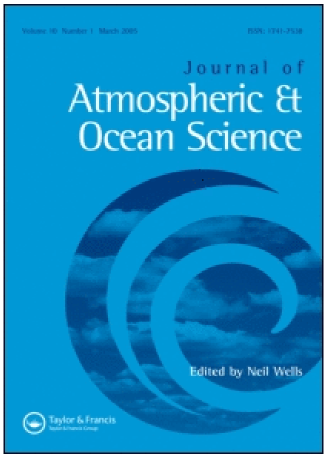

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Influences of atmospheric variability on freshwater input in Galician Rías in winter

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The influence of the preferred modes of variation of the atmosphere in the North Hemisphere on the precipitation variability was evaluated in Galicia (NW Iberian Peninsula). The special location of Galicia requires consideration of the influence of several indices that characterize the atmosphere in order to explain the variability of precipitation and consequently the flow regime of its rivers. We calculate the correlation between the precipitation data obtained from 47 rain-gauge stations covering Galicia from 1977 to 1998 and the five principal teleconnection patterns on the Atlantic area of North Hemisphere (NAO, EA, EA/WR, SCA, and POL). The results obtained show significant correlations between winter precipitation and these patterns, and clear spatial distribution of their influence within Galicia. This result could be related directly to the freshwater discharge in the different Galician Rías each winter, which would improve the hydrodynamical description of these estuaries.

Keywords: Atmospheric variability; Precipitation; Teleconnection patterns; Galicia (NW Spain)

1. Introduction

Estuarine circulation has been the subject of many studies in the last decades because of its main impacts: economical, societal, and environmental (Jones and Millward 2002, and references therein). As a boundary area between the open sea and mainland, estuaries have oceanic and terrestrial influences. To explain its circulation, it is necessary to take into account tidal movements, wind driven currents, and stratification. A main source of stratification comes from the freshwater input of the rivers. This input depends directly upon precipitation. Moreover, freshwater discharge is necessary for an understanding of the physicochemical characteristics of waters along the Iberian continental margin. Their influence can be very important for an understanding of transport in the rainy season. Thus, the presence of strong river plumes in winter was relevant at the time of Prestige oil spill in November–December 2002 (Ruiz-Villareal *et al.* 2006). Moreover, river plumes induce gradients and fronts in seawater that can be related to the well-known

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enhanced productivity of the Atlantic coast associated with the northern part of the Eastern North Atlantic coastal upwelling system (Bode *et al.* 2002).

Galicia is a region characterized by a complex terrain and a great number of short rivers that rise in the mountains in the middle part of Galicia and flow into the Rías, or directly into the ocean. Rivers that flow into the Cantabrian Sea are the shorter ones, due to the location of an east–west range called "O Xistral" near the coast. The most important river of Galicia is the Miño river, whose length is 307 km and in its final part serves as a natural border between Spain and Portugal. Nevertheless, the northwestern part of the Iberian Peninsula is affected by cold fronts associated with low-pressure systems traveling from the north Atlantic, producing between 1000 and 2000 mm of annual precipitation. This quantity of precipitation provokes an increase of river flow, mainly in winter, and freshwater input into the Rías and directly into the ocean.

Several studies point out that the variability of the precipitation has a strong relationship with the main atmospheric circulation modes and therefore, they will have also influence on the river flow regime.

Although the atmosphere can be considered at certain scales as a chaotic system, as a reflection of its internal dynamics some large-scale patterns arise, characterized by the teleconnection indices. In the Atlantic area of the North Hemisphere, NAO (North Atlantic Oscillation) is the dominant pattern of atmospheric circulation variability. Other teleconnection patterns appearing in this area in winter (Barnston and Livezey 1987) are: EA (East Atlantic), EA/WR (East Atlantic/Western Russia), SCA (Scandinavian Pattern), and POL (Polar/Eurasia Pattern).

In this article, the goal is to correlate winter precipitation in Galicia (NW Spain) with those indices. One of the most prominent teleconnection patterns in all seasons is the NAO (Barnston and Livezey 1987). NAO combines parts of the East- and West-Atlantic patterns originally identified by Wallace and Gutzler (1981) for the winter season. It consists of a north–south dipole of anomalies, with one center located over Iceland and the other of opposite sign spanning the central latitudes of the North Atlantic between 35°N and 40°N. The positive phase of the NAO reflects below-normal heights and pressure across the high latitudes of the North Atlantic and above-normal heights and pressure over the central North Atlantic, the eastern United States and western Europe. The negative phase reflects an opposite pattern of height and pressure anomalies over these regions. Both phases of the NAO are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport (Hurrel 1995). These in turn result in changes in temperature and precipitation patterns often extending from eastern North America to western and central Europe.

The SCA consists of a primary circulation center over Scandinavia, with weaker centers of opposite sign over western Europe and eastern Russia/western Mongolia. The SCA has been previously referred to as the Eurasia-1 pattern by Barnston and Livezey (1987). The positive phase of this pattern is associated with positive height anomalies, sometimes reflecting major blocking anticyclones, over Scandinavia and western Russia, while the negative phase of the pattern is associated with negative height anomalies in these regions.

The EA pattern is the second prominent mode of low-frequency variability over the North Atlantic, and appears as a leading mode in all months. The EA pattern is structurally similar to the NAO, and consists of a north–south dipole of anomaly centers spanning the North Atlantic from east to west. The anomaly centers of the EA pattern are displaced southeastward to the approximate nodal lines of the NAO pattern. For this reason, the EA pattern is often interpreted as a southward-shifted NAO pattern. However, the lower-latitude center contains a strong subtropical link in association with modulations in the subtropical ridge intensity and location. This subtropical link makes the EA pattern distinct from its NAO counterpart. This EA pattern is similar to that shown in the Barnston and Livezey (1987) study, but is distinctly different from the EA pattern originally defined by Wallace and Gutzler (1981).

The EA/WR pattern is one of three prominent teleconnection patterns that affects Eurasia throughout year. This pattern has been referred to as the Eurasia-2 pattern by Barnston and Livezey (1987). The EA/WR pattern consists of four main anomaly centers. The positive phase is associated with positive height anomalies located over Europe and northern China, and negative height anomalies located over the central North Atlantic and north of the Caspian Sea.

Finally, the POL pattern appears in all seasons. The positive phase of this pattern consists of negative height anomalies over the polar region, and positive anomalies over northern China and Mongolia. This pattern is associated with fluctuations in the strength of the circumpolar circulation, with the positive phase reflecting an enhanced circumpolar vortex and the negative phase reflecting a weaker than average polar vortex.

Variations of those indices and their correlations with precipitation and temperature values must be studied in order to characterize local weather in North Atlantic. Thus, Hurrel (1996), showed that the NAO accounts for 34% of the observed interannual variance in hemispheric extratropical temperatures, while the NAO and Southern Oscillation together explain 49%. The correlation between precipitation and the NAO for the north of Morocco attains a value of −0.64 (41% of precipitation variance explained) (Lamb and Peppler 1987) and a similar value has been obtained for Portugal (Ulbrich *et al.* 1999).

The influence of the NAO index over the Iberian Peninsula has been previously studied (Zorita *et al.* 1992, Rodo *et al.* 1997, Esteban-Parra *et al.* 1998, Rodriguez-Puebla *et al.* 2001). Thus, Zorita *et al.* (1992) have shown that the relationship between winter precipitation and NAO is more important at the south-western corner of the Iberian Peninsula than in Galicia, where the correlation is between 0.3 and 0.4. Esteban-Parra *et al.* (1998) have obtained the same correlation between NAO and winter precipitation in the northwestern part of Spain, with a greater value at the Southwest and the interior of Spain. This result is also confirmed by Rodriguez-Puebla *et al.* (2001). They have concluded that those regions of the Iberian Peninsula most affected by NAO lay from the southwest to the northeast. On the other hand, Rodo *et al.* (1997) found that correlation of SOI (Southern Oscillation Index) with seasonal winter precipitation was over 50% in the eastern part of Spain, while in Galicia this correlation shows only a weak signal. These results show that Galicia is located in a geographical area of transition subject to complex climate variations, where no single index is able to explain much of its climate variability.

However, the precipitation variability in the Iberian Peninsula, previously mentioned, produces large inter-annual variations in the river flow regime. In fact, Trigo *et al.* (2004) has shown the influence of NAO index in Iberian river flow regimes. They analyzed the temporal evolution of the correlation coefficient between the NAO index on the wet season and the river basin precipitation and river flow for three Iberian river basins (Duero, Tajo, and Guadiana).

The location of Galicia requires a consideration of the influence of other indices representing modes of variation of the atmosphere in the Northern Hemisphere in order to explain the variability of precipitation and consequently to explain the flow regime of its rivers. If a significant correlation between the precipitation and these patterns is found, we could establish a relationship between the atmospheric variability and the freshwater input into Galician Rías in winter.

2. Data

In this work, we have used values of precipitation between 1977 and 1998 from 47 stations of the National Institute of Meteorology covering Galicia (figure 1) from the database CLIMA of the University of Santiago de Compostela (table 1). Precipitation was accumulated for the period December–January–February (DJF) because the influence of these teleconnection patterns are stronger in our area in winter, and river flow is maximal in this period. Only the stations with at least 80% of validated data were considered. The circulation indices, NAO, EA, EA/WR, SCA, and POL, were obtained by applying the RPCA technique (Barnston and Livezey

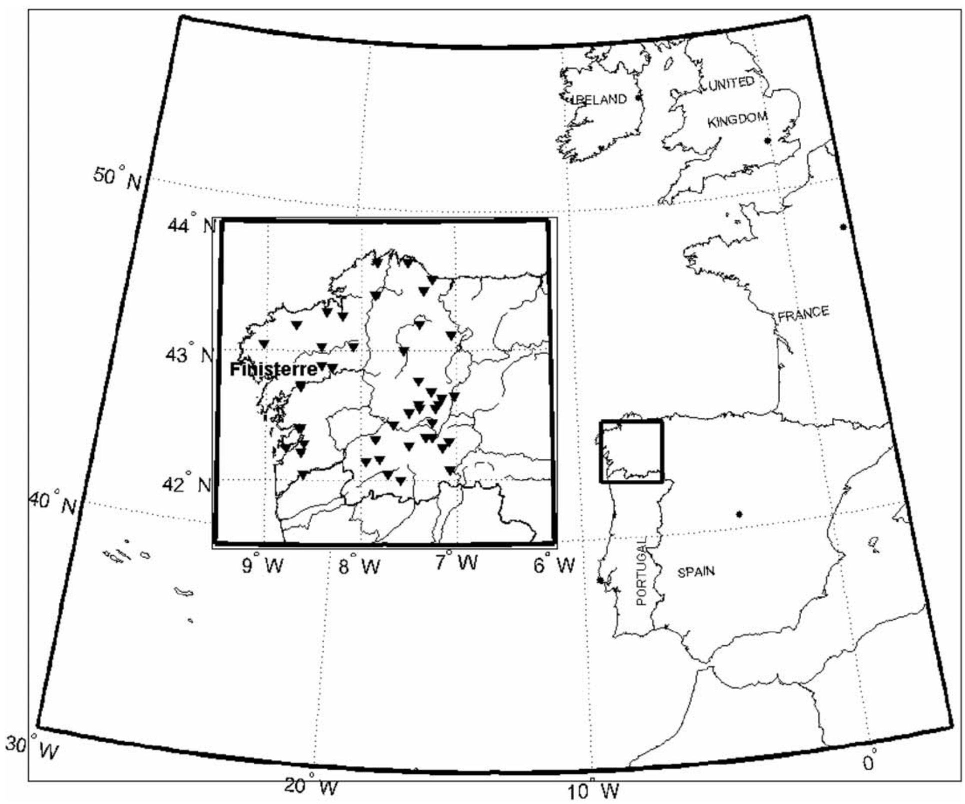

Figure 1. Location of the studied region.

Table 1. Location of the 47 rain-gauge stations used to characterized the precipitation in Galicia.

Name	Longitude (W)	Latitude (N)	Elevation (m)
ACIVEIROS	7°19	42°20	978
A CORUÑA-AEROPUERTO	8°22	43°18	103
A GUDIÑA	7°4	42°5	1440
AIRA PADRON	7°16	42°41	1100
ALLARIZ	7°48	42°10	766
AS PONTES	7°51	43°26	343
BETANZOS	8°12	43°16	38
CANGAS	8°47	42°15	30
CARBALLO	8°41	43°12	106
CASTRELO	9°2	43°3	260
CASTRO DE REI	7°23	43°12	439
CELANOVA	7°57	42°9	519
FOLGOSO DE CAUREL	7°11	42°35	612
FONSAGRADA	7°3	43°7	952
FOZ	7°15	43°33	25
HERBON-PADRON	8°38	42°44	58
LOURIZAN	8°39	42°24	60
LUGO	7°33	43°	450
MASMA	7°20	43°28	71
MONFORTE DE LEMOS 'Iberduero'	7°30	42°31	363
MONFORTE DE LEMOS 'E. Agricola'	7°30	42°31	363
MONTAOS-ORDES	8°25	43°2	306
MONTEDERRAMO	7°30	42°16	900
O BOLO	7°5	42°18	798
ORENSE	7°51	42°19	150
PARAMOS-GUILLAREI	8°36	42°3	45
PONTECESURES	8°38	42°43	20
PRESARAS	8°5	43°2	410
PUEBLA DE BROLLON	7°23	42°33	401
PUEBLA DE BROLLON 'Veiga'	7°24	42°35	400
REDONDELA	8°36	42°17	20
SALCEDO	8°38	42°24	40
SANTA MARTA DE ORTIGUEIRA	7°50	43°41	10
SAN ESTEBAN	7°40	42°26	180
SANTIAGO DE COMPOSTELA	8°25	42°53	367
SARRIA	7°24	42°46	550
SEOANE DO COUREL	7°9	42°38	661
SEQUEIROS	7°15	42°27	280
TOURO	8°18	42°52	316
TRIVES	7°15	42°20	761
VAO	7°9	42°15	711
VEIGA DE BRAAS	7°1	42°39	1150
VIGO-PEINADOR	8°38	42°13	255
VILAR DO COUREL	7°13	42°33	520
VILLADERREI	7°35	42°	657
XINZO DE LIMIA	7°43	42°3	600
XOVE	7°30	43°41	60

1987) to monthly mean 700 mb height anomalies and are available from NOAA's Climate Prediction Center (CPC, http://www.cpc.noaa.gov/data/teledoc/nao.shtml). We also averaged these monthly teleconnection indices for the period DJF.

Changes over the Atlantic and Pacific basins induce decadal-shifts in the atmospheric circulation in the Northern Hemisphere (Watanabe and Nitta 1999).

In 1976, one of those changes in the Northern Hemisphere atmosphere took place (Trenberth 1990) leading to permanent changes in the North Pacific Ocean ecosystem (Hare 2000) and also to changes in the behavior of the modes of variation of the atmosphere. To avoid shifts in the correlation values provoked by these atmospheric changes, we choose the series beginning in 1977.

3. Results and Discussions

With the previously described data we calculate the correlation between the different indices and the accumulated DJF precipitation. These correlations are significant for NAO, EA, EA/WR and SCA with a significance level that exceeds 95%, while POL has no significant correlation with winter precipitation. Averaged results (table 2) show that NAO, EA, EA/WR, and SCA index explain the main variability of precipitation in Galicia.

NAO presents the greater correlation, as it was expected for an area of the Atlantic part of Europe. Galicia is characterized by the passage of cold fronts associated with low-pressure systems traveling from the North Atlantic. The storm track in this area depends strongly on the magnitude of the NAO. Therefore, the state of the NAO in winter will make the passage of cold fronts either easier or more difficult. A positive phase of the NAO will mean that the subtropical Azores High will be strong, preventing low-pressure systems and their associated fronts, to reach Galicia from the North Atlantic.

EA and SCA also play an important role in explaining the variability of winter precipitation in Galicia as can be seen from the correlations (table 2), but with positive values. EA is a north–south dipole, with the centers of action located to the southwest of the NAO dipole. Considering that Galicia is in an area near the latitude where influences of the NAO passes from positive to negative correlations, it is clear that EA must have an important influence on winter precipitation in Galicia. The same happens if we consider EA/WR, which shows an important negative correlation due to the high-pressures center settled over the north of Iberian Peninsula in its positive phase, with a consequent decrease of precipitation over Galicia.

On the other hand, SCA is an east–west dipole. The correlation of this index shows that Galicia is located on a crossroad, between the influence of the Atlantic and that of the continent. SCA dipole has a center of action located over the Scandinavia. In the case of a positive state of the dipole, pressure over Scandinavia will be positive, forcing the storm track to approach the latitude of

Table 2. Correlation coefficients between winter precipitation and different indices.

Index	Mean	Dispersion
NAO	-0.52 ± 0.02	0.16
SCA	0.41 ± 0.01	0.09
EA/WR	-0.39 ± 0.01	0.10
EA	0.30 ± 0.02	0.11
POL	-0.14 ± 0.02	0.14

Galicia, even if NAO or EA do not favor this trajectory. Finally, the POL index presents a poor correlation with precipitation in Galicia. This index represents a north–south dipole, as is the case for the NAO and EA, but with the centers of action located north of the NAO. This location makes these variations of the index not to favor a correlation with an area located south of 40°N.

Moreover, if we look at the correlation of these indices for every station, we can find important differences in the interior of Galicia. For example, if we focus our attention on the NAO index (figure 2) it appears that the poorest correlations are obtained for the stations located in the northern part of Galicia while in the southern

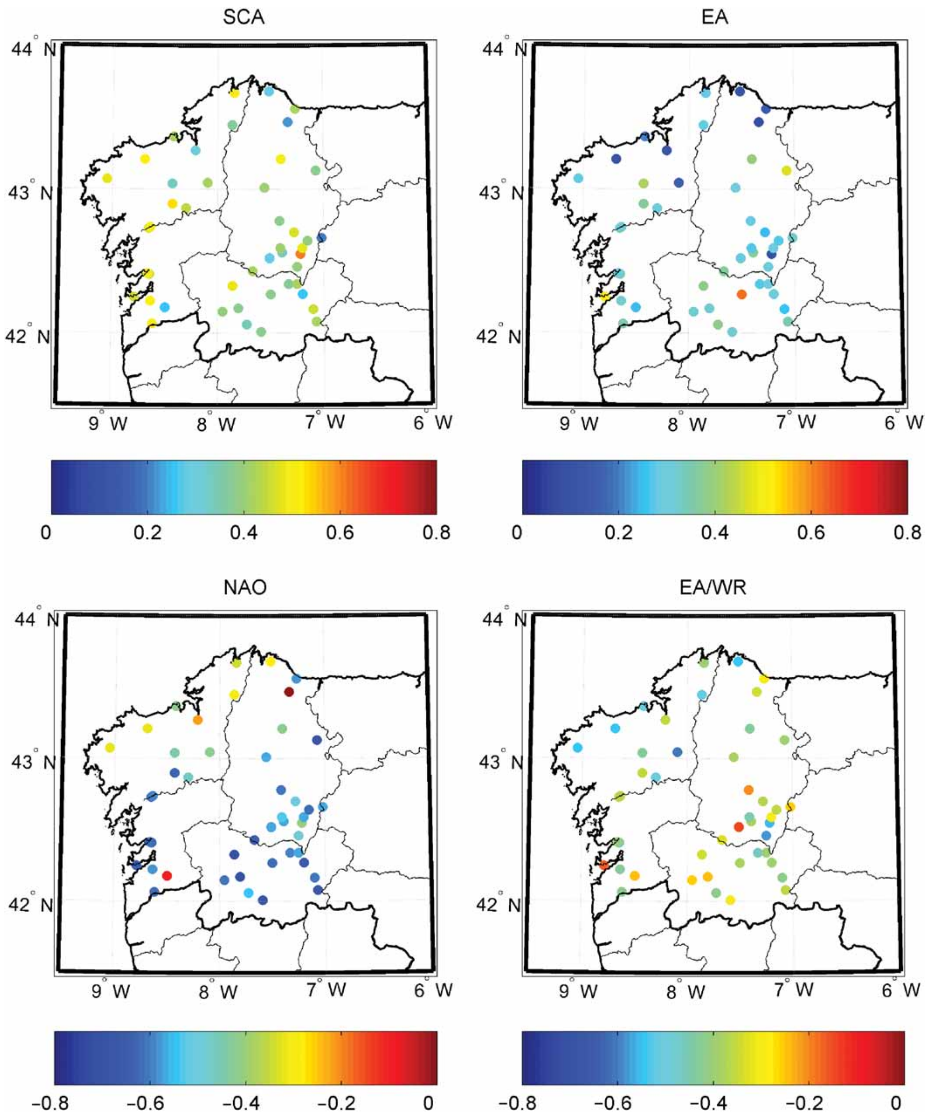

Figure 2. Correlation coefficients between the DJF teleconnection indices NAO, EA/WR, EA, and SCA and the DJF precipitation at each rain-gauge station from 1977 to 1998.

part it is possible to find values nearest −0.7. The reason could be that in the northern area, cold fronts have a weaker influence on the amount of precipitation and winter precipitation are not so sensitive to NAO variations. In the same way, analyzing the other patterns, we can see different influence of these indices inside Galicia.

The pattern of influences of EA/WR shows a negative correlation (figure 2). EA/WR in its positive phase implies the existence of high pressure located over Europe to the north of the Iberian Peninsula. This location prevents the jet stream from approaching Galicia. It passes to the north or to the south of this center leaving more precipitation in Scandinavia and the Canary Islands and dry conditions over Iberian Peninsula, explaining the negative correlation with winter precipitation in Galicia. In the case of negative phase of this index, low-pressure systems will lay to the north of Galicia, leaving a predominantly western–northwestern flow, explaining that the stations mostly affected by this teleconnection pattern in Galicia are those located on the northern coast.

The pattern of influence of the EA on Galicia is almost the same as the NAO, although now the correlation is positive. EA is also a north–south dipole, influencing the trajectory of lows on the North Atlantic. In this way, stations located in the northern part of Galicia are the least influenced by this index, while we found the greatest correlations in the southern part and in the Atlantic coast. The correlations in this case are positive because, as we have explained above, the dipole north–south that characterizes EA pattern is located to the south of the NAO dipole. In this way, a positive EA pattern means that both the subtropical high and subpolar lows in the north Atlantic are strong. The northern part of the dipole is located at a latitude between Newfoundland and Ireland in the North Atlantic. Therefore a positive EA pattern means that low pressure will dominate this area, and in this way, more cold fronts will reach Galician coasts during winter.

Finally, the SCA index presents an east–west pattern where the higher correlations are found in the western part of Galicia. The reason is that SCA influences the storm track. If the index is positive, storm track approaches Galicia, and depressions travel or become established near Galicia. This situation causes a predominantly southwest circulation, leaving more precipitation in the Atlantic area of Galicia. In this way, stations located in the western part of Galicia are more subject to the variations of SCA index, whilst the eastern ones are less sensitive to this index. As expected, correlations between winter precipitation and SCA index are positive, because SCA positive means that high-pressure is predominant over Scandinavia. This high-pressure center tends to push the storm track to the south. Moreover, a positive SCA index implies the existence of low-pressure centers over the Iberian Peninsula.

In a detailed study of these results, it is possible to establish a distribution of the influence of the modes of variation of the atmosphere in Galicia. In figure 3 we can see that EA/WR is the main index on the northern coast of Galicia from Finisterre Cap, whilst the NAO is the main index in the remaining region. On the other hand, the SCA pattern is present in the whole area of Galicia. This result is very significant because, as an Atlantic part of Europe, Galicia is believed to have the most important influence on climate variations from the NAO. However, several previous studies have highlighted that Galicia is not located inside the regions predominantly affected by this pattern (Zorita *et al.* 1992, Rodo *et al.* 1997, Rodriguez-Puebla *et al.* 2001). This apparent contradiction can be resolved by considering figure 3, because the above-mentioned works, that have studied the correlation between NAO and

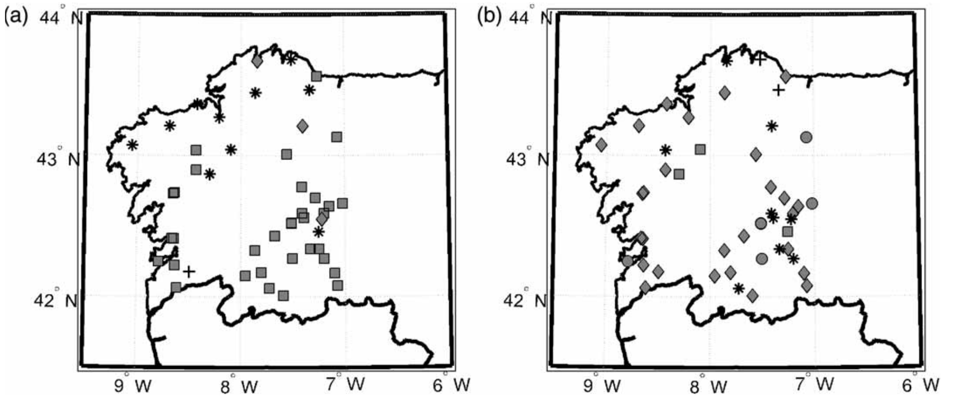

Figure 3. (a) Indices with greater influence, (b) Indices whose influence is the second highest. ■, NAO; $*$, EA/WR; •, EA; ◆, SCA; and +, POL.

precipitation in the Iberian Peninsula, have used only one meteorological station in Galicia located at La Coruña, and which falls into the region most affected by the EA/WR pattern. This introduces a bias in the results, because the rest of Galicia is affected by NAO, with correlation indices greater than previously calculated.

4. Conclusions

Galicia is located in the northwestern corner of the Iberian Peninsula and therefore is a region belonging to the Atlantic part of Europe. As expected with this location, the NAO explains a substantial portion of the low-frequency climate variability, but the special location of Galicia, located in the middle latitudes, near the region where the NAO influences changes from positive to negative values make it necessary to consider other teleconnection indices to explain the variability of winter precipitation. Thus, we have considered correlation of winter precipitation with indices that characterize different patterns of atmospheric variations in the north Atlantic area. In this way, the north–south dipole structures represented by NAO, EA/WR, and EA together with the east–west dipole represented by SCA are responsible for generating climate anomalies and modulating winter precipitation anomalies. Moreover, the influence of these indices depends on the considered areas inside Galicia. NAO is the most important one in the interior and the southern coast, while on the northern coast EA/WR present a greater influence. SCA plays a secondary role in the whole area and finally the influence of EA is also considerable, but lower than SCA. The importance of EA/WR in explaining winter precipitation variability on the northern coast of Galicia can also help to explain the lower influence attributed to NAO in previous works studying the Iberian Peninsula. These results can be applied to the study of the hydrodynamics of the estuaries in Galicia. As was shown in the introduction, rivers in Galicia are short, whose flow is dominated by precipitation. In this way, the variation of precipitation will alter the conditions of the river plume each year, and as a consequence the physicochemical characteristics of coastal waters will be different, with consequences on transport and primary production of those coastal waters. It is interesting to note that the river discharge is more important on the

Atlantic area of Galicia. In this area, NAO and SCA are indices that explain the most of the variability of precipitation, and, for this reason, future studies on the interannual variability of river plumes in this region must take into account both indices. Hydrodynamics of the Rías in winter are very dependent on wind stress and freshwater discharge from rivers located in the estuaries. This is really important due to the high fishery production of the Galician Rías. Knowing the value of these four indices or modes of variation of the atmosphere in the Northern Hemisphere, we could prepare a seasonal forecast of precipitation over Galicia with its consequent application to the knowledge of river flow and its variability, improving our knowledge of the stratification and hydrodynamics of the Rías, and the behavior of the river plumes.

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