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Climate-driven changes in coastal marine systems of western Europe

Eric Goberville[1,2,*], Grégory Beaugrand[1,3], Benoit Sautour[2], Paul Tréguer[4], SOMLIT Team[5]

[1]Laboratoire d'Océanologie et de Géosciences, UMR CNRS 8187 (LOG), 28 avenue Foch, 62930 Wimereux, France
[2]Université Bordeaux I – Laboratoire d'Océanographie Biologique UMR CNRS 5805, Rue du Pr Jolyet, 33120 Arcachon, France
[3]Centre National de la Recherche Scientifique, Université des Sciences et Technologies de Lille, Lille 1, France
[4]Institut Universitaire Européen de la Mer, UMS CNRS 3113, Université Européenne de Bretagne, Technopole Brest-Iroise, Place Nicolas Copernic, 29280 Plouzané, France
[5]Coordinators of the team in 2009: Pascal Claquin and Sébastien Lefebvre (Luc-sur-mer), Eva Bucciarelli and Jacques Guillou (Brest), Pascal Morin (Roscoff), Laure Mousseau (Villefranche-sur-Mer), Patrick Raimbault (Marseille), Nicolas Savoye (Arcachon), Sami Souissi (Wimereux), Renaud Vuillemin and Stéphane Blain (Banyuls)

ABSTRACT: Coastal marine systems, the interface between the ocean and terrestrial realms, are among the most important systems on the planet both ecologically and economically because of their crucial role in earth system functioning. Although direct impacts of human activities on physical, chemical and biological components of these systems have been widely documented, the potential influence of climate variability is less well known. Here, we used data from Service d'Observation en Milieu Littoral (SOMLIT), a marine monitoring programme that has since 1997 collected samples at 12 sites located along the French coasts from 42° to 51° N. Applying standardised principal component analysis (PCA), we documented the year-to-year fluctuations in these coastal systems and evaluated the potential influence of climate variability using data on atmospheric circulation (wind intensity and direction), precipitation and temperature. Our study revealed a pronounced sensitivity of these systems to climate variability. As the impact of climate change may become more prominent in the next decades, this study suggests that climate might strongly influence the marine coastal environment and act in synergism with other anthropogenic pressures to alter the state and functioning of biological and ecological systems and the services they provide.

KEY WORDS: Coastal systems · Climate change · SOMLIT · Anthropogenic impact · Multivariate analyses

INTRODUCTION

Many studies have shown that climate variability influences marine systems ranging from benthic (Kroncke et al. 1998, Warwick et al. 2002) to pelagic (Ohman & Hirche 2001) and from oceanic (Hare & Mantua 2000) to coastal (Attrill & Power 2002). The impact of climate on marine systems is not limited to a particular biological component but generally extends to all ecosystem functional units (Drinkwater et al. 2003). Some studies have documented potential links from phytoplankton to zooplankton to higher trophic levels (Aebischer et al. 1990, Frank et al. 2005, Lehodey et al. 2006). Climate also impacts the biodiversity of marine systems and their spatial and temporal fluctuations, modulating the phenology of many organisms (i.e. their rhythm of reproduction, Edwards & Richardson 2004) as well as their response at both year-to-year and decadal scales (Cury et al. 2002).

Climate influences systems through a number of physical and chemical processes and pathways (Kirby et al. 2009). In coastal systems, in addition to the well-

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*Email: e.goberville@epoc.u-bordeaux1.fr documented direct effects of temperature on organisms (Beaugrand 2004), temperature has an impact on water stratification, which in turn modulates vertical nutrient and oxygen inputs (Sarmiento & Gruber 2006). For example, climate warming is likely to increase the frequency of hypoxia or anoxia events (Diaz 2001, Selman et al. 2008). Atmospheric circulation (sea level pressure and wind direction and intensity), by its action on oceanic currents, also contributes to the horizontal inputs of nutrients and di-oxygen in coastal systems (Cloern 2001, Reid et al. 2003). Wind-induced and/or tidal-induced turbulent mixing are important as they control the onset of the spring phytoplankton bloom (Sverdrup 1953, Legendre & Demers 1984, Cloern 1996, Ragueneau et al. 1996, Gaedke et al. 1998) and the contact rates between prey and predators (Gaedke et al. 1998, Lewis & Pedley 2001, Lewis & Bala 2006). Coastal systems are also strongly influenced by the continent. Precipitation, by its effect on the volume of river discharge, is among the major mechanisms by which the strength of the interaction between the land and the ocean can be modulated (Harley et al. 2006).

The impact of humans on marine ecosystems occurs on a variety of temporal and spatial scales (Dobson et al. 1997). Biodiversity of marine systems is being altered by many human-induced factors including overexploitation of marine resources (e.g. Omori et al. 1994, Jennings & Kaiser 1998), destruction of wetlands and habitat loss (Cloern 2001) and invasion of exotic species (Cariton & Geller 1993, Steneck 1998, Edwards et al. 2001). For decades, this has also included eutrophication as a result of increasing nutrient inputs (e.g. Howarth 1988, North Sea Task Force 1993, Cloern 2001) and perturbation due to dispersion of chemical pollutants in estuarine and coastal waters (e.g. Norse 1993). Fisheries have affected the marine environment both directly and indirectly (Omori et al. 1994, Omori & Norman 1998, Jennings et al. 2001). Teasing out the respective influence of natural and anthropogenic forcing on ecosystems represents perhaps one of the biggest challenges of this century.

Marine coastal systems of western Europe have been monitored since 1997 by Service d'Observation en Milieu Littoral (SOMLIT). Since 1997 this monitoring programme has gathered a database of physical, chemical and biological parameters at 12 sites located along the coasts of France, from the Mediterranean Sea (42° 30′ N) to the English Channel (51° N) on a bimonthly basis (i.e. twice a month). The 12 studies sites have specific hydrographic features. The Atlantic, and especially the English Channel, coastal stations are under the direct influence of Atlantic ocean waters and are characterised by strong tidal forcing (e.g. the Ushant Front; Sournia et al. 1990); however, freshwater inputs can impact their physical and chemical characteristics locally, especially in the English Channel (the River Seine) and in the Bay of Biscay (the Gironde estuary). In the Mediterranean Sea, stations experience weak tidal forcing. The water circulation patterns are typically driven by the Liguro-Provençal current and surface currents flowing in a roughly NE-SW direction, almost parallel to the shoreline (Font et al. 1988). The Rhône River strongly influences freshwater inputs in the north-western part of the Mediterranean Sea.

The main objectives of our study were (1) to examine year-to-year changes in coastal systems monitored by SOMLIT and (2) to quantify the potential influence of climate variability on coastal systems. Both the regional climatic and coastal variability were first characterised and then related to large-scale hydroclimatic forcing. Our analyses suggest a clear influence of climate variability on coastal systems.

MATERIALS AND METHODS

Environmental database: SOMLIT. SOMLIT is a French marine monitoring programme, created by a national institute, the Institut National des Sciences de l'Univers (INSU), which has coordinated activities of a number of marine stations along the French coasts since 1997 (Fig. 1). This programme currently comprises 7 marine laboratories which monitor sampling sites in the English Channel, the Atlantic Ocean and

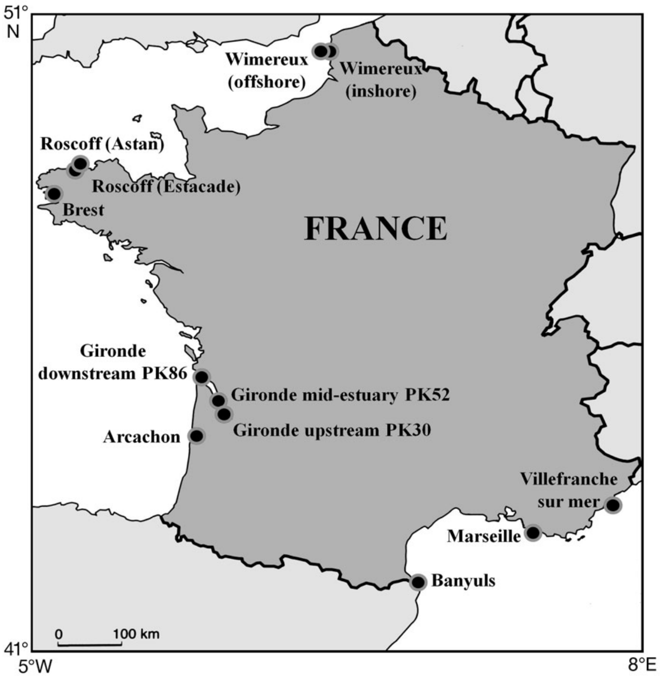


Fig. 1. Location of the Service d'Observation en Milieu Littoral (SOMLIT) sites used in our study

the Mediterranean Sea. At the beginning of the programme, the sampling sites were chosen because they reflected the diversity of systems along the French coasts (e.g. marine, estuarine and mixed systems). In practical terms, the choice of sampling sites was driven by (1) their local or regional environmental benefits, (2) the existence of historical biological or hydro-climatic monitoring and (3) the accessibility for regular sampling and for possible automation in the measurement of some parameters. Coastal systems studied under this programme have a variety of hydro-climatic characteristics ranging from the non-tidal Mediterranean Sea (e.g. Marseille) to the mega-tidal English Channel (Wimereux, see Fig. 1). Sampling has been carried out at least twice a month since 1997. A protocol has been established so that sampling is carried out at all stations at sub-surface and at high tide (for the tidal seas). More details on the monitoring are available at http://somlit.epoc.u-bordeaux1.fr/fr. All data gathered by this programme were considered in this study. It is important to note that because of dependency on meteorological conditions during sampling, the percentage of available data is not always the optimum (Tables 1 & 2).

Climatological variables. In this paper, gridded data on sea level pressure (SLP), wind intensity and its zonal (i.e. the west to east component of the wind) and meridional (i.e. the south to north component of the wind) components were used (Table 3). The wind intensity can be considered as a surface pressure gradient (Henderson-Sellers & Robinson 1986). Defined in this way, when combined, the information on both zonal and meridional wind enables the true average direction and strength of the wind to be calculated from the Pythagorean formula. These data were obtained from the National Centers for Environmental Prediction (NCEP, USA) and the National Center for Atmospheric Research (NCAR, USA). The methodology of the NCEP-NCAR reanalysis data assimilation was discussed in detail by Kalnay et al. (1996) and Kistler et al. (2000), and more information on the numerical procedures was provided by Betts et al. (1996) and Kalnay et al. (1996).

Sea surface temperatures (SST) were used as they can have a large influence on coastal processes (Harley et al. 2006). The data set is based on methods that use high-frequency SST anomalies interpolated in such a way that interpolated temperatures fit spatial modes. The technique takes into account sea-ice concentration to better assess SST at high latitudes and a modified historical bias correction for the period 1939 to 1941 as well as an improved error estimate. The optimum interpolation (OI) SST analysis is produced weekly on a 1° grid, so SST over land and island lakes is filled by interpolation. A full description of the OI analysis can be found in Reynolds & Smith (1994). In the present study, data were interpolated on a grid of 1° longitude × 1° latitude from December 1981 to December 2006 (Table 3).

Precipitation data were used, as this parameter impacts both the input of freshwater and nutrients from land to ocean. Data consisted of monthly values from January 1979 to December 2006, with a spatial resolution of 2.5° longitude × 2.5° latitude. More information on the data can been found at www.cru.uea.ac.uk/cru/data/ncep. All gridded climatological data were analysed between 1997 and 2006.

Large-scale hydro-climatic indices. Three large-scale hydro-climatic indices were selected because of their potential importance in the studied area (Marshall et al. 2001, Beaugrand 2009).

The winter North Atlantic Oscillation index (NAO; Hurrell 1995a) is a basin-scale alternation of atmospheric masses between the subtropical and the Arctic Atlantic (Dickson & Turrell 2000). This oscillation has been correlated with a large range of physical and bio-

Table 1. Data relating to the sites used in this study. For location of sites see Fig. 1

Site	Latitude	Longitude	Period (mm/yy)	Depth sampling (m)	Distance to coast (km)	Bathymetry (m)	River close to site	River flow (m^3 s^{-1})
Wimereux offshore	50° 40′ 75″ N	1° 24′ 60″ E	11/97–12/06	1	9.26	53	Liane	3
Wimereux inshore	50° 40′ 75″ N	1° 31′ 17″ E	11/97–12/06	1	1.85	26	Liane	3
Roscoff Astan	48° 46′ 40″ N	3° 56′ 15″ W	02/00–12/06	1	3.5	60	Penzé	4
Roscoff Estacade	48° 43′ 56″ N	3° 58′ 58″ W	01/97–12/06	1	0.05	3	Penzé	4
Brest	48° 21′ 60″ N	4° 33′ 38′ W	03/98–12/06	2	0.25	10	Aulne	30
Downstream estuary	45° 31′ 00″ N	1° 57′ 00″ W	03/97–12/06	1	2	8.2	Garonne	631
Mid-estuary	45° 14′ 80″ N	0° 43′ 50″ W	01/97–12/06	1	1	7	Garonne	631
Upstream estuary	45° 04′ 10″ N	0° 38′ 30″ W	01/97–12/06	1	0.5	8	Garonne	631
Arcachon	44° 40′ 00″ N	1° 10′ 00″ W	01/97–12/06	3	0.05	6	Eyre	18.8
Villefranche-sur-Mer	43° 41′ 00″ N	7° 19′ 00″ E	01/97–12/06	1	1.85	95	–	0
Marseille	43° 14′ 30″ N	5° 17′ 30″ E	01/97–12/06	1	6.48	60	Rhône	1700
Banyuls	42° 29′ 30″ N	3° 8′ 70″ E	03/97–12/06	3	0.92	27	Baillaury	4

Table 2. Percentages of data available in the SOMLIT database for the studied period and for each site. For location of sites see Fig. 1

Site	Temp. (°C)	Salinity (‰)	Oxygen (ml l^{-1})	pH	Ammonium (µmol l^{-1})	Nitrate (µmol l^{-1})	Nitrite (µmol l^{-1})	Phosphate (µmol l^{-1})	Silicate (µmol l^{-1})	Particulate organic nitrogen (µg l^{-1})	Particulate organic carbon (µg l^{-1})	Suspended matter (µg l^{-1})	Chl *a* (µg l^{-1})
Wimereux offshore	80.13	78.21	89.74	85.26	83.97	85.26	85.26	84.62	88.46	87.82	86.54	87.18	89.74
Wimereux inshore	90.06	87.58	95.65	91.93	90.06	93.79	93.79	93.17	96.27	93.79	93.17	93.79	96.89
Roscoff Astan	96.79	97.33	97.33	86.63	96.79	98.40	98.40	98.40	98.40	73.80	73.80	85.56	97.86
Roscoff Estacade	97.19	97.99	97.59	90.76	98.39	97.99	97.99	97.99	91.57	55.02	55.02	83.53	97.19
Brest	99.79	98.73	98.31	58.05	97.88	98.73	96.61	98.52	98.73	89.83	90.04	58.26	98.73
Downstream estuary	95.51	95.51	86.89	86.89	61.05	65.92	66.29	66.29	50.94	64.04	20.60	87.27	69.66
Mid-estuary	98.63	98.63	93.84	91.44	59.93	66.78	67.47	67.12	53.08	66.44	18.15	91.10	71.92
Upstream estuary	100	100.00	94.37	90.85	60.92	66.90	67.96	67.96	53.52	66.20	19.72	91.55	72.18
Arcachon	99.73	98.92	85.71	86.52	61.99	85.18	81.67	83.29	68.19	83.83	22.37	94.61	95.42
Villefranche-sur-Mer	98.51	97.91	37.16	4.63	0.00	85.82	86.72	84.03	83.88	40.00	36.27	5.37	95.52
Marseille	99.15	93.62	94.47	0.00	94.04	97.02	97.02	96.60	96.60	82.98	82.98	77.87	96.60
Banyuls	79.58	79.58	67.11	44.61	83.55	87.90	58.79	63.71	66.16	26.47	23.82	42.72	87.90

logical indicators or phenomena, e.g. the paths of Atlantic storms and their intensity (Hurrell 1995b), precipitation patterns (Hurrell 1995a), abundances of zooplankton species (Fromentin & Planque 1996, Beaugrand et al. 2000), or fluctuations in the productivity of some fish and invertebrate species (Alheit & Hagen 1997, Anderson 2000).

An index of Northern Hemisphere temperature (NHT) anomalies from 1958 to 2006 was used (Beaugrand 2009). Data were provided by the Hadley Centre for Climate Prediction and Research, Meteorological Office (Exeter, UK).

The Atlantic Multidecadal Oscillation (AMO) is a large-scale oceanic phenomenon, the source of natural variability in the range of 0.4°C in many oceanic regions (Enfield et al. 2001). We used the index constructed from Extended Reconstruction SST (ERSST) data and averaged in the area of 25 to 60° N and 7 to 75° W, minus regression (i.e. detrending is intended to remove the North Atlantic SST anomaly data from the analysis) on global mean temperature (National Climate Data Center, USA: NCDC). This index was downloaded from http://climexp.knmi.nl/. Previous studies have shown that this oceanic oscillation might have a large influence on SST changes (Enfield et al. 2001, Keenlyside et al. 2008).

Analysis 1: long-term spatial and temporal changes in coastal systems. SOMLIT data gather information on physical, biological and chemical properties of the water column structured in space and time. The original 3-way data matrix was therefore composed of 13 parameters × 120 mo (period 1997 to 2006) × 12 stations.

Prior to the analysis, data were averaged per month, and a simple moving average of order 6 was used to remove the effect of seasonality (Legendre & Legendre 1998):

$$y_i = \frac{1}{2m+1}\sum_{i-m}^{i+m} x_i \qquad (1)$$

where y_i is the simple moving average at observation i, m is the number of months, $2m+1$ is the time window with $m+1 \leq i \leq n-m$, with n being the length of the time series.

Only a few statistical techniques exist to analyse such complex tables, e.g. co-inertia analysis (Dolédec & Chessel 1994) and 3-mode principal component analysis (PCA; Hohn 1993). The 3-mode PCA, used by Beaugrand et al. (2000), first calculates 3 classical PCAs on 2-dimensional tables after having transformed 1 table to ensure that the total inertia is identical in each mode (Beaugrand et al. 2000). The analysis then relates the different modes by assessing a core matrix calculated from the eigenvectors of each mode (Beaugrand et al. 2000). In the present study, we only calculated 1 standardised PCA (i.e. subtracting the mean and dividing by the SD to give all parameters the same variation) on the deployed 3-way matrix 120 mo

Table 3. Origin and characteristics of climatic data used in this study. Source: National Centers for Environmental Protection/National Center for Atmospheric Research (NCEP/NCAR). n: number of data. For all climatological variables the spatial resolution of the grid was 1°, with the exception of precipitation for which it was 2.5°. Data were obtained each month

Data	Units	Spatial range	Years	n ($\times 10^5$)
Sea level pressure	hPa	11.5° W to 11.5° E 60.5° to 28.5° N	1948–2006	5.60
Zonal wind	m s^{-1}	11.5° W to 11.5° E 60.5° to 28.5° N	1948–2006	5.60
Meridional wind	m s^{-1}	11.5° W to 11.5° E 60.5° to 28.5° N	1948–2006	5.60
Wind intensity	m s^{-1}	11.5° W to 11.5° E 60.5° to 28.5° N	1948–2006	5.60
Sea surface temperature	°C	11.5° W to 11.5° E 60.5° to 28.5° N	1982–2006	2.37
Mean precipitation	mm d^{-1}	13.75° W to 11.25° E 56.25° to 28.75° N	1979–2006	0.44

× (12 parameters × 12 stations) (Fig. 2), which represents the first stage performed in a 3-mode PCA. This PCA was performed on a correlation matrix. Although the number of variables is greater than the number of observations, our analysis remains valid because we only focused on a limited number of principal components (PCs; a total of 2 here) (Legendre & Legendre 1998). It should also be noted that temperature was not included directly in the analysis but as a supplementary variable, so that it does not contribute to PCs. Eigenvectors were normalised as follows:

$$\mathbf{U}_n = \mathbf{U}\,\mathbf{\Lambda}^{1/2} \qquad (2)$$

where $\mathbf{U}_n$ is the matrix of normalised eigenvectors, $\mathbf{U}$ is the matrix of eigenvectors and $\mathbf{\Lambda}$ is the diagonal matrix of eigenvalues. Thus, the variables in the space of eigenvectors represented the linear correlation with the first and the second PCs (Legendre & Legendre 1998). We used this mathematical property to add temperature as a supplementary variable, simply by calculating the linear correlation (Pearson correlation coefficient) between temperature and the first 2 PCs. Thus, temperature had no weight in the calculation of the PCs. The use of this statistical technique allowed in a single analysis the characterisation of temporal changes, the identification of parameters that contribute to the change and the recognition of locations mainly influenced by the temporal patterns. Prior to the mapping of each eigenvector (12 stations × 13 parameters), the order of each parameter was sorted by performing a PCA on the matrix of eigenvectors acquired after PCA on SOMLIT data. The PCA of eigenvectors identifies parameters that are close to each other in a Euclidean distance sense (Elmore & Richman 2001), thereby providing a new similarity matrix choice.

To examine the influence of each environmental parameter on the first and second PC, we did a sensitivity analysis by re-performing the standardised PCA on a decreasing number of parameters from 12 to 1. It should be noted that even with 1 parameter, there were still 12 sites; therefore, the dimension of the matrix was 120 observations × 12 sites when only 1 parameter remained. The sensitivity analysis was also performed by removing each site from 12 sites to only 1. In such a case, when only 1 site remained, the dimension of the matrix was 120 observations × 12 parameters. Two separate standardised PCAs were also conducted for Mediterranean (matrix 120 observations × 36 parameters and sites) and Atlantic sites (matrix 120 observations × 108 parameters and sites).

Analysis 2: long-term spatial and temporal changes in some climatological variables. Long-term climatological changes were investigated by standardised PCA (Joliffe 1986). The PCA was performed on a correlation matrix with the double objective of identifying major long-term changes in climatological variables (examination of PCs) and locating their geographical patterns (mapping of eigenvectors, Beaugrand 2009). A total of 6 PCAs was performed on the climatological data (Table 3). The analyses were applied in the spatial domain ranging from 14° W to 12° E and from 28° to 61° N (Table 3). For all climatological variables, except precipitation (Table 3), the spatial grid had a spatial resolution of 1° latitude × 1° longitude. As with SOMLIT data, a simple moving average of order 6 was used to remove the effect of seasonality.

Analysis 3: correlation analysis. Correlation analyses were performed between the first PCs obtained from Analysis 1 (year-to-year changes in the coastal environment) and the first PCs from the PCAs performed on (regional) climatological variables (Analysis 2), and all PCs were correlated to large-scale hydro-climatic indices (see Figs. 2 & 8, see Tables 4 & 5). Probabilities were corrected to account for temporal autocorrelation. A Box-Jenkins (Box & Jenkins 1976) autocorrelation function modified by Chatfield (1996) was used to assess the temporal dependence of years. The Chelton formula (Chelton 1984) was applied to adjust the degrees of freedom. This procedure was recommended by Pyper & Peterman (1998).

When ordinary correlations between year-to-year changes in the coastal systems and hydro-climatic variability were greater than 0.5, cross-correlation analyses were performed to examine whether these relationships were direct or occurred with a certain lag. These analyses were performed by lagging months from 1 to 60 (5 yr). To assess the probability of the cross-correlogram, we adjusted the degrees of freedom for each lag and also for temporal autocorrelation. As a result of this procedure, an identical value of correlation for 2 successive lags can have different values of probability, independently of the degrees of freedom lost by the lag itself.

Multiple testing increases the probability of a type I error (i.e. finding too many significant correlations). To correct for this potential bias, the Hochberg (1988) method was applied with $\alpha = 0.05$ for correlations with climatological variables and for correlations with large-scale hydro-climatic indices. This nonparametric correction is considered more robust and less conservative than the Bonferroni technique (Legendre & Legendre 1998).

All methods used in the present study were programmed using MATLAB language.

RESULTS

Year-to-year changes in French coastal systems

A PCA was performed on the 2-way table (120 mo × 12 stations – 12 parameters) with temperature as a supplementary variable. Year-to-year changes in the first PC (24.16% of the total variability) exhibited a period of relative stability until 2001, followed by a pronounced decrease in the trend until 2005 (Fig. 3a, left). Mapping of the first eigenvector indicated that the trend detected by the component is especially strong for sites located in the English Channel, the Celtic Sea and to a lesser extent Arcachon, Banyuls and Marseille (Fig. 3a, right). Parameters that contributed to the changes were mainly nutrients, particulate organic carbon (POC) and to a lesser extent particulate organic nitrogen (PON). The nutrients and POC were positively correlated to the first component so that the reduction observed in the component after 2001 corresponded to a decrease in nutrient concentration for sites located mainly in the English Channel. Salinity was strongly negatively correlated with the first PC for all stations, indicating an increase in salinity after the shift of 2001. The Gironde estuary differed from the other sites, showing a tendency toward an increase in phosphate, silicic acid, particulate matter (PON and suspended particulate matter, SPM) and chlorophyll (chl) *a*.

Year-to-year changes in the second PC (14.13% of the total variability) exhibited a pseudo-cyclical variability of 6 to 7 yr (Fig. 3b, left). Pronounced negative values were observed in the second PC between 2001 and 2005 at the time the first component diminished (Fig. 3a). Mapping of the sorted second eigenvector (Fig. 3b, right) showed that POC, PON, SPM, pH and to

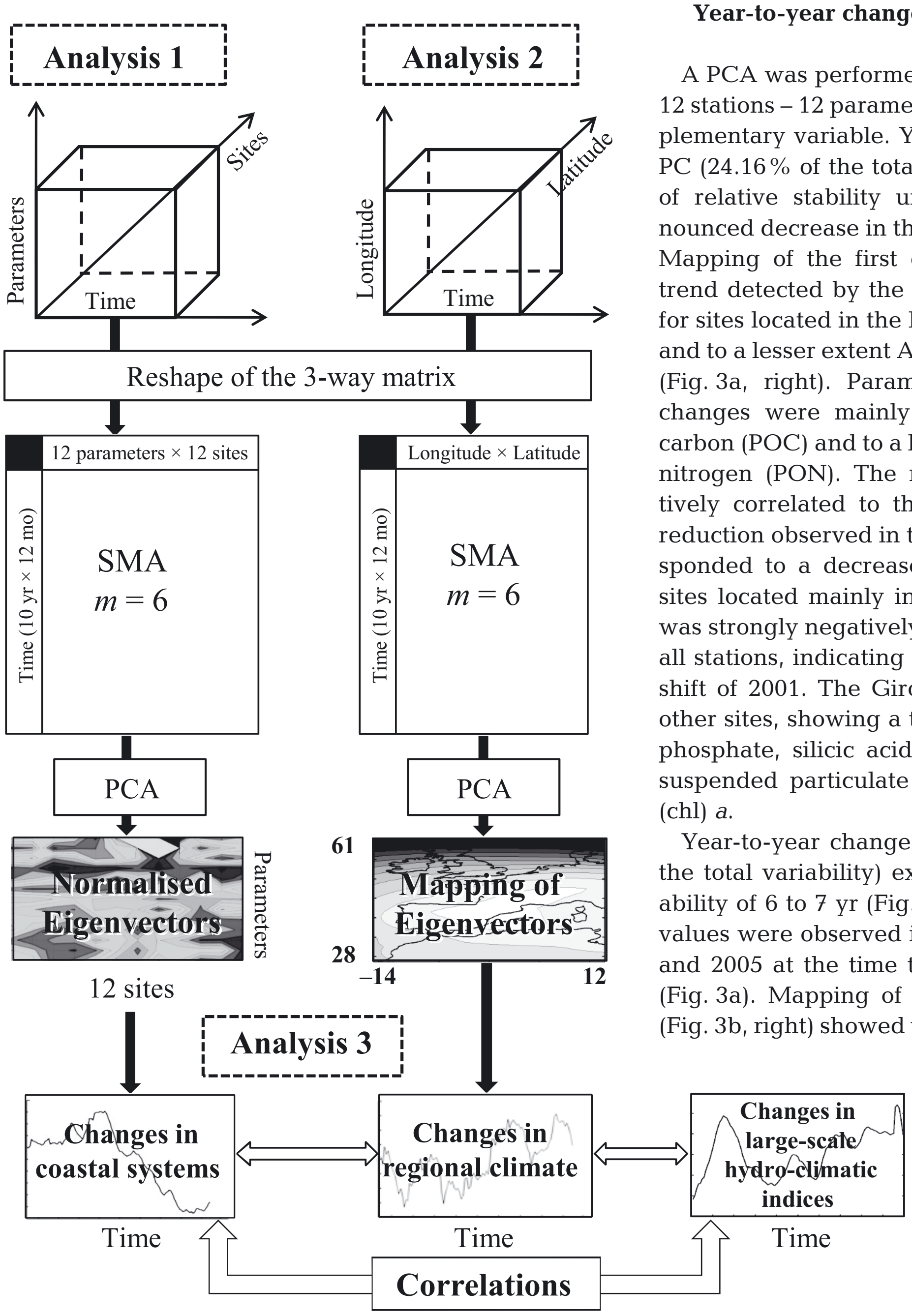
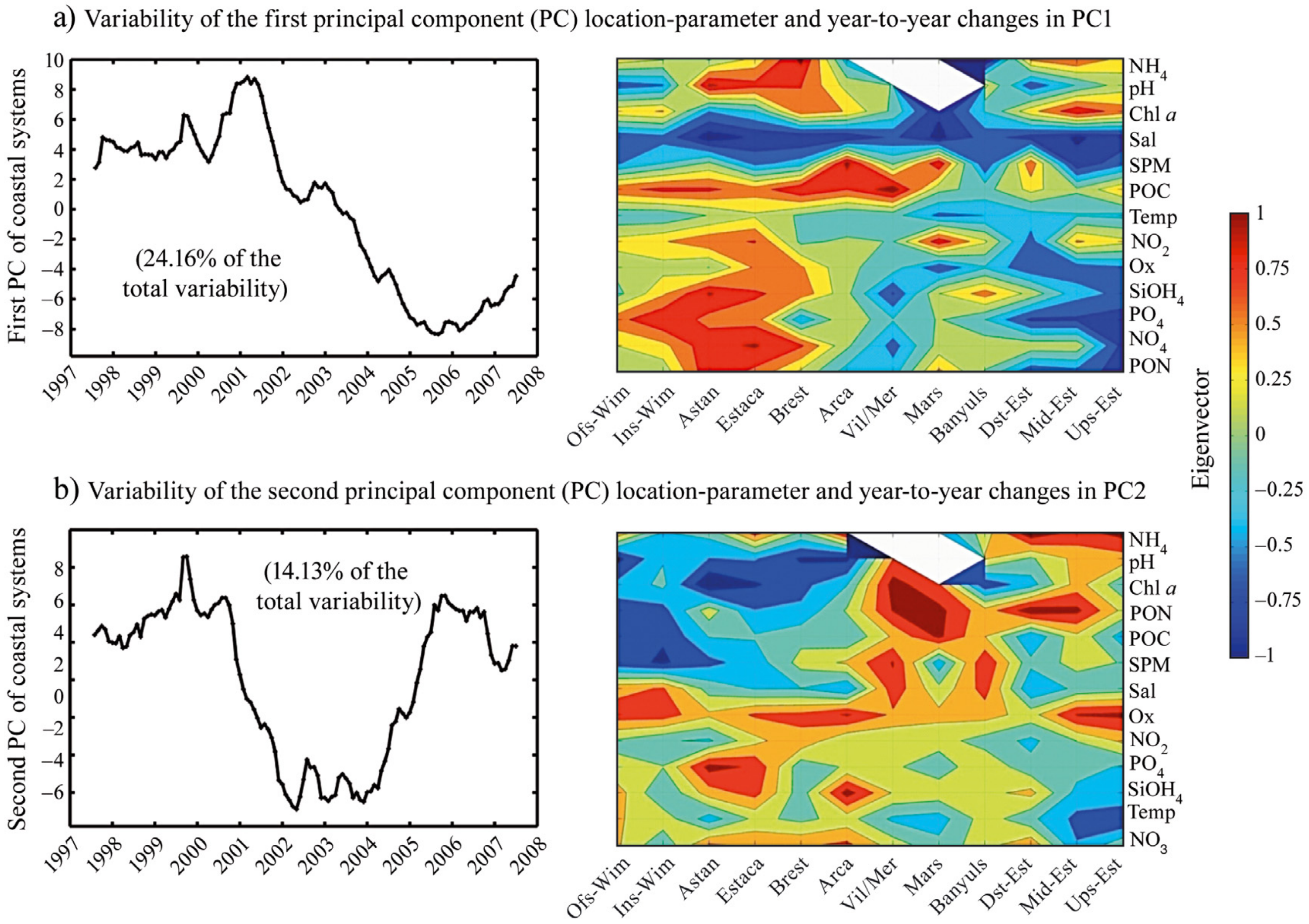


Fig. 2. Statistical analyses applied in this study. SMA: simple moving average of order 6; PCA: principal component analysis; m: no. of months


a) Variability of the first principal component (PC) location-parameter and year-to-year changes in PC1

b) Variability of the second principal component (PC) location-parameter and year-to-year changes in PC2

Fig. 3. Principal component analysis (PCA) of the year-to-year changes in the coastal systems of western Europe in (a) the first and (b) the second principal component (PC) location-parameter (left) and mapping of the first eigenvector (right). Temperature was added in the analysis as a supplementary variable. Sites were ordered from north to south and estuarine sites positioned along the abscissa. Ofs-Wim: Wimereux (offshore); Ins-Wim: Wimereux (inshore); Astan: Roscoff Astan; Estaca: Roscoff Estacade; Brest; Arca: Arcachon; Vil/Mer: Villefranche-sur-Mer; Mars: Marseille; Banyuls; Dst-Est: Gironde PK86 (downstream); Mid-Est: Gironde PK52 (middle); Ups-Est: Gironde PK30 (upstream); Sal: salinity; Ox: oxygen; NH_4: ammonium; NO_3: nitrate; NO_2: nitrite; PO_4: phosphate; $SiOH_4$: silicate; POC: particulate organic carbon; PON: particulate organic nitrogen; SPM: suspended particulate matter; Chl *a*: chlorophyll *a*; Temp: temperature

a lesser extent chl *a* were negatively related to the second PC in stations located in Arcachon and northwards, indicating an increase in the values of these parameters between 2001 and 2005. There was a distinct difference between the western coasts and the Mediterranean Sea. Dissolved di-oxygen was strongly positively correlated with the second component for all the stations, indicating a low-amplitude tendency toward a decrease in di-oxygen concentration everywhere during the period 2001 to 2005.

Environmental temperature was added in the analysis as a supplementary variable because we then calculated correlations between changes in both regional temperature and the first PC. If environmental temperature was included directly in the PCA, the 2 variables (PC1 SOMLIT and regional SST) would not be entirely independent (an important assumption in correlation analysis, see Sokal & Rohlf 1995). Thereby, the variable was removed from the analysis. However, as the eigenvectors show (Fig. 3), the environmental temperature is highly correlated to the first component and therefore the removal of this variable did not affect the first PC.

Results from the sensitivity analysis showed that our conclusions were not greatly affected by removing an increasing number of parameters or sites (Fig. 4). Indeed, the correlation of the first component decreased from 0.994 ($p < 0.05$) when based on 11 parameters to 0.458 ($p < 0.05$) when based on only 1 parameter. Despite the decrease observed in the percentage of variance explained by the analysis, the significant positive correlation suggested that

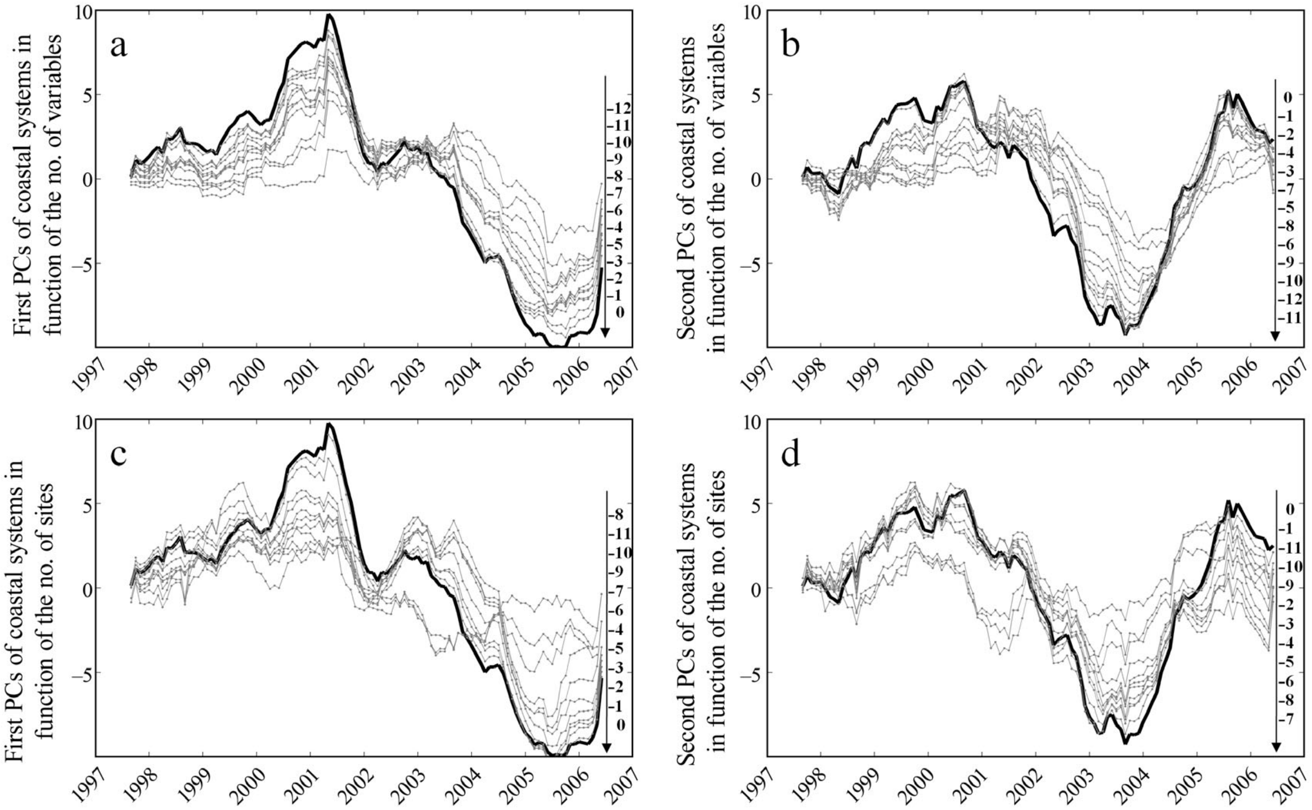


Fig. 4. Sensitivity analysis on the first 2 principal components (PCs) calculated from a standardised principal component analysis (PCA) performed on a decreasing number of parameters and sites. The thick black line represents the PCs when no parameter or site was removed. (a) First and (b) second PC of the PCA performed on the table: time × (observations – variables) based on a decreasing number of variables from 12 to 1. (c) First and (d) second PC of the PCA performed on the table: time × (observations – variables) based on a decreasing number of sites from 12 to 1. '0' indicates that no variable or site was removed; negative values on the graph indicate the number of sites or variables that were removed from the PCA

results were still positively correlated based on only 1 variable. For the second PC, this correlation decreased from 0.996 to 0.637. Our conclusion was also not affected by the removal of sites. The correlation of the first component decreased from 0.998 when based on 11 sites to 0.657 when based on only 1 site; the correlation of the second PC decreased from 0.996 to 0.389.

The 2 separate standardised PCAs confirmed the average correlation between the year-to-year changes in Atlantic and Mediterranean sites observed in Fig. 3 (mapping of eigenvectors). The correlation between the 2 first PCs (Atlantic: 28.47 % of the total variance; Mediterranean Sea: 33.10 % of the total variance) were high (r = 0.69) although at the limit of significance (p = 0.12) when the temporal autocorrelation was taken into account (Fig. 5a). The correlation was low (r = 0.08) and not significant (p = 0.78) when the 2 second PCs (Atlantic: 16.82 % of the total variance; Mediterranean Sea: 17.20 % of the total variance) were examined (Fig. 5b).

Year-to-year changes in regional climate

Six PCAs were performed on the 2-way table (time × space) of each climatological variable to characterise the spatial and temporal changes in regional climate during the period of sampling by SOMLIT. We only describe 4 analyses in detail (zonal and meridional wind, temperature and precipitation), as results obtained on SLP and wind intensity can be deduced from the analyses performed on directional wind.

Changes in atmospheric circulation may strongly affect coastal systems. The examination of the first component (42.65 % of the total variability) of the PCA performed on zonal winds showed, for all regions covering the French coast, a stepwise increase in zonal wind in 2001 and the occurrence of 2 minima around 1999 and 2005 (Fig. 6a). Between 2001 and 2005, an irregular reduction in zonal wind was observed. As the eigenvectors were positive, an increase in the value of the PC should be interpreted as an increase in zonal wind and vice versa. The second component (20.56 %

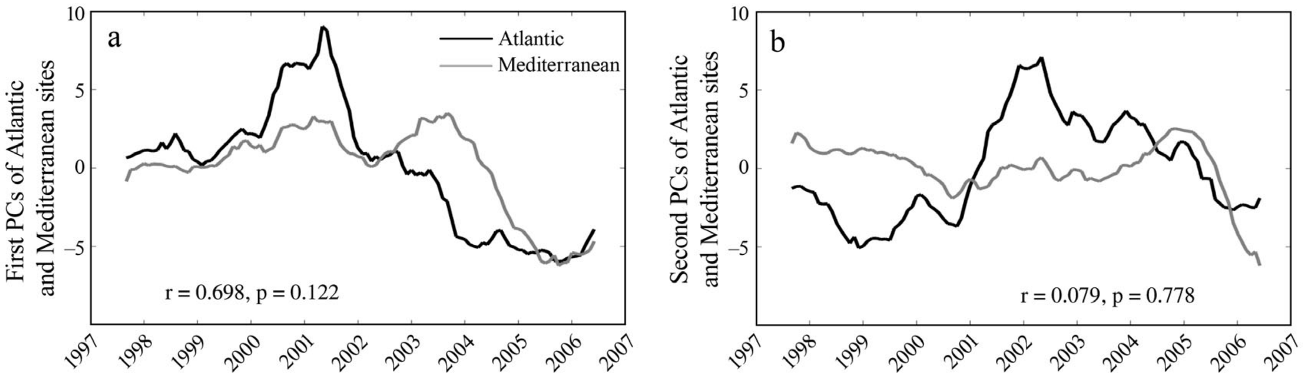


Fig. 5. Comparison of (a) the first and (b) second principal components (PCs) from a standardised principal component analysis (PCA) performed on Atlantic (black) and Mediterranean sites (gray), showing changes in the coastal systems of western Europe. Probabilities were corrected to account for temporal autocorrelation using the method recommended by Pyper & Peterman (1998)

of the total variability) showed a pseudo-cyclical variability of about 4 yr (Fig. 6b). For regions mainly located in the eastern part of the English Channel and Villefranche-sur-Mer where eigenvectors are negative, the component indicated higher zonal winds between 1998 and 2001 and lower winds between 2001 and 2005. Locations of high values in the first and second eigenvectors are obviously related to the boundary between regions of lower and higher SLP (see Fig. S1 in the supplement at www.int-res.com/articles/suppl/m408p129_supp.pdf).

The examination of the first eigenvectors (45.35 % of the total variability) of the PCA performed on meridional winds showed a clear bi-polar pattern (Fig. 7a). Values of the eigenvectors were strongly positive around Spain and negative north of France. Therefore, the first component was not considered to explain year-to-year changes in the French coastal systems.

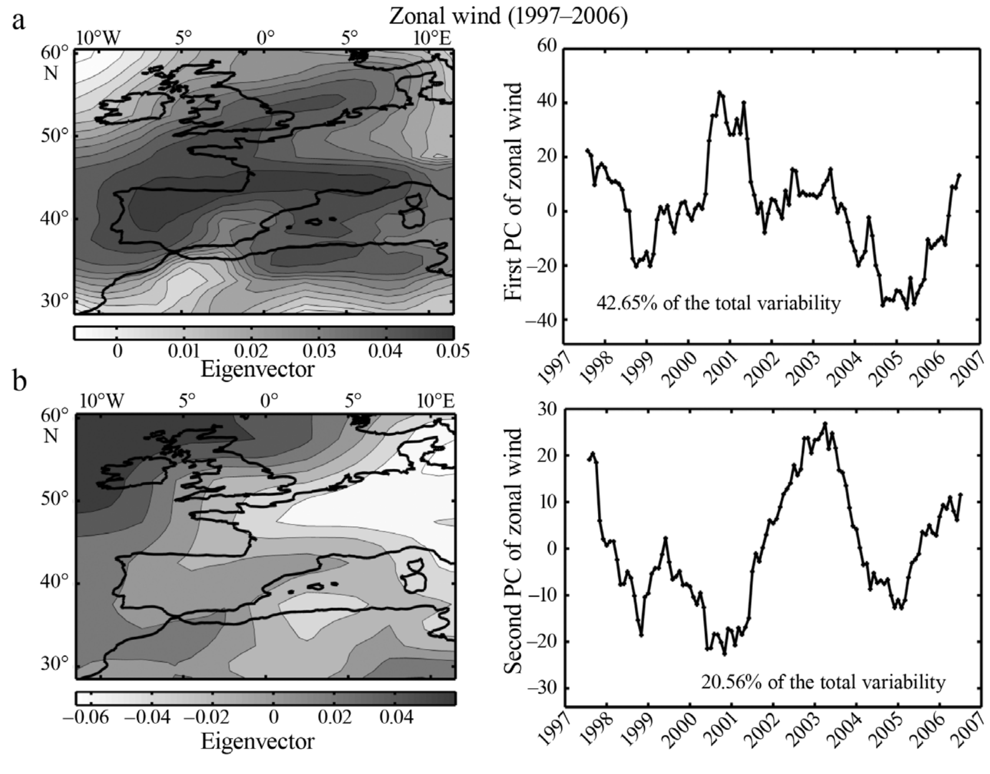


Fig. 6. Principal component analysis (PCA) on the year-to-year changes in zonal wind (1997–2006). Mapping of (a) the first eigenvector (left) and year-to-year changes in the first principal component (PC; right; 42.65 % of the total variability) and (b) the second eigenvector (left) and year-to-year changes in the second PC (right; 20.56 % of the total variability)

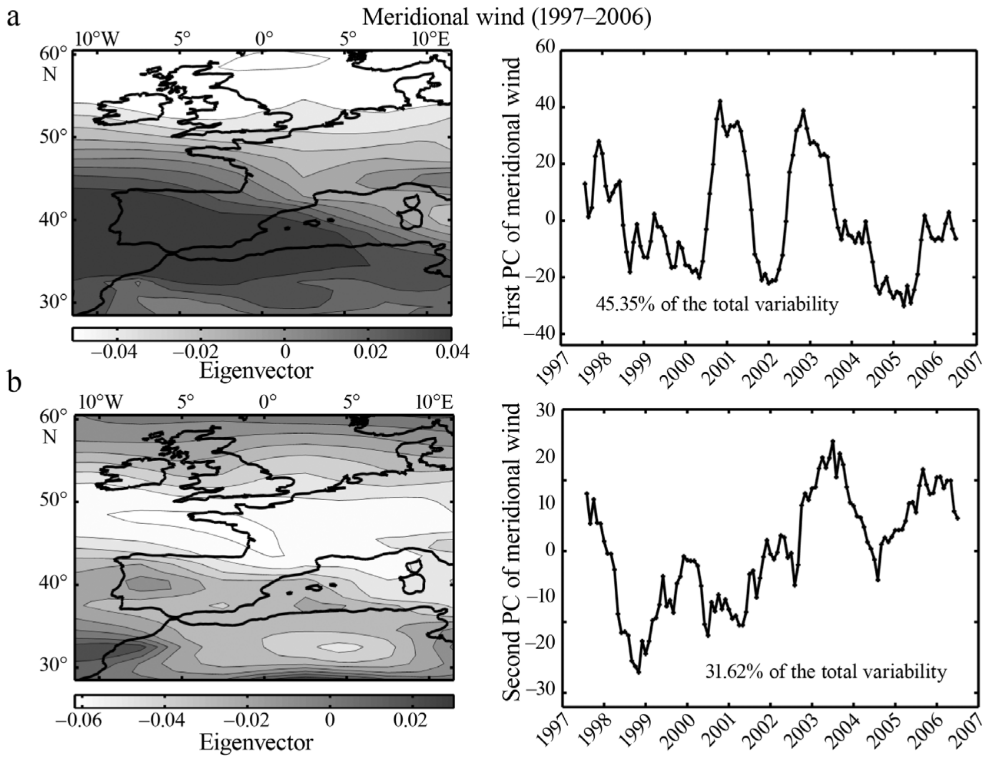


Fig. 7. Principal component analysis (PCA) on the year-to-year changes in meridional wind (1997–2006). Mapping of (a) the first eigenvector (left) and year-to-year changes in the first principal component (PC; right; 45.35 % of the total variability) and (b) the second eigenvector (left) and year-to-year changes in the second PC (right; 31.62 % of the total variability)

The second eigenvectors (31.62 % of the total variability) had great negative values centred around France (Fig. 7b, left). The second component therefore revealed a continued decrease in meridional winds with a superimposed pseudo-cyclical variability. Minima in meridional winds were observed during 1998, 2003 and 2006, and a maximum in 1999. The information gained from both zonal and meridional winds was in general also found in the examination of the PCA performed on wind intensity (see Fig. S2 in the supplement at www.int-res.com/articles/suppl/m408p129_supp.pdf).

Change in atmospheric circulation influences SST. The examination of year-to-year changes in the PC (71.26 % of the total variability) showed high values in 1998 and 2003–2004, and minima in 1999 and 2005–2006 (Fig. 8a). As the first eigenvector was positive, a positive value of the component indicated warmer SST (and vice versa). The component exhibited a cyclical variability, close but slightly greater than an annual cycle and despite the use of the order-6 simple moving average. The second PC (10.35 % of the total variance) detected an anomaly in SST in 2002 (Fig. 8b).

Atmospheric circulation changes also influence precipitation patterns that affect coastal systems through river run-off. Year-to-year changes in the first PC (36.99 % of the total variability) showed an abrupt increase in the value of the component that started at the end of 1998 and ended in 2002 (Fig. 9a). This phenomenon was particularly pronounced in the Mediterranean Sea but also reflected changes occurring over the western coasts of France (see high values in the first eigenvector, Fig. 9a). The second PC (19.92 % of the total variance) exhibited a pseudo-cyclical variability of about 3 yr with opposite consequences in southern and northern regions.

Relationships between year-to-year changes in coastal systems, regional climate and large-scale hydro-climatic indices

Linear correlations between the first 2 PCs that originated from the 6 PCAs and the first 2 components from the PCA performed to investigate year-to-year changes in coastal systems were calculated to test whether such changes were related to changes in regional climate (Table 4).

Results from correlation analyses suggested a concomitant change in coastal systems (as inferred from the first component of the PCA performed on environmental parameters) and atmospheric circulation, tem-

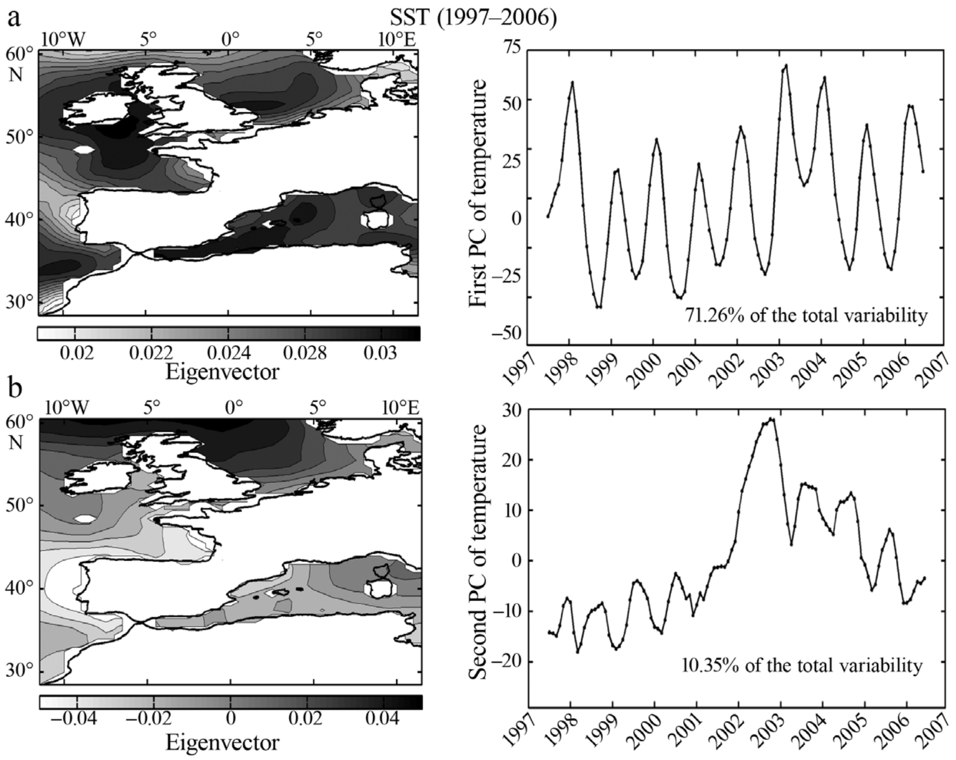


Fig. 8. Principal component analysis (PCA) on the year-to-year changes in sea surface temperature (SST; 1997–2006). Mapping of (a) the first eigenvector (left) and year-to-year changes in the first principal component (PC, right; 71.26 % of the total variability) and (b) the second eigenvector (left) and year-to-year changes in the second PC (right; 10.35 % of the total variability)

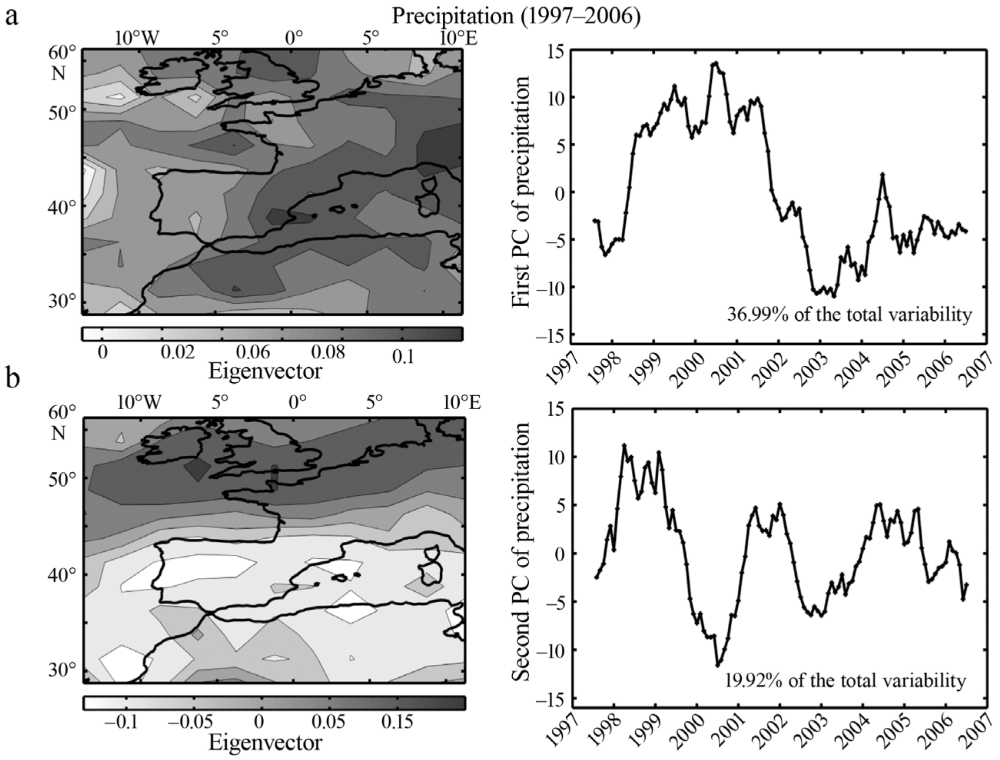


Fig. 9. Principal component analysis (PCA) on the year-to-year changes in mean precipitation (1997–2006). Mapping of (a) the first eigenvector (left) and year-to-year changes in the first principal component (PC; right; 36.99 % of the total variability) and (b) the second eigenvector (left) and year-to-year changes in the second PC (right; 19.92 % of the total variability)

perature and precipitation (Table 4). The link between the changes in the coastal systems and climate was patent. However, a graphical examination of the correlation showed that the link with climate occurred when the forcing was markedly low or high (Fig. 8). For example, high values observed in 2001 of the first component from the PCA performed on the coastal environment coincided with high values of zonal wind and vice versa (Fig. 10b), lower temperatures (not shown) and higher precipitation (Fig. 10e). Taking into consideration interpretations of the PCAs (see Figs. 5–9), this analysis indicated that the changes observed in nutrients, di-oxygen, chl *a* and particulate matter in the Atlantic ocean and the English Channel were positively related to wind intensity, direction and precipitation and negatively related to temperature. The link between environmental and climate change seemed more difficult to detect after 2005.

The second PC originating from the PCA performed on environmental parameters (SOMLIT) was in general less related to climatological parameters (Table 4). A weak but significant link was detected with zonal wind (Fig. 10f) and precipitation (Fig. 10h). However, analysis of the graphs showed that the link was detected for substantial changes in climatological variables and seemed less obvious at the end of the time series.

Examination of potential lags was carried out by cross-correlation analysis for pairs of variables that showed correlations >0.5 (see Table 4). Examination of all cross-correlograms (Fig. 11) suggests that no lag existed between the year-to-year variability in coastal systems and hydroclimate. The slight increase in the value of the correlation was too small (maximum range of correlation between r = 0.704 and r = 0.752 for the cross-correlogram between PC1 SOMLIT data and PC1 zonal wind, Fig. 11b) to be related to a significant lag. This was probably more influenced by the decrease in the degrees of freedom. However, the present analysis is influenced by the application of the order-6 simple moving average.

Table 4. Correlations between the first 2 principal components (PCs) of the principal component analysis (PCA) performed on Service d'Observation en Milieu Littoral (SOMLIT) data and the first 2 PCs of the PCA performed on each climatological variable (SLP: sea level pressure; UWIND: zonal wind; VWIND: meridional wind; IWIND: wind intensity; SST: sea surface temperature; MP: mean precipitation), with probability corrected to account for temporal autocorrelation with the method recommended by Pyper & Peterman (1998); df = 106. p values were also adjusted with Hochberg's procedure (1988) and α = 0.05. Significant correlations (r > 0.5) are in **bold**

Variable	PC	SOMLIT PC			
		1		2	
		r	p	r	p
SLP	1	0.462	0.012	0.046	0.809
	2	**–0.692**	**0.128**	0.333	0.420
UWIND	1	**–0.704**	**0.034**	–0.064	0.870
	2	0.295	0.409	**–0.512**	**0.195**
VWIND	1	–0.451	0.031	–0.233	0.336
	2	**0.658**	**0.156**	–0.375	0.407
IWIND	1	**0.751**	**0.086**	–0.193	0.678
	2	0.224	0.218	0.233	0.285
SST	1	0.320	0.137	–0.405	0.045
	2	0.315	0.606	**–0.709**	**0.114**
MP	1	**–0.657**	**0.229**	**0.574**	**0.233**
	2	0.094	0.592	0.019	0.952

Correlations between coastal environmental and regional climatological changes (annual mean) and large-scale hydro-climatic indices (NHT, AMO and NAO) were calculated between 1997 and 2006 (Table 5). Only NHT anomalies were correlated with changes in the coastal environment. High correlations were found between regional climate and this index, but only SLP was correlated significantly with NHT anomalies after adjusting the probability of considering multiple tests of correlation. Correlations between the state of the NAO and regional climate and changes in the coastal environment were low and insignificant, suggesting a weak impact of the NAO in our region (Table 5). High correlations were found between the AMO and the first PC that originated from the analysis on SOMLIT data. However, after correction to account for multiple testing, the probability of the correlation (i.e. the p value) exceeded 0.05 (Table 5).

DISCUSSION

Results suggest that coastal systems of western Europe located in the 42 to 51° N latitude range were affected by climate variability during the period 1997 to 2006. Strong correlations were found between regional climate and changes observed in the coastal environment, suggesting a substantial impact of climate on the coastal systems of western Europe. Both regional hydro-climatic and coastal changes were influenced by NHT, a large-scale climatological index. However, our study only covers a short time period. According to Southward (1995), long periods of monitoring are required to unambiguously separate the main drivers of changes that can affect a marine system (Hawkins et al. 2003). For example, Fromentin & Planque (1996) detected a strong negative correlation between the state of the NAO and the abundance of *Calanus finmarchicus* in the North Sea for the period 1962 to 1992. As the relationship was highly significant, they attempted to forecast the abundance of the species for a given value of the NAO. However, the correlation broke down after 1996 (Planque & Reid 1998). This example suggests

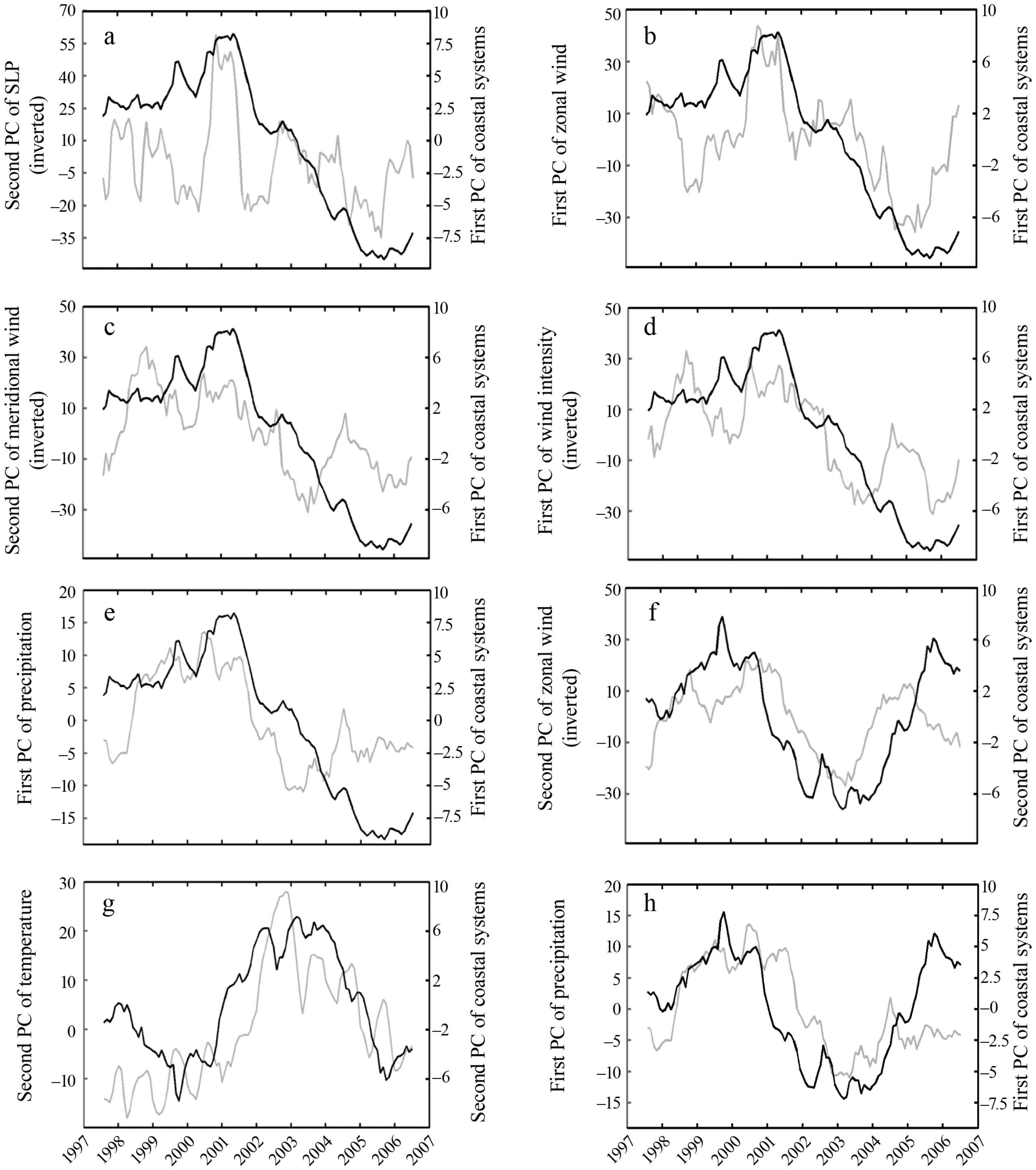


Fig. 10. Year-to-year changes in the coastal systems of western Europe in relation to hydro-climatic forcing. Year-to-year changes in the coastal systems of western Europe (first principal component [PC1] of the principal component analysis [PCA] performed on SOMLIT data; in black) and (a) sea level pressure (SLP; PC2 of the PCA performed on SLP; in gray), (b) zonal wind (PC1 of the PCA performed on zonal wind; in gray), (c) meridional wind (PC2 of the PCA performed on meridional wind; in gray), (d) wind intensity (PC1 of the PCA performed on wind intensity; in gray), (e) precipitation (PC1 of the PCA performed on precipitation; in gray). Year-to-year changes in the coastal systems of western Europe (PC2 of the PCA performed on SOMLIT data; in black) and (f) zonal wind (PC2 of the PCA performed on zonal wind; in gray), (g) sea surface temperature (SST; PC2 of the PCA performed on SST; in gray), (h) precipitation (PC1 of the PCA performed on precipitation; in gray). See Table 4 for the values of correlations. Probabilities were corrected to account for temporal autocorrelation using the method recommended by Pyper & Peterman (1998), p values were adjusted with Hochberg's procedure (1988) and $\alpha = 0.05$

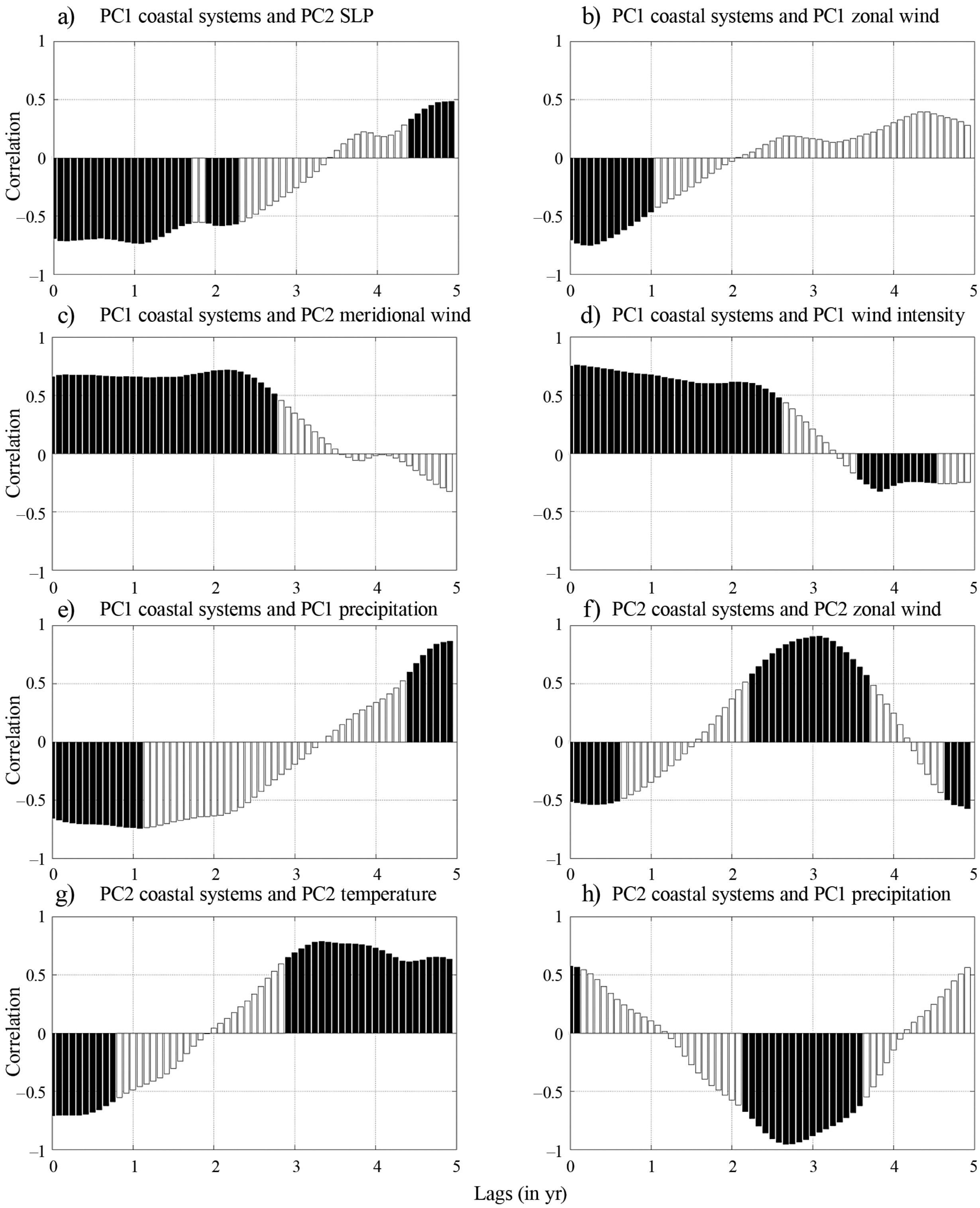


Fig. 11. Cross-correlograms between year-to-year changes in the coastal systems and hydro-climatic variability (only pairs of variables characterised by ordinary correlations >0.5; see Table 4). (a) First principal component (PC1) SOMLIT data and PC2 sea level pressure (SLP), (b) PC1 SOMLIT data and PC1 zonal wind, (c) PC1 SOMLIT data and PC2 meridional wind, (d) PC1 SOMLIT data and PC1 wind intensity, (e) PC1 SOMLIT data and PC1 precipitation, (f) PC2 SOMLIT data and PC2 zonal wind, (g) PC2 SOMLIT data and PC2 sea surface temperature, (h) PC2 SOMLIT data and PC1 precipitation. White bars are not significant; black bars are significant: the significance threshold was set at p = 0.25 after accounting for the reduction in the degrees of freedom due to the lag and the temporal autocorrelation

Table 5. Correlations (df = 8) between the first 2 principal components (PCs) of the principal component analysis (PCA) performed on climatic and SOMLIT data and large-scale hydro-climatic variables (abbreviations as in Table 4). As the time series were too short, correlations were not corrected to account for temporal autocorrelation. However, the p values were adjusted with Hochberg's procedure (1988) and α = 0.05. Significant correlations (r > 0.5) are in **bold**

Variable	PC	North Atlantic Oscillation		Atlantic Multidecadal Oscillation		Northern Hemisphere temperature	
		r	p	r	p	r	p
SLP	1	0.276	0.440	−0.566	0.088	**−0.783**	**0.007**
	2	−0.279	0.434	−0.294	0.410	−0.055	0.880
UWIND	1	0.063	0.928	−0.716	0.020	−0.641	0.046
	2	−0.215	0.551	0.115	0.752	0.462	0.179
VWIND	1	−0.152	0.676	0.308	0.386	0.630	0.051
	2	−0.064	0.860	−0.610	0.061	−0.380	0.279
IWIND	1	−0.100	0.783	0.460	0.181	0.635	0.048
	2	−0.018	0.961	0.253	0.481	0.432	0.212
SST	1	−0.135	0.710	0.338	0.340	0.419	0.228
	2	0.269	0.453	−0.064	0.860	0.494	0.146
MP	1	0.349	0.323	−0.356	0.313	−0.693	0.026
	2	0.425	0.221	−0.519	0.124	−0.231	0.521
SOMLIT	1	−0.344	0.330	0.708	0.022	**0.871**	**0.001**
	2	−0.275	0.442	0.063	0.862	−0.150	0.679

that the relationships between a large-scale climatic phenomenon and some coastal systems may not be constant through time. Such a result also reveals the nonlinearity of the system.

When analysing the effects of climate on marine systems, it is often relevant to separate natural changes from those caused by the confounding influence of human activity (Harley et al. 2006). Long-term monitoring is also preferable to establish a baseline against which perturbations can be better identified. However, most environmental coastal time series are short (e. g. Lindahl et al. 1998, Marty et al. 2002, Fernandez de Puelles et al. 2004). The SOMLIT programme, implemented in 1997, also suffers from lack of background. However, the spatial extent of the programme and the number of parameters measured are unique, compensating in part the short temporal coverage. The large spatial extent of the programme reduces the noise inherent to a sampling site (e. g. local disturbance and forcing), the influence of local hydro-dynamical forcing (e. g. tide, turbulence, frontal structures) and thereby increases the signal to noise ratio that enables the effect of climate to be better detected (Taylor et al. 2002, Beaugrand & Ibañez 2004).

In the regions where changes in nutrients, dissolved di-oxygen and salinity were observed, the positive correlations between chl *a* and the first PC from the analysis performed on SOMLIT data (Fig. 3) also revealed a decrease after 2001. These changes, led by regional climate forcing, are likely to have affected biological systems. Lotze & Worm (2002) and Nielsen (2003) have suggested that variations in nutrients may have subsequent effects on primary production, which can eventually cascade or be amplified through trophodynamics (Frank et al. 2005, Kirby et al. 2009). Many biological changes such as a modification in the grazing rates of zooplankton, a shift in species composition and phenological or biogeographical shifts (Richardson & Schoeman 2004, Winder & Schindler 2004) have been attributed to rising water temperature or changes in physico-chemical characteristics of the water column, at least in temperate coastal systems (Harley et al. 2006, Kirby et al. 2009).

SST appears to be a master parameter governing the changes in the coastal environment (Scavia et al. 2002, Beaugrand 2009). The increase in SST observed after 2001 and particularly pronounced in 2003 (during the summer heat wave of 2003, Fig. 8) might have exacerbated the decrease in nutrients observed mainly along the western coast of France. This phenomenon, combined with the reduction in zonal wind and precipitation, which is likely to have reduced horizontal inputs, could have contributed to the diminution of nutrients observed in these coastal regions. The effect of SST in the water column would be to increase the vertical stratification in the coastal non-tidal regions monitored by the SOMLIT programme and in offshore areas (Diaz & Rosenberg 1995, Bopp et al. 2002), but this phenomenon is not likely to occur in tidal regions because of the mixing by currents. Another impact of temperature is through the amount of di-oxygen that water can hold (i.e. warmer water holds less di-oxygen than cooler water; e.g. Beaugrand et al. 2008). Furthermore, warming increases bacterial production and the metabolism of organisms, augmenting di-oxygen consumption (Najjar et al. 2000). Our study has revealed a small reduction in the concentration of dissolved di-oxygen. This event, observed between 2001 and 2005, is currently too weak to lead to hypoxia or anoxia events, but reveals a possible tendency for the future as suggested by some authors such as Chan et al. (2008). The projected increase in temperature (IPCC 2007) may also place further stress on coastal systems already affected by eutrophication, pollution and harmful algal blooms and exacerbate phenomena of anoxia or hypoxia (Diaz & Rosenberg 1995, Justic et al. 1997, Najjar et al. 2000, Peperzak 2003, Selman et al. 2008).

While many studies to date have focused exclusively on the impact of temperature as an indicator of climate change (e.g. Edwards & Richardson 2004), our results suggest that atmospheric circulation is also an important parameter, as shown by the strong correlations between both zonal circulation and wind intensity and the state of coastal systems (see Fig. 10 and Table 4). After a period of relative stability, the decreases in nutrients, PON, POC and chl *a* in regions located in western France and the reduction in dissolved di-oxygen at all sites (Fig. 3) observed during the period 2001 to 2005 coincided with the decrease observed in the intensity of zonal wind during the same period. Changes in atmospheric circulation influence the Atlantic storm track (e.g. Dickson & Turrell 2000) and affect precipitation patterns (Rogers 1997). Precipitation was also highly related to changes in the state of the coastal systems (Fig. 10, Table 4), a result also found by Harley et al. (2006) for other coastal systems. The reduction in nutrients observed during 2001 to 2005 may have been reinforced by the decrease in precipitation and its influence on drainage and river runoff. In a study of 137 representative rivers around the world, Milliman et al. (2008) suggested that river discharge generally reflected precipitation patterns, themselves a climatic response to oceanic/atmospheric drivers such as El Niño and Southern Oscillation (ENSO) or NAO and AMO (New et al. 2001). Direct human impact (damming, irrigation and interbasin water transfers) could be superimposed to the river flow pattern (Ludwig et al. 2009) and thereby also influence these concentrations in nutrients and particulate matters (e.g. damming in the Ebro River in Spain, Ibàñez et al. 1996). Contrary to Livingston et al. (1997), who showed a reduced nutrient input after drought periods in an estuary located in the Gulf of Mexico, our results (Fig. 3) revealed a particularity of the Gironde that presents a conservative behaviour, except in downstream areas (Irigoien & Castel 1997). This conservative behaviour suggests the absence of intense biogeochemical processes in this estuary (Cabeçadas et al. 1999).

Changes in ocean circulation can affect the regional circulation of shelf and coastal seas (Scavia et al. 2002, Harley et al. 2006). Although reduced wind might also alter physical mixing, the examination of bottom and surface samples for some sites monitored by SOMLIT shows that there are generally no vertical differences and that the system is more likely influenced by horizontal inputs from offshore. In the North Sea, the atmospheric circulation influences the hydrodynamics that modulate the nature of sea water entering from the North Atlantic and the English Channel (Reid et al. 2003). Jickells (1998) stressed that the oceanic inflow had a strong impact on the concentration of nutrients in this sea and that a percentage of 82.68 % of nitrogen input originated from this phenomenon. In contrast to the sites of the Atlantic and adjacent seas considered in this study, Mediterranean waters export a great amount of nutrients to the Atlantic Ocean because of its negative water balance and the resulting water circulation (Hopkins 1985).

Substantial correlations were generally observed between the state of the coastal environment and large-scale climatological indices (Table 5), although not all correlations were significant after correction for temporal autocorrelation and for multiple testing. Beaugrand & Reid (2003) showed that NHT anomalies and SST covaried positively for many months in the eastern part of the North Atlantic, around the British Isles and the North Sea, the influence of which was stronger than that of the NAO. No influence of the NAO on the state of coastal systems was detected, probably because this oscillation only has a modest influence on the regional climatological parameters of the region (Marshall et al. 2001).

The effect of climate depended upon the intensity of the climate anomalies. The scale, the rhythm and the intensity of physical forcing indeed influence biological production (e.g. the theory of ergoclines, Legendre & Demers 1984). Our results showed that both substantial negative or positive forcing were related to changes in the state of the coastal systems, while moderate forcing had no effect (Fig. 10). Such threshold effects are beginning to be widely documented for systems ranging from physical (Rahmstorf 1995, Paillard 2001) to biological and ecological systems (Scheffer et al. 2001, Carpenter & Brock 2006) and reflect a pronounced non-linearity (e.g. the strength of the correlation may vary locally and temporally) and thereby sensitivity of the response of most natural systems to climate change.

Coastal regions, located at the interface between oceanic and terrestrial systems, play a crucial role in earth system functioning (Le Tissier et al. 2006). It is assumed that currently more than 60 % of the world's population live less than 60 km from the sea, increasing the human pressure on these systems at the same time as we are experiencing a period of rapid climate change (IPCC 2007). The spatial and temporal heterogeneity of coastal systems is considerable (Vafeidis et al. 2004), leading to methodological problems in developing global perspectives on the role and scale of the coastal domain in earth system functioning (Kremer et al. 2004, Harley et al. 2006). The acquisition of data by coordinated sampling programmes enables a robust comparison of the heterogeneity between sites to be made and relationships between contrasting coastal systems of western Europe and climate variability to be outlined. Although it is well known that coastal systems are locally strongly impacted by human activities, it remains difficult to disentangle climatic from anthropogenic forcing (Behrenfeld et al. 2006, Le Tissier et al. 2006).

In summary, our results suggest that (1) regional climate through its influence on local atmospheric and ocean circulation and temperature substantially influences coastal systems of Europe in the 42 to 51° N latitudinal range, and that (2) regional climate variability is correlated to an index of global temperature change (NHT anomalies). Our analysis shows that changes observed in nutrients are also detected in chl *a* and indicate that the climatic signal may propagate through the trophodynamics. Monitoring such as SOMLIT should be pursued and perhaps extended, as it represents the only way forward to robustly detect potential alterations of coastal systems in the future.

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