Large-scale hydroclimatic variability in the Bay of Biscay: the 1990s in the context of interdecadal changes

Benjamin Planque, Pierre Beillois, Anne-Marie Jégou, Pascal Lazure, Pierre Petitgas, and Ingrid Puillat


On its western side, the Bay of Biscay is located at the limit between the North Atlantic sub-polar and subtropical gyres, while the eastern and southern sides are bounded by land with a large continental shelf to the east and a narrow one to the south. The sharp continental slope results in a separation between hydrological processes taking place on and off the shelf. On the shelf, mesoscale hydrodynamic features, such as coastal upwellings, river plumes, and freshwater lenses, mostly depend upon regional climate forcing rather than upon the general oceanic circulation. Here, we review how three key regional climate and hydrological forcing factors (sea surface temperature, windspeed and river run-off) have varied during the past decade in comparison with multi-decadal historical records. The 1990s were characterized by warmer temperature and windier conditions than during the previous century, while the river run-off is slightly lower than average and highly variable. The Bay of Biscay lies between two regions where the responses to the North Atlantic Oscillation are opposite, and, as a result, it is expected that the NAO would only account for a very small fraction of the variability observed in temperature, windspeed, and river run-off in this region. Our results confirm this hypothesis.

Keywords: Bay of Biscay, long-term changes, North Atlantic Oscillation, river discharge, temperature, wind.

Introduction

The Bay of Biscay encompasses a region bounded by the Spanish coast to the south at approximately 44°N and the French coast to the east at approximately 2°W, and is open to the North Atlantic Ocean on its western and northern sides. The continental shelf is narrow along the Spanish coast and its extent increases from south to north along the French coast.

Hydrological features in the Bay of Biscay are therefore under the influence of (1) oceanic processes taking place in the North Atlantic and (2) coastal processes associated with the French and Spanish coasts. The shelf break, with a depth reaching more than 4000 m on the oceanic side and less than 200 m on continental shelf, is the natural separation between oceanic and coastally driven hydrodynamic features.

Coastal currents on the shelf are mainly influenced by the coastal topography, river discharges, wind regime, and tides. River discharge generates vertical and horizontal density gradients. This results in density circulation, which under the action of the Coriolis force is oriented northward. By contrast, dominant winds over the Bay of Biscay are westerlies and result in wind-driven coastal currents being oriented principally to the south (Pingree and Le Cann, 1989). The spatial extent and latitudinal position of river plumes results from the interaction of river flow and wind regimes. Offshore parts of river plumes can sometimes become detached and isolated from the main plume structure to become independent mesoscale low salinity lenses (see Puillat et al., submitted). In the southern part of the Bay of Biscay, particular wind regimes can lead to the onset of coastal upwelling. This is the case for northerly winds (upwelling on French coast) or
easterly winds (upwelling on Spanish coast). In the northern part of the Bay of Biscay, contrasting conditions of heat exchanges between atmosphere and ocean, wind/tide mixing and surface haline stratification result in the isolation of a deep "cold pool" (Vincent and Kure, 1969; Vincent, 1973; Puillat et al., submitted). During autumn, a hydrological structure termed a "warm water tongue" can develop in the central part on the continental shelf (Le Cann, 1982; Koutsikopoulos and Le Cann, 1996); the origin of this structure is still unclear. Finally, geographical differences in tidal mixing result in the formation of tidal fronts in the northern part of the bay (Sournia et al., 1990).

In summary, there is a great diversity in the nature of hydrodynamic features in the Bay of Biscay. While the deep regions of the bay may be affected principally by general oceanic circulation, the shelf is characterized by the dominance of mesoscale structures which are strongly influenced by regional or local hydroclimatic conditions. It is therefore expected that variability in the dynamics of mesoscale hydrographic structures on the French continental shelf may result mainly from the variability in climatic factors, such as wind, temperature regime, and river discharge.

On a larger scale, it has been demonstrated that the North Atlantic Oscillation (NAO), the dominant mode of atmospheric interannual variability in the North Atlantic sector, can be related to interannual variability in wind, precipitation, and SST fields over the eastern North Atlantic (Hurrell, 1995). The NAO may therefore be a potential proxy for climatic conditions around the Bay of Biscay (as is often the case for other European regions). However, the way in which the NAO effects translate into local climatic conditions is region-dependent, e.g. wind and precipitation responses to the NAO being opposite in Scandinavian and North African regions (Xie and Arkin, 1996; Reid and Planque, 1999; Pérez et al., 2000). The Bay of Biscay lies between these two extremes and the influence of the NAO on this region has received little attention until now.

Here, we review how three climatic parameters that are crucial to the dynamics of mesoscale hydrological features on the Bay of Biscay shelf (i.e. temperature, wind, and river discharge) have varied during the 1990s, in comparison with previous decades. We also investigate the relationships between these factors and larger climatic fluctuations expressed in the North Atlantic Oscillation (NAO).

Data sources

Wind and air temperature

Data on wind and air temperature (AT) have been recorded by Météo-France at a number of meteorological stations (semaphores) along the French Atlantic coast. Here, we selected data from eight semaphores, namely Ouessant, Pointe du Raz, Penmarch, Pointe du Talut, Saint Sauveur, Chassiron, Cap Ferret, and Biarritz (Figure 1). At each location, wind (speed, direction) and air temperature are recorded at 3-h intervals. The period of available records extends from 1948 to now, although for some semaphores the digitized record starts at a later date (between 1949 and 1958). Mean monthly wind data from the Comprehensive Ocean Atmosphere Data Set (COADS, Woodruff et al., 1993) were also used. COADS data are constituted by monthly averages of climate records over a grid constituted by cells of 2°long x 2°lat over the world's oceans. Here, we selected data from a limited number of COADS grid cells, as indicated in Figure 1. The technique used for aggregating wind data in the COADS data set results in less robust estimates of true wind than those derived from the meteorological stations. This is mainly because the number of samples collected, or their spatial location within a given grid cell, may vary from month to month. However, the period covered by COADS is much longer, as it extends from 1844 to 2000 (over the grid shown in Figure 1), therefore allowing for comparison of recent wind records with historical ones over the past 150 years.

Sea surface temperatures

A first data set, consisting of SST values averaged over 10-day periods and presented on a regular spatial grid was provided by Météo-France. The gridded data (0.5°long x 0.5°lat [9.0°W - 1.5°W, 44.0°N - 48.5°N], Figure 1) result from an interpolation procedure performed on SST measurements from selected vessels, meteorological buoys, and, more recently, satellite. Details on the interpolation procedure can be found in Koutsikopoulos et al. (1998), Ratier (1986), and Taillefer (1990). The Météo-France data are available from 1971 to 2001. As for wind, COADS SST estimates may be less robust than those from the Météo-France data set, but the period covered by COADS is much longer and therefore allows for the study of long-term variability in temperature.

River flows

We selected river outflow measurements from three rivers: the Loire, the Gironde, and the Adour (Figure 1). River flows are derived from the water vertical heights measured at specific locations. The empirical relationship between water height and flow varies through time and is difficult to estimate
for extreme low or high levels owing to the limited number of calibration measurements available for these extreme levels. Here, we have not accounted for the uncertainties in flow estimations when comparing flows through time for the three rivers. Daily river flow data are available for the period 1843–2000 for the Loire, 1978–2000 for the Gironde, and 1984–1999 for the Adour.

NAO index

The North Atlantic Oscillation (NAO) index is defined as the difference between the normalized winter (December to March) sea-level pressures measured at Stykkisholmur (Iceland) to represent the Iceland Low and at Lisbon (Portugal) to approximate the Azores High pressure cell. Values of this index are available from a number of sources. Here, we have used the data provided by the National Center for Atmospheric Research in Boulder for the period 1864–2000 (http://www.cgd.ucar.edu/cas/climind/nao_winter.html).

Data transformation and analysis

Since different data sets have distinct temporal resolutions, we have standardized the series by calculating monthly averages prior to analyses (except for the winter NAO). Temperature, river discharge, and winds vary seasonally, and we have often
used anomalies rather than parameter values to correct for seasonal effects. Monthly anomalies are obtained by subtracting the long-term mean value for the same month of the year from the raw data. Wind data can be used in several ways. Here, we have concentrated on scalar windspeed only. In the case of river discharge, we have log-transformed the anomalies when necessary to correct for the very skewed statistical distribution of discharge values. We applied no transformation to the NAO data.

Correlation analysis has been used to investigate the relationships between series of distinct parameters or between spatially distinct series of the same parameter. We have accounted for the presence of autocorrelation in the series by either correcting the number of "true independent observation" (i.e. degrees of freedom), or by first-differencing the time-series prior to testing for correlation, using the methods of Pyper and Peterman (1998), Thompson and Page (1989), and Chatfield (1996) outlined in Fox et al. (2000).

Results

Temperature


<table>
<thead>
<tr>
<th>AT (Chassiron)</th>
<th>SST (Météo-France)</th>
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<tbody>
<tr>
<td>SST (Météo-France)</td>
<td>R = 0.70 (n=28, n*=10, p&lt;0.01)</td>
</tr>
<tr>
<td>SST (COADS)</td>
<td>R = 0.79 (n=28, n*=13, p&lt;0.01)</td>
</tr>
<tr>
<td>SST (COADS)</td>
<td>R = 0.97 (n=28, n*=18, p&lt;0.01)</td>
</tr>
</tbody>
</table>

Over the past century, COADS records show an increase in the mean annual SST of 1.03°C (Figure 2). The analysis of monthly increase from COADS data indicates that this warming exists for every month (Table 2), but it is more pronounced during the winter season (December through to March) with 1.21°C/100 years. The Météo-France data set allows for geographical comparison of the rates of temperature change during the recent decades (1970s to 1990s). It is clear from Figure 3 that recent warming has taken place over the whole

Figure 2. Sea surface temperature anomalies in the Bay of Biscay derived from the COADS data set. Dots indicate monthly anomalies; the thin line shows the annual anomalies and the heavy line the long-term trend estimated by polynomial regression (order 5).
Table 2. Average monthly differences in SST between 1991–2000 and 1901–1990 from COADS. **Significant at the 1% level, *significant at the 5% level, ns: not significant.

<table>
<thead>
<tr>
<th>Month</th>
<th>DeltaT (°C)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.62 (**)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Feb</td>
<td>0.78 (**)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Mar</td>
<td>0.73 (**)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Apr</td>
<td>0.55 (**)</td>
<td>0.001</td>
</tr>
<tr>
<td>May</td>
<td>0.59 (**)</td>
<td>0.002</td>
</tr>
<tr>
<td>Jun</td>
<td>0.14 (ns)</td>
<td>0.278</td>
</tr>
<tr>
<td>Jul</td>
<td>0.31 (ns)</td>
<td>0.130</td>
</tr>
<tr>
<td>Aug</td>
<td>0.79 (**)</td>
<td>0.003</td>
</tr>
<tr>
<td>Sep</td>
<td>0.47 (ns)</td>
<td>0.052</td>
</tr>
<tr>
<td>Oct</td>
<td>0.36 (ns)</td>
<td>0.067</td>
</tr>
<tr>
<td>Nov</td>
<td>0.60 (**)</td>
<td>0.004</td>
</tr>
<tr>
<td>Dec</td>
<td>0.60 (**)</td>
<td>0.002</td>
</tr>
</tbody>
</table>

The increase in windspeed expressed in the COADS data is seen for all seasons (Table 3), but is most significant outside the winter period.

Along the French coast the trends in windspeed revealed by data from meteorological stations vary with geographical locations. On average, annual mean windspeed has decreased in the southern part of the Bay, while it has increased in the northern part (Figure 5). Nevertheless, these trends are small in comparison with the degree of interannual variability at each station.

River flows

The comparison of monthly flow anomalies between the Loire, Gironde, and Adour rivers reveals a very strong synchrony between all three rivers (Table 4) and the two types of test conducted for the detection of synchrony (adjusted number of independent observations and first-order differencing) are highly significant. We have therefore considered the Loire series, which goes back to the mid-19th century, as an acceptable proxy for river run-off along the whole French Atlantic coast.

A plot of interannual changes in the Loire run-off (Figure 6) shows a strong degree of interannual variability, with some extreme low and high values. During the 1990s, the Loire discharge has been average to low in comparison with the past 150 years. A large degree of interannual variability in flow has been observed during the 1990s, but extreme values (high or low) have not gone beyond the range of previously observed minimum or maximum flows.
Figure 4. Scalar wind anomalies in the Bay of Biscay, derived from the COADS dataset. Dots indicate monthly anomalies, thin line shows the annual anomalies and heavy line the long-term trend estimated by polynomial regression (order 5).

Table 3. Average monthly differences in scalar wind between 1991–2000 and 1901–1990, from COADS. **Significant at the 1% level, *significant at the 5% level, ns: not significant.

<table>
<thead>
<tr>
<th>Month</th>
<th>DeltaW (m.s⁻¹)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>1.36 (ns)</td>
<td>0.058</td>
</tr>
<tr>
<td>Feb</td>
<td>0.42 (ns)</td>
<td>0.281</td>
</tr>
<tr>
<td>Mar</td>
<td>0.27 (ns)</td>
<td>0.302</td>
</tr>
<tr>
<td>Apr</td>
<td>1.33 (**)</td>
<td>0.001</td>
</tr>
<tr>
<td>May</td>
<td>1.40 (**)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Jun</td>
<td>1.73 (**)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Jul</td>
<td>1.19 (**)</td>
<td>0.002</td>
</tr>
<tr>
<td>Aug</td>
<td>0.91 (**)</td>
<td>0.002</td>
</tr>
<tr>
<td>Sep</td>
<td>1.67 (**)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Oct</td>
<td>2.00 (**)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Nov</td>
<td>1.65 (**)</td>
<td>0.002</td>
</tr>
<tr>
<td>Dec</td>
<td>1.05 (*)</td>
<td>0.044</td>
</tr>
</tbody>
</table>

NAO and other parameters

During the past 150 years, the relationship between the winter NAO index and the winter SST, wind and Loire run-off appear to be weak. The three plots on Figure 7 reveal scattered data, and the fractions of variance explained by the NAO for SST, scalar wind, and river run-off, respectively, amount to 8%, <1%, and 6%. Although we have restricted our analysis to the use of simple linear regressions, it is clear from the scatter of the data that other models would only have provided little improvement, if any, in the amount of variance explained. Despite these weak relationships, the correlations between NAO, SST, and river run-off are significant, after

Figure 5. Time-series of annual mean anomalies in wind speed (m.s⁻¹) from eight meteorological stations along the French coast (see Figure 1 for geographical locations of the stations). Heavy lines show long-term trends estimated by linear regression.
Table 4. Correlations between monthly anomalies in flow from the Loire, Gironde, and Adour rivers. R: Pearson correlation coefficient, n: number of observations, n*: number of observations corrected for serial autocorrelation. Results in italics show correlation analysis on first-order differenced series.

<table>
<thead>
<tr>
<th></th>
<th>Gironde</th>
<th>Adour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loire</td>
<td>R=0.80, n=276, n*=156, p&lt;0.01</td>
<td>R=0.70, n=192, n*=117, p&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>R=0.75, n=275, p&lt;0.01</td>
<td>R=0.56, n=191, p&lt;0.01</td>
</tr>
<tr>
<td>Gironde</td>
<td>R=0.88, n=192, n*=123, p&lt;0.01</td>
<td>R=0.79, n=191, p&lt;0.01</td>
</tr>
</tbody>
</table>

There is no apparent relationship between NAO and windspeed (r = -0.02, n = 137, n-corrected = 121 and p = 0.39).

There are two main reasons why these relationships can be significant but weak over the past 1.5 centuries. The first is that the true underlying relationships are weak. The second possible reason is that the relationships may be time-dependent, i.e. that periods when a relationship exists alternate with periods with reversed or absence of relationship, resulting in an apparent absence of relationship. To investigate the possible time dependence of

Figure 6. Annual discharge from the Loire river (thin line) and fitted long-term trend estimated by eigen vector filtering (heavy line). Dashed line indicates mean annual flow over the entire period of records.

Figure 7. Sea surface temperature anomalies (left), scalar wind anomalies (middle), and log-transformed run-off of the Loire river (right) plotted against the NAO winter index. Each parameter has been averaged for the period Dec-Mar to match the period over which the NAO index is calculated. Closed circles indicates years 1991-2000.
the NAO effects, we have calculated decadal correlations between NAO, SST, windspeed, and river run-off (Figure 8). For all the decades studied before the 1990s, the correlation between the NAO and SST is positive. This suggests that the relationship between NAO and SST is weak, but is robust through time. In this context, the 1990s are distinct from the previous decades, with a slightly negative (and not significant) correlation. Decadal relationships between NAO and windspeed have been both positive and negative in the past, and the relationship presents an apparent persistence of several decades, with the correlation gradually changing from positive to negative values and vice versa. During the 1990s, the correlation is close to zero. In the case of river run-off, both positive and negative correlations with the NAO have been observed, but decades with negative relationships are the most frequent. As for SST and windspeed, the correlation coefficient is close to zero during the 1990s.

Discussion

The comparison of recent hydroclimatic records with historical ones is strongly dependent upon the comparability of data collected over a long period of time. During the past 1.5 centuries, changes in sampling intensity or design and modifications of the instrumentation used to record hydroclimatic parameters have occurred, and the results presented here are conditional on the consistency of historical data sets. In the case of temperature, the correspondence between the results obtained with three independent data sets suggests that the changes observed in recent decades (since the 1950s) reflect the true variability in the temperature in the Bay of Biscay. The true correspondence between COADS monthly averages and historical 3-h records from coastal meteorological stations is difficult to establish because of the large differences in sampling frequency and geographical variability. This is particularly so for the wind data. Indeed, wind records vary greatly over small spatial and temporal scales, so that 3-h records from meteorological stations cannot readily be compared to monthly averages calculated over large oceanic areas. In the case of river run-off, measures of flow are derived from measures of river height at particular points using empirical correspondences between river height and river flow. Changes in the locations of river height measurement, and natural and human induced variations in the shape of river bottoms, have led to changes in these empirical relationships and potential biases in the flow estimates. The very strong correspondence in flow anomalies between the three rivers studied suggests that, despite these changes, the historical records for recent decades reflect the true variability in river discharge along the western coast of France. For the longer term, the comparability of data collected more than a century ago with contemporary data is difficult to assess and long-term trends in river discharge are therefore uncertain.

Since 1989, the Bay of Biscay is on average warmer than usual at all seasons and all locations. The warming, however, is greater in the southeastern part of the bay and during the winter season. This is consistent with the observations by Koutsikopoulos et al. (1998) of the warming in the southeastern Bay of Biscay during the period 1972–1993, and confirms the warming trend for the whole of the 1990s. The latitudinal gradient in SST is reinforced by the geographical differences in warming trends, with rapid warming of warmer water in the South and slower warming of colder water in the North.
Assuming that the series of windspeeds derived from COADS is consistent through time, the records suggest that average windspeed in the Bay of Biscay has increased during the 20th century to reach maximum values in the 1990s – it being most evident outside the winter season. These maximum windspeed values are similar to those recorded in the mid-19th century. Coastal records from meteorological stations provide some indications about the geographical variability of the trend in wind, with increasing windspeed in the northern part of the bay (consistent with the results of Pirazzoli, 2000) and decreasing speed in the south. As for temperature, the latitudinal gradient in windspeed is reinforced with decreasing speed in the south. As for temperature, the latitudinal gradient in windspeed is reinforced with strong winds getting stronger in the North and weak winds getting weaker in the South. The warming that has taken place during winter in the southern part of the bay occurs in parallel with a decrease in windspeed in the same area and for the same months (as recorded at Biarritz meteorological station), which suggests that a decrease in wind mixing may be partly responsible for the warming in this region. In such a case, the warming would not necessarily reflect an increase in the heat content of the southern Bay of Biscay, but the presence of a stronger and/or shallower thermocline which would distribute most of the heat content in the upper part of the water column. In addition, the more rapid warming in the southern part of the Bay of Biscay in comparison with the north, may reflect the differences in tidal mixing intensity between the two areas (Pingree et al., 1982; Le Cann, 1990). Indeed, lesser mixing in the south can result in more rapid increase in SST than in the north. Alternatively, changes in SST observed in the southeastern Bay of Biscay may result from a true change in heat content driven by advective transport of warmer water. Variations in the flow of warm East North Atlantic Central Water (ENACW, Pingree, 1994) towards the southeastern Bay of Biscay could drive such changes in water temperature. This possibility is supported by the observations carried out during the 1990s along a hydrographic section off Santander which suggest increase in the eastward flow of ENACW (González-Pola and Lavin, submitted, this issue).

Previous studies conducted on mesoscale hydrological structures in the Bay of Biscay have revealed that there is great spatial and temporal hydrological variability on this scale (e.g. see Dickson and Hughes, 1981; Pingree and Le Cann, 1992; Koutsikopoulos and Le Cann, 1996; Froidefond et al., 1998; Lazure and Jégou, 1998). Here, we have not directly studied the mesoscale structures, but instead some of the hydroclimatic factors that influence the development and dynamics of these structures. Results from Puillat et al. (submitted) show that variability in climatic patterns can be transferred to mesoscale hydrodynamic structures. It is therefore expected that the strong degree of interannual variability in the forcing factors observed in our results (Figures 2, 4, and 6) has had a major influence upon the development of the mesoscale hydrodynamics in the Bay of Biscay during the past century.

The link between temperature, wind, river runoff, and general climatic conditions, if there are any, is not expressed in the NAO signal (Figures 7, 8). The relationships are weak and changeable through time, except for SST. The 1990s are characterized by particularly weak relationships and in any case the NAO index accounts for only 8%, <1%, and 6% of the interannual variability in winter SST, wind, and river run-off. The NAO is a large-scale oscillation that affects temperature, wind, and precipitation fields over the North Atlantic, but these effects are region-dependent. For example, Hurrell, (1995) showed that precipitation was positively correlated to the NAO in the northern part of Europe while negatively related in southern Europe. A similar result is presented in an analysis of global precipitation fields by Xie and Arkin (1996). Similarly, positive phases of the NAO have been associated with warmer conditions in Northern Europe but cooler ones in the subpolar gyre region, and with greater windspeed in the northeastern part of the North Atlantic but lower windspeeds in most of the subtropical North Atlantic (Reid and Planque, 1999). The Bay of Biscay has a particular geographical status with regard to the NAO effects, as it lies close to the line of no correlation with the NAO for precipitation, temperature, and wind. This geographical status explains the very poor or lack of response of these three parameters to the NAO, and strongly suggests that direct physical or biological responses to the NAO are not to be expected in the Bay of Biscay.

Despite this lack of apparent effect of the NAO, it is likely that the development of distinct mesoscale physical structures in the Bay of Biscay is associated with particular large-scale climatic situations. Techniques for relating large-scale climatic situations or weather regimes to smaller-scale weather patterns exist in terrestrial meteorology (see, e.g., von Stroh et al., 1993; Plaut and Simonnet, 2001; Simonnet and Plaut, 2001). Such downscaling methods have not yet been used to relate weather regimes to mesoscale hydrography. It is expected that they should prove useful in the case of the Bay of Biscay.

In conclusion, the 1990s have been exceptional with regard to SST and wind, but river discharge has varied within its natural range. The way in which the variability in these factors has been reflected in the onset and dynamics of mesoscale hydrological structures needs further investigation. Variations in these parameters cannot be directly related to the NAO. The role of the general and slope circulation...
on the hydrology of the French continental shelf, or of atmospheric circulation patterns not reflected in the NAO signal, is likely to be of greater importance than the NAO itself.

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References