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Atmospheric modes influence on Iberian Poleward Current variability

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ABSTRACT

The inter-annual variability of the Iberian Poleward Current (IPC) along the northwestern coast of the Iberian Peninsula (IP) (40–43°N) and its intrusion in the Cantabrian Sea (Navidad, 6–8°W) were analyzed in terms of the atmospheric forcing. The January Sea Surface Temperature (J SST) was obtained from the advanced very high resolution radiometer (AVHRR) NOAA satellite from 1985 to 2006. It is a well documented fact that the existence of a tongue of water warmer than the surrounding ones (IPC) which circulates along the western Iberian shelf edge, turn eastward around Cape Finisterre, and enters in the Cantabrian Sea generating Navidad at the beginning of every winter. However, in the present study it has been highlighted that there are several years (1986, 1987, 1992, 1997, 1999, 2004 and 2005) during which water from coast to the adjacent shelf is much colder than the oceanic one remarking a weak or inexistent IPC during these Januaries. In addition, the dependence of SST on the most representative regional patterns with some influence upon the eastern North Atlantic region was analyzed by means of correlations between November–December atmospheric modes and J SST. The considered modes were: North Atlantic Oscillation pattern (NAO), Eastern Atlantic pattern (EA), Eastern Atlantic Western Russia pattern (EA/WR), Polar/Eurasia pattern (POL) and Scandinavia pattern (SCA). This analysis reveals that two atmospheric patterns (N-D NAO and N-D EA/WR) are responsible of the main variability of the J SST of the western and northern IP. J SST is negatively correlated with N-D NAO and positively correlated with N-D EA/WR. Multivariate analysis involving both modes provides correlation coefficients on the order of 0.7 on both coasts (western and northern). The influence of both modes on J SST was observed to be on the same order of magnitude but with different sign. These correlations were physically interpreted by means of an analysis of extreme events and Sea Level Pressure (SLP) composite analysis.

1. Introduction

Poleward flows circulating along the eastern continental margins are a universal feature in the winter circulation of the upper ocean at subtropical and middle latitudes. These flows are driven by density forcing associated with larger scale meridional thermal gradients. Close to coast, the density gradients are balanced by onshore flow that adjusts at the shelf generating intensified surface currents toward the poles (Peliz et al., 2003). Such kind of flows can be observed along the upper continental slope off the west coasts of other continents as for example: the Leewin Current off western Australia (e.g. Cresswell and Golding, 1980; Thompson, 1987; Smith et al., 1991; Ridgway and Condie, 2004; Meuleners et al., 2007), the Davidson Current off western United States (e.g. Hickey, 1979), the Haida Current off western Canada (e.g. Thomson and Emery, 1986) and also off the western European margin (e.g. Huthnance, 1984).

The Iberian Poleward Current (IPC) has been commonly characterized by means of the infrared satellite images of the Advanced Very High Resolution Radiometer (AVHRR) during the last two decades (Pingree and Le Cann, 1989; Frouin et al., 1990; Haynes and Barton, 1990). The IPC is a narrow (25–40 km) slope-trapped tongue – like structure that flows northerly along a distance exceeding 1500 km off the coasts of the Iberian Peninsula (IP) and southeast France. It is a salty surface current (about 200 m deep) geostrophically trapped by the bathymetric discontinuity at the shelf break – upper slope zone. Satellite observations indicate that the thermal signature of the current is between 1 and 1.5 °C warmer than the surrounding ones (Frouin et al., 1990). Meridional density gradients, the slope and wind forcing interactions are the mechanisms for generation the IPC (Gil and Gomis, 2008).

It is a well-documented fact that the IPC normally arrives to the Cantabrian Sea at the beginning of every winter (e.g. Ambar et al., 1986; Pingree and Le Cann, 1989; Frouin et al., 1990; García-Soto et al., 2002; Gil, 2003). The January warm water extension of the IPC along the Cantabrian Sea has been referred to as Navidad (Christmas) because it starts to be evident

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near Christmas and New Year. Due to the inability of the poleward flow to follow the abrupt changes of topography, such as Cape Ortegal and Cap Ferret Canyon, the IPC exhibits a turbulent nature producing the apparition of some unstable structures and separating eddies in the Bay of Biscay region (e.g. Pingree and Le Cann, 1993; García-Soto et al., 2002). The SST inter-annual variability of Navidad was studied by García-Soto et al. (2002) by means of AVHRR satellite archive from 1979 to 2000. They highlight the exceptional Navidad developments and winter warming in January 1990, January 1996 and January 1998. To examine the cause of the Navidad inter-annual variation, the January SST was compared with North Atlantic Oscillation Index (NAO) for the preceding months (November–December) which represent the first mode (32% of variance) of low frequency variability over the North Atlantic with the amplitude most pronounced during winter, near the period of Navidad development. They found that the winter warming in the southern Bay of Biscay during marked Navidad years was negatively correlated with NAO values for the preceding months.

NAO, Eastern Atlantic (EA), Eastern Atlantic Western Russia (EA/WR), Polar/Eurasia (POL) and Scandinavia (SCA) patterns are the most representative regional patterns of atmospheric variation in the Northern Hemisphere, with some influence upon the eastern North Atlantic region. These circulation patterns, which have the amplitude more pronounced during winter, are indicators of large-scale decadal change and play a key role in long-term variability of winds across the North Atlantic affecting rainfall (Zorita et al., 1992; Rodríguez-Puebla et al., 1998; Esteban-Parra et al., 1998; Lorenzo and Taboada, 2005), river discharges (Trigo et al., 2004; deCastro et al., 2006) and coastal upwelling intensity (deCastro et al., 2008a, 2008b). In fact, Zorita et al. (1992) and Esteban-Parra et al. (1998) showed correlation coefficients between the (DJF) NAO index and rainfall ranging from −0.3 to −0.4 in Galicia (north–west of IP). Other work by Rodríguez-Puebla et al. (1998) found a correlation coefficient between the December NAO index and the annual precipitation from −0.10 to −0.15 for the IP. In the same analysis, the authors found correlation coefficients with the annual rainfall: 0.3–0.4 for the April EA pattern; 0.05–0.1 for the October of the previous year's SOI; and 0.35–0.4 for the December SCA. Lorenzo and Taboada (2005) found the following significant correlations between the atmospheric patterns and (DJF) precipitation in Galicia for the period 1977–1998: −0.52 NAO, 0.41 SCA and −0.39 EA/WR. Trigo et al. (2004) found that the (JFM) river discharge of the main Atlantic IP rivers are well correlated with (DJF) NAO index for the period 1973–1998 (−0.76 for Duero, −0.77 for the Tajo and −0.79 for the Guadiana). In addition, deCastro et al. (2006) found the following significant correlations with (DJF) Miño river discharge for the period 1970–2005: −054 for (FMA) NAO, 0.63 for (JFM) SCA and −0.46 for (JFM) EA. The same authors (deCastro et al., 2008a) found that the zonal Ekman transport (Q_x) in Galicia during the wet season (NDJF) for the period 1966–2006 is mostly characterized by the EA pattern (−0.65 with a significance level greater than 95%) with a little influence of the NAO pattern (0.19, >95%). With respect to the correlations during the upwelling season (July–October), deCastro et al. (2008b) found that the main upwelling anomaly variability can be explained in terms of the EA pattern, showing a significant negative correlation along the entire western coast of the IP with a maximum value of −0.5 at 38°N. The NAO pattern is the second most influential atmospheric mode, with influence on the upwelling index showing a significant positive correlation only between 38°N and 41°N.

Only a brief description about the most representative regional patterns with some influence upon the eastern North Atlantic region will be given here. The reader is referred to http://www.cpc.noaa.gov/data/teledoc/telecontents.shtml for more detailed information about these indices. NAO consists of a north–south dipole of geopotential anomalies with one center located over Greenland and the other one spanning between 35°N and 40°N in the central North Atlantic. The EA pattern consists of a north–south dipole that spans the entire North Atlantic Ocean with the centers near 55°N, 20–35°W and 25–35°N, 0–10°W. The anomaly centers of the EA pattern are displaced southeastward to the approximate centers of the NAO pattern. The EA/WR pattern is one of three prominent teleconnection patterns that affect Eurasia through the year. This pattern consists of four main anomaly centers. The POL pattern consists of one center over the polar region and centers of opposite sign over Europe and northeastern China. The SCA pattern consists of a primary circulation center over Scandinavia, with a weaker center of opposite sign over Western Europe.

Many authors (Zorita et al., 1992; Esteban-Parra et al., 1998; Rodríguez-Puebla et al., 1998; Lorenzo and Taboada, 2005; deCastro et al., 2006, 2008a, 2008b) have pointed out that these atmospheric patterns influence variables such as precipitation (Miño river discharge) zonal Ekman transport and upwelling in the western IP but that a single pattern cannot describe the majority of the variability of these variables over the region. They observed that the atmospheric patterns follow a different trend structure, in such a way that the most prevalent index depends on the chosen period of time and on the variable under study. The northwestern coast of the IP and the Navidad region is upon NAO influences but in an area near the latitude where influences pass from positive to negative correlations. In this sense, the main variability of these variables is better explained by means of four atmospheric patterns (NAO, SCA, EA and EA/WR).

The aim of the present study is to analyze the dependence of the January IPC on the atmospheric forcing from 1985 to 2006. This study was carried out by means of January SST (J SST from now on) data in the northwestern IP region (from 40°N to 45°N and from 5°W to 15°W). The study starts with the identification of the years under high and low IPC. Although this analysis has been previously carried out by other authors (García-Soto et al., 2002; Peliz et al., 2005), it allows comparing the present area under study with some adjacent areas considered in other studies. The influence of the most representative regional modes affecting the eastern North Atlantic region (NAO, EA, EA/WR, POL and SCA) is analyzed. As far as we know NAO was the only mode considered in previous studies dealing with IPC. The correlation between atmospheric modes and IPC is physically interpreted by means of an analysis of extreme events and a Sea Level Pressure (SLP) composite analysis.

2. Methods

SST data were obtained from the NOAA/NASA AVHRR (http://poet.jpl.nasa.gov). The SST computation from AVHRR radiances is discussed in McClain et al. (1985). The Pathfinder SST data are available from 1985, and they are distributed in a variety of resolutions and temporal averages. Each data product is obtained as either an ascending (daytime) or descending (night-time) image. These data are produced as daily composites, which are defined as spatial bins of all temperature retrievals at a maximum resolution of 4 km. From the daily products, 8 d, monthly and yearly composites are formed. In our study we chose a spatial resolution of 4 km and a temporal average of 8 d for the period from 1985 to 2006. We only considered the night-time image in order to avoid the solar heating effect.

For our purposes, the area limited by 40–45°N, 5–20°W was examined from a global data set. The particular choice of the region is due to two main reasons; first, it is close to the start of the IPC, Peliz et al. (2003) affirm that the Western Iberian Winter Front is frequently observed between 38°N and 40°N; second, the area under scope includes the first important gyre of the IPC since the current changes direction abruptly following the Iberian topography between Cape Fisterre and Cape Ortegal (A and B in Fig. 1).

The inter-annual variation of the IPC and the influence of the external forcing on the IPC SST were analyzed in terms of the SST anomaly (SSTa) spatially averaged for different regions (from coast to shelf break area and open ocean). SSTa represents the SST value for every January from 1985 to 2006 minus the mean J SST calculated from 1985 to 2006. In particular, January was selected as the month under study since, according to previous studies (García-Soto et al., 2002), IPC is likely to be well developed in the area under study, stretching from the Atlantic to the Cantabrian coast, during this month. In addition, Alvarez et al. (2003) detected the intrusion of poleward water into Galician estuaries by the end of January 1998. However, strong events have also been observed before and after January (see for e.g. Frouin et al. (1990), who used data sampled during late November and early December). In the present study, surface water between coastline and 1500 m isobath is considered as water from coast to the adjacent shelf break area (Fig. 1, polygons I and II) and, surface water measured in the region between 17–19°W and 40–44°N as open ocean water. This last region will be considered a control area in the present study.

The used procedure can be summarized as follows: (i) the above mentioned polygons were selected. In average, each polygon contains a few hundreds of points; (ii) SST data inside the polygon were spatially averaged to obtain a mean SST value every eight days (the periodicity of the data base). This spatial mean was only calculated when the number of valid points inside the polygon was higher than 10%. (iii) J SST was calculated by averaging the valid SST values during that month. A maximum of four valid images can be available during January. This series will be correlated with atmospheric patterns corresponding to the previous November and December. According to García-Soto et al. (2002) a lag of one or two months between atmospheric modes and SST can be expected due to the typical winter values of the IPC.

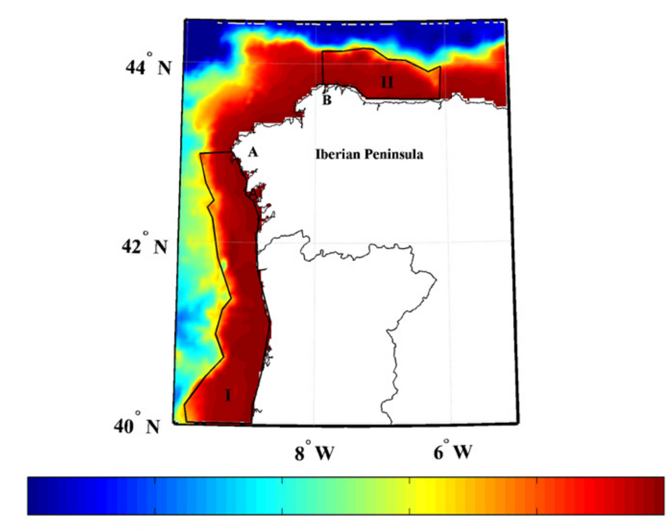

Fig. 1. Area under scope corresponding to the northwestern Iberian Peninsula. Polygons I and II are the areas selected to analyze SST values along the western (40°N–43°N) and northern (6°W–8°W) Iberian Peninsula shelf break area, respectively. The location of Capes Finisterre and Ortegal are marked with A and B, respectively. Colorbar corresponds to depth.

An EOF analysis could also be considered to calculate the principal components to be correlated with atmospheric modes instead of using the average value described above. However, this approach was discarded due to the presence of voids in the SST images due to cloud coverage, which is high in winter months. These voids are, in average, on the order of 30% in every polygon, which would force to perform the EOF analysis based on a non-negligible percentage of interpolated values.

An alternative approach would consist in considering the zonal temperature gradient (Peliz et al., 2005) instead of the absolute temperature. The main advantage of this approach is that it allows neglecting inter-annual fluctuations associated to other events different from IPC. However, the main drawback of this alternative method is the extreme dependence on the choice of the reference area. Actually, a sensitivity test was carried out using the polygon defined in Peliz et al. (2005), whose mean temperature was correlated with the mean temperature of adjacent polygons shifted 1° in latitude or longitude. The observed correlation with adjacent polygons provided R values on the order of 0.6. This fact discards the use of this technique due to the important biases associated to the particular choice of the reference polygon.

The standardized monthly values of NAO, EA, EA/WR, POL and SCA indices were obtained from the Climate Prediction Center (CPC) at the National Center of Environmental Prediction (NCEP) (http://www.cpc.noaa.gov/data/teledoc/telecontents.shtml). Rotated principal component analysis (RPCA) was used to identify the Northern Hemisphere teleconnection patterns and indices. This procedure isolates the primary teleconnection patterns for all months and allows time series of the patterns to be constructed (Barnston and Livezey, 1987). Teleconnection indices are available from 1950. Correlations between the atmospheric modes were performed without any significance, both during the period of time under study (from 1985 to 2005) and during the period of time for which data are available (from 1950 to 2005).

SLP data were obtained from reanalysis data from a cooperating project between the NCEP and the NCAR (www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml). The goal of this joint effort is to produce new atmospheric analyses using historical data (1948 onwards), as well as to produce analyses of the current atmospheric state (CDAS). The data are defined on 90°N to 90°S, 0–357.5°E, with a spatial resolution of 2.5° × 2.5°. Daily data from 1985 to 2005 on a 10°N to 80°N, 60°W to 80°E grid were selected for the present study.

3. Results and discussion

3.1. Inter-annual variability of IPC

AVHRR infrared SST images of the northwestern IP region (from 42°N to 45°N and from 5°W to 12°W) during January were averaged from 1985 to 2006 in order to observe the main features of the IPC (Fig. 2). Note that the considered region is slightly smaller than the area under scope mentioned in previous section, which permits magnifying the main features of the IPC. On the one hand, the considered temperature range is smaller (only 3° in latitude) which enhances the observed temperature gradients. On the other hand, the open ocean area was considerably reduced enhancing the differences between the near shore area and the shelf break area.

A more or less continuous band of colder water is observed along the near-shore area of the western coast. According to Fiuza (1983) and desChamps et al. (1984), it corresponds to water cooled as a result of net heat loss from surface during the previous autumn months. Between the 150 m isobath and the 1500 m isobath there is a tongue of water warmer (∼14.0 °C) than the surrounding coastal and ocean water which circulates along the western Iberian shelf edge. A warm (∼13.8 °C) and thin filament is observed to turn eastward from Cape Finisterre (point A in Fig. 1) to Cape Ortegal (point B in Fig. 1). Finally, a tongue warmer (∼13.4 °C) than the surrounding coastal and ocean water is observed again in the Cantabrian area. In addition to the IPC features, the meridional thermal gradient is observed in ocean water with mean temperatures ranging from 14 °C at 42°N to 12.5 °C at 45°N.

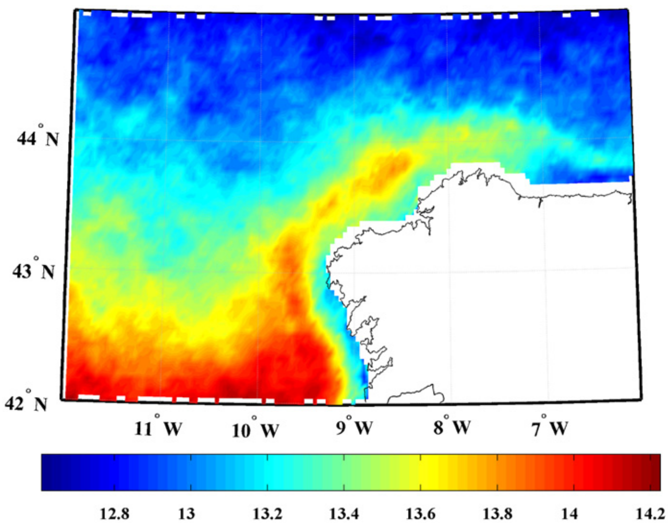

Fig. 2. January AVHRR infrared SST (°C) image of the northwestern Iberian Peninsula region from 42° to 45°N and from 5°W to 12°W averaged from 1985 to 2006.

January satellite SST images measured from 1985 to 2006 show years (e.g. 1989, 1990, 1996 and 1998) with a marked IPC turning eastward around Galicia and stretching along the whole extent of the Cantabrian shelf and slope (Fig. 3a–d). In these years the IPC temperature is between 14 and 15 °C. In addition, years without IPC influence were also detected (e.g. 1987, 1994, 2000 and 2004) and depicted in Fig. 4a–d. During these years, water temperature does not surpass 13 °C in the IPC region. White spots represent cloud coverage. The rest of the years correspond to a weak IPC influence or to satellite images with cloud coverage strong enough to make impossible to determine the IPC extent. The years with the most marked thermal increment (1990, 1996 and 1998) correspond to exceptional Navidad years described by García-Soto et al. (2002).

The analysis of J SST shows a high inter-annual IPC variability for the period 1985–2006. The SST difference between the polygon I region and the surrounding ocean region (ΔSST_a) is showed in Fig. 5. During several years (1990, 1996, 1998, 2001 and 2003) water within the polygon I is warmer, reaching peak values close to 1.5 °C in 1990 and 1996, in good agreement with

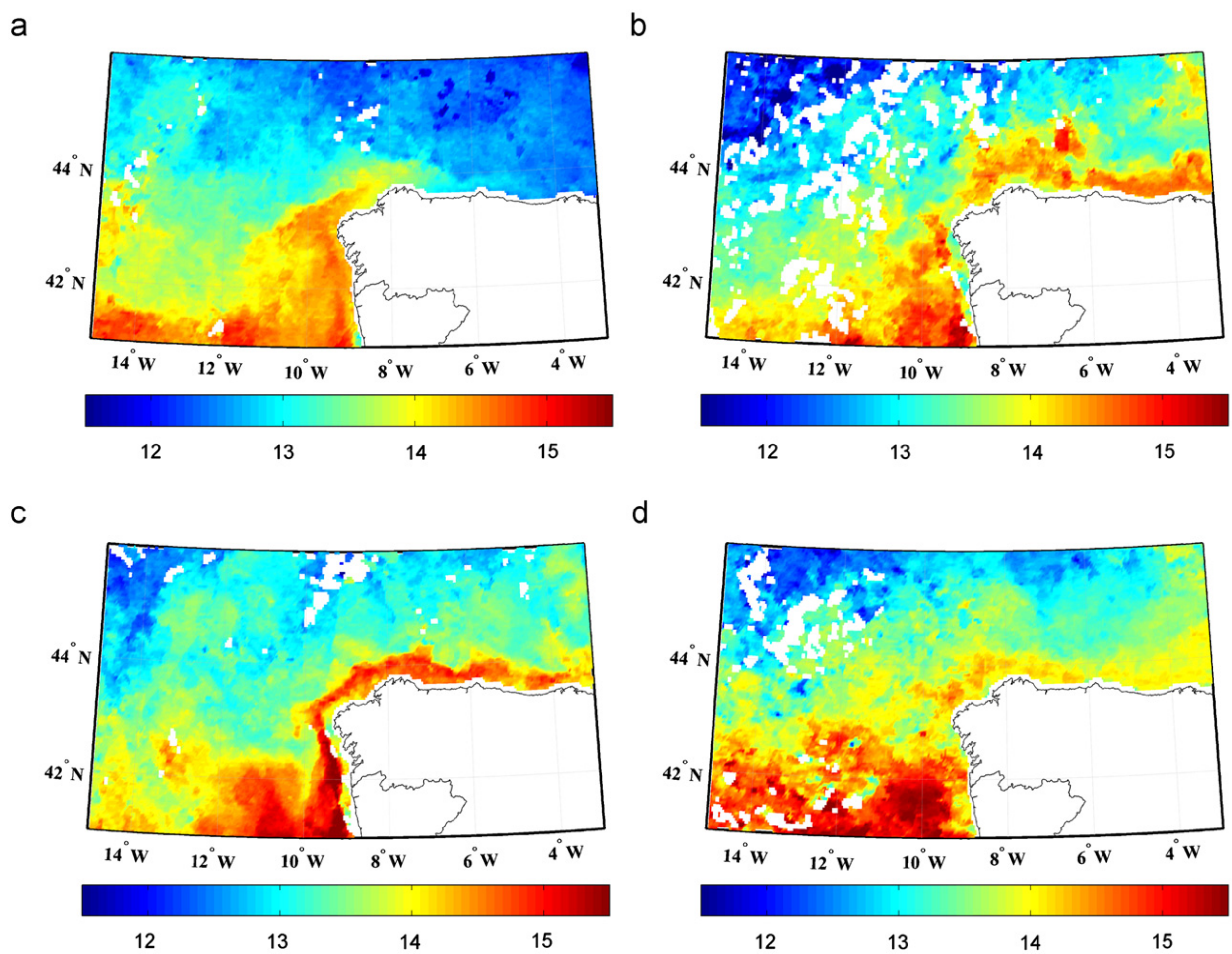

Fig. 3. January satellite SST images (°C) measured from 1985 to 2006 with a marked IPC turning eastward around Galicia and a Navidad stretching along the whole extent of the Cantabrian shelf and slope. These years correspond to (a) 1989, (b) 1990, (c) 1996 and (d) 1998.

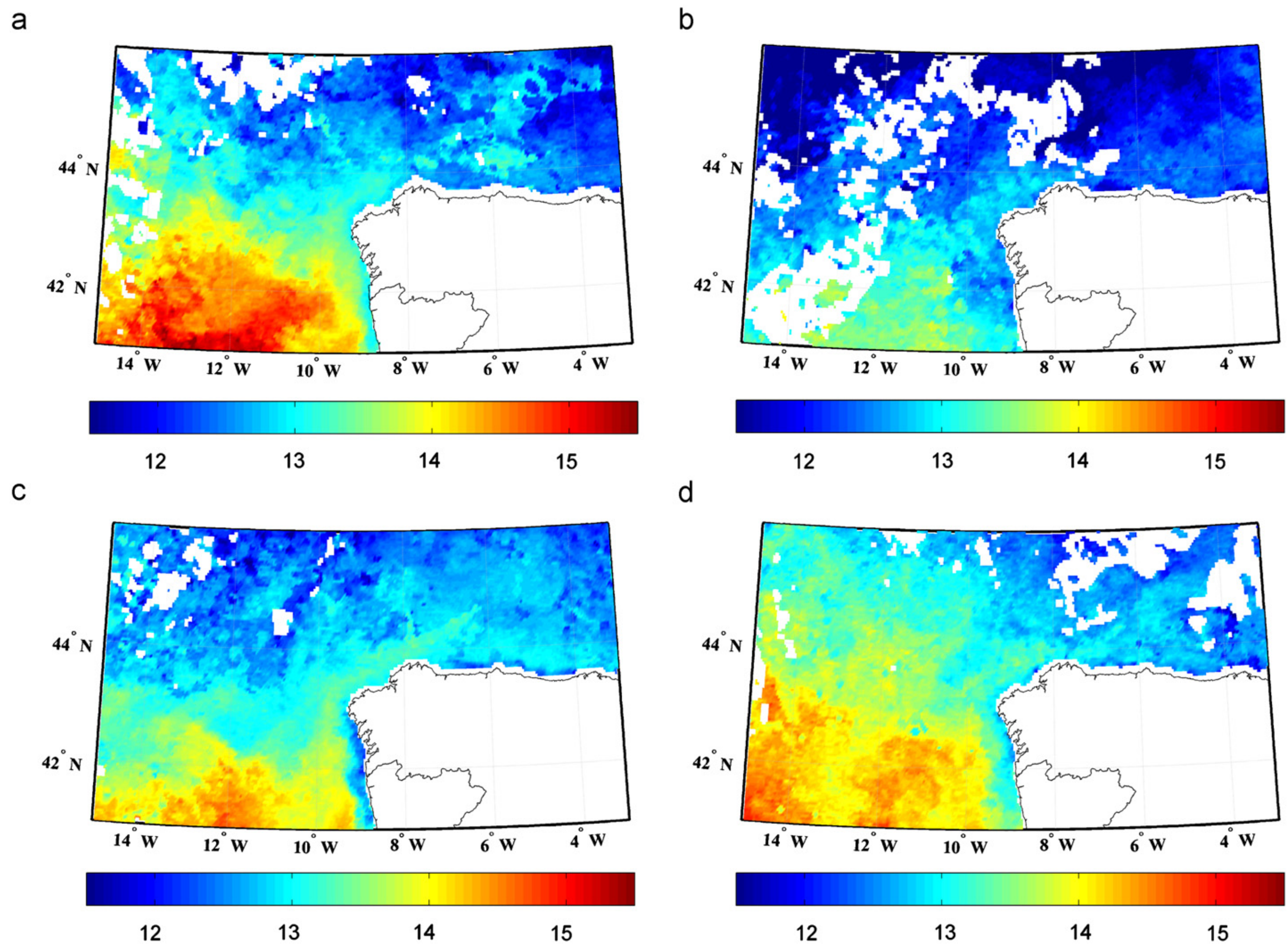

Fig. 4. January satellite SST images (°C) measured from 1985 to 2006 under weak or inexistent IPC. These years correspond to (a) 1987, (b) 1994, (c) 2000 and (d) 2004.

values provided in Frouin et al. (1990). These years show a strong IPC along the western coast of the IP. In addition, during other years (1987, 1992, 1997, 1999, 2004 and 2005) water in polygon I was observed to be much colder than ocean water indicating an inexistent IPC. For the rest of the years (e.g. 1985 or 2002) the existence of an IPC is not clear because temperature of coastal water (which is lower than the shelf water in winter) can make the difference between water in the polygon I and oceanic water confuse.

3.2. Atmospheric modes influence on IPC inter-annual variability

The influence of the most representative atmospheric patterns on the J SST will be analyzed in this subsection. It is a well-known fact that teleconnection patterns reflect large-scale changes in the atmosphere which can influence temperature, rainfall and storm tracks over vast areas. Because some lag between J SST and atmospheric modes could be expected due to the typical slope current velocities (10–30 cm s^{-1}) (Huthnance et al., 2002; García-Soto et al., 2002; Peliz et al., 2003), the previous November and December months were considered for the atmospheric modes to be correlated with the J SST. The study was carried out in two regions, western IP and northern IP (Table 1).

With regard to the western IP (polygon I in Fig. 1), two atmospheric modes are necessary to explain the main variability of J SST: the N-D NAO and the N-D EA/WR patterns. The N-D NAO

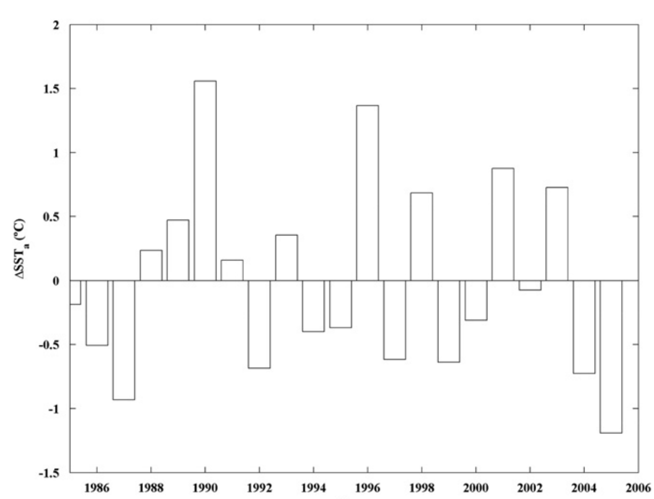

Fig. 5. Surface temperature difference (ΔSST_a in °C) between water in polygon I and oceanic water along the western coast of the IP (40°–44°N and 17°–19°W).

pattern is negatively correlated with J SST with a correlation coefficient of −0.54 and a significance of 99%. In addition, the N-D EA/WR pattern is directly correlated with J SST with a correlation coefficient of 0.47 and a significance level of 97.5%. The correlation between the rest of the atmospheric modes and the J SST has no statistical significance.

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Table 1
Correlation coefficients between atmospheric indices in November and December and January SST (°C) in the northwestern Iberian Peninsula (from 40°N to 45°N and from 6°W to 10°W) from 1985 to 2006.

Atmospheric Indices	*WIP Polygon I*	*NIP Polygon II*
N-D NAO	−0.54[a]	−0.52[a]
N-D EA/WR	0.47[b]	0.41[c]

[a] Correlation coefficients higher than 99%.
[b] Correlation coefficients higher than 97.5%.
[c] Correlation coefficients higher than 95%.

With regard to the northern IP (polygon II in Fig. 1), the same two atmospheric modes are also necessary to explain the main variability of the J SST: the N-D NAO and the N-D EA/WR patterns. Once again, the N-D NAO pattern is negatively correlated with the J SST with a correlation coefficient of −0.52 and a significance level of 99%. In addition, the N-D EA/WR pattern is directly correlated with a correlation coefficient of 0.41 and a significance level of 95%. The correlation between the rest of the atmospheric modes and the J SST has no statistical significance.

The correlations between N-D indices and J SSTa were also examined at a location away from the coast. The area ranging from 17°W to 19°W in longitude and from 40°N to 44°N in latitude was chosen for this comparison. Note that the area is at least 6° away from the coast and covers the latitudes used in previous comparisons, both for the western and the northern IP. The observed correlations were much weaker than in previous cases. Actually, the most important correlation was observed with N-D EA/WR showing a correlation coefficient of 0.20 and a significance level lower than 80%. This proves that significant correlations are only restricted to a region close to the continental margin.

The observed results show the dependence of J SST along the adjacent shelf on two atmospheric modes NAO and EA/WR. The regional relation between the negative phase of the NAO and Navidad is also discussed in García-Soto et al. (2002) from their selective comparison limited to the years of marked Navidad. They observed that the J SST values were tightly associated with negative values of the N-D NAO index but they did not analyze the influence of other atmospheric modes. They only speculated that the northerly component of the wind stress might relax or even reverse allowing water near surface in the Iberian continental slope to move poleward. Changes in the correlation can be probably due to the different periods under study and to the spatial extent of the area. Other authors (Peliz et al., 2005) did not observe significant correlation between NAO and SST for the period 1985–2001. However, they used a zonal gradient of temperature instead of an absolute temperature, which can strongly bias the observed results due to the choice of the reference area as mentioned above. The study area selected by these authors is considerably displaced to the south compared to our area and it can also present a mixture between coastal and oceanic features due to its square shape, which is not linked to bathymetry as in the present study.

Once the J SST has been observed to depend on two different atmospheric indices (NAO and EA\WR) with a similar correlation coefficient, a multivariate fitting to both indices was performed. Note that the different indices are uncorrelated since they correspond to the principal components of an EOF analysis (Barnston and Livezey, 1987). The obtained correlations have been summarized in Table 2. Values on the order of 0.7 have been obtained for the two areas under study (polygons I and II), which are considerably higher than the ones obtained when fitting to a single index. Fitting to more than two indices did not provide additional improvement in the correlation coefficient so remarking the independence on the rest of the atmospheric patterns. The coefficients of the multivariate fitting corresponding to the bilinear equation SST$=a+b$ NAO$+c$ EA/WR are also shown in Table 2. Note that the coefficient affecting the NAO (EA/WR) index is negative (positive) in agreement with the sign of the correlation coefficient of both modes previously described in Table 1. In addition, the magnitude of both coefficients is similar, which also agrees with the amplitude of the coefficients shown in Table 1. Physically, this reveals the similar dependence of J SST on both atmospheric modes.

An open question is the stationarity of the observed correlation. deCastro et al. (2006) showed the existence of a non-stationary correlation between both rainfall and Miño river discharge and several atmospheric modes. That correlation (Fig. 8 in their paper) is observed to vary in time when 22-year periods are considered. However, the series used in the present study is too short to allow a similar analysis.

3.3. Analysis of extreme events and SLP composites

The previous correlation analysis can only be considered as an exploratory way to show that J SST in the IPC region can be influenced by N-D NAO and N-D EA/WR atmospheric modes. Two methods have been considered to give a physical interpretation to those correlations: (1) analysis of extreme events and (2) analysis of SLP composites.

The three years with the most extreme positive J SSTa conditions in western and northern IP regions (1990, 1996 and 1998) were considered the extreme cases. All of them correspond to a well-developed IPC with a J SSTa greater than 0.7 °C. In the western IP (Table 3), N-D EA/WR and N-D NAO atmospheric patterns contribute with their phases and amplitudes to generate an extreme positive J SSTa. The same dependence on those indices can also be observed in the northern IP (Table 4).

The position of the Azores high and Iceland low can be observed in Fig. 6 for the years under well-developed January IPC (1990, 1996 and 1998, crosses) and for those without January IPC

Table 2
Correlation coefficient (R) and coefficients of the multivariate fitting corresponding to the bilinear equation SST$=a+b$ NAO$+c$ EA/WR.

Polygon	*R*	*a*	*b*	*c*
I	0.78	14.2	−0.4	0.5
II	0.73	13.3	−0.5	0.5

Table 3
Three extreme positive SSTa (°C) values observed during January in the western IP from 1985 to 2006, and NAO and EA/WR corresponding to the previous November–December months.

Year	J SSTa	N-D NAO	N-D EA/WR
1990	0.86	−0.50	0.40
1996	1.12	−1.55	0.75
1998	0.93	−0.95	0.90

Table 4
Three extreme positive SSTa (°C) values observed during January in the northern IP from 1985 to 2006, and NAO and EA/WR corresponding to the previous November–December months.

Year	J SSTa	N-D NAO	N-D EA/WR
1990	1.23	−0.50	0.40
1996	1.27	−1.55	0.75
1998	1.22	−0.95	0.90

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(1987, 2004 and 2005, circles). Note that the pressure fields used to detect the highs and lows correspond to December of the previous year as marked in the figure. The position of the highs and lows are displaced southward for the years with well-developed IPC compared to the years without IPC. This result is in good agreement with observations by Frouin et al. (1990) who pointed out that the location of the Azores-Iceland dipole was anomalously positioned southward during the winter of 1983–1984 when well-developed IPC conditions were sampled.

In addition, SLP composite difference was calculated both in the western (Fig. 7a) and in the northern (Fig. 7b) IP regions. Januaries from 1985 to 2006 were grouped in two different sets, a positive set with SSTa $> 0.5\sigma$(SSTa) and a negative one with SSTa $< -0.5\sigma$(SSTa). For each set, SLP corresponding to the previous November and December was averaged obtaining two maps (SLP^+ and SLP^-). Finally, the SLP composite difference was calculated as the difference between both maps ($SLP^+ - SLP^-$). In both regions, the SLP composite difference resembles the combination of the EA/WR pattern (http://www.cpc.noaa.gov/data/teledoc/eawruss_map.shtml) and the characteristic NAO dipole but with the anomaly centers inverted (http://www.cpc.noaa.gov/data/teledoc/nao_map.shtml). The inversion of the NAO dipole explains the negative correlation. Two low pressure centers and a high pressure center were detected. Low pressure centers

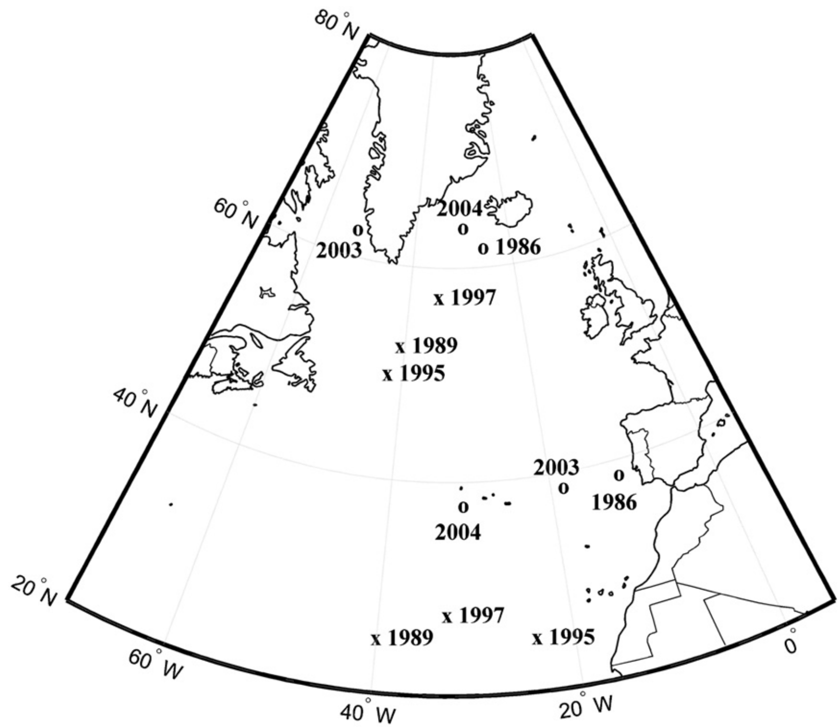

Fig. 6. Position of the Azores high and Iceland low for the years under well-developed January IPC (crosses) and without January IPC (circles) calculated from the previous December sea-level pressure. The years marked in the figure correspond to the pressure field, so the Januaries under scope are year+1.

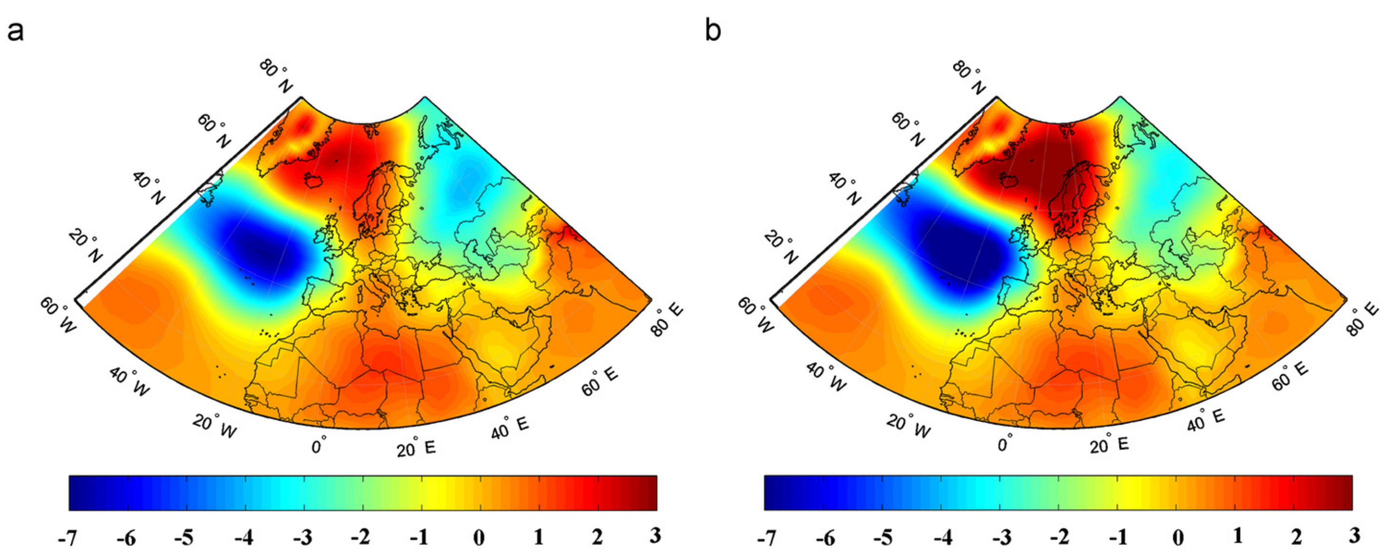

Fig. 7. SLP composite difference in the western (a) and in the northern (b) IP region (in mbar). Januaries from 1985 to 2006 were grouped in two different sets, a positive set with SSTa $> 0.5\sigma$(SSTa) and a negative one with SSTa $< -0.5\sigma$(SSTa). For each set, SLP corresponding to the previous November and December was averaged obtaining two maps (SLP^+ and SLP^-). Finally, the SLP composite difference was calculated as the difference between both maps ($SLP^+ - SLP^-$).

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were detected between 40°–60°N and 60°–20°W and between 50°–80°N and 40°–80°E. The first low pressure center coincides with the low pressure center of the NAO dipole and the second one with one of the low pressure centers of the EA/WR cuadripole. In addition, the high pressure center is located between 60°–80°N and 30°W–10°E coinciding with the high pressure centers of the NAO dipole and the EA/WR cuadripole.

SLP composite difference reveals the combination of the EA/WR cuadripole and the NAO dipole but with the anomaly centers inverted which explains the negative correlation with this index. This pattern shows a low pressure center in front of the west coast and northwestern corner of the IP producing southerly winds blowing at shelf. These persistent southerly winds induce the development of a poleward current along the IP and its intrusion into the Cantabrian Sea producing the phenomenon called Navidad.

4. Summary

The variability of the Iberian Poleward Current is studied along the Northwestern corner of the Iberian Peninsula from 1985 to 2006. The main findings of this study can be summarized as follows:

- IPC characterized by a mass of warm water flowing along the shelf break was only observed in some years during the period under study. In fact, in 54% of the years under study the IPC was weak or inexistent. The warming was especially intense during January 1990, 1996 and 1998 in agreement with previous research by García-Soto et al. (2002).
- The temperature water along the shelf break (IPC) is influenced by two atmospheric modes (NAO and EA/WR) which can explain most of the SST variability along the western and the northern IP. This correlation is only restricted to the region close to the continental margin as proved by the fact that no significant correlation was found between atmospheric indices and oceanic SST.
- For both coasts (Western and Northern) the SST is always negatively correlated with NAO and directly correlated with EA/WR.
- Multivariate analysis corroborated the simultaneous dependence on both atmospheric patterns. Correlation coefficients on the order of 0.7 were observed when fitting SST values to both indices. The magnitudes of the fitting coefficients corresponding to both indices were similar but with a different sign. This fact can provide some forecast skill as shown in Lorenzo et al. (2009) where SST and river discharge are correlated.

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