, 11.48◦E) in northern Italy, and San Fernando, Cádiz (36.28◦N, 6.12◦W) in Southwestern Spain. To obtain the rest of Northern Hemisphere teleconnection indices utilised in the study the Climate Prediction Center (CPC) utilise the Rotated Principal Component Analysis (RPCA) method used by Barnston and Livezey (1987), but utilizing monthly mean standardized 500-mb height anomalies obtained from the NCEP/NCAR Reanalysis (CDAS) in the analysis region 20°N-90°N. This procedure isolates the primary teleconnection patterns for all months and obtain the index time series.

2.2 Drought identification: The Standardised Precipitation – Evapotranspiration Index

Drought definition makes difficult to conceive a universal drought index. Therefore, there are many indices and different criteria to identify and investigate different types of droughts (Svodoba and Fuchs, 2016). However, it is basically caused by an imbalance between water supply and demand. Considering this criteria, the Standardised Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) was chosen to identify dry conditions in the MLSHD during the period 1980-2017. This index is based on the same methodology of the Standardised Precipitation Index (SPI) (Mckee et al., 1993). However, as an advantage , over common precipitation based drought indices (e.g. the SPI) it considers the effects of temperature through the reference evapotranspiration (Eto) in the monthly climatic water balance (*D*) represented in equation 1. The precipitation (accumulated over a period of time) in the SPEI stands for the water availability, while ETo stands for the atmospheric water demand. Therefore, the SPEI combines the changes the atmospheric evaporative demand with the multiscalar nature of the SPI (Beguería et al., 2014), which allows the assessment of the response of different ecological, hydrological and agricultural systems to drought (Vicente-Serrano et al., 2012). In consequence, it has been applied to a large variety of ecosystems ~~widely utilised~~ across the world for identifying dry and wet conditions, and evaluating drought recurrence. It was also chosen for this study because the results of Vicente-Serrano et al. (2014) described how drought severity has increased in the past six decades (1954–2014) in natural, regulated, and highly regulated basins of the IP as a consequence of greater atmospheric evaporative demand resulting from temperature rise.

$$D = (P - Eto) \quad (1)$$

Eto is a climatic parameter that expresses the evaporating power of the atmosphere at a specific location and time of the year (Allen et al., 1998). In the absence of meteorological data required for applying the Penman-Monteith equation, which is recommended by the Food and Agriculture Organization (FAO) of the United Nations in the FAO Bulletin 56 (Allen et al., 1998), we used the method proposed by Hargreaves and Samani (1985) based on temperature data to estimate the Eto according to Equation 2:

$$Eto = 0.408 * Ch * Ra * \left(\sqrt{Tx - Tn}\right) + (Tm + 17.8) \quad (2)$$

where Ch = 0.0023; Ra is the extraterrestrial radiation (derived from the latitude and the month of the year), and Tx, Tn and Tm the maximum, minimum and mean temperature respectively. By this method we do not consider relative humidity and wind speed are also important factors to determine the vapour density above the soil surface and the aerodynamic resistance for vapor transport, permitting more realistic *Eto* values and consequently drought assessment (Bittelli et al., 2008; Vicente-Serrano et al., 2010; WMO, 2012; Davarzani et al., 2014). However, even though the Penman-Monteith offers a more accurate estimation of reference Eto than the Hargreaves formula (López-Moreno et al., 2009; Tomas-Burguera et al., 2017), results of Vicente-Serrano et al., 2014 showed that Eto in Spain estimated by the Hagreaves-Samani method for the period 1961 – 2011, had the closest agreement with the Eto obtained by the Peaman Monthie method in terms of temporal evolution and magnitude respect other eleven methods. These authors also found high correlations between Eto obtained by both methods in the northwest IP.

The resultant *D* in equation 1 were aggregated at different time scales, following the same procedure as the SPI. According to Vicente-Serrano et al., (2010), Beguería et al., 2014 and Vicente-Serrano and Beguería, 2016, for calculation of the SPEI at different time scales the most suitable statistical distribution to model the *D* series is the log-logistic distribution, is given by equation 3.

$$F(D) = [1 + (\frac{\alpha}{D-\gamma})^{\beta}]^{-1} \quad (3)$$

where α, β, and γ represent the scale, shape, and location parameters that are estimated from the sample *D*. Finally, the SPEI is obtained as the standardized values of *F(D)*. For the calculation of the SPEI the R package available at: http://cran.r-project.org/web/packages/SPEI is utilised. It includes all the recommendations proposed by Beguería et al., (2014).

We avoid considering that any precipitation below the mean constitutes a drought. Therefore, the classification of drought categories according to SPI values proposed by Agnew (2000) (Table 1) was utilised in this study. Other authors have also employed this classification for investigating drought in the IP (e.g. Vicente-Serrano et al., 2006; Páscoa et al., 2017). This classification despite to be pre-established is built by probability classes rather than magnitudes of the SPI, and is therefore suggested as a more rational approach, with a most noticeable effect at the demarcation of mild and moderate droughts (Agnew, 2000). A drought episode occurs every time the SPEI1 is continuously negative and reaches the value of −0.84 or less. The onset of an episode is the month in which the episode begins, the peak is the month in which the episodes reach the highest negative value of SPEI1 and the end is the last month that SPEI1 is negative. The threshold of -0.84 corresponds to 5% probabilities, whereby drought is only expected 2 years in 10, which reduce the incidence of mild meteorological droughts. The duration is computed as the sum of all months from the onset with negative values, and the severity is calculated as the sum of all SPEI values (in absolute values) during the episode.

Table 1. Standardised Precipitation-Evapotranspiration Index (SPEI) classification according to Agnew (2000).

SPEI	Probability	Category
> 1.65	0.05	Extremely humid
> 1.28	0.10	Severely humid
> 0.84	0.20	Moderately humid
> -0.84 and < 0.84	0.60	Normal
< -0.84	0.20	Moderately dry
< -1.28	0.10	Severely dry
< -1.65	0.05	Extremely dry

To identify the principal patterns of drought variability in the MLSHD, an Empirical Orthogonal Functions (EOF) analysis (Preisendorfer 1988; von Storch 1995) was utilised. The EOF analysis is not based on physical principles, however, the technique aims to decomposes observed datasets into two components that captures most of the observed variance in space (eigenvalues) and time (eigenvectors), making easier to study the principal modes of variability of the SPEI1 time series for every grid point of the MLSHD. The percentage of the total variance explained by each eigenvector is be able to explain most of the variance exhibited by the drought. This method has been extensively used to investigated droughts at global (e.g Dai, 2011) and regional (Wang et al., 2017, 2019) scale.

Trend analysis was perfomed using the the Mann-Kendall Test (Mann, 1945; Kendall, 1975) of Prewhitened Time Series Data in Presence of Serial Correlation using the von Storch (1995) approach. This approach ensures to avoid possible autocorrelation of the series due to the strong seasonality of the input variables to calculate the SPEI. This method is often used to analyze the trend change of hydro-meteorological time series such as precipitation, runoff , temperature, drought index, etc.

2.2 The Standardised Streamflow Index

The Standardised Streamflow Index (SSI) (Vicente-Serrano et al., 2012) was used for assessing the possible impact of the propagation of dry and wet conditions accumulated from several temporal scales through the hydrological cycle over the

~~streamflow of the Miño and Limia rivers. According to these authors, one advantage of the SSI is that it is measured in the same units that are used for other climatological drought indices, such as the SPI and SPEI, thereby allowing comparisons between hydrological and climatological droughts.~~

2.3 The Standardise Runoff Index (SRI)

The Standardise Runoff Index (SRI) ~~SRI~~ is ~~utilised~~ applied to assess the time evolution of hydrological drought in the MLSHD. To computed this index ~~is utilised~~ the same approach employed by McKee et al. (1993) for the SPI is here used. According to these authors the procedure can be applied to other variables relevant to drought, e.g., streamflow or reservoir contents. Thus, the Gamma distribution ~~was utilised~~ is used for fitting monthly runoff data for accumulation periods up to 24 months.

2.4~~3~~ Weather type classification methodology ~~Weather type computation~~

Synoptic systems are linked to the dominant climate in any region of the planet. These systems represent the general circulation of the atmosphere through different configurations of variables. For this reason an objective classification scheme based on the methodology adopted by Trigo and DaCamara (2000) from the Jenkinson and Collison (1977) and Jones et al. (1993) circulation schemes is applied to obtain the dominant circulation weather types (WTs) over the IP. The method uses daily MSLP values obtained from the ERA-Interim reanalysis for the period 1980-2017 on 16 different points over the IP (dots shown in Figure 1) in order to build a set of indices associated with the direction and vorticity of the geostrophic flow, namely total shear vorticity (Z), southerly shear vorticity (ZS), westerly shear vorticity (ZW), total flow (F), southerly flow (SF), and westerly flow (WF). The area used to compute WTs is the same as used by Ramos et al. (2014) and it comprises in longitude from 20ºW to 10ºE and in latitude from 30 to 50ºN. The regional indices are computed as follows (Equations 3 to 8) according to the procedure described in Ramos et al. (2014) and Trigo and DaCamara (2000) taking into account the 16 points named as p_x (x going from 1 to 16 according to the number of the point represented in Figure 1).

$$SF = 1.305[0.25(p_5 + 2 \times p_9 + p_{13}) - 0.25(p_4 + 2 \times p_8 + p_{12})] \quad (3)$$

$$WF = [0.5(p_{12} + p_{13}) - 0.5(p_4 + p_5)] \quad (4)$$

$$ZS = 0.85 \times [0.25(p_6 + 2 \times p_{10} + p_{14}) - 0.25(p_5 + 2 \times p_9 + p_{13}) - 0.25 \times (p_4 + 2 \times p_8 + p_{12}) + 0.25(p_3 + 2 \times p_7 + p_{11})] \quad (5)$$

$$ZW = 1.12 \times [0.5 \times (p_{15} + p_{16}) - 0.5 \times (p_8 + p_9)] - 0.91 \times [0.5 \times (p_8 + p_9) - 0.5 \times (p_1 + p_2)] \quad (6)$$

$$F = (SF^2 + WF^2)^{1/2} \quad (7)$$

$$Z = ZS + ZW \quad (8)$$

Following this approach, 26 WTs are initially identified (10 pure, 8 anticyclonic hybrids and 8 cyclonic hybrids). Pure directional WTs (Northeastern (NE), Eastern (E), Southeastern (SE), Northwestern (NW), Western (W), Southwestern (SW), North (N), South (S)) are those showing |Z| < F with the direction defined by $\tan^{-1}$ (WF/SF) (180° added if WF is positive). If |Z| > 2F then the circulation would be considered cyclonic (C) (if Z > 0) or anticyclonic (A) (if Z < 0). As not all the circulation patterns can be associated with a pure (directional/cyclonic/anticyclonic) type, 16 hybrid circulations are defined as a combination of A and C circulation with directional WTs. In this case F < |Z| < 2F. As in other previous studies we distributed the few cases (<2%) with unclassified situations among the 26 classes. The unclassified situations occur when the module of the total shear vorticity (Z) is less than the standard deviation of Z/2 and simultaneously the total flow (F) is less than the square root of the sum of squared westerly and southerly flows. Following Trigo and DaCamara (2000) in the frequency computation, the 26 WTs are regrouped in the 10 "pure" ones – thus each of the 16 hybrid types count equally as a half occurrence to each of their corresponding pure directional and cyclonic/anticyclonic types (e.g. one case of CNW is included as 0.5 in C and 0.5 in NW).

The methodology here described is able to daily identify the weather pattern (from the WT listed above) present over the area of study. From this daily information and in order to study the WTs influence on monthly SPEI series, the monthly frequency of occurrence for every pure WT is computed for the period 1980-2017.

2.54 Wavelet coherence analysis

Wavelet coherence (WC) analysis is used to identify which frequency bands within two time series are co-varying (Torrence and Webster, 1999). This definition is similar to that of a traditional cross correlation, and the WC can be considered as a localised correlation coefficient in time-frequency space (Torrence and Compo, 1998; Grinsted et al., 2004). For this assessment, the SPEI at the temporal scale of 1 month (SPEI1) and six monthly series of teleconnection patterns, namely the BEST, WeMO, NAO, AO, EA, and SCAND were utilised by initially applying Equation 102, as follows:

$$R_n^2(S) = \frac{\left|S\left(s^{-1}W_n^{XY}(s)\right)\right|^2}{S\left(s^{-1}\left|W_n^{X}(s)\right|^2\right) * S\left(s^{-1}\left|W_n^{Y}(s)\right|^2\right)} \quad (210)$$

where S is a smoothing operator and XY are the two series. The WC ranges from 0 to 1; if the value is closer to 1, then the correlation between the two series is higher. The cross-wavelet coherence analysis was performed ~~at 95 significance level~~ using the biwavelet R package (https://CRAN.R-project.org/package=biwavelet) with the wtc wavelet function and at 95 significance level with 1000 Monte Carlo randomizations. An advantage of WC over the classical cross-correlation analysis is that the phase relationship is calculated such that the degree to which two time series are positively or negatively related can be measured as both a function of time and period (Shulte et al., 2016).

3. Results and discussion

3.12 Drought conditions

The northwest IP is and a homogeneous region in terms of the total P variance over the IP (Rodriguez-Puebla et al., 1998; Muñoz-Díaz and Rodrigo, 2005), and consequently, the influence of droughts (Russo et al., 2015). Such regions can be delineated using precipitation datasets and conventional approaches such as principal components clustering procedures, indices, etc. (Mallants and Feyen, 1990; Awan et al., 2015; Bharath, and Srinivas, 2015). As our aim is to investigate meteorological droughts in the MLSHD, it was primarly performed an EOF analysis utilising the SPEI at one month temporal scale (SPEI1). At this time scale, the SPEI is the best indicator of the monthly water balance of the region. The results in Figure 3 reveal the spatial characteristics of the first three leading EOF modes, which explain 97.8% of the total spatial variability of the SPEI1 in the MLSHD. Because the spatial patterns of the rest EOFs explain very low percentages are not shown. In particular, the EOF1 (93%) is characterised by all negative values, which indicate that occurrence of dry or wet conditions in the MLSHD manifest themselves homogeneously throughout its entire length. The spatial coefficients of EOF2 separate the eastern high lands from the north and west of the MLSHD, while the EOF3 reveal the north-south spatial differences. However, both explain a just a 2.6% and 2.2% respectively. According to these findigs the MLSHD can be considered an homogeneus hidroclimate region.

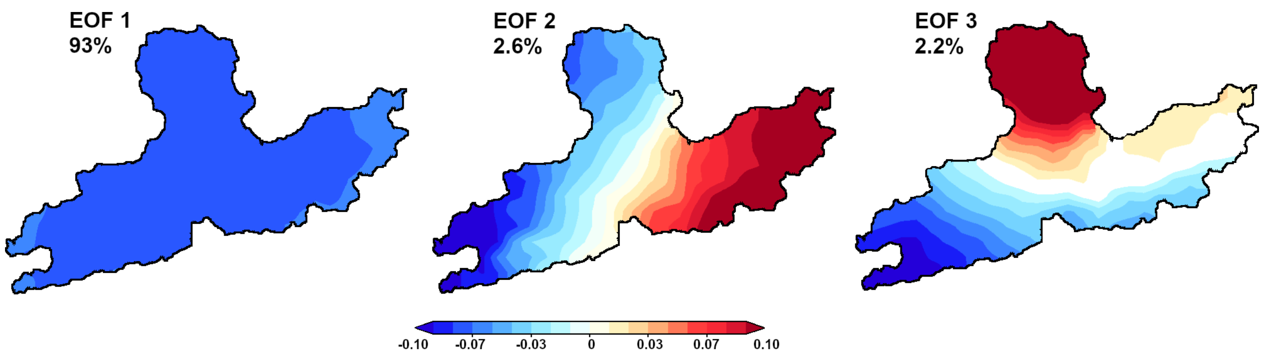


Figure 3. First three leading EOF modes of the SPEI1 series for the period 1980 – 2017.

Figure 3a shows the temporal evolution of the SPEI1 computed for the MLSHD during 1980–2017. The high variability of the series made it difficult to identify the most extensive (in terms of duration) and intense (in term of severity) periods affected by dry or wet conditions. However, this regions is and a homogeneous region in terms of the total P variance over the IP (Rodriguez-Puebla et al., 1998) and consequently the influence of droughts (Russo et al., 2015). However, dry conditions prevailed in periods such as 1989–1992, 2004–2005, and 2015–2017, which was is in agreement with results obtained by other authors for the NWIP north western IP through different indices, who also reported them for several time scales (e.g. Garcia-Herrera, 2007; Andrade and Pereira, 2015; Spinioni et al., 2016; Ojeda et al., 2019). At this time scale, the negative values of the SPEI are primarily related to meteorological drought, which is unable to diagnose the agricultural, hydrological, and socioeconomic types of drought. However, ~~it is~~meteorological droughts ~~an indicator that~~ can be perceived as the initial cause of further types of droughts, ~~because~~ since these ~~types of drought~~ are triggered by the deficit of P combined with high temperatures and significant Eto. The identification of meteorological drought episodes affecting the IP has been a topic of research during the last ~~few~~ years (e.g. Lana et al., 2006; Lorenzo-La Cruz et al., 2013; González-Hidalgo et al., 2018). As a ~~A~~ drought episode is considered to occurs every time the SPEI1 is continuously negative and reaches the value of −0.84 or less; ~~this thresholds~~this threshold is identified by the black dashed line in Figure 3. ~~The threshold of -0.84 (dashed line in Figure 3) identifies the moments in which the criterion is met for a drought episode occurring in the MLSHD.~~ The onset ~~(month in which the episode begin)~~, end ~~termination~~ ~~(last month of the episode)~~, and length ~~(total number months)~~ of these episodes are shown in Figure 3b. According to the visual analysis, the ~~length of these episodes~~frequency of long episodes increased after 2003. ~~A trend analysis~~.

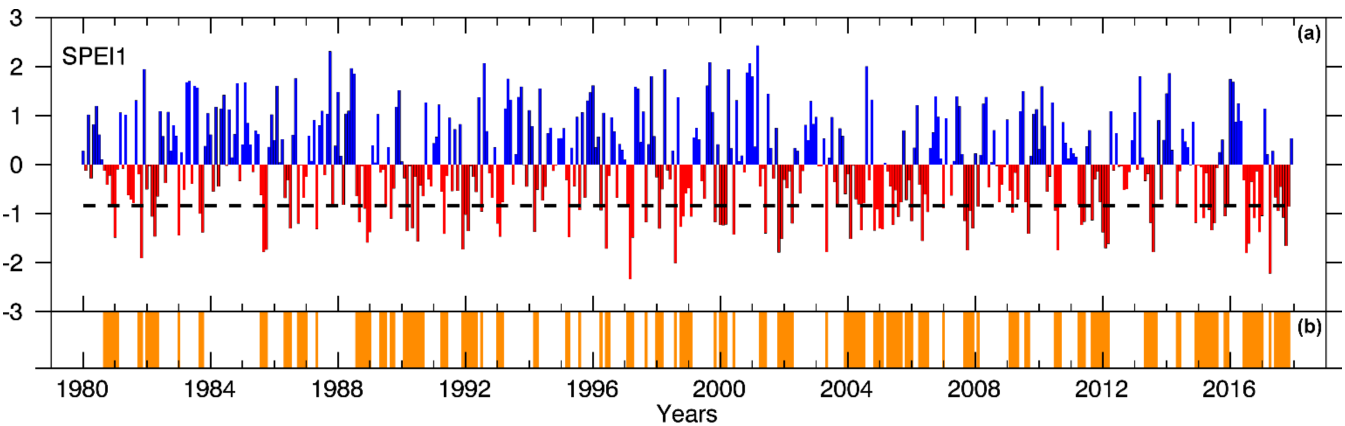


Figure 3. Wet (blue bars) and dry (red bars) conditions according to the Standardised Precipitation-Evapotranspiration Index at the 1 month temporal scale (SPEI1) (a) and dry episodes (orange bars) (b) during 1980–2017.

Results of Sáez de Cámara et al. (2015) note noteworthy tendency toward less wet days with a decreasing trend in the average precipitation per wet day for western and central north IP. A tendency analysis for the period of study reveals a small trend in the series of the SPEI1 (statistically significant at $p < 0.05$) (Table 2). Vicente-Serrano et al. (2011) also found that mean duration of drought episodes in the north western IP increased by approximately 1 month in the last 30 years of 1930–2006 (difference not statistically significant) as a consequence of the increase in potential evapotranspiration. For the number of drought episodes, their duration, and severity, the trends are not statistically significant.

~~A trend~~tendency analysis ~~for the period 1980–2017 revealed a small statistically significant ($p < 0.05$)~~ ~~trend of the SPEI1; calculated using the Wald~~ Mann-Kendall ~~test with t-distribution of the test statistic) trend in the series of the SPEI1~~ ~~during~~

the period of 1980–2017 (Table 2). Vicente-Serrano et al. (2011) found that mean duration of drought episodes in the north western IP increased by approximately 1 month in the last 30 years of 1930–2006 (difference not statistically significant) as a consequence of the increase in potential evapotranspiration, while a most recent study revealed that for the period 1950–2010, the same region was affected by a decrease in the number of consecutive wet days (Casanueva et al., 2014). Vicente-Serrano et al. (2011) found that the mean duration of drought episodes in the north western NWIP increased by approximately 1 month in the last 30 years of 1930–2006 as a consequence of the increase in PET (differences are not statistically significant). However, for a longer period (1950–2010), the north western NWIP was affected by a decrease in the number of consecutive wet days (Casanueva et al., 2014). According to our results, none of these results can be corroborated form our study as trends detected in both severity and duration are not statistically signifcant the duration of the drought events over the MLSHD increased at a rate of 0.02 mo/y in the last 37 y. For the same period, the severity increased at a rate of 0.03 mo/y and the number of episodes was 0.01/y. However, none of these results were statistically significant. The trends were analysed by taking into account the mean value for each of the events starting in a specific year for the period of 1980–2017.

Table 2. Trend analysis of the 1 month Standardised Precipitation-Evapotranspiration Index (SPEI1) series and the duration, severity, and number of events per year. The slope represents the trend, and significant trends are marked with an asterisk. Significance is calculated using the Wald test with t-distribution of the test statistic, and the trend is considered significant when $p < 0.05$.

	Slope	**Units**	***p* value**
SPEI1	-0.00079*	$year^{-1}$	0.0409
Number of Episodes	0.01	episodes/year	0.260
Duration	0.02	month/year	0.520
Severity	0.03	$year^{-1}$	0.260

Extreme Ddrought events can disrupt food production systems and can thus be a significant natural trigger for famine (Wilhite, 2000) and for the MLSHD can directly affect the hydroelectric production. The top 10 driest episodes in the period under study according to their severity are shown in Table 3. This selection was createdmade to develop further analysis based on extreme meteorological dry conditions. In this table are also represented the the onset, and the terminationpeak, end, peak value and duration and severity of each episode. represent the first and last month of the episode and the peak is the lower SPEI1 values reached in the episode.

Table 3. The 10 most severe drought episodes that affected the Miño-Limia-Sil Hydrographic Demarcation from 1980 to 2017. The drought episodes are organised based on their severity from high to low, and the onset (first episode month), termination (last episode month), peak (lower SPEI1 value during the episode), and duration are shown.

Episode	**Onset**	**Peak**	**Termination End**	**Peak value**	**Duration**	**Severity**
E1	Jun/2016		Jan/2017	-1.80	8	7.7
E2	Sep/2011		Mar/2012	-1.70	7	7.0

E3	Dec/2014	Aug/2015	-1.34	9	6.1
E4	Dec/2003	Jul/2004	-1.52	8	6.0
E5	Feb/1990	Sep/1990	-1.56	8	5.8
E6	Aug/1988	Jan/1989	-1.60	6	5.7
E7	Jun/2017	Nov/2017	-1.66	6	5.6
E8	Nov/2001	Apr/2002	-1.80	6	5.4
E9	Sep/2007	Dec/2007	-1.74	4	5.1
E10	Dec/1991	May/1992	-1.72	6	4.9

The SPEI evaluates dry and wet conditions. However, it is not possible to know the separate behavior of each variable, P or ETo. That is why in the Figure 4 are illustrated the accumulated P during each drought episode (solid lines) listed in table 3, as well as the percentiles 5 (p05), 10 (p10) and 25 (p25) of the accumulated P for the same period of months (disconitued lines), but considering the whole study period (1980 – 2017). The order of the episodes in this figure is determined by the month of the beginning of them. Accumulated P during June and July of the E1 was between the p05 and p10, but later was between p10 and p2. In the E7 the accumulated P was between p10 and p25 from June to August, and afterword, from September to November it was even drier, between p05 and p10. For the rest of the episodes the accumulated P was never above the p25, confirming the precipitation deficit.

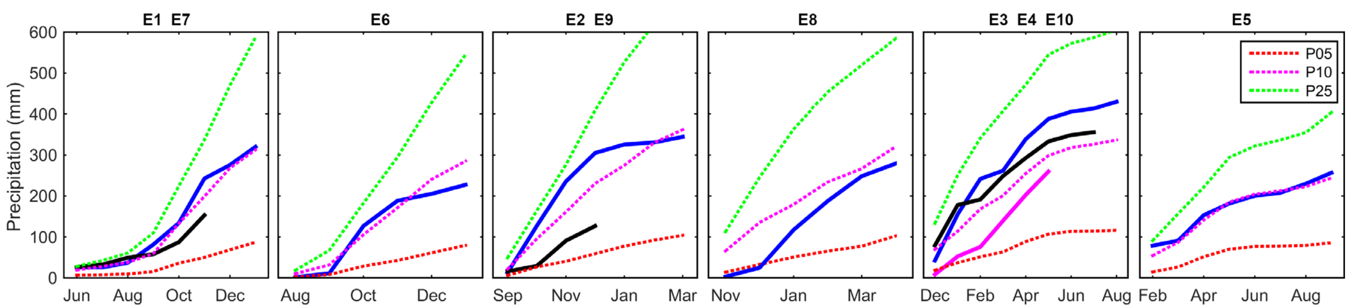


Figure 4. Accumulated P during each drought episode listed in Table 3 (solid lines), and the percentiles 5 (p05), 10 (p10) and 25 (p25) of the accumulated P for the same period of months (disconitued lines), but considering the whole study period (1980 – 2017).

The spatial variability of droughts is a concern for decision making of water resources policy and managenment. In Figure 4 are shown six annual leading modes of EOF, which explain 94% of the total spatial variability of the SPEI1 for those months when the SPEI ≤ -0.84 in the MLSHD (represented in Figure 3b). These represent potential physical modes of drought variability in the MLSHD. The first eigenvector (EOF1) explains 61%. This pattern is very homogeneus, with close negative values in all the MLSHD, indicating a great spatial similarity of the main drought pattern and the predominant influence of large-scale factors. Althoug, a visual analysis of EOF1 also shows a small logitidinall difference with more intense negative values on the eastern part of the MLSHD (farther from the coast). As expected, the following characteristics of EOFs represented in Figgure 4 show major spatial differences. The EOF2 explain a 17% of the total drought variability. In it, the major differences are observed between the eastern part of the region, where prevail positive values, and the rest of the territory with negative values, indicating different spatial drought magnitudes. In Figure 1 can be observed that the eastern of the MLSHD is characterised by major elevation. Theefore, spatial drought variability in this pattern can be explained by orographic differenes. The EOF2 explain the 9% of spatial drought characteristics, determined by a gradient from positive to negative values from the coastal zone to the northeast. The remaining EOFs show a greater variability and lower percentages of explained variance.

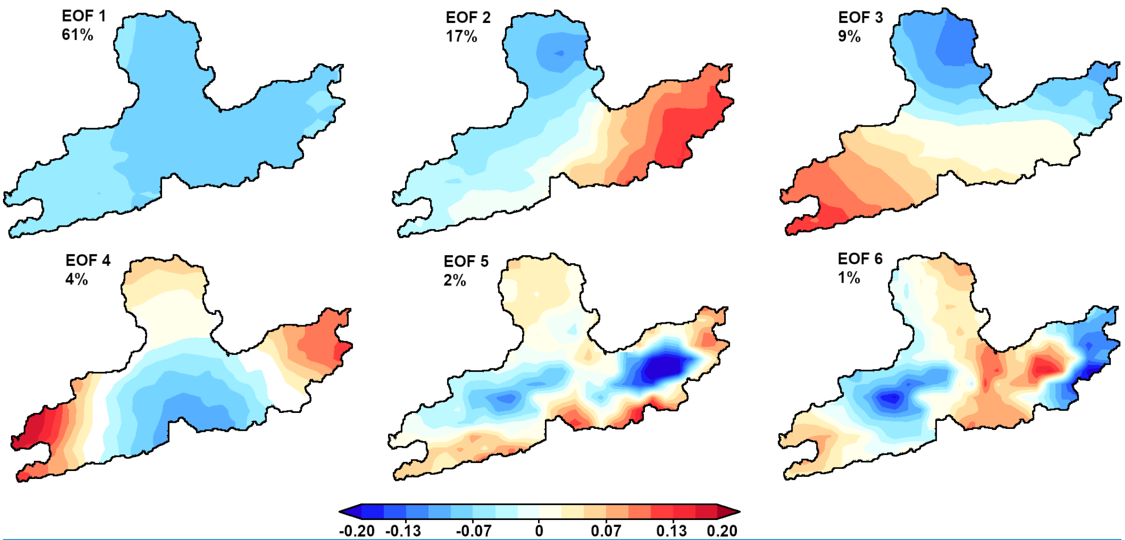


Figure 4. Six leading modes of EOF for the SPEI1values ≤ -0.84.

3.2~~3~~ Relationship between the circulation weather type classification and drought conditions

The MSLP fields and anomalies for the 10 pure WTs responsible for the major variability in atmospheric circulation over the IP are shown in Figure 4. These anomaly composites are obtained after removing the respective grand means computed for the period 1981-2010. These patterns (obtained using the same methodology) have previously been used to investigate the relationships between the atmospheric circulation and precipitation variability (e.g. Cortesi et al., 2014; Ramos et al., 2014) or drought conditions in the IP (e.g. Russo et al., 2015). Here we aim to determine the association of large-scale atmospheric circulation over the IP with drought conditions that affected the MLSHD during 1980-2017. The reddish (blueish) isolines in Figure 4 identify the higher (lower) values in the MSLP absolute fields and the positive (negative) values of MSLP anomalies. The NE configuration (Figure 4a) is characterised by a transition from a strong high-pressure region over the eastern Atlantic Ocean extending to the northwestern Iberia and the MLSHD, and lower pressures over Africa. The anomaly field (Figure 4b) shows that this high pressure centre is displaced towards northeast, to the west of the UK. In the E and SE configurations (Figure 4a), the high-pressure system is shifted northwards and centred over the Cantabrian Sea and the Celtic Sea in the E circulation, while in the SE circulation it is centred over France and the southern UK. The anomaly fields (E and SE; Figure

4b) show an intensification up to 8-10 hPa of these high pressure systems. In the S pattern, higher pressure values occur over central Europe and lower pressure values (1010 hPa) over the Northeast Atlantic (Figure 4a) which become up to 8-10 hPa lower (Figure 4b). In the SW WT high-pressure values are limited to the most southern areas in the North Atlantic and a well-developed low-pressure system (1000 hPa) is located over Northeast Atlantic (Figure 4a). The anomaly fields show an intensification of these systems to the northwest region of Iberia– up to -20 hPa (Figure 4b). In the W and NW configurations the low-pressure systems are shifted northwards and north-eastwards towards the UK, respectively, while the Azores high establishes (Figure 4a). The corresponding anomaly fields illustrate the intensification of these low-pressure systems (Figure 4b). The high-pressure systems identified in the case of the NW configuration are more intense in the N WT (Figure 4a) and the anomaly shows a northward displacement of these systems, covering all the Atlantic regions, while low-pressure systems are more developed over the Gulf of Lion, in the Mediterranean (Figure 4b). Finally, the C WT represents low relative pressures centred over the western IP (Figure 4a) which intensify, while positive anomalies develop to the northern regions, west of the UK (Figure 4b); the opposite occurs for the A configuration which represents an intense Azores high, extended towards Europe (Figure 4a). The anomaly shows that under these conditions the high-pressure systems intensify over the IP and southwest Europe (Figure 4b).

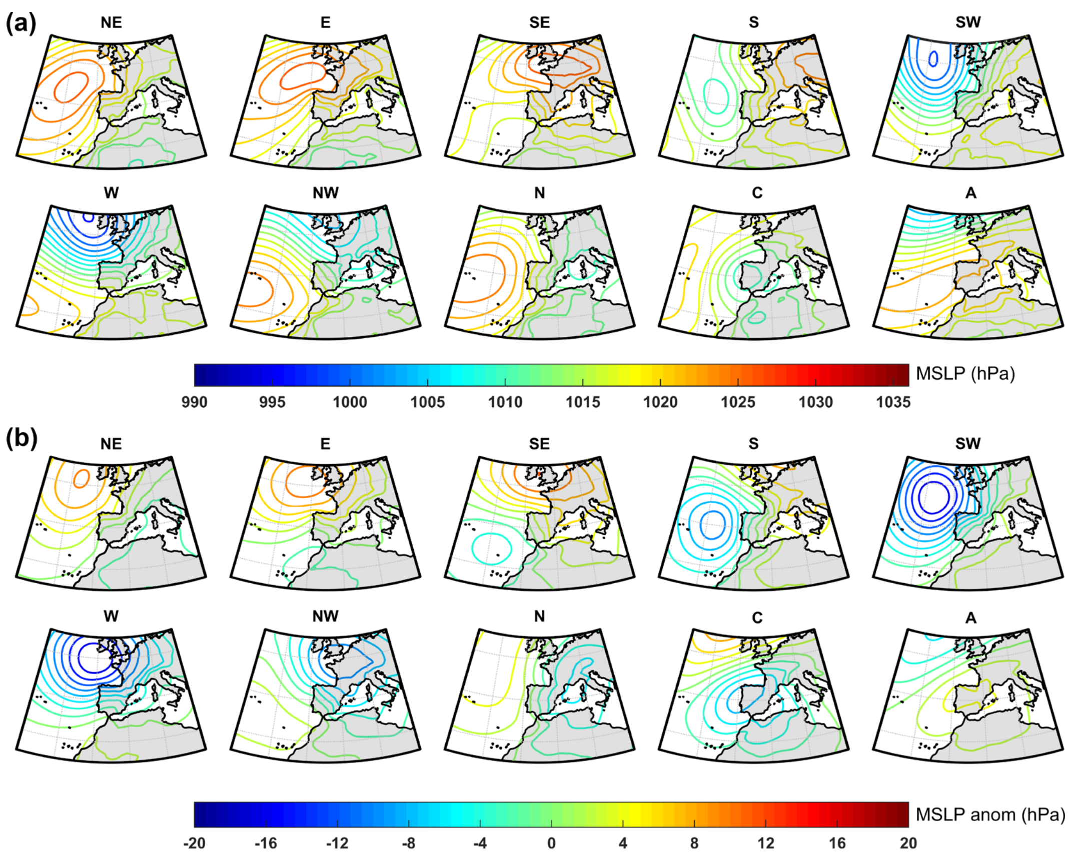


Figure 54. Mean sea level pressure (MSLP) fields (a) and anomaly (b) fields' configuration of the 10 pure weather types (WTs) for the period 1980-2017. The contour interval is 2 hPa.~~Mean sea level pressure field configuration of the 10 pure weather types (WTs) for the period 1980–2017. The contour interval is 2 hPa.~~

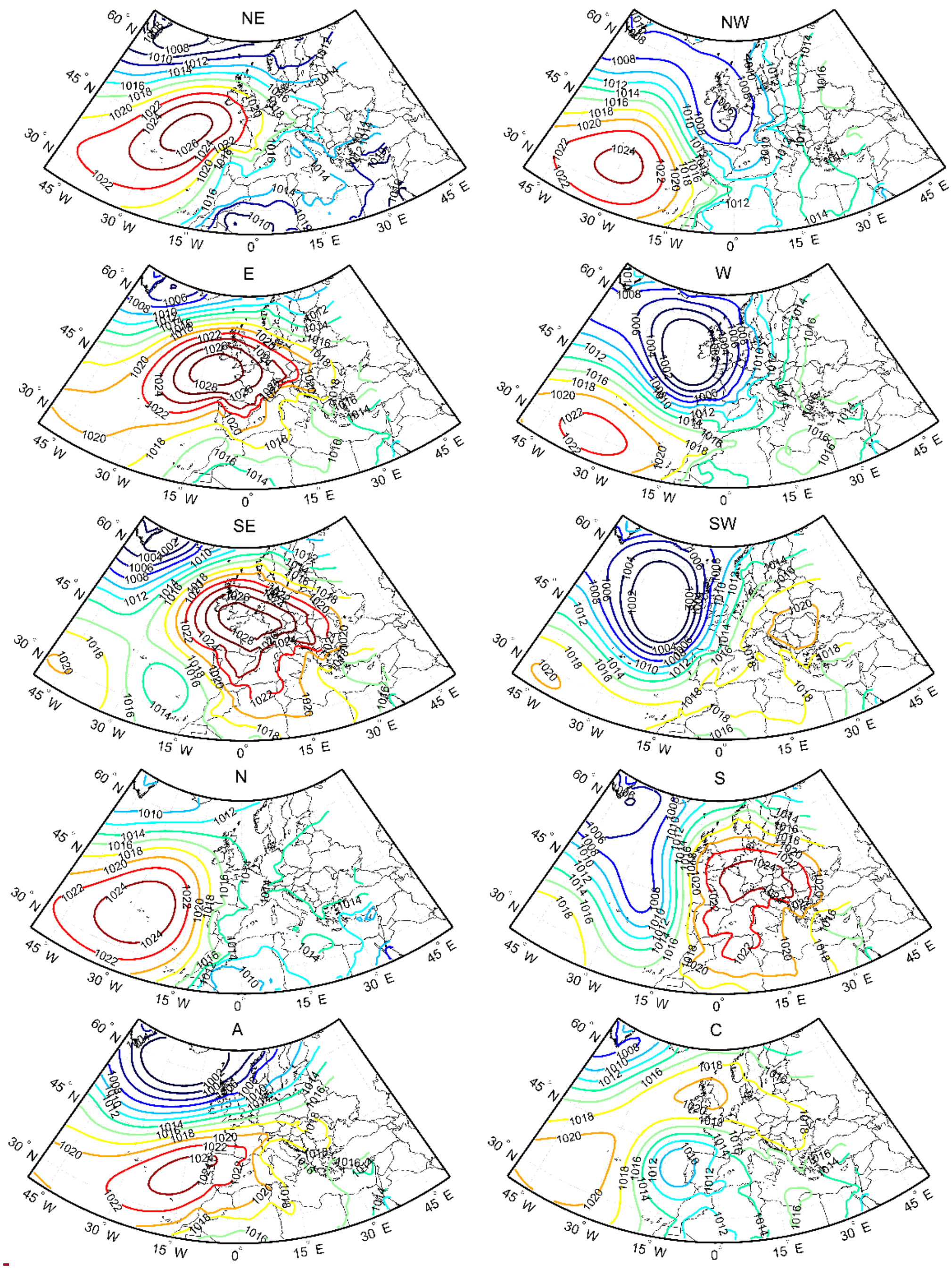


Figure 4. Mean sea level pressure field configuration of the 10 pure weather types (WTs) for the period of 1980–2017. The contour interval is 2 hPa.

The correlations between the monthly percentage values of the occurrence of each of the pure WTs and the SPEI1 time series are shown in Figure 65. WTs and SPEI1 time series were de-trended before correlation computation. In the figure highlight the The significant positive correlations found with the SW, W, and NW WTs are highlighted. The results suggested that an ehnacement of air massesmoisture arriving to the MLSHD from the west from these directions were are responsible for wetter conditions over the MLSHD , which was is in agreement with the results of Russo et al. (2015), but for the whole north western NWIP. Indeed, air masses from the SW, W, NW and C usually associated to inbound baroclinic structures, Atlantic storms and Atmospheric Rivers (Eiras-Barca et al. 2018) carry moisture from the Bay of Biscay (BB) and the Tropical and Subtropical North Atlantic corridor (TSNA) to the MLSHD, both principal sources for precipitation over the Galicia and northern Portugal (Drumond et al., 2011). In addition, tThe C circulation WT appearsed to be mostly positively correlated with SPEI1; however, in generalfor almost all months the correlations were are not statistically significant. The extratropical cyclones and synoptic-scale fronts associated reaching the IP during winter months and early spring normally produce large accumulated rainfall and play an important role on the hydrological cycle in northen Portugal and Galicia (Paredes et al., 2006; Añel et al., 2012; Hénin et al., 2019).

Contrastingly, the atmospheric circulation associated with the frequency of NE, E, and SE WTs arewas negatively correlated with the SPEI1 time series in all months, thereby suggesting that their predominant circulation from these regions predominance f was is directly related to the dry conditions over the target region MLSHD. Negative correlations between the SPEI1 and the A shown in Figure 6 mostly occur during winter months are shown in Figure 6 This also occurred with the between the SPEI1 and the A circulation WTcorrelations; however, these were are lower and not significant during several months. On the contrary, the correlations between SPEI1 and C are mostly positive, but mostly not statistically significant. Finally, as expected, monthly correlations between the atmospheric circulation associated with WTs N and S with the SPEI1 have generally opposite sign values, in addition to being very low and not significant. A trend analysis showed that there is no statistically significant trend in the series of any WT.

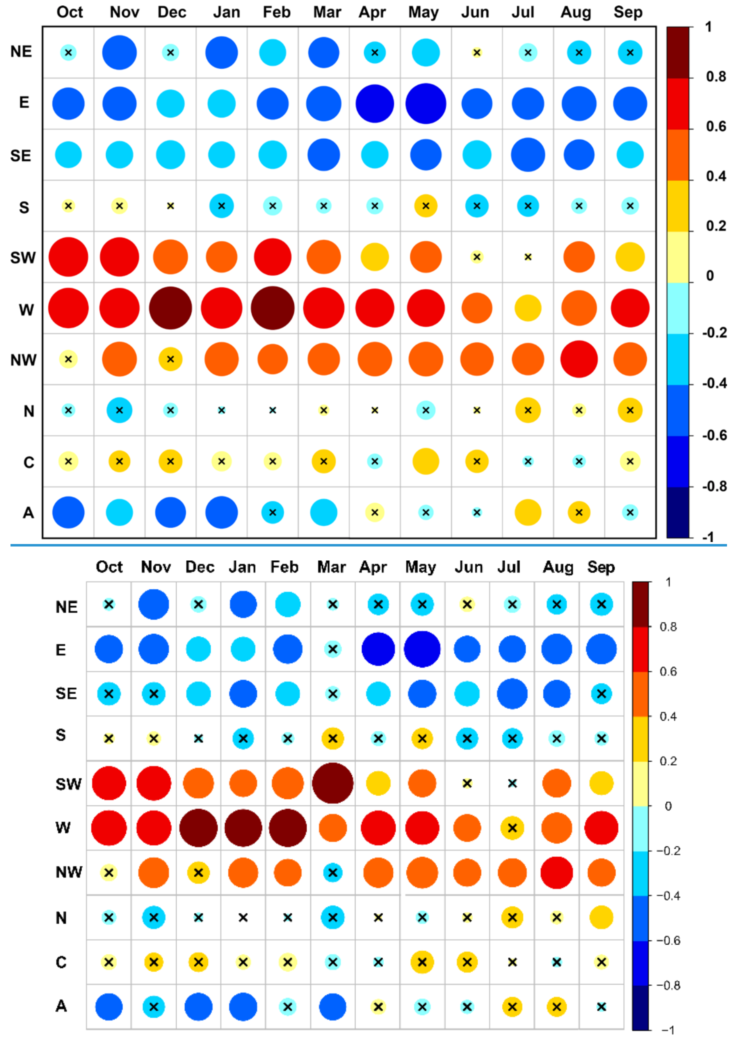
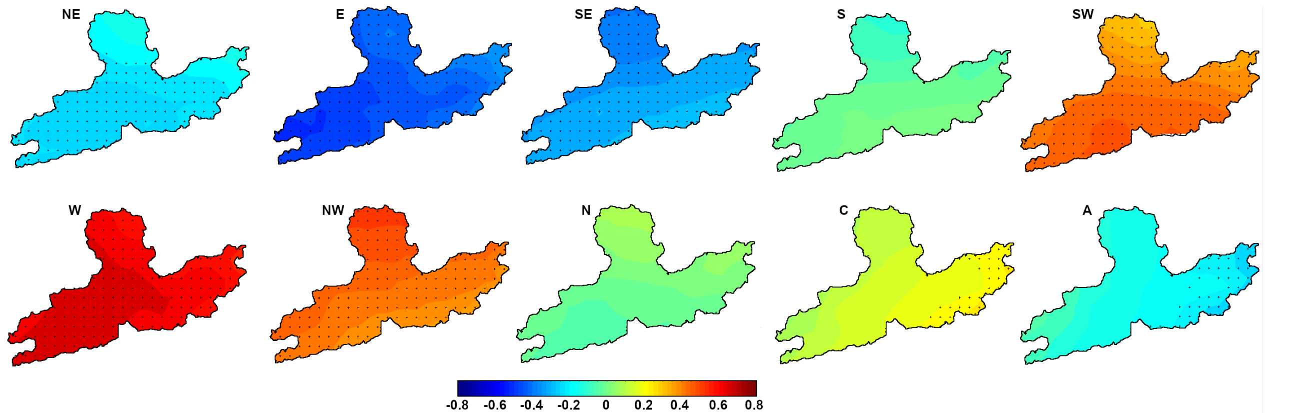


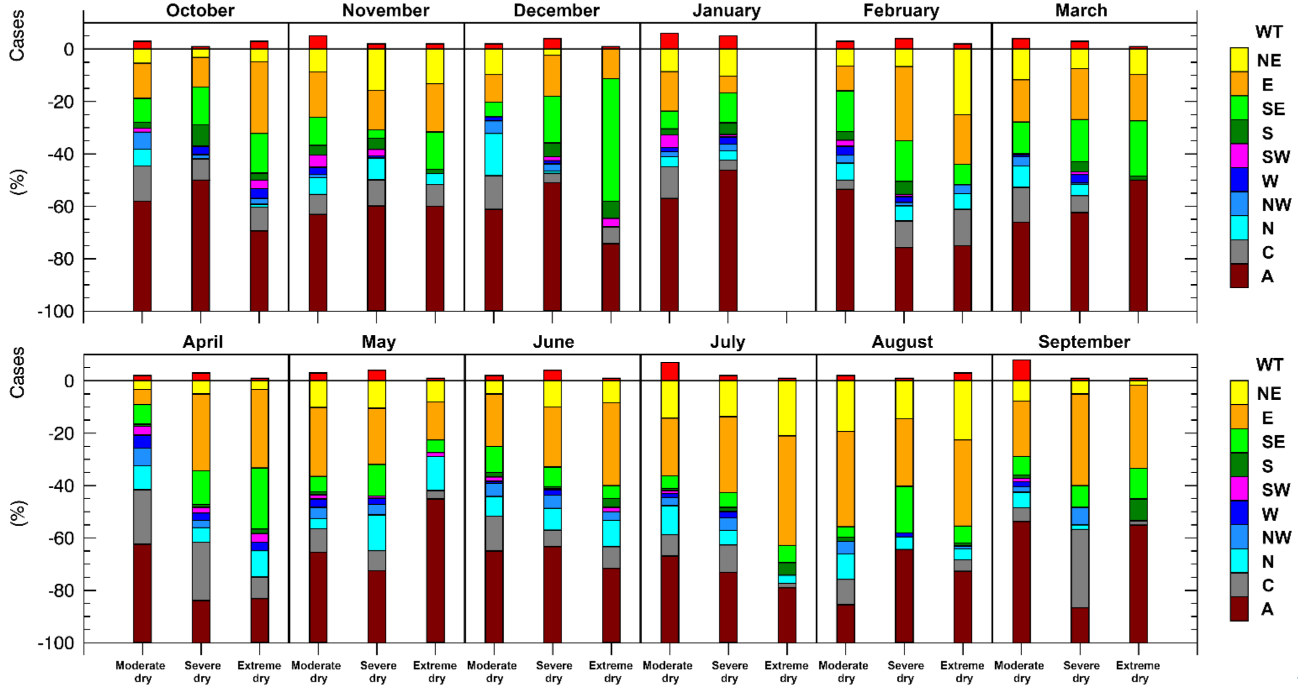
Figure 56. Correlations (statistically significant at $p < 0.05$) between the detrented series of 1 month Standardised Precipitation-Evapotranspiration Index and the monthly percentage of occurrence of each of the pure weather types for 1980–2017. The size for the circles is proportional to the correlation values. The x's inside the circles in the figure represent not statistical significant correlations at $p <$ 0.05.

The spatial pattern of correlations between detrended series fo the SPEI1 and the climatic teleconnections appear in Figure 7. Despited

The observed local variations of the corre-lation coefficient show a west to east coastal decrease of the (negative) correlation, with highest (negative) valuesat the southwestern margins.



In order to understand how distinct WTs might affect drought severity in the MLSHD, Figure 7 shows the monthly frequency (expressed in percentage) of each WT under different drought categories (moderately dry, severely dry, and extremely dry) according to the SPEI classification shown in Table 1. The months of October under moderately dry conditions ~~were~~ are associated with the prevalence of A, E, and C ~~circulation~~ WTs. Octobers affected by severely dry conditions ~~were~~ are associated with a major percentage of A circulation, but for those under extreme drought conditions it seemed that E circulation highly increased with respect to previous drought categories, while there was a slight decrease in the frequency of A circulation. ~~Additionally, the most frequent WT in the~~ For those Novembers affected by moderate, severe, and extreme drought conditions the most frequent WT was the A circulation, which imposes~~d~~ an atmospheric flux from the north. For severely and extremely dry months of December, the frequency of WTs change~~d~~ with respect to those of previous months, and an increase in the percentage of SE circulation ~~was~~ is observed. ~~This WT was characterised by a high-pressure centre located in the north of France and the south of England~~. ~~The months of~~ January months under moderate and severe drought conditions ~~were~~ are characterised by a major percentage of atmospheric conditions governed by the A pattern. When the severity increased in February, the percentage of occurrence of A ~~circulation~~ WT decrease~~d~~, while E ~~circulation~~ prevaile~~d~~ under moderate drought conditions together with NE and A circulation when February was affected by extreme drought conditions. The opposite occurr~~ed~~ in March, when the A WT increased from moderate to extreme drought. April is normally considered the beginning of the dry season; under moderately dry conditions, the predominant WT was A circulation, but under severely and extremely dry conditions, the most frequent WTs were E and SE circulation. In the following months (May to September) affected by different drought categories, the combination of WTs E and A was the most frequent according to the percentage observed in the figure.



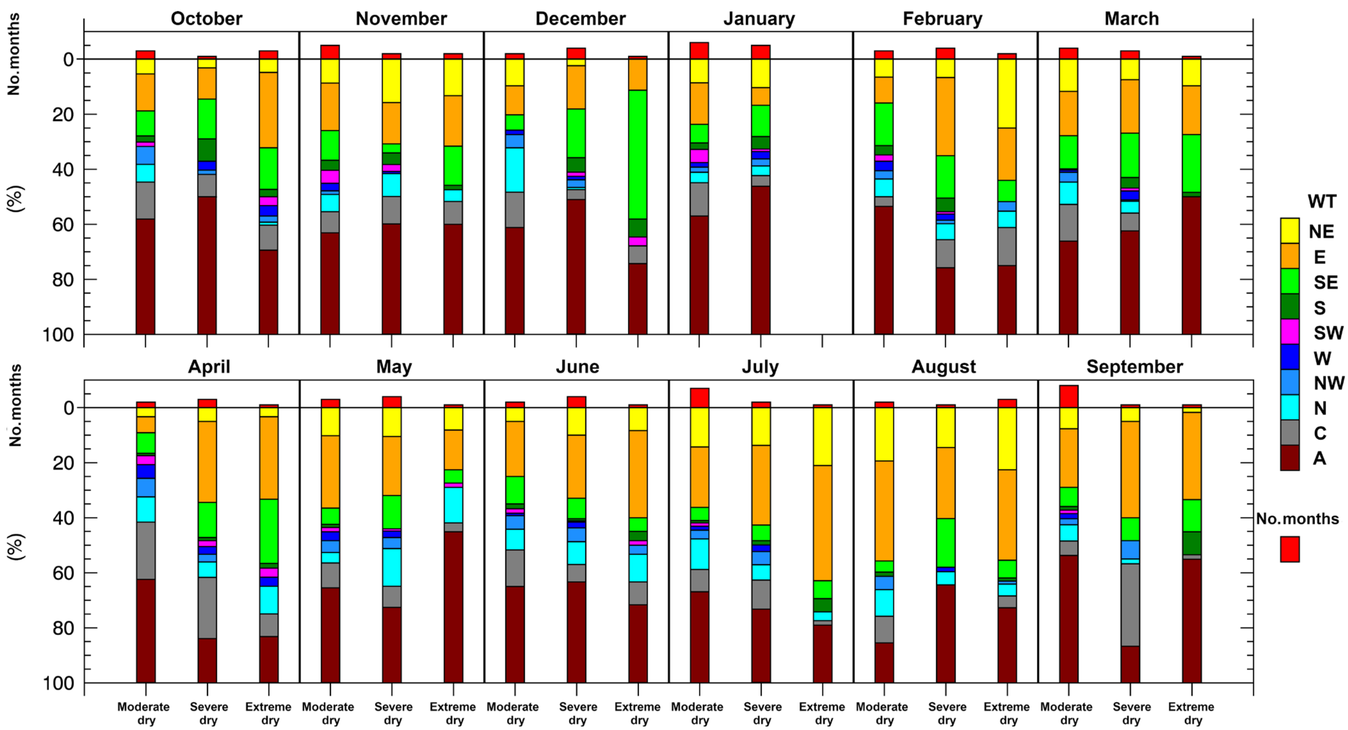


Figure 7. Monthly percentage of occurrence for every WT associated with moderate, severe and extreme dry conditions. The red bars represent the number of times that each month was affected by each drought category. The anomaly of the percentage of occurrence of the 10 most severe events associated with each weather type (WT).

The most severe drought episodes are also investigated. Figure 8 shows the accumulated SPEI1 (red line) during the 10 most severe drought episodes listed in Table 3. The coloured areas in this figure represent the WTs occurred for every day of the episode. In this figure WTs are grouped taking into account the the monthly correlation results presented in Figure 6. A visual analysis allows us to conclude that during the temporal evolution of all episodes the most frequent WTs are the eastern (SE-E-NE) (yellow colour) and A (orange colour). For most of the episodes the eastern circulation seems to be specially related to the drought intensification, being the most common WT during the peak month of each event.

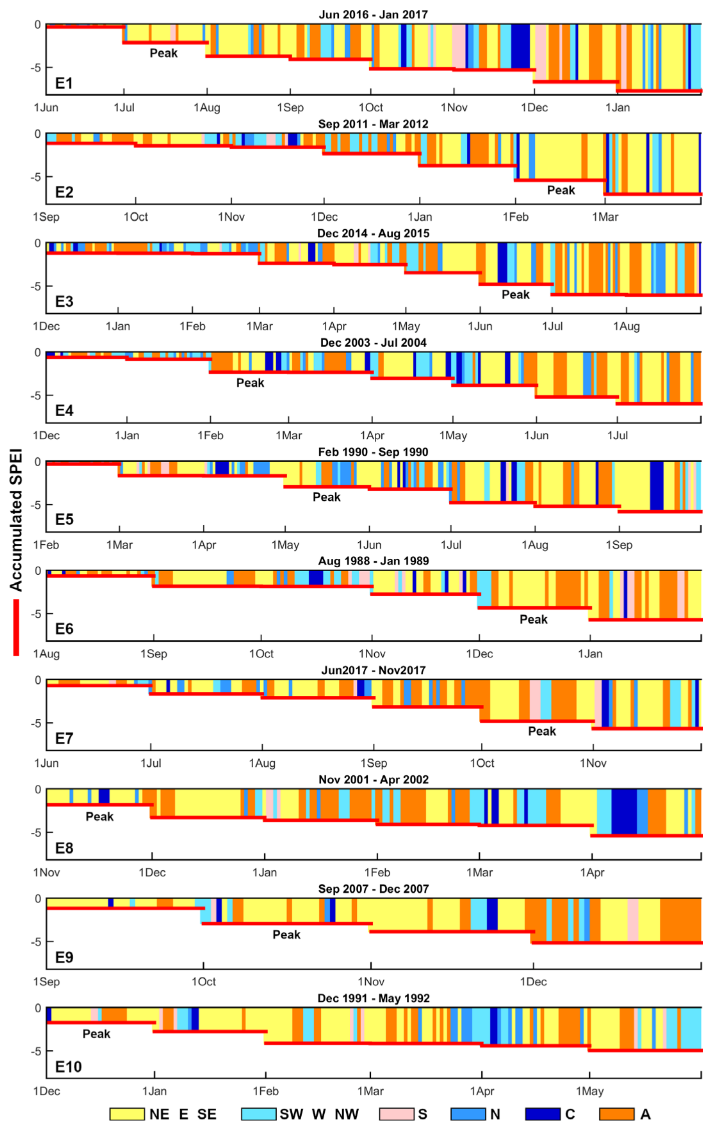


Figure 86. Accumulated SPEI1 (red line) during the 10 most severe drought episodes listed in Table 3, and daily WTs agrupped

The information showed in figure 8 is summarised in Figure 9. This shows the anomaly in the percentage of occurrence for every pure WT presented during the 10 most severe events. ~~-~~The anomaly was calculated for the complete duration of each drought ~~event~~ episode, and referred to the 1980–2017 mean value for the same months. The eastern (NE, E, SE), A and S WTs experiment mostly positive anomalies, in accordance with the results described above. Conversely, in most of the episodes the anomaly of western circulations (NW, W, SW), N and C, decrease. The largest anomalies ~~appeared~~ appear for the W circulation, and ~~showed~~ show reductions of between 2.5% and 5.7%. Similar results ~~were~~ are observed when the total number of severe events ~~was~~were considered (Figure S1).

~~associated with the drought events. C circulation also decreased associated with drought events; however, the reduction was lower.~~

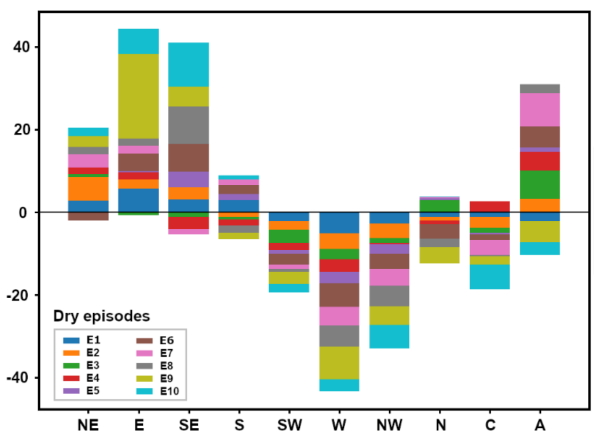


Figure 8~~6~~. The anomaly in the percentage of each weather type associated with the 10 most severe drought episodes showed in Table 3.

According to Drumond et al. (2011), the nature of rainfall variability over the north of Portugal and Galicia is associated with the moisture transport from two dominant moisture sources, namely the Bay of Biscay and the Tropical and Subtropical North Atlantic corridor; the latter extends from the Gulf of Mexico to Africa from 16°N to 40°N. Figure~~s~~ 9~~8~~ ~~and 9~~ show the anomaly of the VIMF and its divergence for the onset, peak, and termination of the drought episodes listed in Table 3. Episode 1 (E1) was the driest, and was ~~characterised~~ associated ~~by~~to anticyclonic circulation of the VIMF located to the southwest of the MLSHD, which moved to the north ~~and~~ imposinged the moisture flux anomalies from the northeast. This ~~was~~ is supported by prevailing A and NE WTs, which decreased in percentage when ~~the~~ drought ~~condition~~ disappeared, in accordance with the increased frequency of C, W, and SW circulation and negative anomalies of the VIMF divergence. E2 began in September 2012 when intense positive anomalies of the VIMF divergence over the MLSHD ~~suggested~~ indicate that ~~divergence of the~~ moisture flux divergence prevailed, while A and NE WTs were the most frequent. The peak of this episode occurred in

February 2012 when intense anticyclonic anomalies of the VIMF dominated the North Atlantic and had a centre to the north-northwest of the target region. In accordance, NE and E circulation were the most frequent over the IP. Drought conditions disappeared (in April 2012) when negative anomalies of the VIMF divergence affected the MLSHD, ~~which was~~ in association with cyclonic circulation anomalies of the VIMF with the centre located over England. Correspondingly, the most frequent circulation patterns were C and NW. The third and fourth driest episodes began in December of 2014 and 2003, respectively. In both months, the most prominent circulation patterns were associated with A ~~and C~~ WT~~s~~. ~~However,~~ A~~a~~nticyclonic anomalies of the VIMF ~~were~~ ~~observed~~ with centre over the North Atlantic ~~and~~ affected the MLSHD; these anomalies were more intense in December 2014, when positive anomalies of the VIMF divergence covered almost all the IP. The peak of E3 occurred in July 2015 with intense VIMF anomalies from the Atlantic Ocean that reached the northern portion of the IP; however, over the MLSHD, both negative and positive VIMF divergence anomalies ~~were~~ are observed. The last month of E3 was August 2015 because~~;~~ the SPEI changed to a positive value in September 2015 owing to negative anomalies of the VIMF divergence ~~observed~~ over the ~~NWIP~~ north western IP and the influence of ~~C~~ cyclonic anomalies of the VIMF, which were in accordance with an increase in the percentahe of the W WT~~circulation~~ with respect to that in the previous stage of the episode. In the peak of E4, are observed positive anomalies of ~~the~~ VIMF ~~anomalies~~ divergence over the MLSHD ~~indicated an increase associated with anticyclonic circulation in agreement of the~~ and a major frequency of the A WT. This episode ended when the anomalies on the moisture flux from the west favoured the occurrence of convergence, despite the fact that the most frequent WT was A, followed by W. E5 began in February 1990. ~~when~~ In this month t~~t~~he VIMF anomalies over the IP show~~ed~~ ~~clear~~ an intense anticyclonic circulation accompanied by positive divergence anomalies over all the IP, and a high frequency of A circulation.

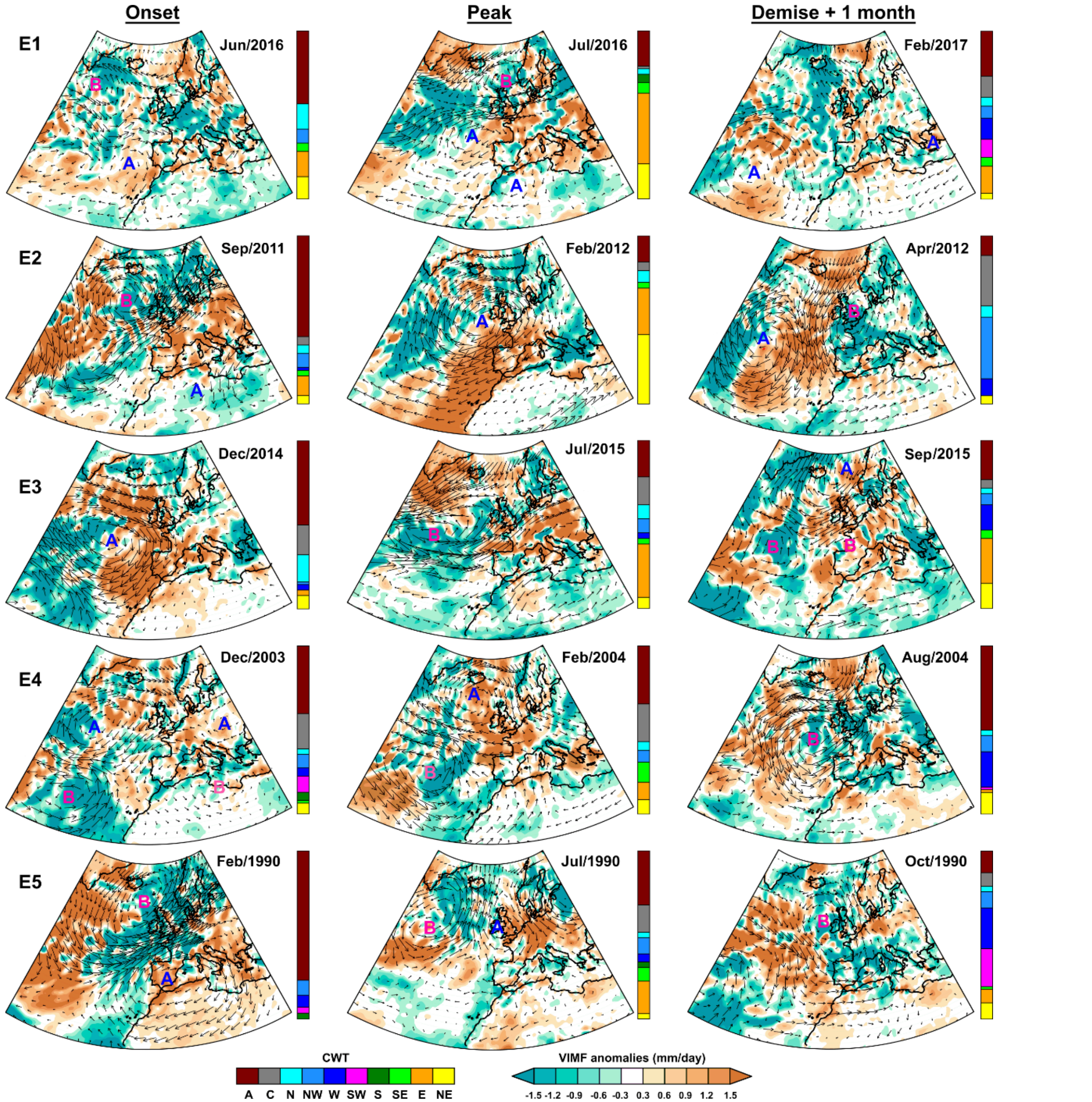


Figure ~~9~~8. The monthly anomaly of the VIMF (in arrows) and its divergence (shaded) during 1980–2017 for the onset, peak, and 1 month after the termination of each of the ~~five~~ ten most severe drought episodes (Es) shown in Table 3. Anticyclonic (cyclonic) centres of the VIMF anomaly circulations are represented as A (B). Vertical bars show the monthly percentage of each pure weather type (WT).

~~In Figure 9, t~~The VIMF anomalies ~~of~~ in the onset of E6 ~~are shown;~~ in August 1988 ~~was~~ are characterised by an anticyclonic circulation centre ~~of the VIMF~~ to the southwest of the MLSHD, and cyclonic circulation in the northwest, which were both over the Atlantic Ocean (Figure 9). The VIMF divergence anomalies ~~showed~~ show prevailing divergence conditions. The latitude location of both centres ~~was~~ is opposite in the peak of the episode (December 1988), when ~~and~~ the centre of the anticyclonic circulation of the VIMF ~~was associated with an intense anticyclone in the~~ is observed in north western~~NW~~IP. ~~that~~ It ~~was~~ is in accordance with the major frequency of the A WT. This episode ended when ~~the major~~ moisture flux anomalies ~~was anomalous from the~~ reached the MLSHD from the ~~NW~~northwest , ~~and~~ in combination with negative anomalies of the VIMF divergence over the MLSHD~~prevailed.~~ ~~suggested the occurrence of convergence~~ . In the onset of E7, as well as in E6, anomalous cyclonic~~C~~ circulation of the VIMF ~~was~~ is observed with a centre located to the ~~NW~~ northwest of Ireland. This situation ~~changed~~ is different at the peak of the episode ~~-~~with the prevailing frequency of A and NE WTs and anticyclonic circulation of the VIMF with the centre located to the northwest and near the MLSHD. When this centre moved westwards and the moisture flux anomalies arrived at the MLSHD from the north, which was shown in the WT, then dry conditions disappeared. In E8, the onset coincided with the peak of the episode. The atmospheric conditions in November 2001 ~~revealed~~ were characterised by the prevalence of E and NE WTs and positive anomalies of the VIMF divergence associated with the anticyclonic circulation revealed by the VIMF anomalies over the North Atlantic Ocean to the northwest of the MLSHD. This episode ended in April 2002 owing to a positive SPEI1 value in May 2002. In this month~~, which was when the~~ the pattern of VIMF anomalies ~~suggested~~ ~~suggests~~indicate that MLSHD received moisture ~~flux~~ from the combination of the cyclonic anomaly of the VIMF with the centre in Ireland, and the VIMF anticyclonic~~e~~ anomalies with a centre in the north Atlantic Ocean ~~and~~ around 40°N. Owing to this combination, the WTs with the greatest prevalence were those that imposed circulation from the west. As well as in the previous episodes, in E9 and E10, the onset was characterised by anticyclonic anomalies of the VIMF with the centre located to the northwest of the MLSHD over the Atlantic Ocean, and both also showed a cyclonic circulation of the VIMF near the coast of northwest Africa and positive anomalies of the VIMF divergence over the MLSHD. In the onset of E9, the most frequent WTs were NE, E, and SE, while those in E10 were SE, A, and E. In E10, the peak ~~was also in~~ coincided with the onset, and the VIMF anomaly patterns ~~were~~ is very similar to those of the E9 peak, with anticyclonic circulation with centre located to the northwest of the MLSHD near Ireland, ~~which also occurred~~ as it happened in the peaks of E2, E5, E6, and E7. Both episodes ended owing to negative anomalies of the VIMF divergence (specially in E10) ~~associated with VIMF~~as well as VIMF anomalies from the west ~~in E9 and C circulation in E10.~~

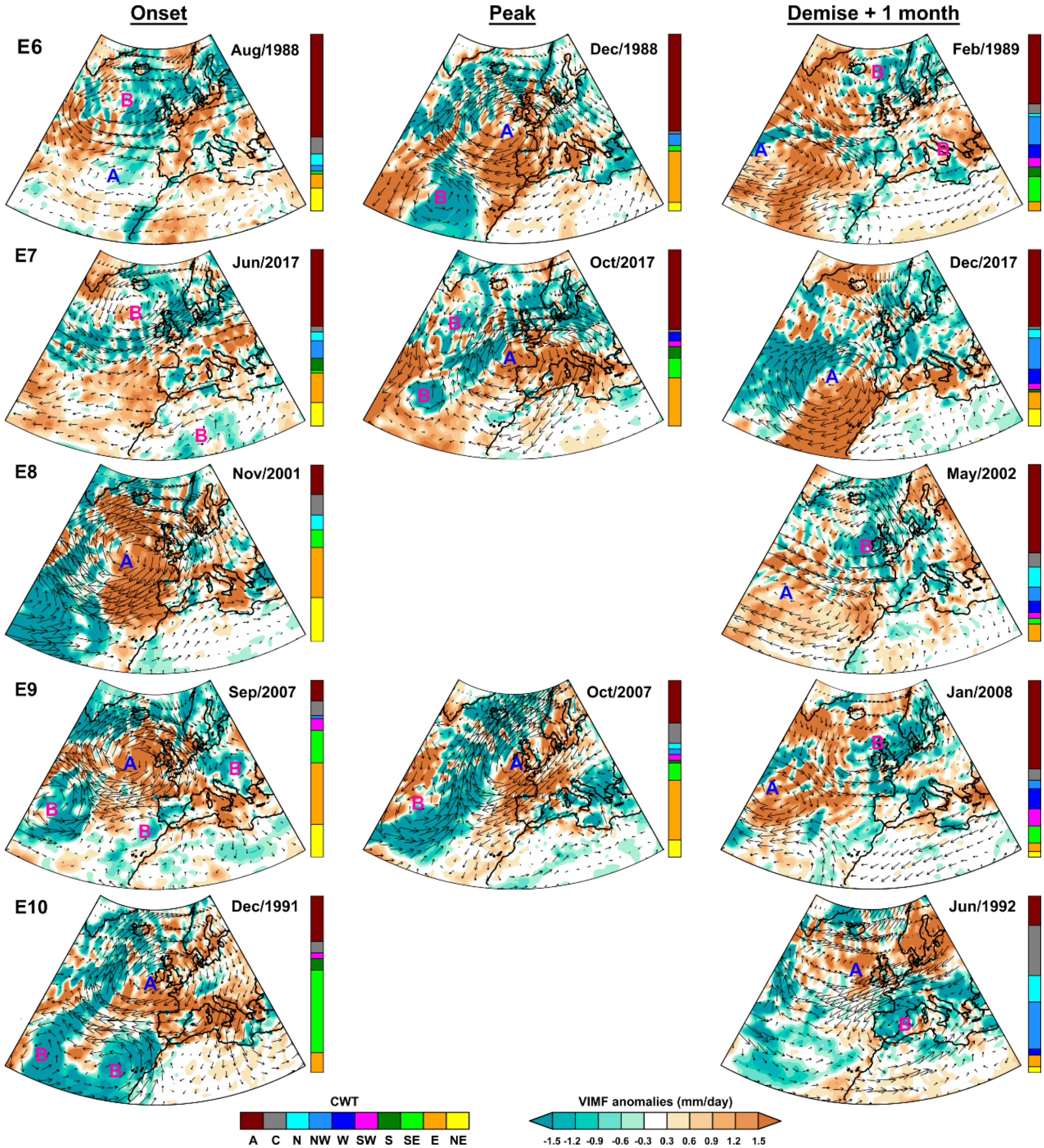


Figure 9. Continuation As Figure 8 but Continued for Episode 6 to 10. For E8 and E10, the month of the onset is also the month of the peak.

3.34 Relationship between drought and modes of climate variability

Figure 10a shows the correlation between the BEST, NAO, EA, AO, and, SCAND, and WeMO series and AMO climatic indices with SPEI1 to 24 in order to determine any causal effect between atmospheric and oceanic teleconnection patterns and dry and wet conditions in the MLSHD. The results revealed a major link between the SCAND (positive correlation) and AO (negative correlation), particularly at short temporal scales of the SPEI (SPEI1 1 to SPEI4 4 months). Theis occurred because the SCAND pattern (initially referred to as the Eurasia-1 by Barnston and Livezey (1987)) in its positive phase was is characterised by positive height anomalies over Scandinavia and western Russia, , which sometimes reflected major blocking anticyclones, over Scandinavia and western Russia, but with, but weaker centres of the opposite sign over south and western Europe and eastern Russia, while the negative phase show is sed the opposite. Results of Rodriguez-Puebla et al., (1998) show the heterogeneous correlation between the SCAND index and the annual precipitation over the IP; however, confirmed that annual precipitation variability in the northwestern of IP is related to the SCAND December pattern. On the contrary, the AO index is defined as the leading empirical orthogonal function using monthly mean 1000 hPa anomaly data over 20°N–90°N, and ranges from positive to negative values depending on the pressure anomalies in the Arctic region (Thompson and Wallace, 1998). Associated to the positive phase of the In the case of the AO, its positive phase is characterised by aA band of strong winds circulating around the North Pole, associated to the positive phase of the AO, which keep colder air within the polar region and correspond to a deepening of the Azores High and the strengthening of the polar and subtropical jets over the Euro-Atlantic region (Ambaum et al., 2001). In the negative phase, this ring becomes weaker, thereby permittingallowing the southwards penetration of Arctic air masses and an increase in the magnitude of the total eddy energy fluxes into the Euro-Atlantic region (Rivière and Drouard, 2015), which clearly affects the hidroclimatic conditions in the northwest IP (deCastro et al., 2006) and explains the negative correlations obtained with the SPEI. According to Wanner et al. (2001), the AO is similar to the NAO in many aspects. The NAO explains the meridional displacement of atmospheric mass over the North Atlantic area (usually expressed by the standardised air pressure difference between the Azores High and the Iceland Low) (Wanner et al., 2001). The negative phase of the NAO is associated with centre weakness of the Azores High and a southwards position in the storm tracks, thereby resulting in wet conditions over the IP (Trigo et al., 2002). The correlations in figure 10a demonstrates that both influence the water balance (throught the SPEI1) in the MLSHD on the same SPEI temporal scales the MLSHD water balance. However, the NAO teleconnection is characterised by a meridional displacement of atmospheric mass over the North Atlantic area (usually expressed by the standardised air pressure difference between the Azores High and the Iceland Low) (Wanner et al., 2001). The negative phase of the NAO is associated with centre weakness of the Azores High and a southwards position in the storm tracks, thereby resulting in wet conditions over the IP (Trigo et al., 2002). Although, the correlations with AO are major, These findings indicatinge that AO index may be a better than NAO to explain the atmospheric influence on dry/wet conditions in northwest of the IPthe MLSHD. Nevertheless, Therefore, we also found negative correlations between the NAO and the SPEI for the 24 temporal scales. the NAO index has been also traditionally defined as the normalized pressure difference between a station on the Azores and one on Iceland (Hurrell, 1995; Jones et al., 1997) and therefore the correlations with the SPEI could also be different.

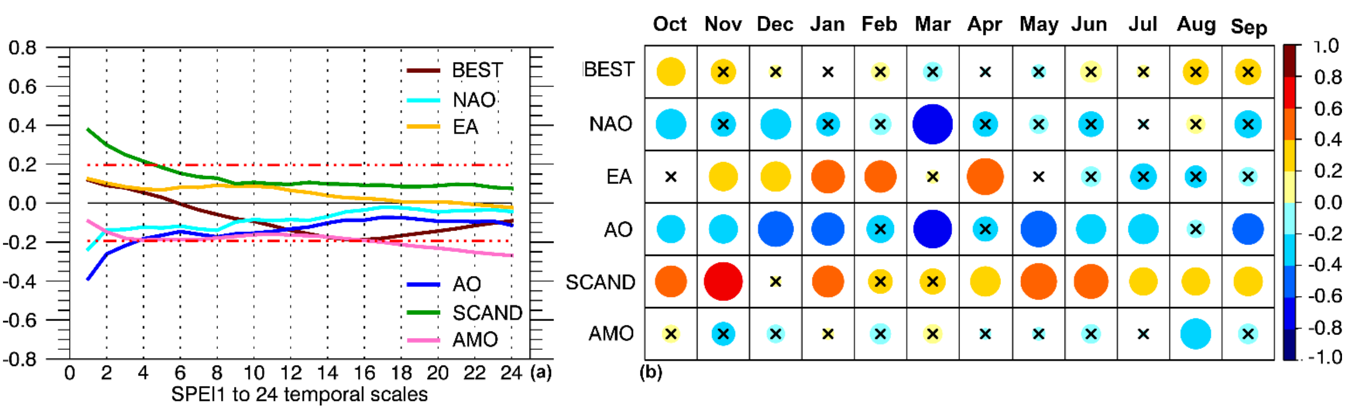
The mean annual and seasonal rainfall decrease across the IP during the last decades (second halve of the last century) has been traditionally associated with the lost of the high-rainfall circulation types (cyclonic) and with the increase of the low-rainfall types (anticyclonic), consistent with the positive trend in the NAO duringthe same period [Trigo et al., 2004]. However, at the regional scale, the decreasing trends in NIB [Rodrigo andTrigo, 2007] cannot be explained with the increase in the NAO positive modes during the last decades: lowand nonsignificant correlations are found between precipitation anomalies and the NAO signal, at least since1865 (coincident with the longest instrumental records in the region).

In the case of the ENSO, namely the strongest ocean-atmosphere coupling phenomenon on the interannual time scale, at first the correlations between the SPEI ~~were~~ are positive with the BEST index, but ~~were~~ very low (< 0.2) and not significant; these became negative when correlations were made with SPEI values computed from the past 6 months to 24 months, but were also not statistically significant. This suggests a poor association between the ENSO (El Niño and La Niña) and the occurrence of dry and wet conditions in the MLSHD. Findings of García et al., (2005) show that influence of ENSO is not significant on the P over Galicia. Though, according to Dai and Tan (2017), a warm (cold) ENSO enhances the negative (positive) AO phase, which is directly related to the MLSHD hydroclimate. Positive and insignificant correlations were found with the EA, and ~~in the case of~~ and finally with the We~~A~~MO, positive correlation appear with all SPEI time-scale, being significant with SPEI1.

Because the correlations in Figure 10a were greater with SPEI1 than with SPEI at other scales, a second correlation analysis was conducted in order to determine the relationships between the SPEI1 and the teleconnections, but at monthly scales (Figure 10b). In Figure 10b ~~T~~the correlations with the BEST index are~~were~~ positive but low and not significant, except for ~~in~~ spring (March, April, and May) when the *r* values ~~were~~ are negative. The results of Muñoz-Díaz and Rodrigo (2004) also show that in winter, there is no ENSO influence, which is possibly because of the predominance of the NAO during spring, ~~and~~ when La Niña leads to a low probability of drought in the north of the IP. Loenzo et al., (2010) investigated the predictability of the spring rainfall in northwestern IP from sea surfaces temperature of ENSO areas for the period 1951–2006. They con~~con~~cluded that ~~for the period 1951–2006~~ ~~the~~ negative phase of ENSO, “La Niña”, almost always announces dry springs in northwestern IP. However, the positive phase of ENSO, “El Niño”, does not anticipate the appearance of wet springs. Similar monthly correlations ~~were~~ were obtained between the NAO and AO with SPEI1; however, as expected from the results of Figure 10a, it seemed that the AO ~~was~~ is the most related with the SPEI1 variability, and consequently to ~~to~~ monthly dry and wet conditions in the MLSHD throughout the hydrological year, especially in the winter and spring months (December to May). This ~~was~~ in in agreement with Mazano et al. (2019), who argued that the AO and NAO patterns have a significant impact on droughts in winter over large areas of the IP. ~~However, these authors utilised the SPEI3.~~ However, at local and regional scale results may differ. In a previous study Rodriguez-Puebla and Nieto, (2010) revealed that positive (negative) NAO induce an east-west decreasing gradient of drier (wetter) conditions over the IP, an east-west. Most recent findings of Sáez de Cámara et al., (2015) describe a complete lack of correlation between P anomalies and NAO for central and eastern north IP. These authors also show that from the late 1980s to 2005 ocurred an increase in the frequency of extreme circulation modes within each NAO positive and negative phases, both inducing negative precipitation anomalies and long-lasting dry spell in north IP. That is, special care must be taken when associating a positive trend of the NAO with the increase of dry conditions in the entire IP.

Positive correlations between the EA and SPEI1 were clearly observed from November to May. The results of Casanueva et al. (2014) also revealed a positive correlation between the EA index and P and the consecutive wet days over the ~~NWIP~~ northwest IP during the boreal winter. The SCAND pattern was also positively correlated during all months of the year, but no significant correlations were found in December, February, and March. In a 300 mb height field typical for the positive phase of the SCAND, a weak trough appeared over the northeastern Atlantic in association with the centre of a major cyclonic anomaly and the North Atlantic storm-track activity as represented by the 850 mb polewards eddy heat flux, which weakened around Iceland and northern Europe, whereas the storm track extended eastwards into southern Europe through England (Bueh and Nakamura, 2007). Finally, the WeMOi shows positive significant correlation with SPEI1 from January to November, but specially in summer. This is surprising, since previous studies show that WeMOi is particularly asscoaited with the precipitation variability in the eastern eastern part of the Iberian Peninsula and the south of France (Martín-Vide and Lopez-Bustins, 2006).

~~Finally, there was no clear evolution of monthly correlations between the SPEI1 and AMO, and only significant negative correlations were found in August. Since the AMO was uncertain, it remained unknown whether it represented a persistent long-term periodic (10–30 y; 50–80 y) driver in the climate system (Knudsen et al., 2011), thereby affecting the IP weather at a longer periodicity (Abrantes et al., 2017).~~



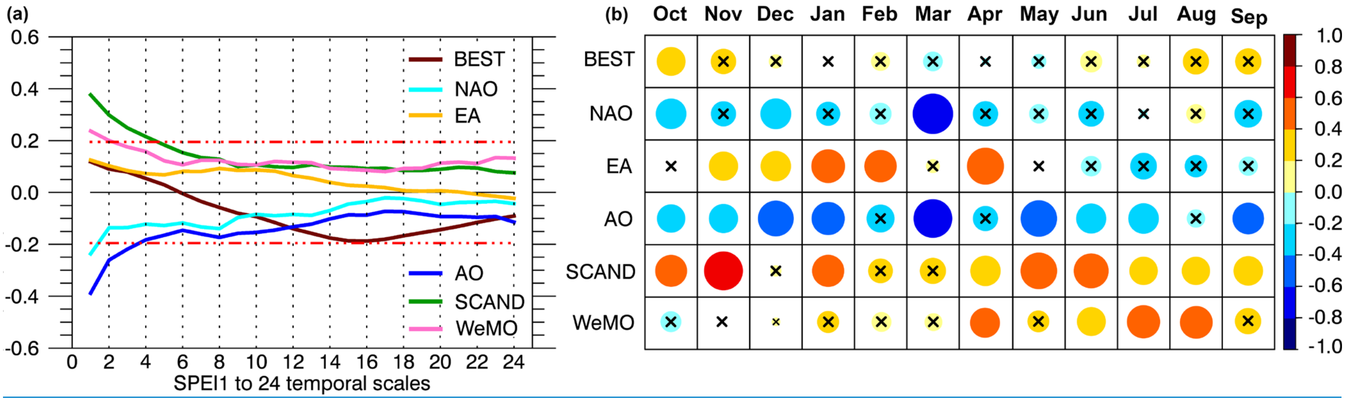


Figure 10. Correlation between the bivariate El Niño Southern Oscillation time series (BEST), North Atlantic Oscillation (NAO), East Atlantic (EA), Arctic Oscillation (AO) and, Scandinavian Pattern (SCAND monthly time series), and)Atlantic Multidecadal Oscillation (AMO) and the 1 mo Standardised Precipitation-Evapotranspiration Index (SPEI1) at 24 temporal scales (a) and the monthly correlation between the same climate indices and the SPEI1 (b) for the period of 1980–2017. Not statistical significant correlations at 95% confidence level are identified with and x. The size of the circles is proportional to the correlation value.

Results of a WC analysis shows in Figure 12 the frequency bands and time intervals of the co-variations between SPEI1 and differente modes of climate variability represented by climatic indices

The temporal variability of dry and wet conditions according to the SPEI1 in the MLSHD was is also investigated by studying the potential links that may exist with climatic modes of variability represented by for the (i.e., BEST, EA, WeMOi, AMO, NAO, AO, and SCAND) indices, but utilising a WC method. The coloured shading indicate the magnitude in the coherence as represenetd in the colour bar, which varies from 0 to 1 and indicates the timescale variability in the correlation between the two time series. Warmer colors (red) represent regions with significant interrelation, while colder colors (blue) signify lower dependence between the series.

The results are shown in Figure 11. The coherence power between two series is shown as red to blue (strong to weak), and the black contours represent the locally significant ($p < 0.05$) power of the red-noise spectrum. The grey line depicts the cone of influence (COI), while the black arrows indicate the phase relationships between the climate indices and SPEI1 and are denoted by arrows; those for in-phase point right, anti-phase point left, climate indices leading the SPEI1 by 90° point up, and SPEI1 leading the climate indices by 90° point down. reveal that The BEST showsed strong but intermittently significant interannual coherence with SPEI1 from year to year in the period of the 13–75 months band; besides, while a significant correlation was is observed from 1980 to 1990 and for the 40–60 months band, but it was is outside the COI until the end of 1982. In this time scale the straight downward arrows indicate that BEST index leads the SPEI1 in phase by 90º, which suggest that after warm(cold) ENSO phase led the dry/wet conditions in the MLSHD.

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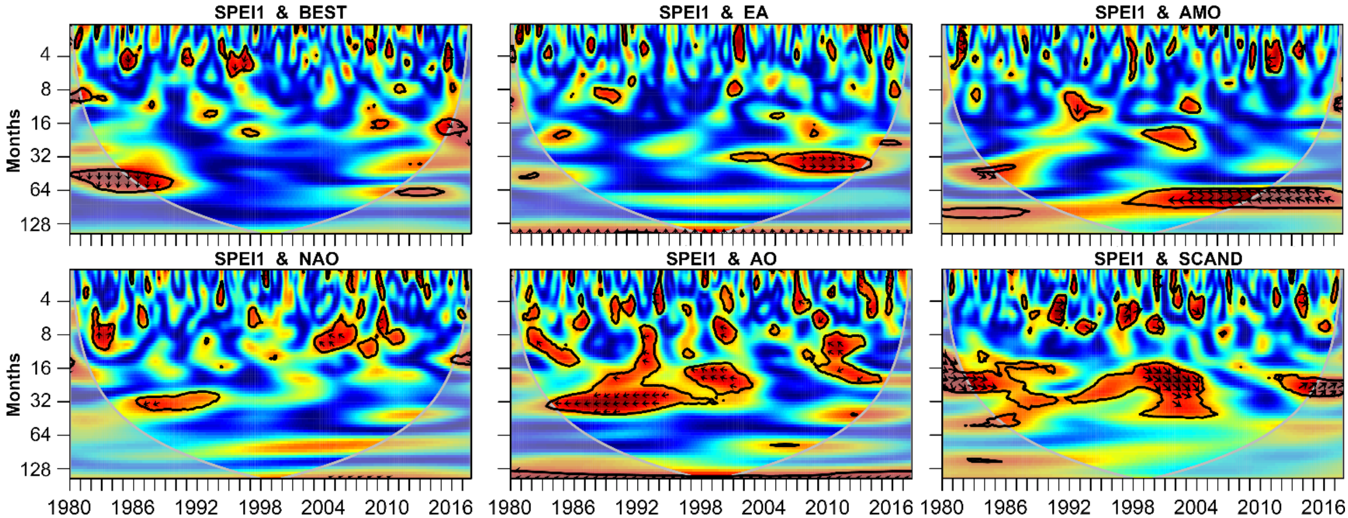
In the case of the EA ~~and AMO~~, there ~~was~~ is a frequent, significant co-oscillation with the SPEI1 in the high-frequency 0–6 years band. However, from approximately the end of the 2000s to 2012, there was a high coherence peak in the low-energy regions (for nearly 30–45 months) ~~. Negative coherent correlation occurred with the AMO after 63 mo from approximately 1996 to 2009.~~ The coherence beteween SPEI1 and WeMOi expose frequent interannual and

~~The~~ F~~f~~indings of Hurrell (1995) ~~showed~~revealed that ~~the~~ NAO has a rich combination of low frequencies from intraseasonal to interannual time scales, and low frequency from decadal to multidecadal time scales. This signal was represented in positive coherence with the SPEI at high frequencies, as observed in Figure 11. This relationship become~~came~~ strong between 4 months and 12 month in the periods ~~of~~ 1982–1984 and 2004–2012. At a longer temporal scale (30 months to 34 months), strong coherence ~~was~~ is also observed ~~in~~ for the period ~~of~~ 1986–1994. The authors argued the prominent role of the NAO in the ~~NWIP~~ north western IP climate. Results of Añel et al., (2005) ~~0~~suggest that NAO and precipitation in Galicia could be related at a time scale of 8 years. ~~whereas the influence of ENSO is not significant~~.

However, compared with those in the NAO, oscillations in the AO were manifested in the SPEI1 over most of the period on intermittent wavelengths from 2 months to 6 months, but most significantly from 6 months to 36 months (3 years) when the left-pointing arrows ~~showed~~ show an anti-phase relationship (negative correlation), thereby indicating that the AO and SPEI1 moved in the opposite direction (when one is maximum, the other is minimum and vice versa). Finally, the significant coherence between the SPEI1 and SCAND pattern reveal~~ed~~ the recurring influence of this teleconnections pattern, particularly between 1990~~1~~ ~~and~~ to 2000~~9~~ along with the 0–8 months periodic bands and at low frequencies (from approximately 14~~2~~ months to 40 ~~34~~ months) during longer and continuous periods, when arrows pointing to the right-down ~~right-pointing arrows showed~~ indicate that the SPEI1variable is leading. ~~a phase relationship~~.



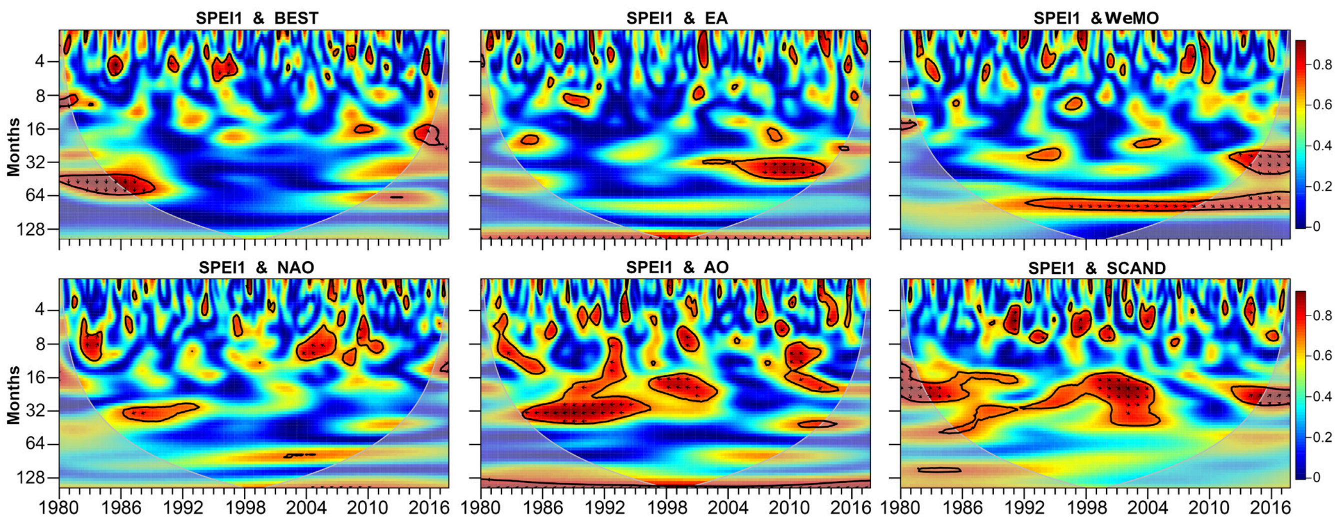


Figure 11. Wavelet coherence between the ~~1-mo Standardised Precipitation Evapotranspiration Index (~~SPEI1~~)~~ and the series of teleconnection patterns, namely the bivariate El Niño Southern Oscillation time series (BEST), East Atlantic (EA), ~~Atlantic Multidecadal Oscillation (AMO),~~ North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and Scandinavian Pattern (SCAND). The colours from blue to red indicate the increasing coherence. Areas enclosed by a black line correspond to statistically significant cross-wavelet powers at the 95% level. The grey line depicts the cone of influence (COI). The black arrows indicate the phase condition. The phase relationships between the climate indices and SPEI1 are denoted by arrows for in-phase pointing right, anti-phase pointing left, climate indices leading the SPEI1 by 90° pointing up, and SPEI1 leading the climate indices by 90° pointing down.

3.4~~5~~ Drought propagation

A deficit in P coupled with higher evaporation rates leads to a meteorological drought that may propagate into the soil up to the crops, thereby leading to an agricultural drought and a hydrological drought when both the groundwater and streamflow are affected. However, drought propagation through every component of the hydrological cycle depends on the severity of the drought event as well as the characteristics of the catchments (Van Lanen, 2006; Wang et al., 2016). In this section Wwe investigated the possible response of the runoff through the SRI possible response of the SMroot (Figure 12a) and the streamflow (Figure 12b and c) due to drought conditions assessed from at several back time scales according to the SPEI1 to SPEI24. Correlations values in Figure 132a shows the that maximum runoff variability correlation values between the SRI with is well associated with the first temporal scales (1 and 2 months) of the the SPEI inalong all the hydrological year. However, hight correlations during all SPEI temporal scales highligth for from the previous 2 months to 6 months during the rainy season, and particularly in October, November, and December December, January and February, thereby suggesting that surface runoff the SMroot during the rainiest months also depended on dry/wet conditions from previous the dry seasonmonths. From April to July September, the highest correlations were are more restricted to the previous 2-4 months, while at the end of the dry season (August–September), this relationship increased with the temporal scale of SPEI, which was computed considering the accumulated balance from the previous 4 months to 6 months. Malfunction According to statistically significant correlation in July (a driest month) the surface runoff variability is also affected by dry/wet conditoons from previos 4 – 21 months. Besides the SPEI is based in a water balance, the runoff seems that vary directly associated to the P annual cycle in the MLSHD. The maximum correlations in thisese figures indicated the ideal best climatic time scale over which the runoff changes measured by the SRI, respond to dry/wet conditions according to the SPEI.

which to monitor hydrological droughts (Lorenzo-Lacruz et al., 2013). However, this relationship is complex and can vary as a function of several factors, including river basin features and water regulation (López-Moreno et al., 2013; Vicente-Serrano et al., 2014).

Figure 13b illustrate the monthly response rate (in percentage) of hydrological drought (SRI ≤ -0.84) to drought at different timescales according to SPEI1 to SPEI24 less or equal to -0.84. Dry conditions revealed at all temporal scales of the SPEI (1 – 2 months) have a outstanding different response rate of hydrological drought across the hydrological year. The larger respose (> 50%) occurs from October to April, and particularly in January, February and March (the rainiest months). In these months the rate of months under hydrological drought is also highly affected by drought condition from several moths ago. This is in agreement with the correlation showed in Figue 13a. From May to Septemeber the P over the MLSHD decrease, and the rate reponse of hydrological drought reach about the 20%. A possible explanation to this is that evapotranspiration may be a determinat factor on the modulation of dry conditions during these months, and the runoff is more sensitive to rainfall.

This analysis reveal the direct response of hydrological drought focused on the of months focuses on the probable impact of drought conditions across several temporal scales over the main streamflow of the main rivers through the SSI values computed with the Miño River discharge recorded at the hydrological station in Ourense and the Limia River discharge registered at the hydrological station of Albufeira Do Alto Lindoso in northern Portugal, respectively. Positive and statistically significant correlations were mainly observed during the rainy season and with the SPEI from approximately 1 month to 12 months in both locations, which indicated that in both locations, the streamflow during the rainy season could not be explained only by local P and may have been influenced by the long-term drought or wet conditions accumulated from previous months. The correlation patterns were very similar; however, in the driest months of July and August, the streamflow of the Miño River at Ourense seemed to be more dependent on dry/wet conditions beginning after the previous 6 months until 24 months. In contrast, for the same months, the correlations decreased for all temporal scales in Albufeira Do Alto Lindoso. The maximum correlations in these figures indicated the ideal climatic time scale over which to monitor hydrological droughts (Lorenzo-Lacruz et al., 2013). However, this relationship is complex and can vary as a function of several factors, including river basin features and water regulation (López-Moreno et al., 2013; Vicente-Serrano et al., 2014).

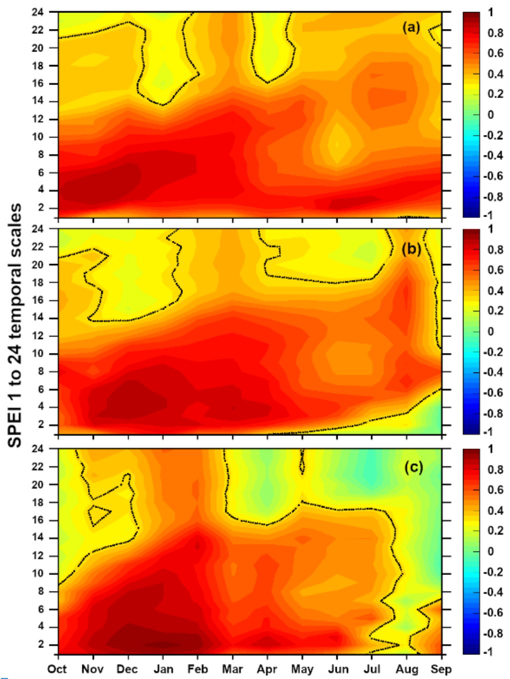


Figure 12. Monthly correlations among root zone soil moisture (SMroot) anomalies for the entire Miño-Limia-Sil Hydrographic Demarcation (MLSHD) (a) and the Standardised Streamflow Index (SSI) for the Miño River (b) at the hydrological station of Ourense and that for the Limia River at the hydrological station of Albufeira do Alto Lindoso (c) with the Standardised Precipitation-Evapotranspiration Index (SPEI1 to SPEI24) in the MLSHD. Dotted lines represent significant correlations at $p < 0.05$. For (a) and (b) the analysis was performed for the period of 1980–2017 and for (c) the available period was 1992/1993–2017.

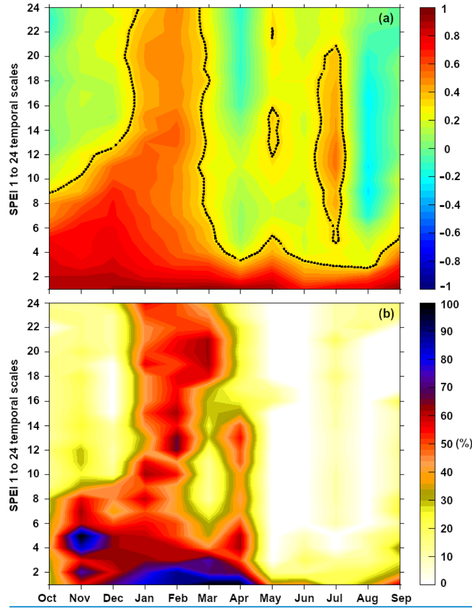


Figure 12. Monthly correlations among the Standardised Runoff Index (SRI) for the entire Miño-Limia-Sil Hydrographic Demarcation (MLSHD) (a) with the Standardised Precipitation-Evapotranspiration Index (SPEI1 to SPEI24) in the MLSHD. Dotted lines represent significant correlations at $p < 0.05$. Period 1980–2017.

4. Conclusions

The MLSHD is an hydroclimate region that experienced similar drought features. In this study, the temporal evolution of meteorological drought in the MLSHD and its relationship with different types of ~~C~~WTs were investigated. For this reason, the SPEI was utilised at the temporal scale of 1 month, which revealed that most frequent drought conditions affected the MLSHD in the periods ~~of~~ 1989–1992, 2004–2005, and 2015–2017. A daily WT classification for the entire IP was used to investigate the atmospheric circulation associated with different drought categories in the MLSHD. The results revealed the frequency of the WTs ~~prone~~ trend to dry conditions (A, SE, and E) and a general negative trend of C and west WTs (SW, W, and NW).

The most influential teleconnection patterns for dry but also wet conditions in the MLSHD were the AO and SCAND, followed by the NAO, which was in agreement with previous results for the region. Particularly, the AO and SCAND were also representative of a cause-effect relationship over stretches of the SPEI over longer periods and years. Considering that several studies have identified the NAO pattern as the dominant pattern for the Euro-Atlantic region and despite similarities between the AO and NAO representations discussed in the literature, the perspective that modulation of P and consequently dry conditions in the MLSHD ~~in the NWIP~~ may be associated with the middle latitude jet stream and centres of action located over the Arctic and North Atlantic Ocean to the north of Spain. A periodic significant coherence between the SPEI1 and other teleconnection patterns (BEST, EA, and AMO) was also detected in the high-frequency region, and a linear correlation analysis for all SPEI temporal scales revealed that greater significant relationships occurred with the SPEI1, although in the case of the BEST and AMO they were not statistically significant. In conclusion, this study provided some information that is fundamental to understand the climate forcing of rainfall variability and the occurrence of dry conditions in the MLSHD, which is an important hydrological and socioeconomic region of the ~~NWIP~~north western IP. Furthermore, these results will support hydrometeorological forecasting in the region.

Finally, drought conditions may affect the soil moisture and agricultural development in the area. This influence was higher in winter and lower in summer months, as ~~the~~ moisture availability was related to the drought cumulative effect on the previous 2 months to 6 months. From these results, it could be concluded that summer conditions may affect ~~the~~ moisture availability in humid months. Similar results were found for the river streamflow, as the SPEI1 to SPEI12 series were highly correlated with the river discharge in the humid months.

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