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Links between circulation weather types and teleconnection patterns and their influence on precipitation patterns in Galicia (NW Spain)

M. N. Lorenzo,[a]* J. J. Taboada[b] and L. Gimeno[a]
[a] *Faculty of Sciences, Campus de Ourense, University of Vigo. E-32004 Ourense, Spain*
[b] *Meteogalicia. Santiago de Compostela, Spain*

ABSTRACT: An automated version of the Lamb weather type classification scheme was used to study the relationship between atmospheric circulation patterns and rainfall in the northwestern part of the Iberian Peninsula, which is an important area of crossing influences of the different teleconnection patterns of the Northern Hemisphere. We calculated the correlation between the most important teleconnection patterns that affect this area and the different types of weather circulation. In this area, anticyclone weather types are the most frequent in any part of the year. The frequency of occurrence of W and SW situations is also significant in autumn and winter. The correlation between weather types (WT) and teleconnection patterns showed that the North Atlantic Oscillation (NAO) index has significant correlations only in winter, while other patterns, such as the Eastern Atlantic (EA), have significant correlations in the other seasons. As a result of these correlations, the EA is a more relevant pattern than the NAO for describing the Galician climate throughout the year. We also calculated correlations between the North Hemisphere Annular Mode (NAM) and the different types of weather types. The NAM shows significant correlations throughout the year. Hence, the NAM is more relevant than the NAO, which is its local manifestation. Copyright © 2007 Royal Meteorological Society

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1. Introduction

The study of rainfall and its variability in a region is one of the most important fields of study in the climate sciences, because of its social and economic implications (Collier and Krzysztofowicz, 2000 and references therein). Galicia is located in the northwestern corner of the Iberian Peninsula (Figure 1). It lies in a north Atlantic region that is characterized by the passage of cold fronts associated with lows travelling across the north Atlantic, mainly in autumn and winter, which allows the possibility of heavy rain episodes.

The inter-annual variability of rainfall in Galicia can be related to variations in the atmospheric configuration in the Northern Hemisphere (Lorenzo and Taboada, 2005; DeCastro *et al*., 2006). Our study area lies in between the influence of several large Northern Hemisphere teleconnection patterns as shown in Figure 2. They were calculated correlating the monthly time series of the different patterns and the monthly standardized height anomalies from 1950 to 2005 (Section 2 for more information about data). The area shown is wider than the area of the Figure 1 in order to see clearly the patterns. The storm track in this area depends strongly on the North Atlantic Oscillation (NAO) (Trigo, 2006). Other teleconnection patterns, such as the Scandinavian Pattern (SCA) or the Eastern Atlantic (EA) are also important for explaining variability in precipitation (Blackburn and Hoskins, 2001; Lorenzo and Taboada, 2005; DeCastro *et al*., 2006). It has been found that correlations between winter rainfall in Galicia and the NAO index have a value of −0.52, while correlations with other indices are lower, but significant. The correlation of winter precipitation with the SCA pattern in this period has a value of 0.41, while the same correlation with the Eastern Atlantic/Western Russia (EA/WR) and the EA gives results of −0.39 and 0.30 respectively (Lorenzo and Taboada, 2005). Those results are in agreement with other studies of the Iberian Peninsula. Thus, Zorita *et al*., 1992 showed that the relationship between winter precipitation and the NAO is more important at the southwestern corner, with the correlation of NAO and winter precipitation for Galicia (northwestern corner) lying between 0.4 and 0.3. Esteban-Parra *et al*., 1998 obtained the same correlation between the NAO and winter precipitation in the northwestern part of Spain, with a greater value occurring at the southwest and the interior of Spain (García *et al*., 2005). This result is confirmed in Rodriguez-Puebla *et al*., 2001. The values of the correlation between winter precipitation and the NAO are slightly lower than the value obtained in Lorenzo

* Correspondence to: M. N. Lorenzo, Faculty of Sciences, Campus de Ourense, University of Vigo. E-32004 Ourense, Spain.
E-mail: nlorenzo@uvigo.es

and Taboada, 2005, because in the cited works (Zorita *et al*., 1992 and Esteban-Parra *et al*., 1998) only one meteorological station in Galicia was used, such a station is located in an area of Galicia less influenced by the NAO (Lorenzo and Taboada, 2005). They concluded that those regions of the Iberian Peninsula most affected by the NAO lay from the southwest to the northeast, while Galicia lies to the northwest. For this reason, it is important to consider the correlation with other indices that represent different modes of variation of the atmosphere in the Northern Hemisphere.

In this work, we studied rainfall variability in Galicia over the whole year by using an automated scheme for classifying the synoptic weather situations. Automated classifications of synoptic weather types were initially developed for the British Isles (Jones *et al*., 1993), and then adapted for other areas, such as Portugal (Trigo and DaCamara, 2000) or the southeastern corner of the Iberian Peninsula (Goodess and Palutikof, 1998). These classifications differentiate between meteorological situations by describing them in terms of circulation parameters or local weather elements. Their wide range of application in climatology, biometeorology, atmospheric physics, and chemistry makes them a useful tool for forecasting (Laaidi, 2001; Buchanan *et al*., 2002; Hongisto and Joffre, 2005).

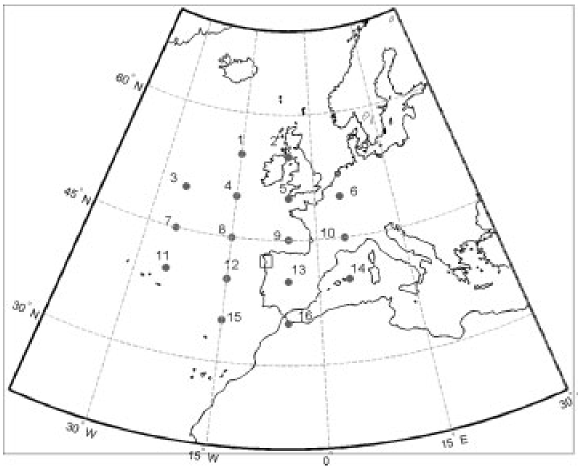

Figure 1. Pressure grid points used for classification of weather types. The small square marks the location of the study area over the NW corner of Iberia.

In recent years, this kind of automated classification has been used to study the variability and changes in the characteristics of the rainfall (Goodess and Jones, 2002; Paredes *et al*., 2006). In the context of climate change, such a method of classification will also be useful for relating teleconnection patterns, such as the NAO, to the various synoptic weather situations. It is for this reason that the European Cooperation in Scientific and Technical Research (COST) Action COST733 (http://www.cost733.org/) project was initiated. The main objective of COST733 is to achieve a general numerical method for assessing, comparing, and classifying typical weather situations in the European regions.

2. Data

(1)

(a) To calculate the synoptic weather types the National Center for Atmospheric Research (NCAR) reanalysis data (2.5° × 2.5° longitude–latitude) of the daily sea level pressure (SLP) were used for the period January 1950–December 2005 (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html). We need 16 grid points to calculate the circulation types with

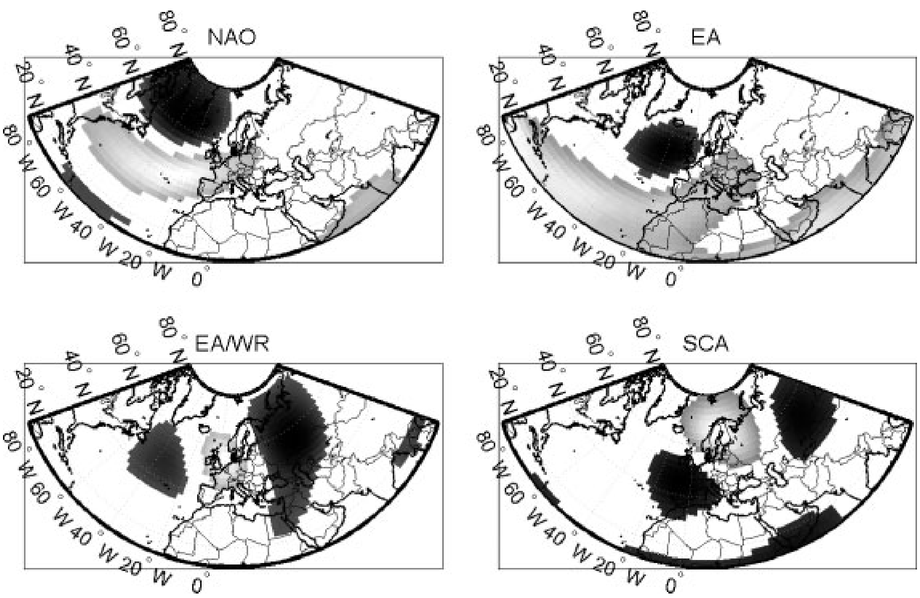

Figure 2. Spatial patterns of the main teleconnections over the Atlantic Northern Hemisphere. The figures represent the temporal correlation between the monthly standardized height anomalies at that point and the monthly teleconnection pattern time series from 1950 to 2005. The data were obtained from the Earth System Research Laboratory (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.pressure.html).

the procedure developed in Trigo and DaCamara, 2000. The points considered are shown in Figure 1. They are located between 35–55°N and 25 °W–5 °E.

(b) For the same period (January 1950–December 2005), we have also considered from the Earth system Research Laboratory the monthly standardized height anomalies calculated from the reanalysis data (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.pressure.html) to elaborate the spatial patterns of the main teleconnections over the Atlantic Northern Hemisphere shown in Figure 2.

(2) For daily precipitation data between January 1950 and December 2005, we have used the precipitation series for the Lourizán Station as a representative point for the precipitation in Galicia and in the northwestern part of the Iberian Peninsula. The data were supplied by Xunta de Galicia (Consellería de Medio Ambiente).

(3) We used the precipitation data for the area shown in Figure 1 (35–65 °N, 35 °W–30 °E) from the Global Precipitation Climatology Project (GPCP) of the Global Energy and Water Cycle Experiment (GEWEX) between December of 1979 and December of 2004. These data were used to calculate the correlation between the precipitation of the Lourizán Station and the precipitation of the study area (Figure 6). The GPCP was established with the initial goal of providing monthly mean precipitation data on a 2.5° × 2.5° latitude–longitude grid.

(4) The teleconnection indices were obtained from the Climate Prediction Center of the NOAA (http://www.cpc.noaa.gov/data/teledoc/nao.shtml) between 1950 and 2005. The procedure used to identify the Northern Hemisphere teleconnection patterns and indices is the Rotated Principal Component Analysis (RPCA) (Barnston and Livezey, 1987). This procedure isolates the primary teleconnection patterns for all months and allows time series of the patterns to be constructed. The daily and monthly Northern Hemisphere teleconnection indices have been changed as of 1 June 2005. With these new data, the patterns considered in our paper exist in all months conserving their independency from each other.

3. Synoptic weather type classification for Galicia (NW Spain)

We adopted the procedure developed in Trigo and DaCamara, 2000, which in turn was adapted from procedures developed by Jenkinson and Collison (1977) and Jones *et al.* (1993). Southerly flow (SF), westerly flow (WF), total flow (F), southerly shear vorticity (ZS), westerly shear vorticity (ZW), and total shear vorticicty (Z) were computed using SLP values obtained for the 16 grid points (p_1–p_{16}) as shown in Figure 1.

Note that these points were moved 5° to the north compared with the study of Trigo and DaCamara, 2000, in order to centre our area in the grid. National Center for Atmospheric Research reanalysis data of the SLP were used to obtain the daily SLP covering the period January 1950–December 2005. We used the following expressions when calculating the indices:

$$
\begin{aligned}
SF &= 1.350[0.25(p_5 + 2p_9 + p_{13}) \\
&\quad - 0.25(p_4 + 2p_8 + p_{12})] \\
WF &= [0.5(p_{12} + p_{13}) \\
&\quad - 0.5(p_4 + p_5)] \\
ZS &= 0.85[0.25(p_6 + 2p_{10} + p_{14}) \\
&\quad - 0.25(p_5 + 2p_9 + p_{13}) \\
&\quad - 0.25(p_4 + 2p_8 + p_{12}) \\
&\quad + 0.25(p_3 + 2p_7 + p_{11})] \\
ZW &= 1.12[0.5(p_{15} + p_{16}) - 0.5(p_8 + p_9)] \\
&\quad - 0.91[0.5(p_8 + p_9) - 0.5(p_1 + p_2)] \\
F &= (SF^2 + WF^2)^{1/2} \\
Z &= ZS + ZW
\end{aligned}
$$

Conditions established to define different types of circulation were the same as in Trigo and DaCamara, 2000:

(1) Direction of flow was given by tan-1(WF/SF), 180° being added if WF is positive. The appropriate direction was computed using an eight-point compass, allowing 45° per sector.
(2) If $|Z| < F$, flow is essentially straight and considered to be of a pure directional type (eight different cases, according to the directions of the compass).
(3) If $|Z| > 2F$, the pattern was considered to be of a pure cyclonic type if $Z > 0$, or of a pure anticyclonic type if $Z < 0$.
(4) If $F < |Z| < 2F$, flow was considered to be of a hybrid type and is therefore characterized by both direction and circulation (8 × 2 different types)

These rules allow 26 different weather types. However, for this study we adopted an approach similar to that of Jones *et al.*, 1993 and Trigo and DaCamara, 2000 and retained only ten weather types (NE, E, SE, S, SW, W, NW, N, C, A).

Composite maps of each weather type were computed for the period January 1950–December 2005, to ensure that each type represents different synoptic conditions. We computed all these weather types identically for all months of the year; in Figure 3, we show the annual average signature of the different weather patterns. NE cases are characterized by high pressures settled over the west of Ireland and low pressures in the Mediterranean Sea. In the case of E types, high pressures lie over the British Isles and low pressures dominate North Africa. For S weather types, high pressures are almost in the

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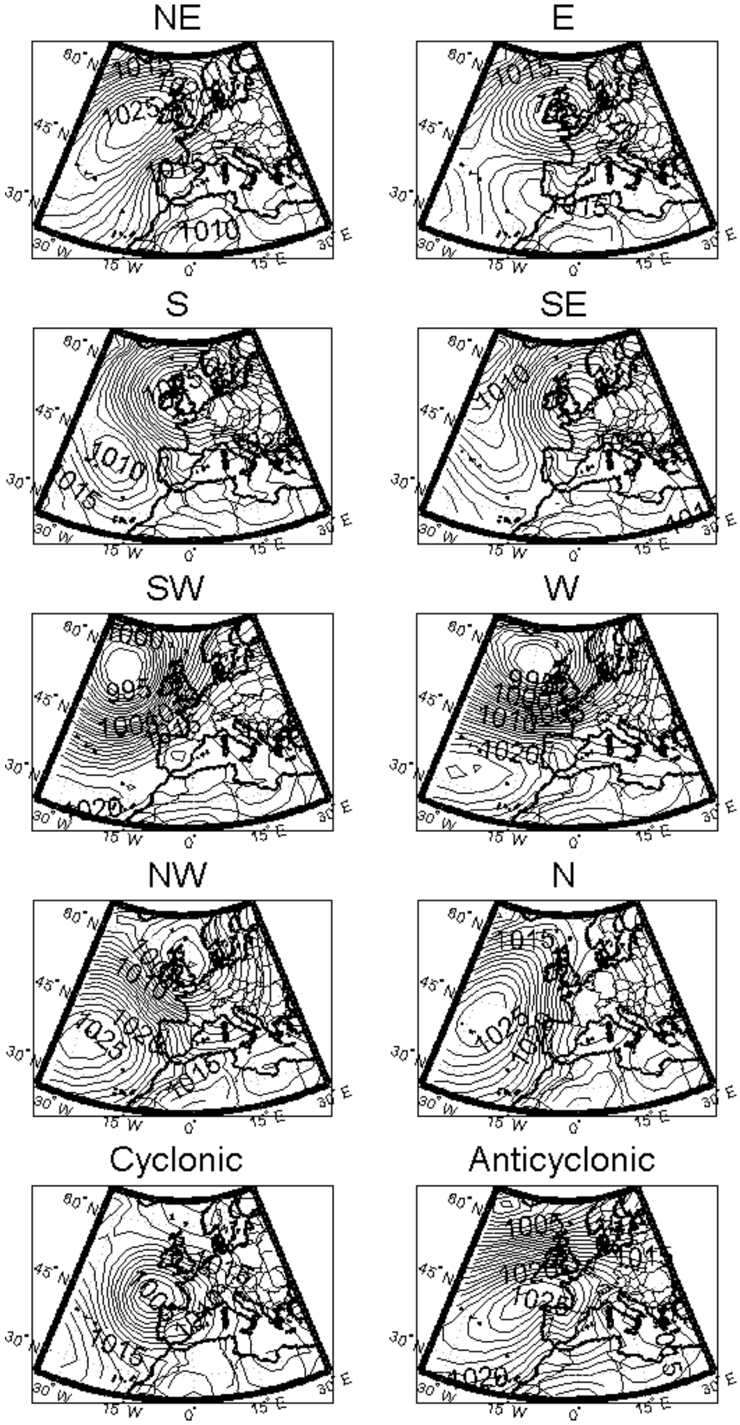

Figure 3. Annual average SLP fields characteristic of the 10 basic synoptic weather types considered in the study area.

same place as in E cases, but low pressures become established in the North Atlantic. SE types are similar to S types, but with low pressures dominating the North Atlantic and North Africa. SW cases show a depression to the west of Ireland with a large anticyclone over the Iberian Peninsula and the rest of Europe. W cases are characterized by depressions over the North Atlantic and the north of Europe, with high pressures over the Azores. The weather type of NW is responsible in winter for polar maritime air reaching the northwest of the Iberian Peninsula, while *N* cases approach arctic maritime masses of air to the area under study. Both NW and N types present large depressions established in Scandinavia and high pressures in the Atlantic, north of the Azores. Cyclonic and anticyclone types show low and high pressures, respectively, both established just NW of the area under study.

Figure 4 shows the relative frequency of each synoptic weather type for every month of the year. Anticyclone cases are the most frequent in any month of the year, with maxima occurring in the summer months. By contrast, cyclone types have a maximum in May; followed

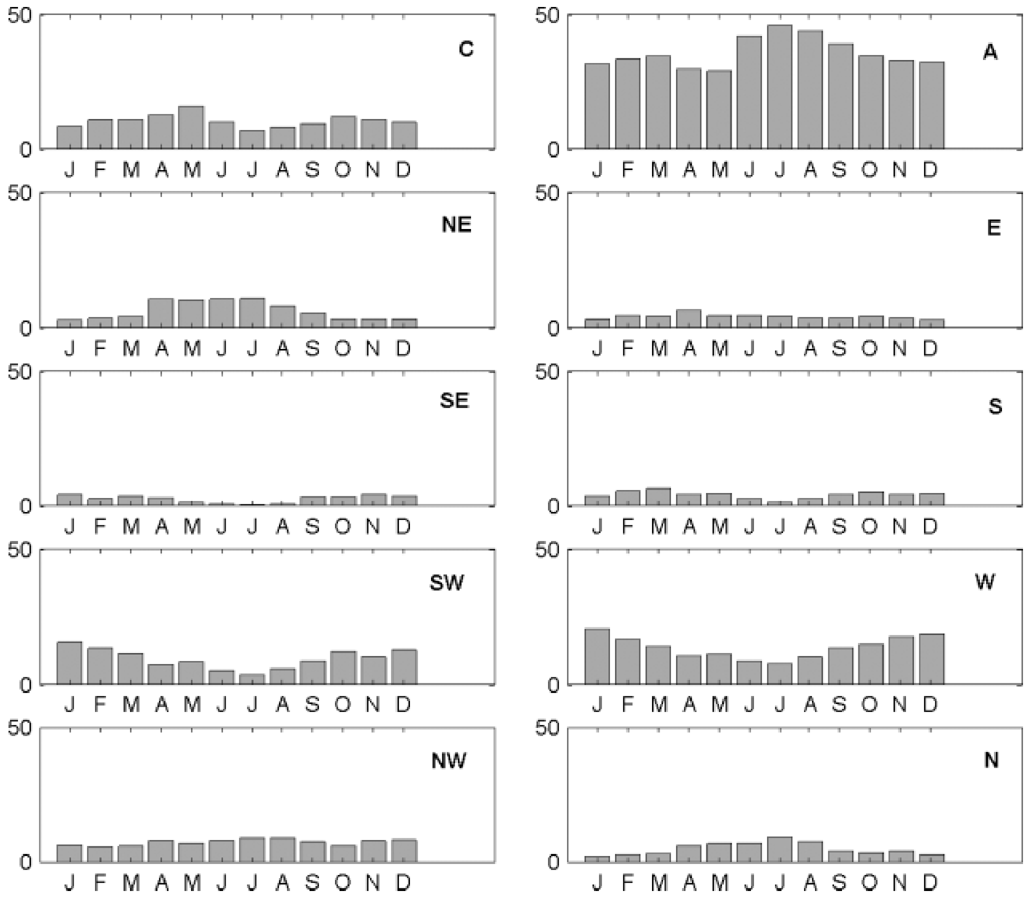

Figure 4. Mean monthly frequency percentage of the synoptic weather type for each month.

by a secondary maximum in October. This means that these weather types tend to appear in spring and autumn. However, the frequency of their occurrence is not negligible at any period throughout the year. The NE cases show a maxima in spring and summer, while they are almost irrelevant in autumn and winter. The E, SE and S types occur with a very low frequency throughout the year. The SW and W cases follow the same behaviour, with maxima in autumn and winter, showing a seasonal behaviour opposite to NE type. Finally, the NW type tends to appear with a similar frequency in all months. The N cases show a maximum in summer.

We have made a comparison between the different weather types found with our grid, with the grid used by Trigo and DaCamara (2000) and with the ones obtained by James (2006) where daily-mean 500 hPa geopotential height field and daily-mean, mean-sea-level pressures are used to calculate the different weather types. In this last method, a grid similar to our grid centered in the point 44 °N, 8 °W was used. In this comparison, we observed variations between the different types and in their ability to represent the rainfall in the area of study. In Figure 5 we can see the rainfall explained by each weather type obtained with the three methods for the common period from 1950 to 2005; the calculations were carried out with the precipitation data of the Lourizán station (Section 2). The results show the importance of the grid location and the method used to compute the weather types. If we look at the rainfall explained by each weather type on a seasonal scale, we can appreciate that the method of Trigo and DaCamara, 2000 with the grid displaced 5° to the north gives quantities more adapted to the local climatology than the other two approaches. Thus in winter SW, W explain more rain than C types, due to the location of Galicia to the north of Portugal, more exposed to the winter Atlantic lows travelling at latitude north of the Iberian peninsula. This difference is maintained more or less all along the year. Note how the effect of a displacement of the grid is bigger than the effect due to the introduction of a new variable in the calculations of the weather types.

4. Results and discussion

4.1. Relationship between rainfall and synoptic weather types

In order to demonstrate the ability of each synoptic weather type to represent rainfall in Galicia, we considered the Lourizán station to be a point that is representative of the precipitation in the northwestern part of the Iberian Peninsula. This station has a large series of data that underwent a quality control procedure with substitutions made for poor quality and some missing data, similar to the one used in the NCDC (National Climate Data Center, NOAA) for GHCN (Global Historical Climate Network) database (Peterson *et al.*, 1998).

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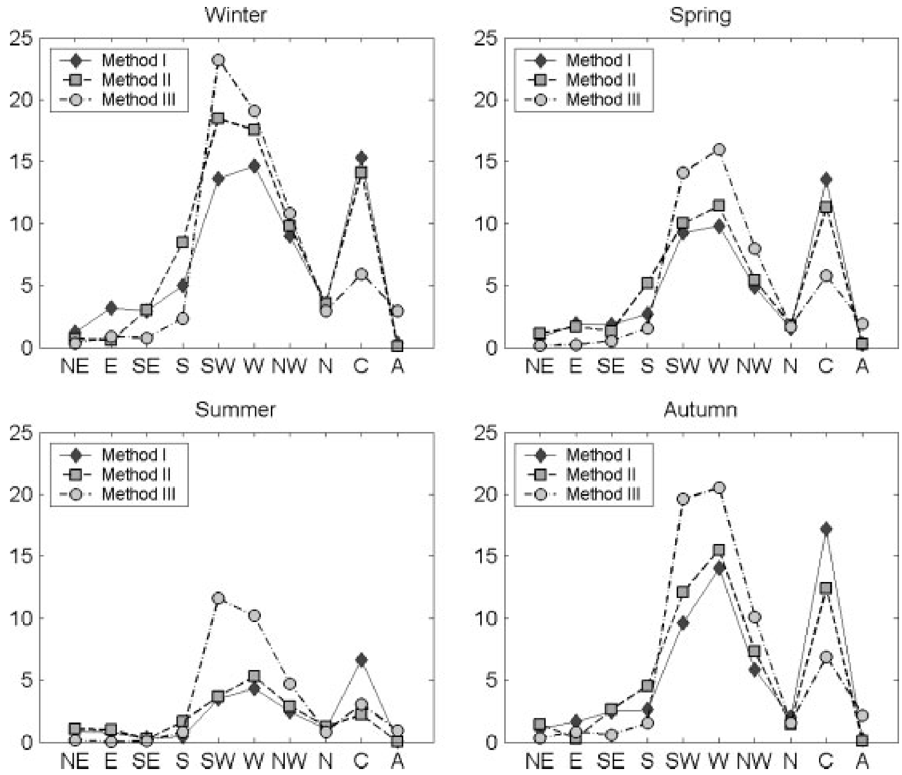

Figure 5. Rainfall explained by each weather type at a seasonal scale, depending on the method of calculation and the grid position between 1950 and 2005. Method I correspond to calculations made with weather types found with our grid, method II with the weather types obtained by James 2006 and method III represent the results obtained with the weather types calculated by Trigo and DaCamara (2000).

Quality control for this station gave a result of only 0.01% of missing data and 90% of correlation with neighbour stations. Figure 6 shows the correlation between the variability in precipitation of Lourizán station, and the variability in precipitation of the chosen area (data from the GPCP), between December of 1979 and December of 2004. The figure shows that the precipitation data from Lourizan station is representative of the precipitation within the area considered for evaluating the impact of the synoptic weather types.

We calculated the average rainfall explained by each weather type, considering the entire year and each season (Table I). For the whole year, it is evident that there is a correspondence between synoptic characteristics and the average rainfall induced by each weather type. Thus, the cyclonic type is a synoptic situation that produces more rain, followed by W and SW cases. By contrast, northern and eastern types induce less rainfall and the anticyclone pattern induces any conditions with virtually no rain. This situation is maintained if we consider each season separately. Those results are in agreement with recent results (Santos *et al*., 2005) relating to large-scale atmospheric flow with wintertime rainfall. These authors show that over northern Portugal the C regime is particularly meaningful.

From the daily rainfall data, we constructed five categories of rainfall magnitude: no rain, light rain, moderate, intense and very intense, following the method adopted in previous works (Osborn *et al*., 2000; Osborn and Hulme, 2002; Gallego *et al*., 2006). This classification was done

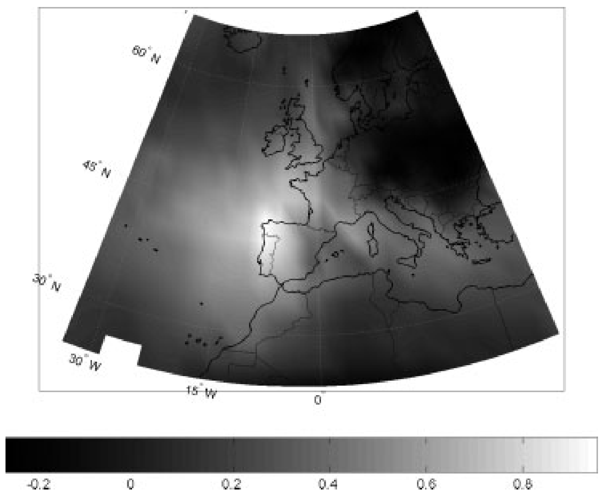

Figure 6. Correlation value between the monthly precipitation data of Lourizán station in Galicia and the monthly precipitation data of the study area obtained with GPCP covering the period December 1979–December 2004.

(1) taking into account the whole year and (2) separately for each season. The definitions of each category are presented in Table II.

Using this classification, we analyzed the contribution of each synoptic weather type to the different categories of precipitation. As we can see from Figure 7(a), for the whole year, Cyclonic, W and SW regimes are responsible for the vast majority of very intense precipitation event, with smaller contributions from NW and S types. The

Table I. Average rainfall explained by each weather type at the annual and seasonal scales.

Tipo	Annual	Winter	Spring	Summer	Autumn
NE	0.91	1.22	0.77	0.87	1.06
E	1.86	3.18	1.94	0.74	1.69
SE	2.36	2.94	1.82	0.33	2.45
S	3.02	5.00	2.70	0.43	2.61
SW	10.31	13.64	9.26	3.48	9.61
W	11.80	14.63	9.79	4.35	14.05
NW	5.37	8.99	4.86	2.43	5.86
N	1.70	3.47	1.57	1.05	2.01
C	13.41	15.34	13.57	6.63	17.22
A	0.21	0.31	0.28	0.08	0.21

Anticylonic, E, NE, SE and S weather types induce no precipitation for most of the time. Moderate and intense episodes follow a distribution similar to that found for very intense ones, while light rains are explained almost equally by all weather types. If we consider these classifications for each season (Figure 7(b)), we can see that the very intense episodes occur mostly in autumn and winter, but that a significant number occur in spring. In summer, Anticyclonic situations are the predominant weather type, but even in summer, Cyclonic and W situations induce a significant percentage of very intense rain episodes.

4.2. Relationship between synoptic weather types and different regional circulation indices

The next step was to compute the correlation coefficient between different circulation indices and the various weather types. In the Atlantic area of the Northern Hemisphere, the NAO is the dominant pattern of atmospheric circulation variability. Other teleconnection patterns that appear in the Northern Hemisphere (Barnston and Livezey, 1987) are the Scandinavian Pattern (SCA), the Polar/Eurasia Pattern (POL), the EA, and the (EA/WR). The NAO is the most important one in our area, but the EA, EA/WR and SCA are also significant – Lorenzo and Taboada, 2005 and DeCastro *et al*., 2006, found that winter rainfall in Galicia is explained mainly by four indices (NAO, EA, EA/WR and SCA). The influence of four different indices, three representing north-south dipoles and another representing an east-west dipole, means that Galicia is located in an area that is subject to a wide variety of influences (Figure 2). Moreover, this influence has been shown to vary inside Galicia, establishing different areas of influence. Hence, it is necessary to compute the correlation index between the four large-scale teleconnection indices and all the defined weather types. This work has been done before for other geographical areas and considering important teleconnection patterns such as NAO, Pacific-North American (PNA) and El Niño–Southern Oscillation (ENSO), (McCabe and Muller, 2002; Sheridan, 2003).

Table III and Figure 8(a)–(d) show the results obtained for this correlation matrix on a seasonal basis. We will refer only to correlations with a statistically significant at the 99% level, printed in bold in Table III.

In Figure 8(a), we can see that in winter, the most significant correlations are found between the NAO and cyclonic and anticyclone weather types. The anticorrelation with cyclonic types means that a positive NAO index will reduce greatly the appearance of these weather patterns in winter, therefore inducing reduced rainfall. At the same time, we will experience an increment of anticyclone winter weather types. Anticorrelation with SE weather type is not very significant, because these are not very frequent in winter in Galicia. The EA also correlates positively with SW and W weather patterns, which are very common in winter and, on average, induce almost the same quantity of rain as the cyclonic weather type. Over the last few decades, the EA has seemingly followed a trend comparable with the NAO in winter (Figure 9). This is meaningful if we consider that the influence of this pattern falls on the southeast of areas of the NAO pattern. A trend to positive values of the two indices will yield fewer cyclonic types, but more SW situations, leaving the overall level of rainfall unaffected. The EA also presents negative and significant correlations with NE, N and A weather patterns. Thus, with a positive EA, winters will not be as cold. The EA/WR presents significant negative correlations with W and NW weather types. These two situations are very common in winter, particularly W types, and are the second rainiest. However, there is also a positive correlation with anticyclonic episodes. The SCA index is an east-west dipole and in the last few decades it has followed a trend opposite to that of the NAO index (Figure 9). If this behaviour is maintained in the next century, it will result in a negative SCA index and more anticyclonic weather patterns.

Table II. Definition of each category of precipitation for the different seasons and for the whole year.

Period	Light	Moderate	Intense	Very intense
Winter	0 mm < PRCP < 3 mm	3 mm < PRCP < 9 mm	9 mm < PRCP < 21 mm	PRCP > 21 mm
Spring	0 mm < PRCP < 2 mm	2 mm < PRCP < 6 mm	6 mm < PRCP < 15 mm	PRCP > 15 mm
Summer	0 mm < PRCP < 1.5 mm	1.5 mm < PRCP < 4 mm	4 mm < PRCP < 10 mm	PRCP > 10 mm
Autumn	0 mm < PRCP < 2 mm	2 mm < PRCP < 8 mm	8 mm < PRCP < 19 mm	PRCP > 19 mm
Annual	0 mm < PRCP < 2 mm	2 mm < PRCP < 7 mm	7 mm < PRCP < 17 mm	PRCP > 17 mm

PRCP is precipitation per day.

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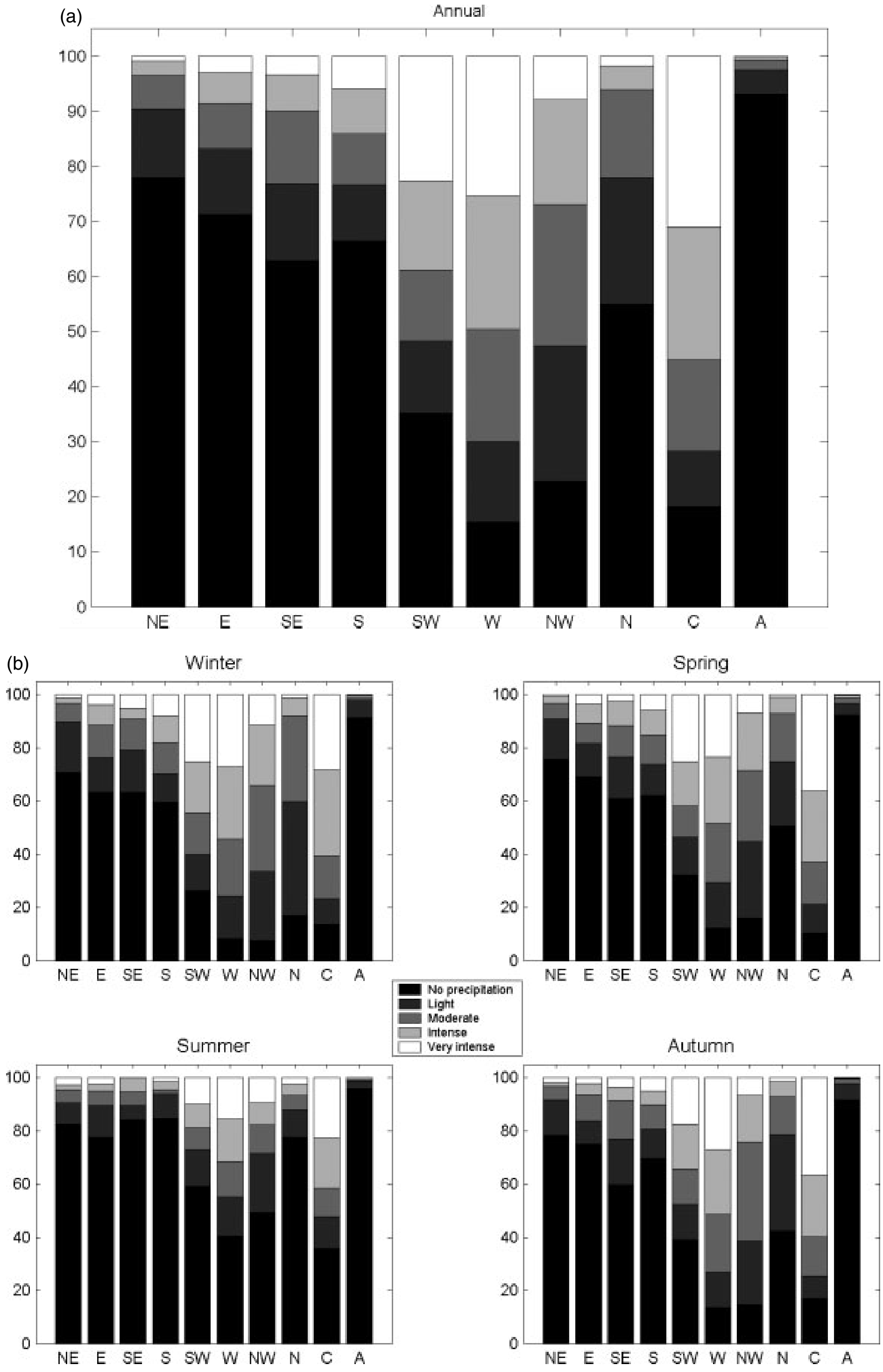

Figure 7. Contribution of each synoptic weather type to the different categories of precipitation: (a) annual. (b) for each season.

In Figure 8(b), we can see that in spring, the NAO does not have any correlation with statistically significant trends at the 99% level with synoptic weather types. The EA pattern presents a negative correlation with NE and E situations and positive with SW weather types. Hence, a positive EA index will translate into a spring with more rain in Galicia. There are also positive correlations of the EA/WR with SW weather patterns. The SCA presents a significant positive correlation with cyclone weather types. This positive correlation is explained because in spring, the positive phase of SCA pattern shows a marked low centre on the Iberian Peninsula.

In Figure 8(c), the greatest correlation in summer seems to be between the EA pattern and E weather types, but E patterns appear only with a frequency of 3%. As expected, anticyclone weather types are the most frequent patterns in summer and appear with a frequency of 44%. The highest correlation value considering this synoptic situation is negative with the SCA. There is also a positive correlation between the NAO and the

Table III. Correlations between the teleconnection patterns and the frequency of synoptic weather types for each season. (Values in bold represent correlations with a statistically significant at the 99% level).

Winter	NE	E	SE	S	SW	W	NW	N	C	A
NAO	−0.05	−0.26	**−0.40**	−0.24	0.04	0.25	−0.10	−0.10	**−0.59**	**0.46**
EA	**−0.39**	−0.01	0.06	−0.01	**0.50**	**0.34**	−0.18	**−0.45**	0.16	**−0.43**
EA/WR	0.03	0.15	0.30	0.31	0.04	**−0.42**	**−0.57**	−0.07	−0.19	**0.39**
SCA	0.17	0.08	−0.17	−0.02	0.15	0.17	0.19	0.06	0.25	**−0.42**
Spring	NE	E	SE	S	SW	W	NW	N	C	A
NAO	−0.13	0.05	0.03	−0.09	−0.07	−0.08	0.11	−0.16	0.02	0.17
EA	**−0.43**	**−0.35**	−0.08	−0.16	**0.41**	0.24	0.09	−0.08	0.17	0.04
EA/WR	−0.20	0.03	0.15	0.03	**0.39**	−0.04	−0.08	−0.27	0.07	−0.02
SCA	0.16	−0.30	−0.13	−0.15	−0.02	0.04	0.21	0.12	**0.39**	−0.25
Summer	NE	E	SE	S	SW	W	NW	N	C	A
NAO	**0.37**	0.24	−0.05	0.20	−0.05	−0.27	−0.32	0.06	0.10	−0.18
EA	**−0.33**	**−0.53**	0.09	0.00	0.23	0.21	0.23	−0.13	−0.15	0.30
EA/WR	0.04	0.18	−0.11	−0.02	0.11	0.00	−0.06	−0.23	0.21	−0.13
SCA	0.20	0.21	−0.09	0.12	−0.11	−0.23	0.08	0.19	0.22	**−0.35**
Autumn	NE	E	SE	S	SW	W	NW	N	C	A
NAO	0.16	−0.02	−0.01	−0.07	−0.23	−0.20	−0.02	0.05	−0.20	0.31
EA	**−0.41**	−0.29	−0.22	0.01	**0.40**	**0.38**	0.29	−0.22	−0.06	−0.17
EA/WR	−0.19	**0.48**	0.27	**0.33**	−0.12	−0.23	−0.29	−0.05	**0.34**	−0.10
SCA	0.03	−0.31	−0.24	−0.16	0.08	0.32	0.52	0.32	0.27	**−0.51**

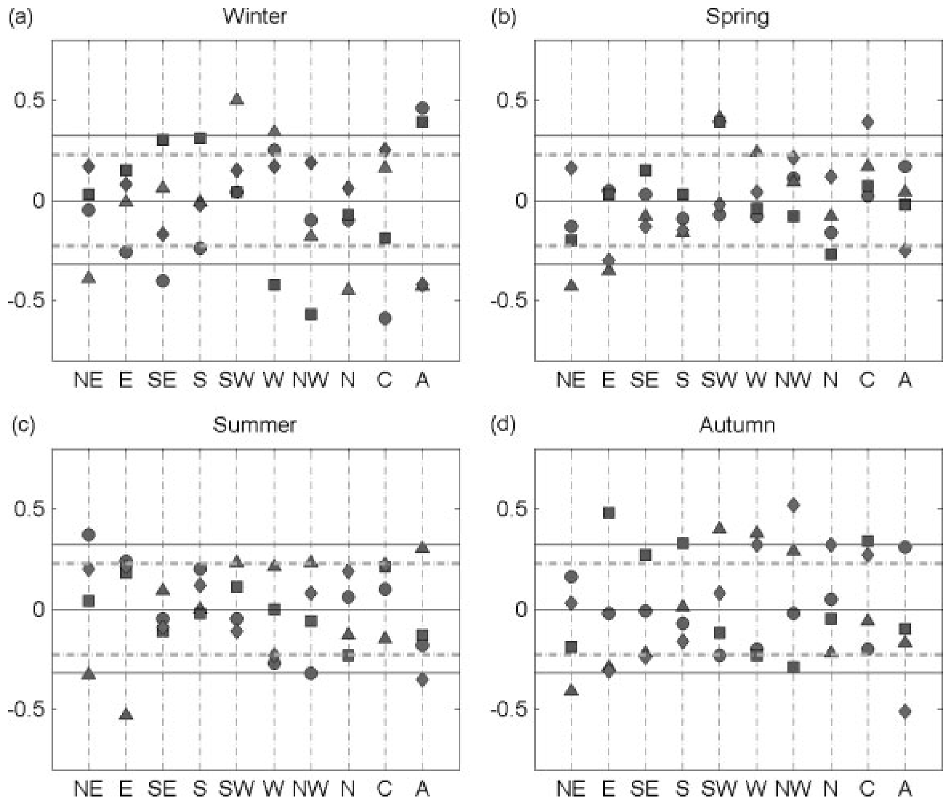

Figure 8. Correlations of NAO (circles), EA (triangles), EA/WR (squares) and SCA (diamonds) with the different synoptic weather situations for the different seasons. The dashdot horizontal lines correspond to correlations statistically significant at the 95% level and the solid horizontal lines correspond to correlations statistically significant at the 99% level.

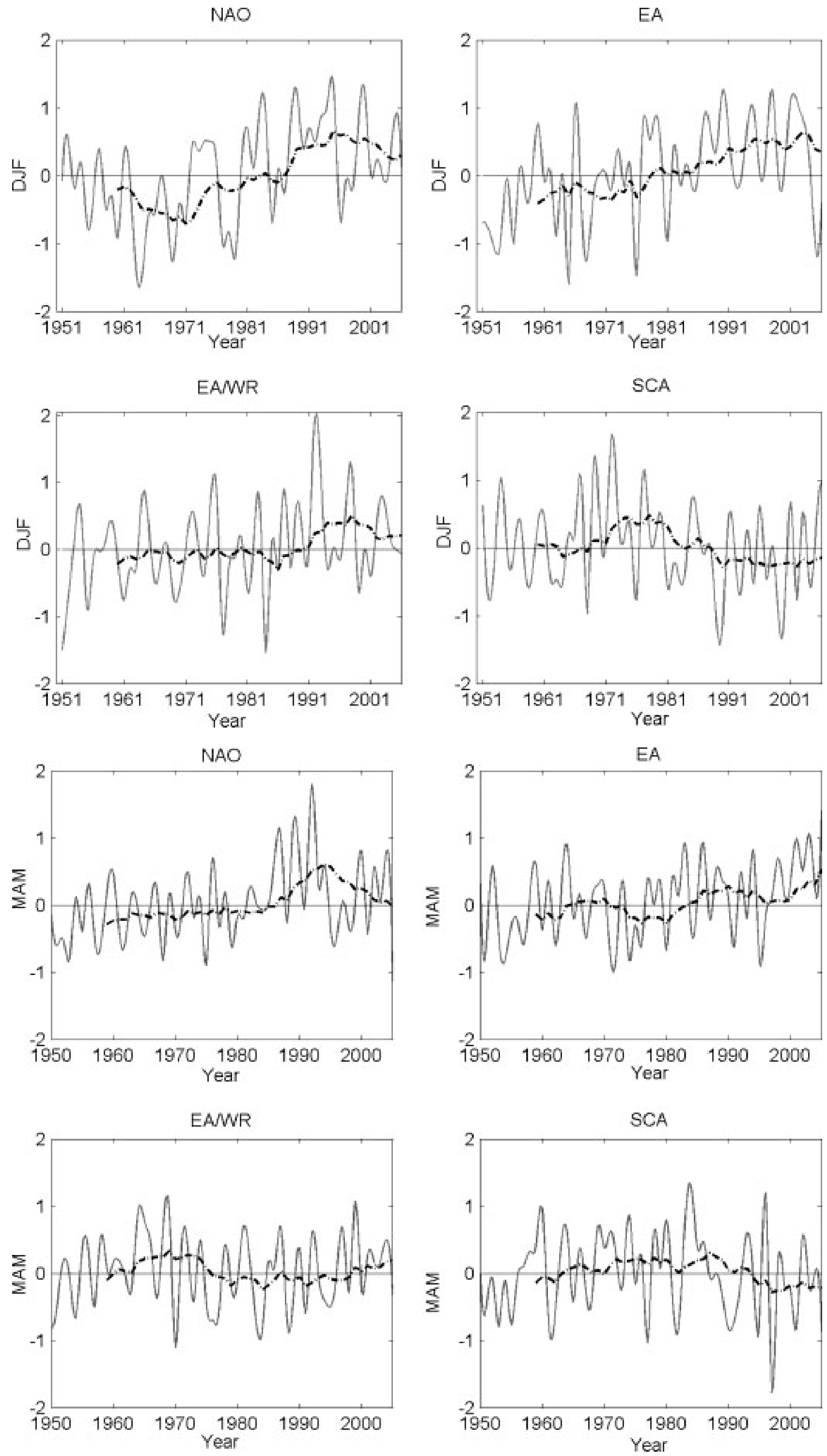

Figure 9. Behaviour of the different teleconnection patterns in winter (DJF), spring (MAM), in summer (JJA) and autumn (SON). Dashed lines indicate the 10-year moving average for the period 1950–2005.

NE weather type and negative between the EA and NE weather patterns.

In Figure 8(d) it is important to consider that the SCA has the greatest (negative) correlation with the anticyclone type, the most frequent pattern in this season. There is also a significant positive correlation between the EA and SW-W weather patterns, resulting in more rain if the EA index is positive. The correlation of the EA with NE patterns is negative. Finally, the EA/WR presents a strong positive correlation with E weather types, and significant and positive correlations with C and S weather patterns. The strong positive correlation between EA/WR and E weather types can be explained because of the high pressure centre settled over the north of the Iberian Peninsula in the positive phase of this pattern in autumn, while significant correlations with C and S weather types

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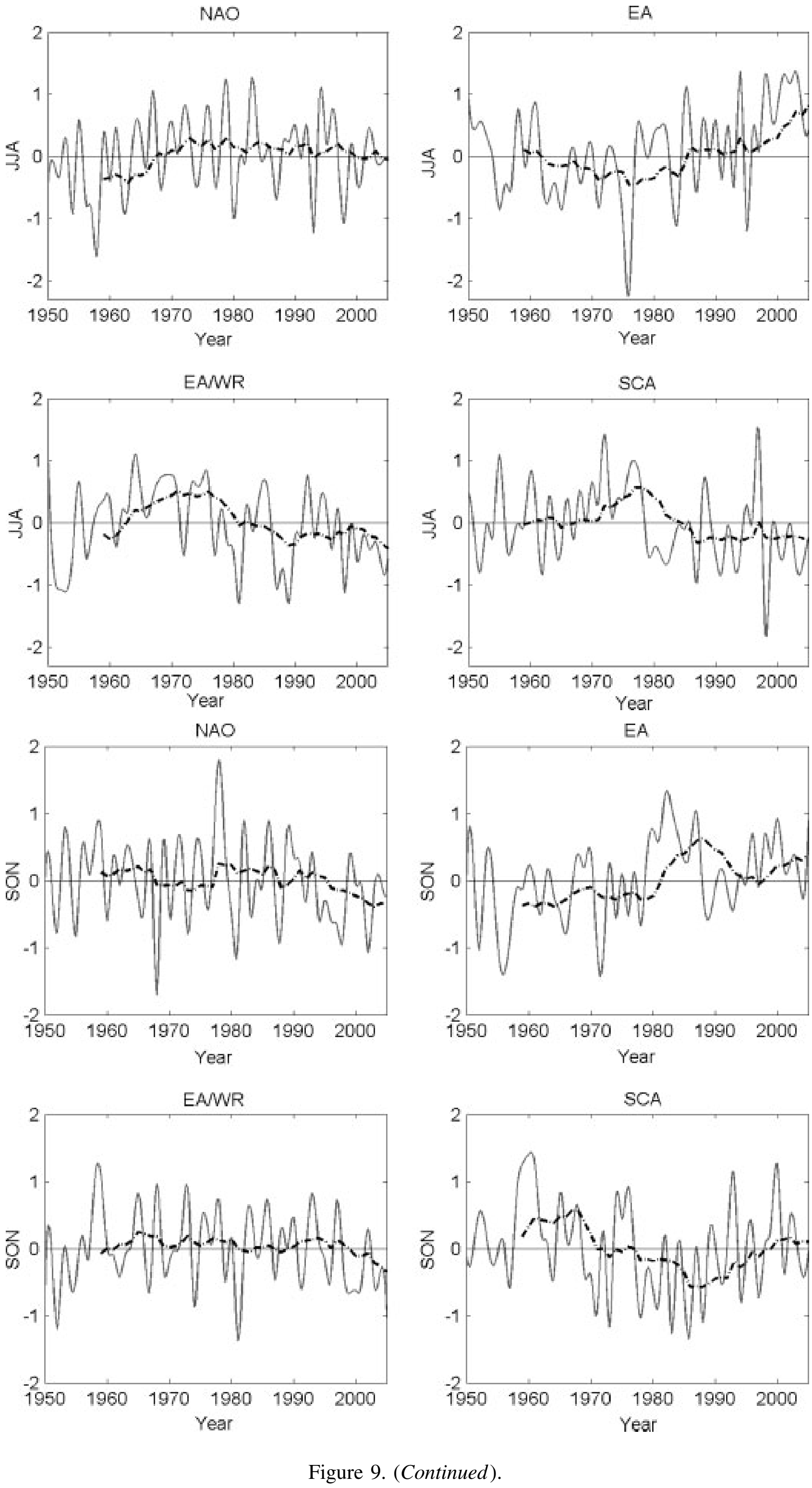

Figure 9. (*Continued*).

are provoked by the low pressure that dominates the Azores area.

We have also studied the behaviour of the different teleconnection indices over the last 56 years (Figure 9). As was mentioned above, it is possible to determine that in winter, the shifts of the index at the decadal scale are in phase. The NAO, EA and EA/WR were predominantly in their positive phases during the 1990s, while the SCA was in its negative phase during this decade. This tendency is not maintained throughout the rest of the year. Thus, in spring the NAO and EA show similar tendencies as in winter, but the EA/WR and SCA do not present any tendency. In summer, the NAO does not present any decadal oscillation. The EA changed from having negative values prior to the 1980s to positive values later, while the EA/WR and SCA have the opposite trend. Finally, in autumn, the NAO, EA/WR and SCA do not present any marked tendencies, while the EA changed

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from having negative to positive values in the 1980s. The EA is the only teleconnection pattern that maintains the same tendency throughout the year.

4.3. Relationship between synoptic weather types and different global circulation indices

In addition to studying regional patterns, we considered the correlations between the frequency of the synoptic weather types and the most known global patterns: the ENSO, the Northern Hemisphere Annular Mode (NAM), the Quasi-biennial Oscillation (QBO) and the Circumglobal Teleconnection pattern (CGT). The CGT was mentioned for the first time in Ding and Wang, 2005. It is a pattern that takes place in the summertime mid-latitude circulation of the Northern Hemisphere. The QBO dominates the variability of the tropical troposphere (Baldwin *et al*., 2001). The ENSO is also a tropical teleconnection, which takes place in the Pacific. However, some studies have found influences of this pattern on the Iberian Peninsula (e.g. Rodo *et al*., 1997). The NAM can be defined as a teleconnection pattern all over the Northern Hemisphere. In 1998, Thompson and Wallace introduced the hypothesis that the NAO is the local manifestation of a global pattern called the North Hemisphere Annual Mode (Thompson and Wallace, 1998). This Annular Mode is the result of the coupling between stratospheric polar vortex and tropospheric circulation. Previous studies had found a correlation between the strength of the polar stratospheric vortex and geopotential anomalies in the middle troposphere in the North Hemisphere. Hence, it is expected that NAO ought to have a significant influence on WT in the area under study.

With the ENSO, we used three different indices: the Southern Oscillation Index (SOI), the NINO-SST, and the Multivariate ENSO Index (MEI) to take into account the atmospheric part of the pattern, the oceanic part, and a mix of the two, respectively. We found no significant correlation with any of these indices. The Quasi-Biennial zonal wind Oscillation only showed a significant correlation in winter, with the cyclone situations. On the other hand, the QBO in summer influences W situations in autumn. With the CGT, which is present only in summer, we found no significant correlation with any weather type. From this, we may conclude that the influence of these three patterns (ENSO, QBO and CGT) is small in the determination of the frequency of appearance of the different weather types throughout the year over the region under study.

With the NAM, we found significant correlations with both cyclone and anticyclone types in winter, spring and autumn. These last two cases are particularly interesting because they were not observed with the NAO, the regional manifestation of the NAM on the Atlantic area. We also found significant correlations in summer with NE and NW and in winter with NW situations. Table IV shows the values of these correlations. The correlations with a statistically significant at the 99% level are printed in bold.

5. Conclusions

We adapted the Lamb weather type classification scheme and applied it to Galicia, a region located in the northwestern corner of the Iberian Peninsula, following the work of Trigo and DaCamara, 2000 with a displacement of 5° to the north in the SLP calculation points after making a comparative study between different grids and method to calculate the weather types. The more important results are as follows:

- The anticyclone weather type is the most frequent pattern throughout the year. Western and southwestern types have also an important frequency of appearance in autumn and winter.
- Cyclonic, western and southwestern are the weather types that explain the most important quantity of rain throughout the year.
- Correlation values between teleconnection indices and the monthly frequencies of different weather types show that the EA pattern has significant correlations in all seasons. Of particular importance is the positive correlation with W and SW weather types, which explains the tendency for increasing rainfall in spring, summer and autumn when comparing the 1960–1977 and 1990–2005 periods. In winter, this tendency is balanced by the tendency of the NAO pattern to be in its positive state in the last two decades, which implies a greater occurrence of anticyclone situations and a lesser occurrence of cyclonic ones, which in turn has resulted in reduced rainfall in winter.
- Thus, the inter-annual variations in the frequency of the main weather types (W, SW, C, A) is determined to a great extent by the EA pattern in spring, summer and autumn, which makes this pattern a very prominent atmospheric mode of variation in Galicia.
- The NAM has significant correlations in winter, spring and autumn with cyclones and anticyclones, which are

Table IV. Correlations between the NAM and the frequency of synoptic weather types for each season (values in bold represent correlations with a statistically significant at the 99% level).

NAM	NE	E	SE	S	SW	W	NW	N	C	A
Winter	−0.01	−0.14	−0.14	0.07	0.10	−0.11	**−0.38**	−0.23	**−0.53**	**0.57**
Spring	−0.17	0.26	−0.14	−0.18	−0.06	−0.03	−0.06	−0.04	**−0.33**	**0.38**
Summer	**0.36**	0.13	−0.07	−0.05	−0.03	−0.22	**−0.36**	−0.03	0.10	−0.03
Autumn	0.10	0.08	0.22	0.06	−0.21	−0.20	−0.25	0.00	**−0.32**	**0.38**

the most common weather types. This being so, the NAM achieves greater relevance.

From these results, we may conclude that with four regional large scale atmospheric modes (NAO, SCA, EA and EA/WR) and one hemispheric mode (NAM) it is possible to explain the variability of the main synoptic weather types on Galicia. In turn, these synoptic weather types allow us to explain the variability of rainfall in the northwestern corner of the Iberian Peninsula. Moreover, the relationships between atmospheric circulation and synoptic weather types found here do not simply improve our understanding of inter-annual variations in the rainfall of the region. Eventually, we could also establish a forecast system using the predictability of the atmospheric teleconnection patterns; and using the CDC reforecast dataset (a dataset of 15 ensemble forecasts from 1979 to 2005, which is made with a version of the NCEP MRF 1998 model), we can attempt to shed light on the prediction of frequency of the synoptic weather types for a period valid in climatological time. This forecast system would allow us to elaborate special plans related mainly to the water resources in the region.

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