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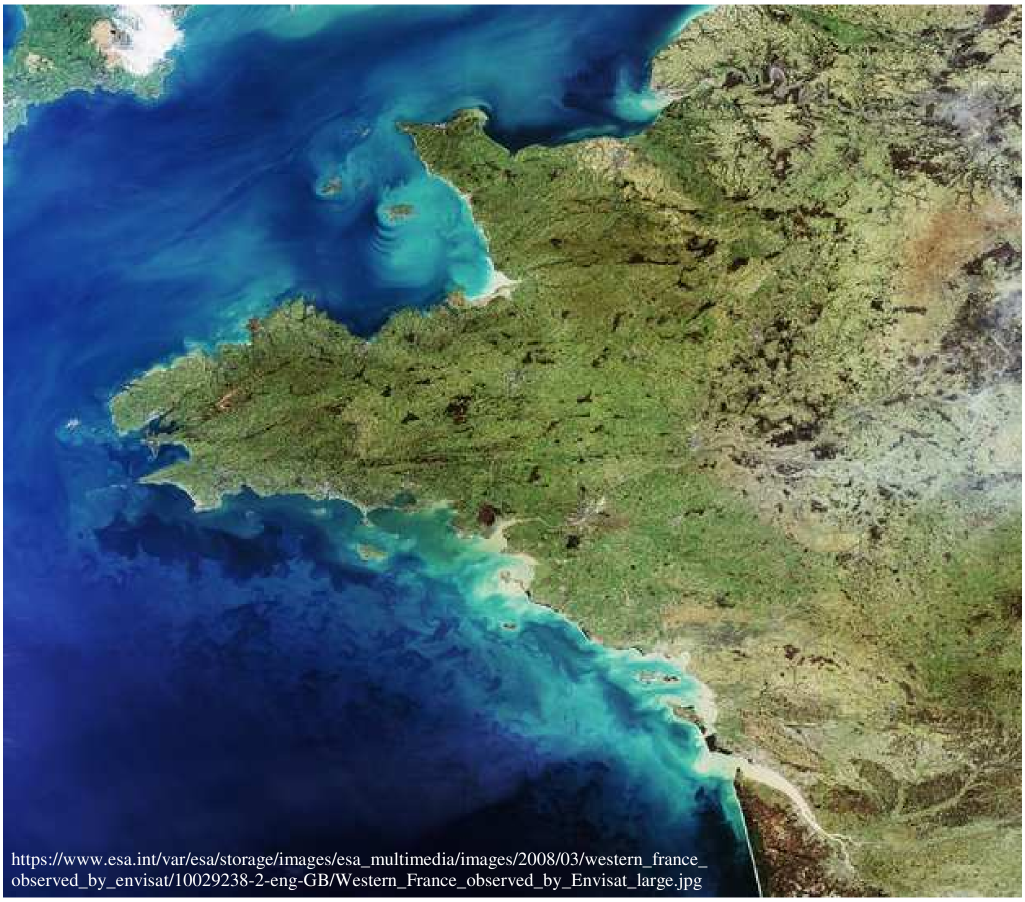

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Local and climate-driven changes in the French coastal marine systems

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1. INTRODUCTION

Over the last decades, climate and anthropogenic impacts have critically accelerated the rate and magnitude of changes observed in several biomes and especially in coastal systems (IPCC, 2015). Even if these areas only represent 7% of the earth surface, they shelter around 50% of the marine biodiversity and provide 59% of the total economic value of the earth systems (de Groot et al., 2012). At the interface between the ocean and the continent, coastal systems play a crucial role in earth system functioning and were reported as the most impacted biomes by the combined effects of climate and anthropogenic forcings (Halpern et al., 2008; Lima and Wethey, 2012) (Millennium Ecosystem Assessment, 2005).

On one hand, the direct impact of human activities has been widely documented. Pollution by nutrient enrichment and inputs from the catchment basin is actually one of the most threatening forcing on coastal systems: human inputs would enhance the algal growth of the best competitors (microalgae) to the detriment of the development of phanerogams (Östman et al., 2016). Yet the phanerogams are more productive, they also provide a shelter and act as a nursery to some benthic invertebrates and fishes (Duarte, 2002). The major nutrients' cycles have been altered because of fossil fuel combustion (carbon cycle), fertilizer production (nitrogen cycle; Seitzinger et al., (2010)), by leguminous crops (silica cycle; Galloway et al., (2004)) and waste waters or mining (phosphorous cycle; Bouwman et al., (2005)). The fate of a consequent fraction of these components is to end-up at sea by run-offs either to rivers or directly to the coastal systems. Also, humans impact the coastal systems directly by intense fisheries and the coastal planning that induces dragging. On the other hand, Goberville et al., (2010) highligthed the strong influence of climate variability on chemical and biological components alongside the french coast. They suggested that this may act in synergy with the anthropogenic pressures to alter the biogeochemical functioning of the coastal systems. Climate influences systems through a number of physical and chemical processes and pathways such as water stratification which may impact in turn nutrients and oxygen inputs and thus phytoplankon productivity (Kirby and Beaugrand, 2009). Climatological forcings act at different scales such as large-scale hydro-climatic indices (NAO, AMO, NHT among others) which summarize the hemisphere climate evolution that may be assessed through different parameters such as the sea surface temperature (SST), the wind direction and intensity, the sea level pressure (SLP) and the precipitation (Goberville et al, 2010). These variables summarize the evolution of climate at the continent scale. The above variables are computed through models whereas the local meteorology can be assessed on site and might greatly differ within a hundred kilometres.

The responses to forcing of such complex and dynamic ecosystems could occur in a non-linear way (Chaalali et al., 2013; Cloern et al., 2010; David et al., *accepted*) and cross-scale interactions could have important influences on ecosystem processes and services by changing the pattern–process relationships across scales (Peters et al., 2007). Mounting evidence suggests an alteration of the biodiversity from species to communities, leading to a potential erosion of ecosystems resilience (Hughes, 2000; Parmesan and Yohe, 2003). Such alterations on ecosystems and biodiversity could result in abrupt ecosystem shifts, that is to say *sudden, substantial and temporally persistent changes in the state of an ecosystem (Beaugrand et al., 2014; deYoung et al., 2004, 2008)*, (Carpenter and Brock, 2006). Moreover, those alterations may have significant consequences on human societies through the drop of ecosystem services to human (food production, recreational services), to other living species (nutrient cycling, pollination) and also to the equilibrium of the planet (water supply, soil formation (Barnosky et al., 2012; Costanza et al., 1997)). In marine and coastal systems, climate change is far from being negligible and may be as important as anthropogenic pressures on ecosystem services.

As an example, Beaugrand et al., (2010) quantified to 50% the role of climate versus fisheries in explaining the cod redistribution at the Atlantic Ocean scale.

With the increase of computer data storage and satellite data acquisition, numerous studies dealing with the influence of global climate onto marine systems have been made over the last decade (the keywords “climate change” are associated to more than 10 thousand papers in 2016 and 2017 on Web of Science). However, these studies were mainly focussed on the effect of global change onto the biology of marine organisms, especially on pelagic compartments such as phyto- or zooplankton as well as their influence on higher trophic levels.The understanding of the biogeochemical changes is of primary importance to explain the shifts observed at the coastal system scale. The services described in Costanza et al., (1997) and de Groot et al., (2012) involve the main nutrients, temperature and the oxygen, all of them being key parameters to the biological component of the ecosystems.

In this context, the observation surveys are precious tools to identify the year-to-year variability of biogeochemical processes as well as biota compartment for marine and coastal ecosystems and thus predict their future change in relation with the climate and anthropogenic pressures (Hays et al. 2005).

The main objective of this study was to analyse how the long-term variability of the climate, the local meteorology, river flows and biogeochemistry have influenced the physico-chemical conditions along the French coast. This work was previously realized by Goberville et al (2010) with the 10-years series available by the SOMLIT marine monitoring program that begun in 1997 on 12 sites located along the French coasts from 42° to 51° N. We decided here to revisit this work with a 20-year survey, adding data describing the long-term evolution of river characteristics integrating the catchment basin and its output at in order to consider the anthropogenic pressures.

2. MATERIAL AND METHODS

2.1. Study sites and systems

Twelve stations representing 8 systems along the French shoreline were considered for this study. Four stations belonging to two systems are located along the English Channel: two in the Eastern English Channel (EEC) (Point C and Point L), and two in the Western English Channel (WEC) (Astan and Estacade; Figure 1 and Table 1). One station is located in the Iroise Sea (Portzic, in the Channel of the Bay of Brest), at the interface between the English Channel and the Atlantic Ocean. Two systems are distributed along the Atlantic Ocean: the Arcachon Bay (Eyrac) and the Gironde Estuary (pk30/pk52/pk86). Finally, three systems are located in the Mediterranean Sea: the Banyuls Bay (Sola), the Marseille Bay (Frioul) and the Villefranche Bay (Point B). Three of these systems are sampled at two (eastern English Channel and western English Channel) to three Gironde Estuary) stations along a continent-to-ocean gradient. These ecosystems are monitored since 1996 within the scope of the SOMLIT (see section 2.3) and encompass a large part of the diversity of systems encountered along the French coast with different and varied characteristics.

Their diversity is illustrated:

• by several kinds of geomorphological characteristics (littoral, semi-enclosed or open systems) with various water column height (less than 10 meters to 80 meters in closed or open areas),

•by different tidal regimes (micro, meso and megatidal) and a large range of turbidity (with a suspended matter concentration ratio of 1:1000),

Table 1: Description of sampling sites and their main characteristics

ECOSYSTEM	TYPE OF SYSTEM	STATION	DEPTH AT SAMPLING STATION (M)	TIDAL RANGE	TROPHIC STATUS
EASTERN ENGLISH CHANEL	Littoral system	Point C, Point L	21 ; 50	Megatidal (7.7m)	Eutrophic
WESTERN ENGLISH CHANEL	Littoral system	Estacade, Astan	11 ; 60	Megatidal (7.5m)	Mesotrophic
BREST BAY	Semi-enclosed ria	Portzic	10	Megatidal (7.6m)	Mesotrophic
ARCACHON BAY	Semi-enclosed lagoon	Eyrac	8	Mesotidal (4.2m)	Mesotrophic
BANYULS BAY	Open bay	Sola	27	Microtidal (centimetric)	Weakly oligotrophic
MARSEILLE BAY	Open bay	Frioul	60	Microtidal (centimetric)	Oligotrophic
VILLEFRANCHE BAY	Semi-enclosed bay	Point B	80	Microtidal (centimetric)	Oligotrophic
GIRONDE ESTUARY	Estuary	pk30, pk52, pk86	8 ; 7 ; 8	Macrotidal (5m)	Eutrophic

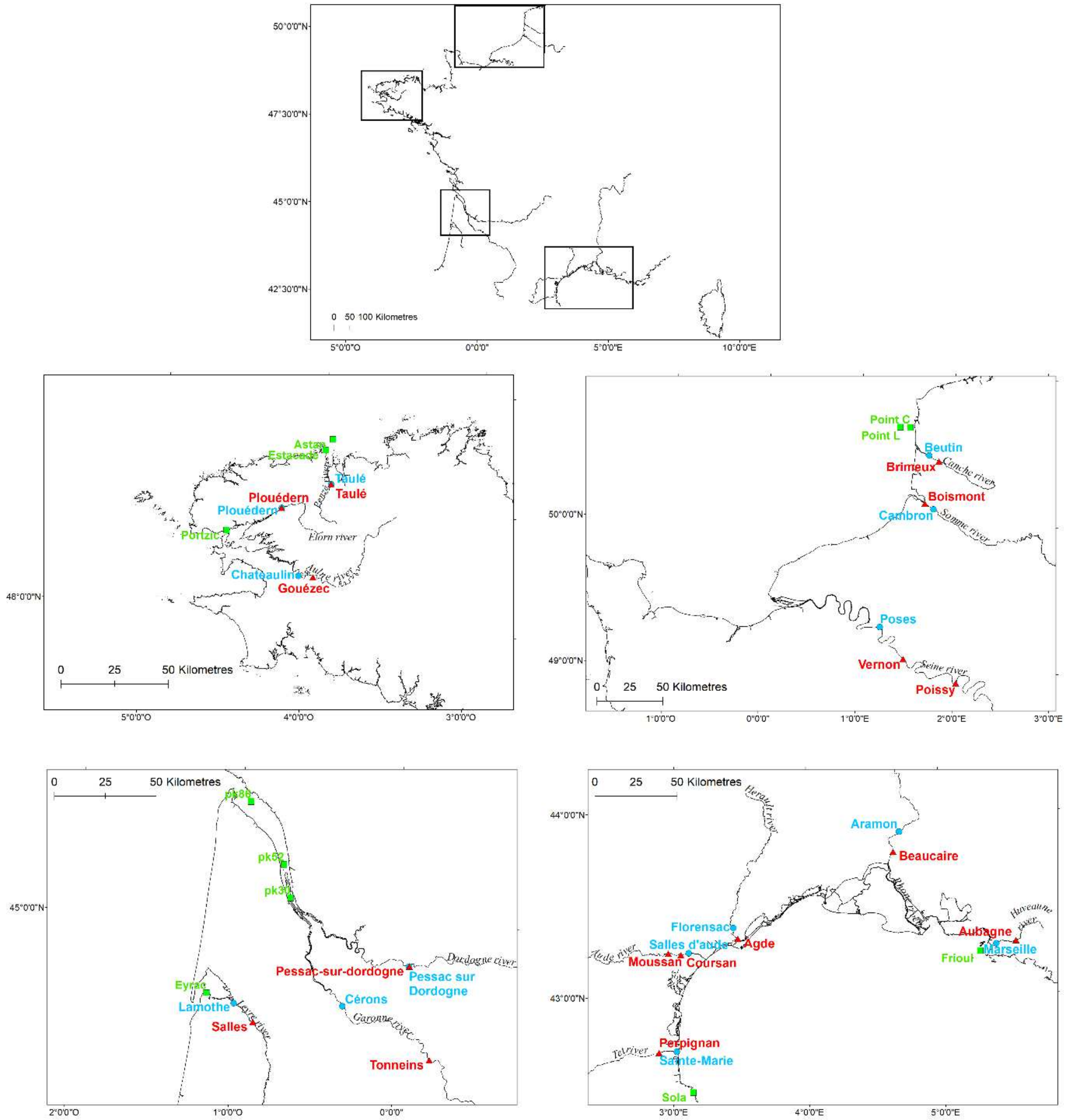

Figure 1: Map representing the different stations used in this study. Blue: riverine nutrients stations; red: rivers flows stations; green: SOMLIT stations

• by several trophic statuses (from oligotrophic to eutrophic systems),

• by a different relative importance of freshwater *vs* marine influence (mean salinity varying from 0 to 38 and river flows ranging from few to hundreds cubic meters per second

• by a different influence of continental inputs (through catchment basins areas ranging from 524 to 104200km²; table 2) for which agricultural lands range from 12.02% to 74.42% of the total catchment basin (annex I)).

• by a restricted range of local climate (annual mean water temperature ranging from 12.59°C to 18.54°C).

These systems are thus good working areas to evaluate how the coastal ecosystems behaved facing global forcings and how local *vs* global features act on their responses.

2.2. Variables

Core parameters of the water column are physical, physicochemical and biogeochemical parameters. They were approached within the scope of the SOMLIT strategy. In order to fully englobe and understand how marine coastal systems evolved and reacted to drivers along the past two decades, climate, meteorological and continental variables were also considered.

2.2.1. CORE PARAMETERS

Twelve parameters were considered: temperature, salinity, dissolved oxygen, ammonium, nitrates, nitrites, phosphate, silicates, particulate organic carbon, particulate organic nitrogen, suspended matter, chlorophyll a. They were sampled bimonthly to monthly at the surface of the water column over the two last decades (1997-2016).

These parameters are of primary importance in the coastal systems functioning and its variability. The temperature influences the ecosystems functioning through direct (e.g. temperature usually boost biological processes) and indirect (e.g. water column stratification and thus vertical nutrient and oxygen inputs; Goberville et al., 2010; Sarmiento and Gruber, 2006) effects. Salinity is a marker of riverine influence. Suspended matter is mostly a marker of sedimentary hydrodynamics (resuspension, river load). Nitrates, ammonium, nitrites, phosphate and silicates, as nutrients, control primary, and especially phytoplankton, production, which is at the base of the trophic web. Chlorophyll a is used as a marker of phytoplankton biomass. Finally, particulate organic carbon/nitrogen are useful variables to quantify and qualify the organic matter.

2.2.2. LARGE SCALE HYDRO-CLIMATIC INDICES

We used the usual large-scale hydro-climatic indices which are known to have an impact in Western Europe. They integrate the overall system variability in terms of hydro-climatic events and thus summarize the climate influence on coastal systems (Goberville et al., 2014). The North Atlantic Oscillation (NAO), the Northern Hemisphere Temperature (NHT), the Atlantic Multidecadal Oscillation (AMO), the Eastern Atlantic Pattern (EAP) and the Artic Oscillation (AO) were considered.

The AMO is an index of Northern Atlantic temperatures (Enfield et al., 2001). It could be the source of 0.4°C differences in oceanic regions and represents the evolution of sea surface temperature after removing the human impact. In contrast, the NHT anomalies are based on a reference value, here the 20th century sea surface temperature average, taking into account the human impact. Anomalies reported over 0 reflect a measured temperature above the 1901-2000 temperature average (Beaugrand and Reid, 2003).

The principal component (PC)-based indices of the NAO are the time series of the leading Empirical Orthogonal Function (EOF) of Sea Level Pressures (SLP) anomalies over the Atlantic sector. The NAO index tracks the movements of the Islandic low and Azores high. Positive values of the NAO is related to stronger than average westerlies (dominant western winds) over the middle latitudes (30 to 60°N), i.e. intensified weather systems over the North Atlantic and wetter weather over the western Europe (Hurrell, 1995; Hurrell and Deser, 2009). The EAP is the second most prominent mode of low-frequency variability over the North Atlantic. It is structurally similar to the NAO and consists of a north-south dipole of anomalies centred on the North Atlantic from East to West (Barnston and Livezey, 1987).

Finally, the AO was a large scale mode of climate variability characterized by winds circulating counter clockwise at around 55°N. When in positive phases, a ring of strong winds tends to restrain colder air to polar region. When the AO is negative, cooler air temperature and increased storminess are observed in the middle latitudes.

2.2.3. WESTERN EUROPE METEOROLOGY

Regional meteorology on Western Europe was also considered: sea surface temperature (SST), precipitation, sea-level pressure (SLP), intensities of total, meridional and zonal winds. The SST was important to consider since temperature has a direct impact on organisms' biology as well as on water stratification and regulates upwelling fluxes. Precipitation has both a direct and an indirect effect on coastal systems. The direct influence is observed when falling in the ocean whereas the indirect influence appears through run-off that contributes to river flows. Atmospheric circulation was assessed through the SLP, wind intensity and its meridional (latitudinal) and zonal (longitudinal) components. The atmospheric circulation contributes to the horizontal inputs of nutrient and dissolved oxygen by its action on oceanic currents and by favouring the mixing of river water (Reid et al., 2003). It also supports the direct (wind-induced) or indirect (tidal-induced) mixing of waters, which contributes to the regulation of biogeochemical cycles and consequently ecosystem functioning.

2.2.4. LOCAL METEOROLOGY

Local meteorology (air temperature, precipitation, solar irradiance, wind intensity and direction) was also considered. As explained above, precipitation has both direct and indirect (through river inputs) effects on coastal system functioning. Air temperature has a direct influence on the sea temperature as well as the water column stratification and therefore influences the biogeochemical and biological compartments. Wind intensity and direction influence sea temperature but also the turbulent mixing, and consequently the biogeochemical and biological compartments.

Irradiance is a parameter used to calculate the photosynthetic active radiation which is used by primary producers (Breton et al., 2017). It also has an impact on sea surface temperature.

2.2.5. CONTINENTAL VARIABLES

Continental inputs have a great influence on coastal system functioning by fuelling these systems in nutrients and particles. River flows, river concentrations in nutrients (NH_4^+, NO_3^-, and $PO4_3^-$) and suspended matter were used.

2.3. Data bases and pre-treatment

The core parameters were retrieved from the SOMLIT web site (http://somlit.epoc.u-bordeaux1.fr/fr/). An overview of the SOMLIT network can be found in Goberville et al. (2010) and Liénart et al., (2017, 2018).

Table 2: Description of catchment basins and their main characteristics

CATCHMENT BASIN (AREA)	RIVER (FLOW IN $m^3.s^{-1}$)	SOMLIT STATION	RIVER MOUTH TO STATION DISTANCE	RIVER FLOW MEASUREMENT STATION	PHYSICOCHEMICAL MEASUREMENT STATION	DATA PROVIDER
EEC (96315 km²)	Canche (13)	Point C / Point L	20 / 20 km	Brimeux	Beutin	Eau France / Agende de l'eau Artois Picardie
	Somme (36)		40 / 40 km	Boismont	Cambron	
	Seine (509)		215 / 210 km	Vernon / Poissy	Poses	Eau France / Agence de l'eau Seine Normandie
WEC (612 km²)	Peinzé (3)	Astan / Estacade	13 / 10 km	Taulé	Taulé	Eau France / Ecoflux
BREST BAY (2 709 km²)	Aulne (26)	Portzic	23 km	Gouézec	Chateaulin	Eau France
	Elorn (6)		50 km	Plouédern	Plouédern	
ARCACHON BAY (3754 km²)	Leyre (15)	Eyrac	15 km	Salles	Lamothe	Eau France / Agence de l'eau Adour Garonne
BANYULS BAY (104200 km²)	Têt (7)	Sola	33 km	Perpignan	Sainte-Marie	Eau France / Agence de l'eau Rhône Méditerranée
	Aude (29)		86 km	Moussan / Coussan	Salles d'aude	
	Herault (31)		93 km	Agde	Florensac	
	Rhône (1640)		212 km	Beaucaire	Aramon	
MARSEILLE BAY (524 km²)	Huveaune (1)	Frioul	7 km	Aubagne	Marseille	Eau France / Agence de l'eau Rhône Méditerranée
GIRONDE ESTUARY (81793 km²)	Garonne (500)	pk 30 / pk52 / pk86	9 / 26 / 61 km	Tonneins	Cérons	Eau France / Agence de l'eau Adour Garonne
	Dordogne (249)			Pessac-sur-Dordogne	Pessac-sur-Dordogne	

Large-scale hydro-climatic indices except the NHT were provided by the National Oceanic and Atmospheric Administration (NOAA) through portals. The AMO was downloaded on https://www.esrl.noaa.gov/psd/data/timeseries/AMO/, the NAO on https://www.ncdc .noaa.gov/monitoring-references/faq/anomalies.php#anomalies, the EAP on http://www.cpc. ,ncep.noaa.gov/data/teledoc/ea.shtml, the AO on https://www.ncdc.noaa.gov/teleconnections /ao/ and the NHT on https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based.

Western Europe meteorological data was obtained thanks to the National Center for Environmental Protection and the National Center for Atmospheric Research (NCEP/NCAR, USA; https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html). The NCEP/NCAR data was gridded reanalyses data. Thus it enabled to cover the whole Western Europe. Precipitation data had a spatial resolution of 2.5 times 2.5° in latitude while other parameters had a 1 times 1° in latitude resolution. The methodology of NCEP/NCAR reanalyses data was discussed in Kalnay et al., (1996) and Kistler et al., (2001) studies and additional information on calculation strategy were available in Betts et al., (1996) and Kistler et al., (2001) (Goberville et al., 2010).

Local meteorological data was provided by Meteo France (air temperature, precipitation, wind intensity, direction and solar irradiance) and by Copernicus Atmosphere Monitoring Service (solar irradiance when not available with Meteo France). Meteo France sites were selected as close as possible to the SOMLIT stations and containing daily data from 1997 to 2016.

Wind intensity available from NCEP/NCAR and from MeteoFrance was approached using the Pythagorean formula on its two components (meridional and zonal; Goberville et al., 2010). The data provides wind direction measured in degrees (from 0 to 360) and the intensity. Even though a wind direction of 359° and of 1° could be physically confounded, their value could not be numerically considered as such. Therefore, the meridional (Vwind) and zonal (Uwind) components were calculated following the equations in annex II.

River flows were obtained through BanqueHydro (http://www.hydro.eaufrance.fr/) and river nutrient concentrations were provided by the concerned Agences de l'Eau (http://www.eau-artois-picardie.fr/qualite-de-leau/visualiser-et-telecharger-les-donnees-sur-la-qualite-des-rivieres; http://www.adour-garonne.eaufrance.fr/coursdeau; http://www.sierm.eaurmc.fr/surveillance/eaux-superficielles/index.php; http://www.qualiteau.eau-seine-normandie.fr/), Ecoflux (Brittany NO_3, PO_4 and SM concentrations; https://www-iuem.univ-brest.fr/ecoflux/observation/acces-aux-donnees) and Naïades (table 2; http://www.naiades.eaufrance.fr/acces-donnees#/physicochimie). Continental stations were chosen as close to the sea-side as possible but 1) upstream the dynamic influence of the tides and 2) containing daily (river flow) to monthly (nutrient and SM concentrations) data from 1997 to 2016.

Some of the coastal systems were influenced by more than one river. In that case the mean river flow weighted by the distance between the river mouth and the study site was used following Liénart et al. (2018) (annex I).

2.4. Numerical approach

Although the SOMLIT samples every week to month depending on the studied system, a first selection was done on the raw data. Indeed, quality codes were provided so only the trustable data was kept, leading to irregular time series (different lags between two measures of the same parameter or parameters with different lags between two measurements). To overcome this issue, the data was monthly regulated using the spline method. As long-term scale was studied, it was necessary to remove the effect of seasonnality from the data. To do so, a simple moving average of order 12 was performed (Legendre and Legendre, 1998).

Among the parameters, we have 12 physical-chemical series, 12 large scale climate indices, 12 parameters corresponding to each of the 2 components per PCA conducted on the grid data of western Europe meteorological data (SLP, zonal wind, meridional wind, wind intensity, SST and precipitation), 5 series of local meteorology and 5 series of loads from continental inputs. All these long-term series (240 data = 20 years * 12 months) were available for 12 stations for physical-chemical and continental series.

Among the few statistical techniques that exist to analyze complex tables with 3 dimensions (Stations X Time X Parameters), we used the 3-mode principal component proposed by Hohn (1993) and used in oceanographic sciences by (Beaugrand et al., 2000)and Goberville et al (2010) according to several ways. Both ways were used in our analysis due to their complementarity. The 3-mode Principal Component Analysis (PCA), used by (Beaugrand et al., 2000) estimated 3 classical PCAs on 2-dimensional tables after having transformed 1 table to ensure that the total inertia is identical in each mode. Rp corresponded to one matrix with parameters in column and the stations/dates as rows, Rt corresponded to one matrix with the dates in column and the stations/parameters as rows and Rs to one matrix with the station in column and the dates/parameters as rows. The analysis then relates the different modes by assessing a core matrix calculated from the eigenvectors of each mode (Beaugrand et al. 2000).

Such analysis allowed them to obtain groups of parameters (from the Rp matrix), groups of stations (from the Rs matrix) as well as groups of dates (with the Rt matrix) that behave as the same way. Cluster analysis using Euclidean distance and ward method (so that the intra-group variance is minimised) were performed on each space in order to regroup geographical zones, parameters and time periods with common evolution. In contrast, Goberville et al (2010) calculated 1 standardized PCA (normalized data per parameters so they presented the same range of variation) on the deployed 3-way matrix 240 months for the rows and 12 parameters × 12 stations for the columns), which represented the first step in the classical 3-mode PCA. Such analyses allowed to obtain a global evolution over the 20 years of the analysis through the

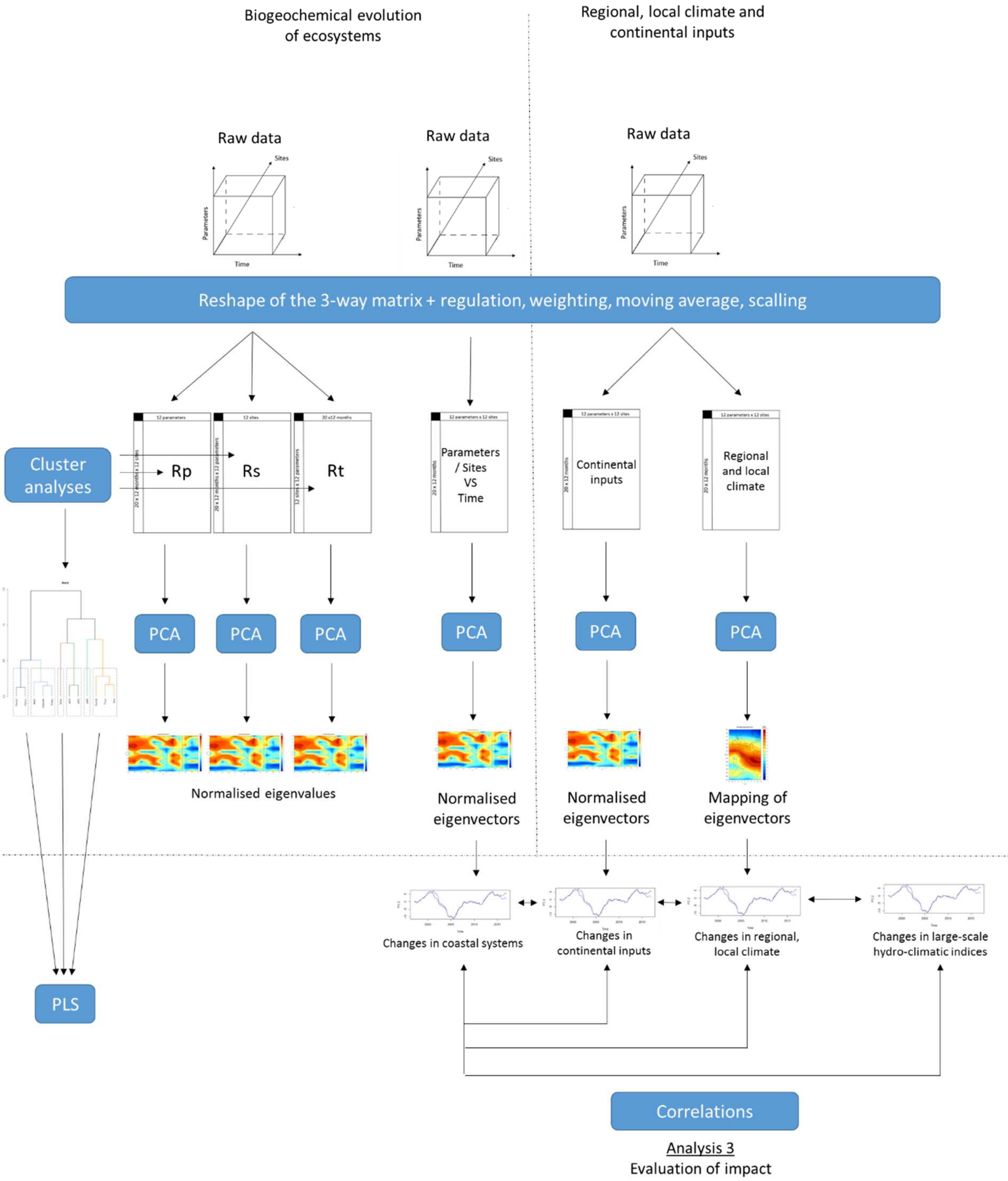

Figure 2: Statistical analyses performed in this study. Rp: parameters mode; Rs: sites mode; Rt : time mode ; PCA: Principal Component Analysis; PLS: Partial Least Square

2 first axis and compare them to the long-term evolution of the climate, meteorological and freshwater inputs indices. The evolution of biogeochemical parameters was correlated to the evolution of each of the forcings in order to highlight the influence of the forcings on the evolution of ecosystems. Because the data was scaled prior the PCAs, the normality was respected so a Pearson correlation could be done. As multiple testing increased the number of significant correlations (type I error; Goberville et al., 2010), p-values were adjusted following (Hochberg, 1988) to corrected the potential error. The global trend of the forcings were the coordinates of the individuals on the correlation circle, plotted against time.

All analyses were executed using the R software and its packages.

3. RESULTS

3.1. Global variability of the French coastal systems

A PCA was executed on the 2-way matrix (240 months x 12sites/12 parameters) according to Goberville et al. (2010). Year-to-year changes in the first principal component (24.73% of the total variability) showed a short increase until the end of 2001, folowed by a sharp decrease in the trend until december 2016 (figure 3a). Mapping of the eigenvectors (figure 3b) revealed that the trend illustrated by the first component was particularly strong and positive for sites located in the English Channel (point C and L) and for the Frioul station (Marseille) while strong and negative for the Gironde Estuary (pk 86, 52 and 30). The parameters that contributed the most to the changes were the particulate organic matter (POC, PON), the suspended matter (SM), the salinity (negatively), the chlorophyll-a and to a lesser extent nutrients (mainly NO_3^-, $Si(OH)_4$).

The positive correlation between POC, PON, SM, chlorophyll-a, some of the nutrients and the trend meant that the reduction observed after 2001 coincided with a diminution of

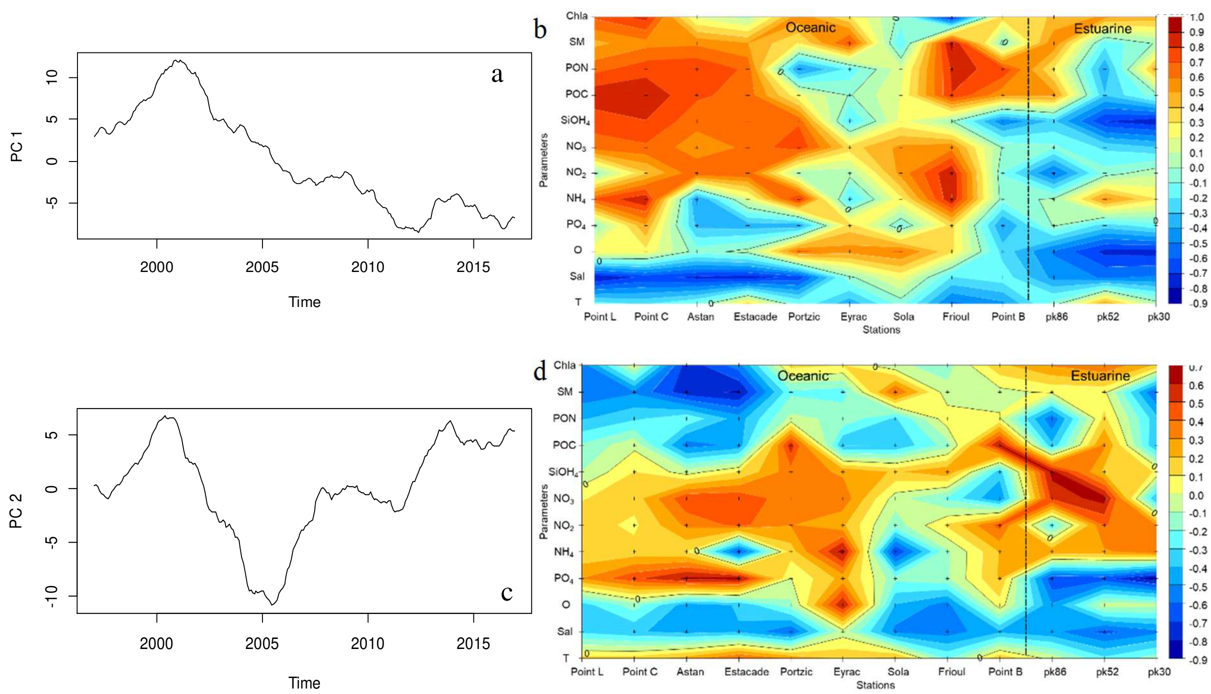

Figure 3: Principal Component Analysis (PCA) of the year-to-year variability of the French coastal systems in the first principal component (a) and the second PC (c) as well as the mapping of the first eigenvector (b,d)[1]. Sites were ordered from north to south and estuarine stations on the right. T: temperature; Sal: salinity; O: dissolved oxygen; PO_4: orthophosphate; NH_4^+: ammonium; NO_2^-: nitrite; NO_3^-: nitrate; $Si(OH)_4$: silicates; POC: particulate organic carbon; PON: particulate organic nitrogen; SM: suspended matter; Chla: chlorophyll-a; PC: Principal Component

[1] Figure 3b and 3d (and followings) illustrate the strength of the correlation between each combination of sites x parameters and the year-to-year changes of the coastal systems PCs (figure 3a, 3c and followings).

nutrients concentration in the English Channel and in Marseille while it corresponded to an increase in the estuary (principally at the middle and the upstream estuary). Salinity was negatively correlated to the trend almost at all sites meaning that salinity increased along the French coast between 2001 and 2012.

Year-to-year changes in the second PC (14.44% of the total variability) showed a pseudo-cyclical variability of approximatively 10 years. PC2, showed an increase until late 2000, a strong decrease in the trend until late 2005, an increase in 2006 until a back at the beginning level. A plateau was spotted from the end of year 2007 to mid-2012, completing the first period, followed by an increase in the trend. Mapping of the second eigenvector (figure 3d) exposed that the sites located in the English Channel and especially the Gironde Estuary were the most strongly correlated to the trend. The Mediterranean Sea was less represented on the second component. Nutrients and to a lesser extent temperature were positively correlated to the trend while salinity was negatively correlated at all sites except in the Arcachon Bay (Eyrac).

The second PC revealed an opposition in the trend between salinity on one hand, temperature and nutrients on the other hand. This opposition was particularly strong for the years 2000 to 2010. Temperature and nutrients concentration seemed to decrease along with the oceanic coast and in the estuary while salinity seemed to increase almost everywhere from 2006.

The major information of the overall variability of the coastal systems is that a consequent shift occurred in 2001 (seen on the two first PCs; figure 3a, 3c) while eigenvectors showed a discrimination between sites.

3.2. The influence of the different drivers on the coastal systems year-to-year variability

3.2.1. GLOBAL FEATURES

The relationships between the variability of the global coastal systems and the drivers were highlighted through Pearson's correlations (figure 4). The main point was that either the first or the second PCs were correlated to all the climatological variables, to local meteorology and to all the continental inputs. In contrast, only the AMO and the NHT, the two large-scale hydro-climatic indices based on the temperature, were correlated. Therefore, both climatological and continental drivers do influence the long-term variability of the coastal systems.

Only the first PC of the 3-mode PCAs of the drivers that presented a p-value lower than 0.001 were reported. The first PC represented almost 50% of the total variability of the drivers. They were represented jointed with the PC of the coastal variability with which they were the most correlated.

3.2.2. CORRELATION WITH LARGE-SCALE CLIMATE INDICES

The inverse of both the AMO and the NHT were represented for a better readability toward the coastal systems first PC. As a consequence, a represented decrease represented an increase and inversely.

The AMO showed a pseudo-cyclical variability of about five years over the twenty considered years as well as a trend toward an increase (Figure 5). Although the AMO was un-trended and un-smoothened, it was tricky to observe its direct effects on the coastal systems on relatively short time series. However, it seemed that the studied period corresponded to an increasing phase of the AMO cycle.

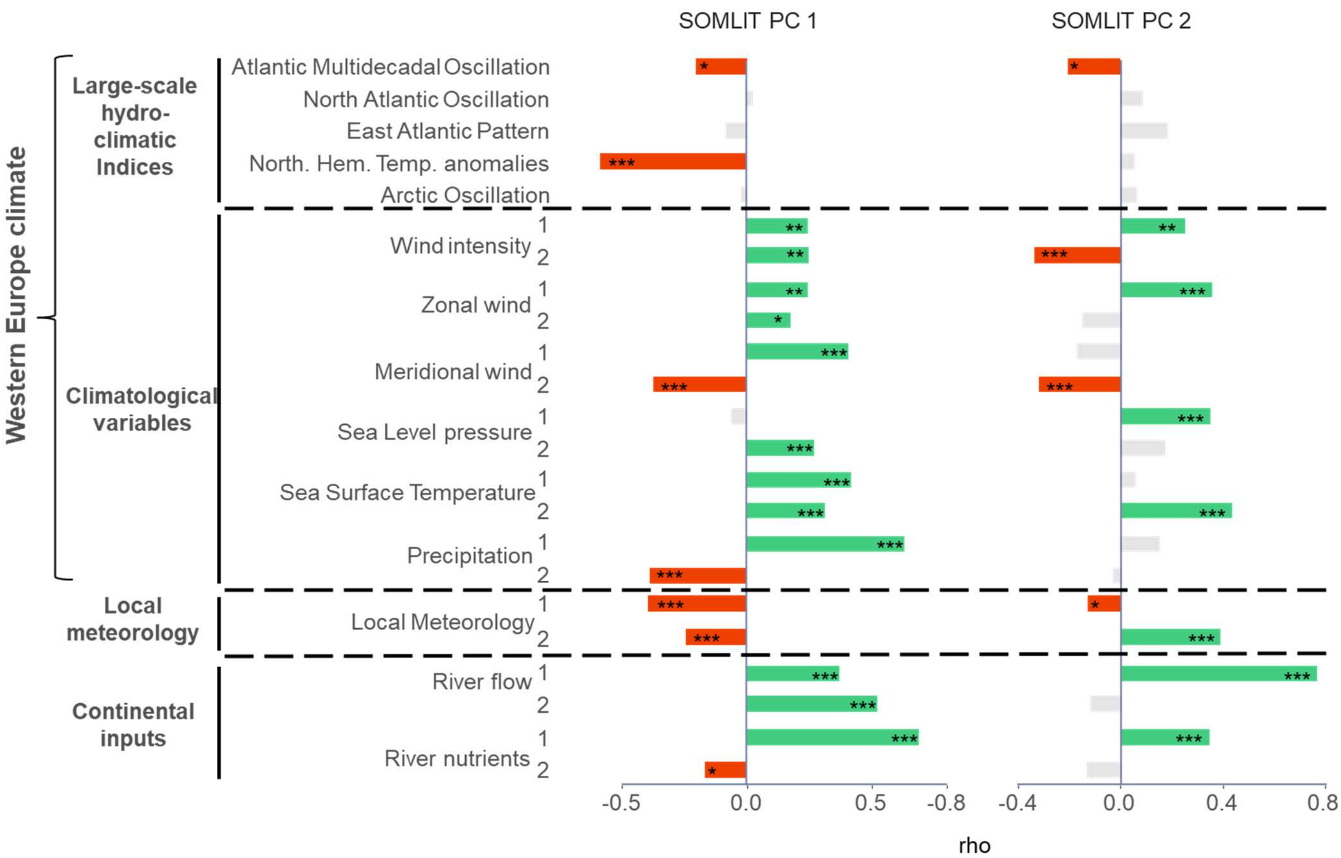

Figure 4: Correlations between the two first Principal Components (PC) of the coastal systems Principal Component Analysis (PCA) and the moving-averaged Large-scale Hydro-climatic Indices and the first two PCs of the PCAs performed on each driver

For the period 1997 to 2008, the variability of the NHT coincided with the variability of the first PC of the coastal systems. Indeed, there was a time lag of 14 months between the NHT and the response on the first PC of the coastal systems variability. However, this trend was less obvious from 2008. A large rise of the anomalies was spotted from 2012 to 2016. The NHT showed a trend toward an increase of the temperature anomalies, so toward an increase of the average temperature.

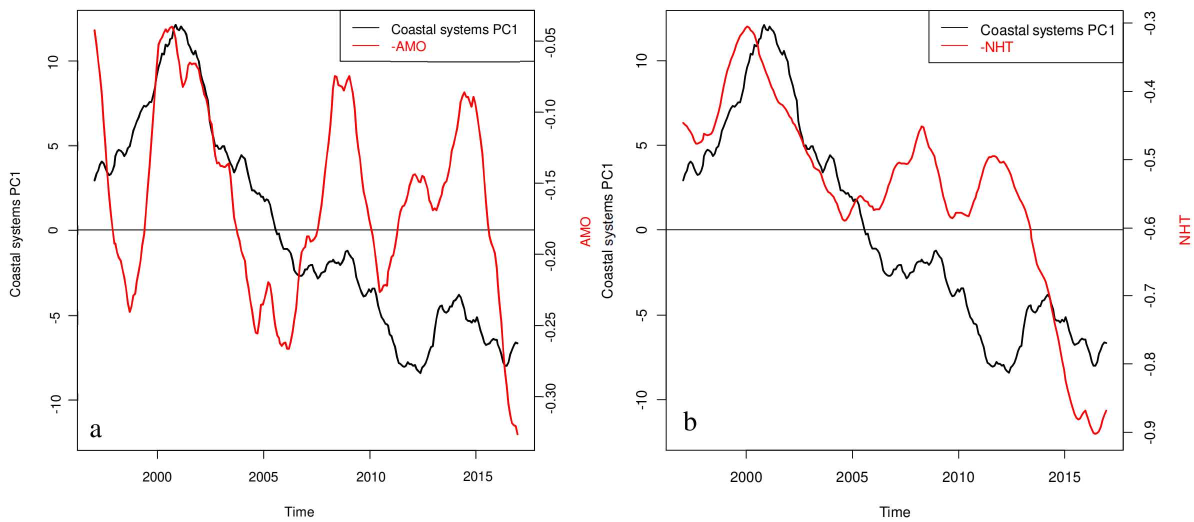

Figure 5: Principal Component Analysis (PCA) of the year-to-year variability of the AMO (a) and of the NHT (b) and the first principal component (PC) of the PCA of the SOMLIT year-to-year variability. AMO: Atlantic Multi-decadal Oscillation; NHT: Northern Hemisphere Temperatures.

3.2.3. CORRELATION WITH WESTERN EUROPE METEOROLOGY

• SST

Year-to-year changes in the first PC of the Sea Surface Temperature (SST) represented almost 46% of the total variability (figure 6a). The variability of SST was well represented on the first PC of the variability of coastal systems until 2010. The first shift in 2001 was well represented on the variability of SST, as well as the decrease following it.
The first PC of SST seemed to respond to a 10-year cycle. Hence, two periods of rising SST occurred between 1997 and 2002 and between 2007 and 2014, respectively followed by two periods where the SST decreased, from 2002 to 2007 and from 2014 to 2016.

Overall, the French coastal ecosystems were well represented on the SST trend which had the same decreasing pattern along the French coast. The English Channel was the most correlated system to this trend (eigenvector > 0.9; figure 6b). The Gironde Estuary and the Mediterranean Sea were the weakest correlated systems (eigenvector ~ 0.65).

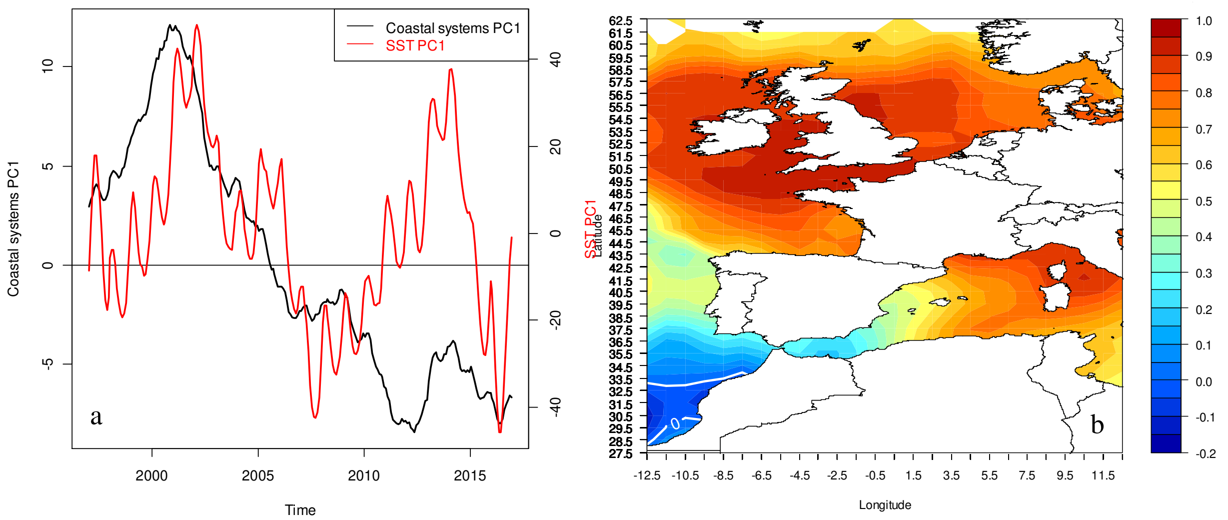

Figure 6: Principal Component Analysis (PCA) of the SST year-to-year variability and the coastal systems first principal component (a) and mapping of the first eigenvector of SST PCA (b). SST: Sea Surface Temperature; PC: Principal Component

• Sea Level Pressure

56.47% of the Sea Level Pressure (SLP) variability was expressed in the first PC (figure 7a). SLP matched the second PC of the coastal systems with a 3-to-4-year lead until 2004.The SLP increased from 1997 to 2000, followed by a sharp drop, therefore a shift in the trend until late 2001. Afterwards, the SLP tended to increase until the end of the time period, with a pattern similar to the coastal systems.

The Eastern English Channel was the less represented system on the SLP trend (eigenvectors ~ 0.5; figure 7b). The representation of French ecosystems along the SLP trend increased with decreasing latitudes reaching correlation of over 0.9 in the western Mediterranean French coast (Sola).

Overall, the French systems were well represented on the SLP trend which was almost the same along the French coast. However, the English Channel was less correlated than both the Atlantic Ocean and the Mediterranean Sea. The averaged SLP increased within the last 15 years, especially along the Mediterranean coast

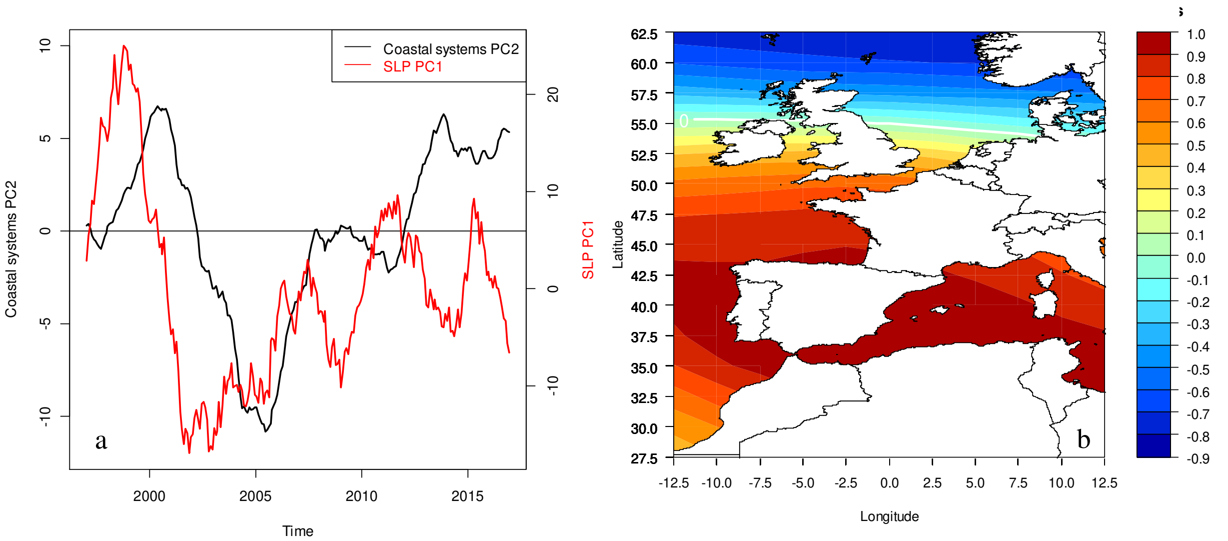

Figure 7: Principal Component Analysis (PCA) of the SLP year-to-year variability and the coastal systems first principal component (a) and mapping of the first eigenvector of the SLP PCA (b). SLP: Sea Level pressure; PC: principal component.

- **Zonal wind**

The variability of the zonal wind first PC (51.23%; figure 8a) coincided with the variability shown on the coastal systems second PC. The trend in zonal wind preceded the coastal variability by 2 to 3 years. The first discrepancies occurred in year 2007. However, the Eastern English Channel was well correlated to the trend (eigenvector > 0.8; figure 8b) whereas a gradient occurred from the North to the South so that the Mediterranean Sea and the Arcachon Bay were not correlated to the trend at all. Thus, the first PC of zonal wind could not be used to explain the year-to-year changes in the French coastal systems.

Graphically, the SLP and the zonal wind had very similar variability. The only difference was that the SLP trend increased after the shift while the zonal wind trend remained constant. It might explain the gradient seen in zonal wind.

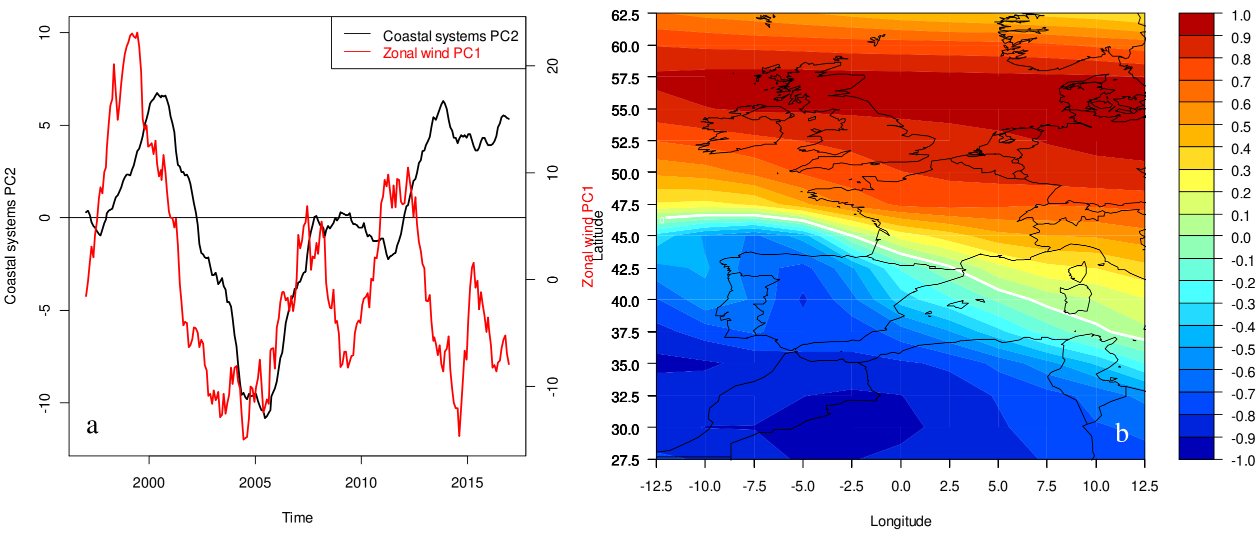

Figure 8: Principal Component Analysis (PCA) of the zonal wind year-to-year variability and the coastal systems second principal component (a) and mapping of the first eigenvector of zonal wind PCA (b). PC: Principal Component

Meridional wind

Year-to-year changes of the meridional wind on the first PC represented 34.30% of the total variability (figure 9a). Whereas the observed shift in zonal wind occurred before the coastal systems shift (2000), the shift in meridional wind occurred later, in mid-2002. However, a steep shift in the dynamic of meridional wind occurred in 2007 without any repercussions on the coastal systems dynamic. From 2010, the variability of the meridional wind and the coastal systems were very similar.

Mapping of the eigenvector (figure 9b) revealed that the English Channel was the most correlated system (eigenvector > 0.8). A clear gradient from North-North-West to South-South-East drove the correlation to the trend. The Mediterranean Sea was poorly represented so that the meridional winds could not be used to describe the overall French coastal systems. However, a slight decrease in meridional wind was observed in the English Channel.

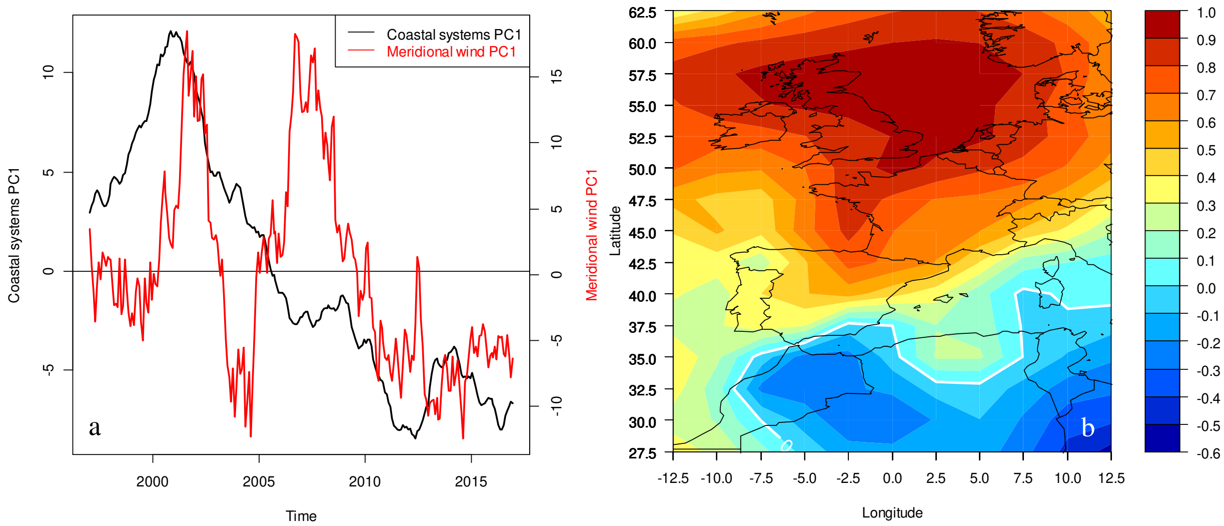

Figure 9: Principal Component Analysis (PCA) of the meridional wind year-to-year variability and the coastal systems first principal component (a) and mapping of the first eigenvector of meridional wind PCA (b). PC: principal component

• Precipitations

Due to a lack of data, the precipitation could only be used to describe the English Channel and the Iroise Sea. The trend explained 29.27% of the total variability (figure 10a) which was the weakest percentage of the regional climate variables. However, the 3 ecosystems were correlated to over 0.8 (figure 10b). Precipitation rates tended to decrease with time.

Precipitations preceded the coastal systems year-to-year changes with a time gap of 2 to 3 years. From 1997 to 2010, the precipitation variability coincided with the coastal systems first PC. The 2013 precipitation peak corresponded to peaks in the atmospheric circulation.

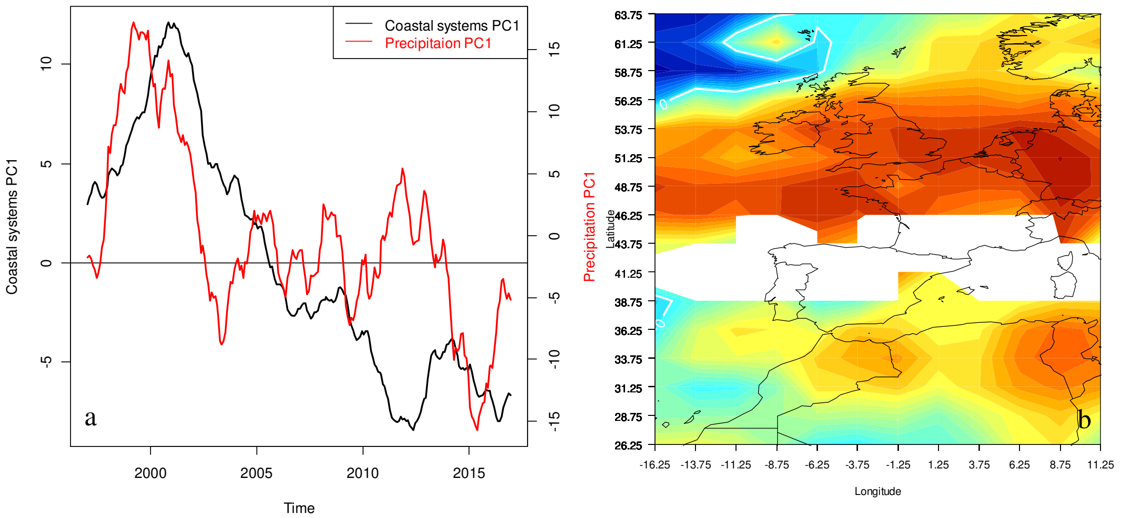

Figure 10: Principal Component Analysis (PCA) of the precipitation year-to-year variability and and the coastal systems first principal component (a) and mapping of the first eigenvector of precipitation PCA (b). PC: principal component

3.2.4. CORRELATION WITH LOCAL METEOROLOGICAL FEATURES

The first two PCs of the 3-mode PCA performed on local meteorology explained 21.18% and 20.66% respectively. The first PC (figure 11a) showed a relatively slow increasing trend with time. Two pics occurred in 2004 and 2007. The second PC (figure 11c) corresponded well to the second PC of coastal systems until 2004. It had a pseudo-cyclical variability with periods of approximately 6 years. Mapping of the eigenvectors revealed that the first PC represented air temperature (figure 11b). Indeed, it was the only parameter correlated over 0.8 (with the

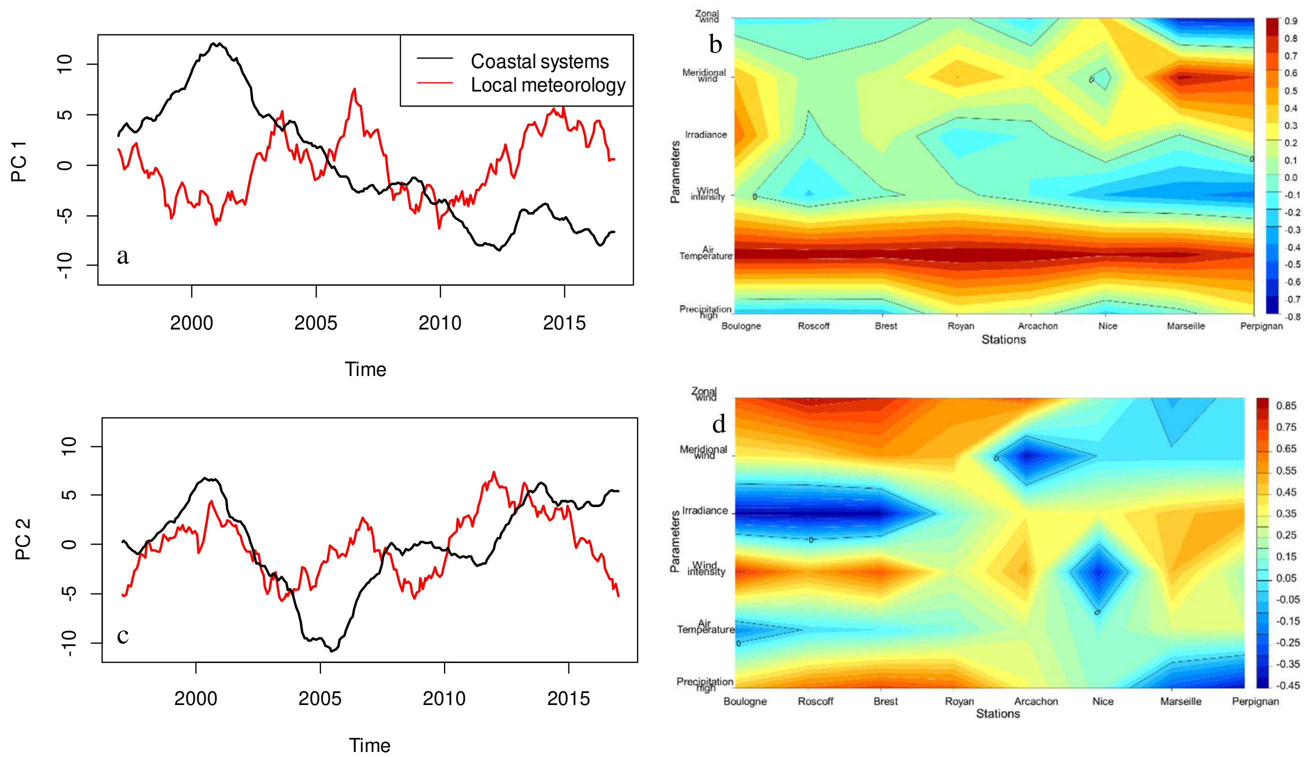

Figure 11: Principal Component Analysis (PCA) of the year-to-year variability of the local meteorology in the first PC (a) and the second PC (c) and the coastal systems first principal component and the mapping of the first eigenvector (b,d). Sites were ordered from north to south. PC: Principal Component

exception of meridional wind in Marseille). Moreover, it was correlated at all the sites. The second PC was a combination of different parameters (zonal wind, irradiance (negative), wind intensity and precipitation; figure 11d). It was mainly correlated in the English Channel and to the Atlantic Ocean. It was noticeable that the precipitations and the zonal wind followed a latitudinal gradient as well as irradiance, to a lesser extent.

3.2.3. CORRELATION WITH CONTINENTAL INPUTS

Both continental concentrations in SM, $Si(OH)_4$, NO_3^- and NH_4^+ brought at the SOMLIT sites and river flows were represented in figure 12. Riverine concentrations first and second PCs explained 34.42% and 16.58% of the total variability, respectively. Riverine flows first and second PCs explained 71.69% and 13.16% of the total variability, respectively. River flows were better represented because one parameter was involved against four in the riverine concentrations.

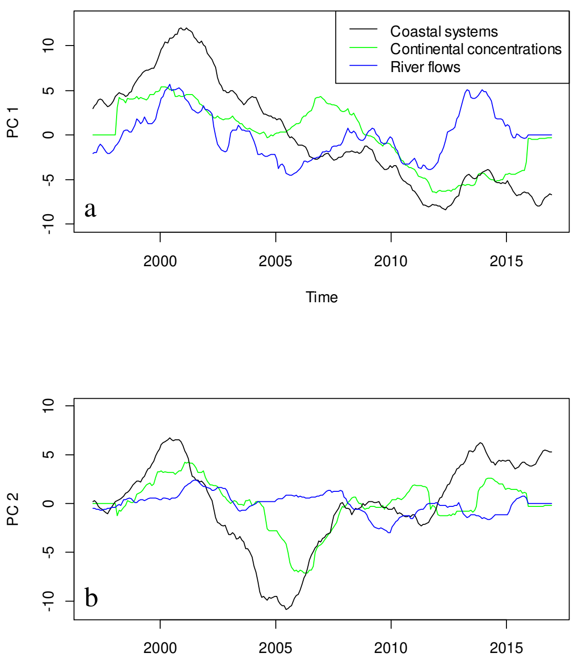

Figure 12: Principal Component Analysis (PCA) of the year-to-year variability of the continental drivers in the first principal component (a) and the second principal component (b) and the coastal systems first principal component. PC: Principal Component

It clearly appeared that both river flows and concentrations year-to-year variability co-evolved with the year-to-year variability of the coastal systems. Whereas the 2001 shift was not obvious, both riverine concentrations and flows had a peak in 2001 in their year-to-year variability (figure 12a), as well as the decrease from 2008 to 2013. The second PCs (figure 12b) also showed a negative peak starting in 2001. Continental concentrations were closer than river flows that remained almost the same along the time period.

3.3. Spatial and temporal variability among sites and parameters

Clustering analysis using ward method were performed on both the parameters and the sites matrices after the 3-mode PCA conducted according to Beaugrand et al (2000). Therefore, groups were made upon the positions of the variables on each of the correlation circles. Ward method enabled to group opposite variables expressed on the same axis.

• Variability among parameters

Four groups of parameters were detected (figure 13). The first group, expressed on the first dimension englobed the nutrients, salinity and the particulate organic and suspended matter. Salinity was opposed to all the other parameters. The first dimension therefore separated highly saline and poorly concentrated waters to highly concentrated and poorly saline waters. The second axis separated dissolved oxygen from temperature. The second dimension differentiated warm and poorly oxygenated waters to colder but more oxygenated waters.

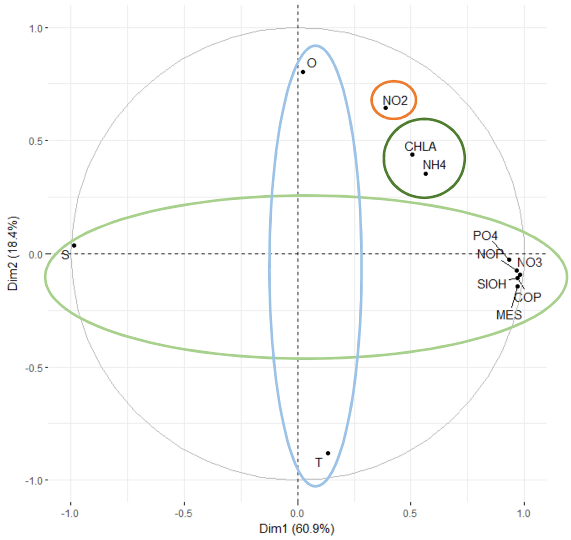

Figure13: Circle of correlation obtain after the parameters mode PCA. A cluster analysis was performed to obtain 4 groups of co-evolving parameters. T: temperature, Sal: salinity, O: dissolved oxygen, PO_4 : orthophosphate, NH_4^+ : ammonium, NO_2^-: nitrite, NO_3^-: nitrate, $Si(OH)_4$: silicates, POC: particulate organic carbon, PON: particulate organic nitrogen, SM: suspended matter, Chla: chlorophyll-a

Two groups were moderately expressed on both the first and the second dimension. One regrouping NH_4 and chlorophyll-a and the second with NO_2.

Variability among stations

Six groups of co-evolving sites were obtained after the Ward cluster (figure 14a). The sites were almost grouped by systems. From the north to the south, the first group was the Eastern English Channel, the second grouped the Western English Channel and the Iroise Sea, the third group is the downstream Gironde estuary, the forth is the upstream estuary, the fifth is the Arcachon Bay and the last one was a combination of the 3 Mediterranean sites (figure 14b).

Moreover, the pattern detected through the cluster of the parameters was confirmed. On the one hand, the Gironde Estuary (low salinity, high nutrients concentrations) was opposed to the English Channel (high salinity, lower nutrients concentrations). On the other hand, the Mediterranean Sea (hot water, low oxygenation) was opposed to both the estuary and the English Channel (colder but higher oxygenated waters).

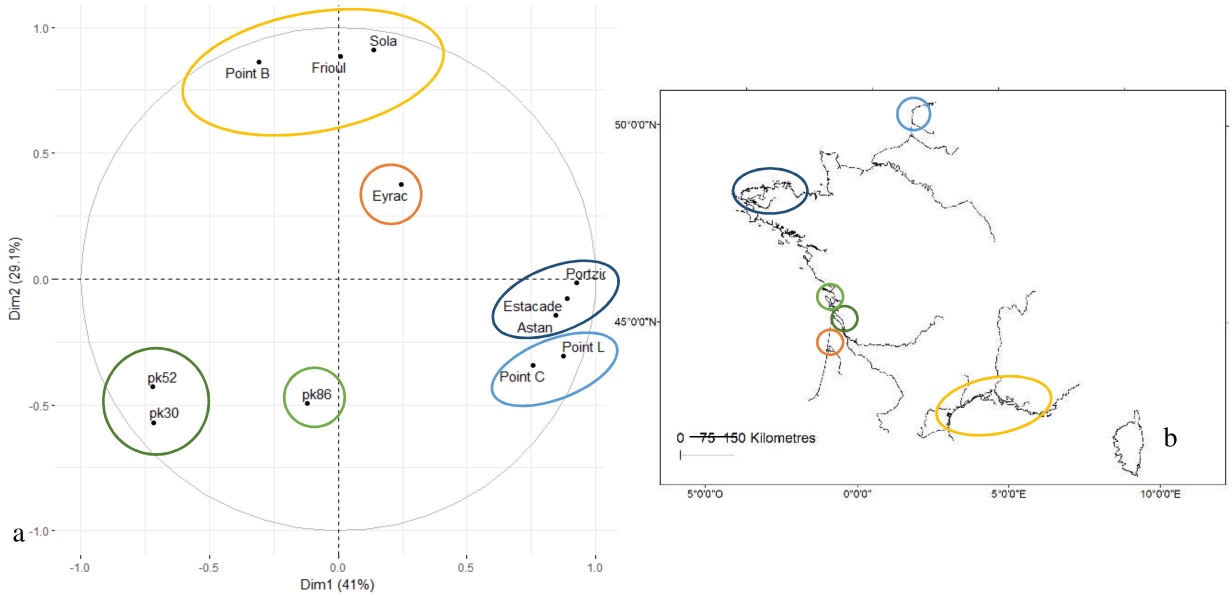

Figure 14: Circle of correlation obtain after the sites mode PCA. A cluster analysis was performed to obtain 6 groups of co-evolving sites (a) and their spatial variability (b)

4. DISCUSSION

4.1. The SOMLIT survey to study the impact of Climate change along the French coast

The observation surveys are precious tools to identify the future change of marine and coastal ecosystems (Hays et al., 2005). In this context, the SOMLIT data offer the possibility of studying coastal system through the *in situ* measurement of 12 biogeochemical parameters at 12 locations and over 20 years. The range of parameters, the spatial coverage of the SOMLIT and even the temporal scope are unique in coastal areas (Goberville et al., 2010). Regarding other *in situ* time series, the "Instituto Español de Oceanographia" (IEO) has also environmental subsurface data series from the 1980s on the Spanish Atlantic coast (Ruiz-Villarreal et al., 2006). In contrast with the IEO survey, the SOMLIT offers a shorter sampling interval (15 days *vs* 1 month) and a higher number of sampling parameters.

Moreover, the improvement of satellites resolution in the recent years enables to gather information on coastal areas at shorter scale but fewer parameters are measured. Optical sensors are used before models are applied to transform the signal into relevant information. This process might induce bias due to modelling (von Schuckmann et al., 2016). The major drawback of satellites data assimilation is that satellites are weather dependant. For example, the measurement of chlorophyll-a is done by integrating the water colour. It is impossible to do precise measurement of such parameters with satellites technology if there are clouds (Ciancia et al., 2016), or if the water colour is driven by other parameters as in estuaries in contrast with *in situ* measurement.

Moreover, the SOMLIT survey defends an inter-calibration policy that

- provides an indication about the data quality that allows to focus a study on reliable data only,
- offers a similar methodological strategy for the sampling and the laboratory analysis of the 12 parameters of the 8 ecosystems located alongside the French coast,
- disposes of a long-term series (20 years of data) that could be used for studying the long-term evolution of the French coastal systems in relation with climate change.

The only inconvenience is that no baseline corresponding to pristine systems exists. A true baseline corresponding to the pre-industrial period would be useful.

Concerning the statistical method employed, the 3-mode PCAs allowed to explore the dataset through the analysis of a 3-dimension database (stations X time X parameters). Both approach of the 3-mode PCAs were compatible. The Goberville approach allowed to obtain a global evolution over the 20 years and to compare them to the long-term evolution of the climate, meteorological and freshwater inputs indices. On the contrary, the Beaugrand approach allowed to obtain groups of parameters and stations that behave similarly on a long-term point of view.

However, the major drawback was the length of the series. Even if the SOMLIT provides a 20-year data set, the correlation with some long-term hydro-climatic indices such as the AMO is weak since the period of its cycle is close 30-40 years (Alexander et al., 2014). Consequently, only a phase of the cycle can be analysed.

4.2. Overall evolution of French coastal systems

The SOMLIT dataset enabled to interpret the biogeochemical last 20 years' long-term evolution of the French coastal systems. Data illustrated a shift that occurred in 2001. This shift resulted in a change of the leading biogeochemical parameters. Among the drivers, western Europe SST, atmospheric circulation and precipitation were those showing a pronounced shift at the same period. The 2001 shift was therefore mainly led by regional climate drivers

4.2.1. LARGE SCALE INDICES

The complexity of the large-scale hydro-climatic indices is partially described in Li et al., (2013). They showed that the NAO is actually a useful predictor of both the NHT and the AMO, especially when the datasets are shorter than the indices cycles.

The AMO is nowadays in a positive phase that started in 1995 according to Alexander et al., (2014). The AMO variability is based on the hypothesis that the Atlantic Meridional Overturning Circulation (AMOC), a combination of wind and density-driven components of the North Atlantic Circulation is observed (Alheit et al., 2014). Even if switches from one phase to another depend on the dataset used as well as on the calculation methodology, previous observations matched with the trend observed in our data, i.e. an increasing trend of the AMO that supposes wetter conditions and lower pressures are observed in the Northern and Eastern Europe respectively (Nye et al., 2014). It is more pertinent to focus on the processes induced by the AMO and the NHT rather than on the indices themselves. Indeed, the AMO is based on the SST and is generating changes in the Western Europe atmospheric circulation and precipitation. These changes have a strong impact on the evolution of the coastal systems as demonstrated by the significant correlations observed in our results (Figure 2).

The negative and significant correlation between the coastal systems and both the AMO and NHT were essentially mathematical links. It appeared because the AMO and the NHT are increasing while the coastal systems reacted mostly linearly after the 2001 shift. Moreover, the AMO can lead to shifts in the ecosystems functioning (Nye et al., 2014). Indeed, the AMO was linked to fluctuations in fish and plankton populations (Alheit et al., 2014). This shows that these indices must therefore be used as very large descriptors indicating indirect effects of global change on coastal systems. However, the only difference between AMO and NHT indices is that the NHT is not separated from the human impact on climate warming. Hence, the same consequences on the Western Europe climate were expected. Because the NHT trend is being sharper than the AMO's, it is possible to point out the anthropogenic impact on climate warming.

4.2.2. CHANGES IN ECOSYSTEMS

Even though the salinity increase was highlighted in all the coastal systems; the decrease of some nutrients, particulate organic and suspender matter in the English Channel and the increase observed in the Gironde Estuary (figure 3) may emphasize differences between sites.

Climate might have affected the nutrients through different pathways, i.e. SST, atmospheric circulation and precipitations. In the non-tidal or areas of 'deep', increasing SST is expected to enhance the water stratification and as a consequence to decrease nutrients vertical mixing.

After the 2001 shift, a pronounced decrease was observed in zonal wind (figure 8) and in precipitation (figure 10). Even if the SLP showed the decrease in 2001 (figure 7), the trend was an increase in pressure (from 2002 to 2016) which is known to be an indicator of warmer weathers. Pressure increase coupled with less wind and precipitations might then have affected the nutrients distribution in the Mediterranean Sea and in deep waters. Indeed, a diminution in winds limited the horizontal inputs of nutrients by its action on currents (Goberville et al., 2010), also, less precipitation brought less particulate matter in the systems, whether directly or indirectly. For shallower sites subjected to tidal regimes, tide induced mixing and could bring nutrients. The depletion might therefore be coupled with other drivers such as the strong salinity rise in the coastal systems (figure 3) that indicated a decrease in freshwater loads and thus in nutrients inputs from the continent. Continental nutrients concentration as well as river flows had slightly decreased over time, from 2001 to 2011 (figure 12). POM and SM also decreased over time in the coastal systems. This confirmed that less continental influence was found in the coastal systems.

Another parameter of interest in the biogeochemical functioning of ecosystems is the dissolved oxygen (DO). DO concentration varies with physical processes (atmospheric/ocean exchanges that are regulated by wind, temperature and salinity to a lesser extent) as well as biological processes (primary production, respiration). Though the DO seemed to decrease in the oceanic systems, it increased in the Gironde Estuary. Over the past decades, a "marinisation" (i.e. an increase in salinity) of this estuary occurred (David et al., 2005, 2007), as a consequence of dragging work, reduced Garonne flow and a reduction of precipitation rates (Chaalali et al., 2013). All these combined effects induced a slight transfer of the maximum turbidity zone, a zone of less DO concentration compared to adjacent areas towards the upper estuary. At the oceanic sites, the temperature was the driving parameter for DO, warmer water dissolving less oxygen than a colder water.

Finally, a slight decrease in chlorophyll-a coincided with the depletion in nutrients observed along the French coast suggesting that this biogeochemical change might have influenced the phytoplankton biomass that in turn would have influenced higher trophic levels. Indeed, Beaugrand and Reid (2003) have shown that the pelagic biologic component responded to SST fluctuations probably indirectly through biogeochemical changes. Climate change leads actually to cascade effects causing for instance migration patterns (Beaugrand et al., 2003; Luczak et al., 2011)

Hence, it appeared that the temperature was not the only indicator of climate change even if it seemed to have a greater direct influence on the biota as suggested by Goberville et al., (2010). The atmospheric circulation was also fundamental because coastal systems are more likely influenced by horizontal mixing than by vertical mixing. Our study showed in complement that riverine concentrations might influence the coastal systems functioning as well.

4.3. Inter-ecosystem variability

The 20-year temporal evolution of the sites and the parameters highlighted two main gradients in the temporal evolution of the coastal systems (figures 13 and 14).

• The first obvious one is a continent-ocean gradient from the upstream sites of the Gironde estuary characterized by a low salinity and a high nutrient and particle concentration towards the sites of the English Channel characterized by relatively high salinity and relatively low nutrient and particle concentration.

• The second one is a latitudinal-like gradient from the warmer Mediterranean Sea to the colder Atlantic Ocean and English Channel. If the main driver that appeared is water temperature (and its negatively correlated dissolved oxygen), this latitudinal-like gradient also corresponds to a gradient of trophic status from the oligotrophic chlorophyll-poor to the eutrophic chlorophyll-rich systems and to a gradient of tidal regime from micro- to macro/megatidal systems.

These gradients indicate that the coastal systems evolved differently over the past two decades depending on their location (proximity to the continent; Mediteranean Sea *vs* Atlantic Ocean and English Channel) and depending on the considered parameters.

Both gradients were function of the physics (water mass and temperature) influencing the biogeochemistry of coastal systems. The idea was therefore to investigate the main forcings of the 20-year evolution and their possible impacts regarding the different spatial groups. Partial Least Square models were applied to investigate the relationships between Western Europe climate, local meteorology, river inputs and the core parameters (figure 15). Only the best statistical representation of the interaction between the forcings and the coastal system were kept (Arhonditsis et al., 2006). For example, the model at Eyrac (Arcachon Bay; PC1) showed a direct link from the global climate to the coastal systems changes. The reason is that the indirect pathways were not significantly correlated from global changes to the system changes. In the present work, these models have to be considered as a first investigation of the complex interactions between forcings and the ecosystem temporal variability and are thus a preliminary step toward a better understanding of these interactions; they may need improvements. In fact, these models give a broad estimation of each system functioning.

For example, riverine SM was kept in the model of the western English Channel/Iroise Sea whereas the sites of the western English Channel are very scarcely influenced by continental discharge.

The models (figure 15) must be interpreted from the bottom to the top, in order to explain the coastal systems variability. Graphically, two distinct features can be observed. Firstly, the Arcachon Bay (figure 15e) and the upstream Gironde estuary (figure 15d) were the two systems with even relationships from the global changes to the water column. Secondly, the English Channel and the Iroise Sea were the systems with the most influenced parameters. It confirmed the results obtained with the whole systems variability PCA (figure 3).

In the oligotrophic Mediterranean Sea, phytoplankton production is deeply limited by nutrient (especially phosphate) availability and thus the phytoplankton dynamic is sensitive to nutrient inputs through river outflow, atmospheric deposition and vertical mixing of the water column (deep water input; Durrieu de Madron et al., 2011). It is therefore interesting that both climate (through direct and indirect effects) and riverine PO_4^{3-} are the drivers of coastal POC and PON, which are deeply dominated by phytoplankton in these systems (Liénart et al., 2017). Also, the model indicates that the long-term variability of coastal suspended matter is regulated by the local meteorology through the river SM. It should be noted that the model has been run for the sites of the bays of Banyuls and Marseille but not for the Bay of Villefranche where no river inputs have been considered in this study, following Liénart et al. (2017, 2018). Thus, the above conclusions are not valid for this latter site.

In the Eastern English Channel, the interaction between climate, local meteorology, river variables and coastal systems is very complex. Climate has both direct and indirect effects on most of the core parameters of the coastal systems; indirect effects occur through the local meteorology, the river variables. In addition, the direct effect of climate onto the coastal biogeochemistry is a positive correlation, whereas the indirect effects lead to overall negative correlations. Similar complexity is also reported for the Western English Channel and in a less extent in the downstream Gironde estuary. In the mid and Eastern English Channel, river dilution panaches are constrained to flow eastward along the French coast, forming a ‘coastal flow’ because of the overall water circulation (Brylinski et al., 1991). This flow fuels the Eastern English Channel in nutrients and consequently particles. The circulation of this coastal flow and especially its closeness to the coast depends on the water currents, so on the wind and on the atmospheric circulation. Hence, the direct and indirect effects of climate to the temporal evolution of the coastal biogeochemistry are likely due to the intensity of the coastal flow and its closeness to the coast that are driven by river flows and local meteorology.

In the upper Gironde estuary, climate drives some coastal variables directly and through local meteorology and eventually river variables. One interesting pathway is the forcing of climate on the local precipitation that forces the SM concentration in the upstream estuary. The latter link is likely indirect through the decrease in river flow even if this link is not significant in the model. In fact, the decrease in river flow is not significant when considering the last two decades but is significant when considering the last four decades. The changes in river flows has induced the marinisation of the estuary and the shift of the maximum turbidity zone toward the upstream (see above), and thus an overall decrease in suspended matter at the studied sites. Also, suspended matter concentration in the rivers drives the POC and PON concentrations in the upper estuary. In the upper estuary, particulate organic matter comes from the rivers as well as through resuspension processes. It is a very turbid part of the estuary where the primary production is almost null (Savoye et al., 2012 and references therein). Concomitant changes in climate index, local meteorology and biogeochemical parameters have already been reported in this system (Chaalali et al., 2013).

In the Arcachon Bay, the model reveals a direct forcing from the climate and from the local meteorology onto some specific biogeochemical variables, which is somewhat difficult to interpret. More interestingly, there is a lack of correlation between climate, local meteorology and river variables on the one hand, and temperature as well as nitrate, silicate and chlorophyll a concentrations on the other hand. These coastal parameters deeply increased during the last two decades (ca. x2 for nitrate and silicate concentrations; + 0.3°C.decade^{-1} for temperature) or during the last decade (x1.6 for chlorophyll a concentration). On the other hand, salinity, river flow as well as nitrate and silicate concentrations did not significantly change for the last two decades (Rodriguez, 2017). Nevertheless, a large decrease in the surface area of the seagrass meadow and its density was reported (Plus et al., 2010) in this system. Less seagrass biomass would have induced less nutrient consumption by the seagrass and thus more nitrate and silicate availability for the phytoplankton. This example of the Arcachon Bay illustrates that beside the three 'universal' kinds of forcings taken into account for running the PLS models, local forcings may have a great influence on the long-term evolution of the biogeochemistry of the coastal ecosystems.

Overall, this first look of the interactions between forcings and coastal variables using PLS models highlighted that 1) climate, local meteorology and river flow and concentration drove the long-term variation of coastal system variables in most of the studied systems 2) through complex interactions that 3) varied over space 4) likely depended on geographical gradients (continent-ocean gradient and latitudinal-like gradient), and that 5) other local forcings may have great effects.

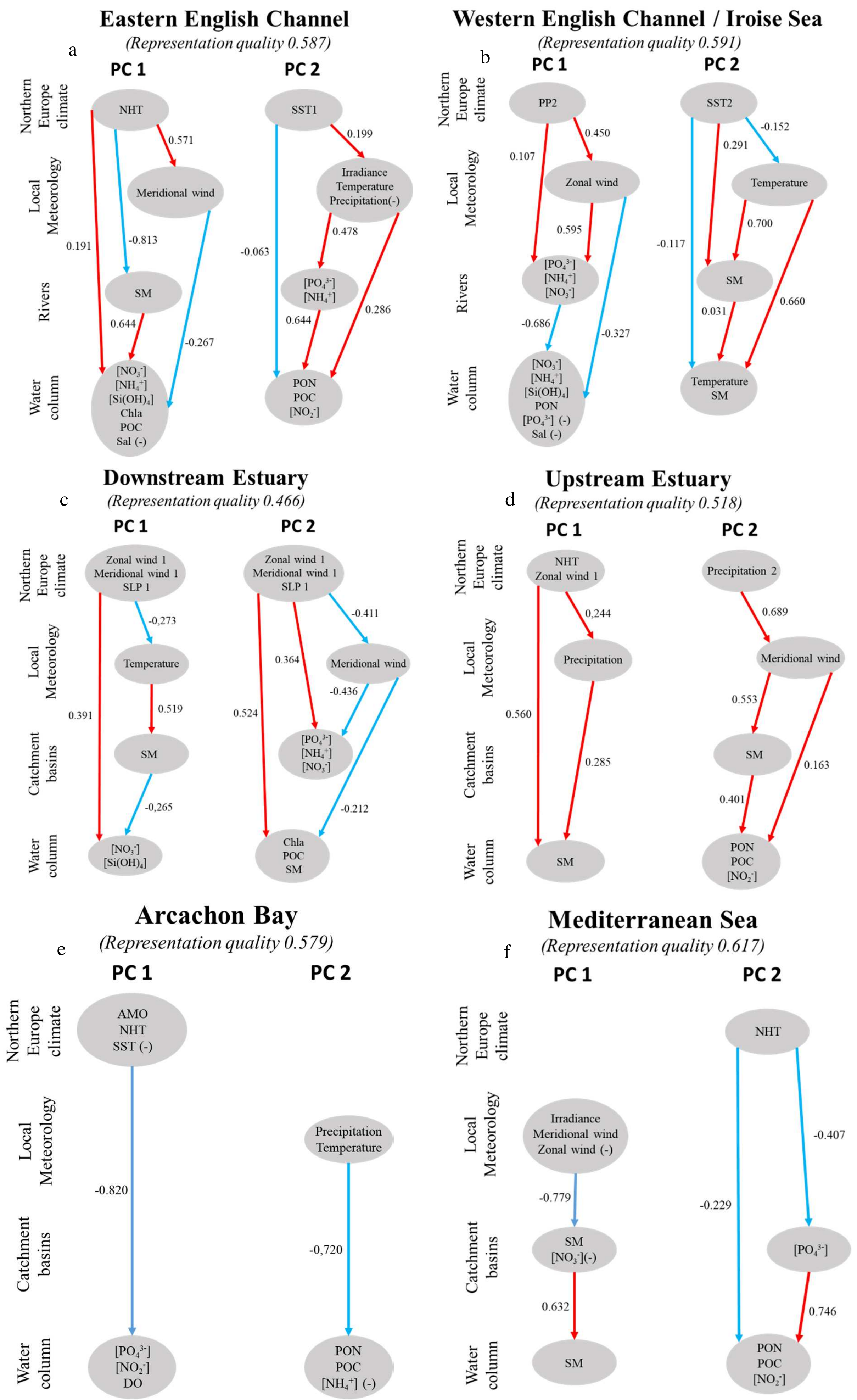

Figure 15: Representation of the 6 PLS models, one for each group identified. Red arrows are positive correlations; blue arrows are negative correlations.

5. CONCLUSION

This report is one of the scarce study with an interest in studying the changes in the coastal systems on the long term, with such a diversity of systems and parameters and encompassing both climatological and continental forcings.

The coastal year-to-year variability enabled us to confirm the 2001 shift showed by Goberville et al., (2010), but on a longer time series (same dataset with the exception of the pH). Moreover, the 2001-2007 coastal systems evolution found in Goberville et al., (2010) remained the same in this study (figure 3), and the 2007-2016 evolution continued to follow the same trend. It supports the fact that the ecosystems were facing the same drivers' influence from 2001 to 2016.

It has been showed that both climatological and continental drivers have an impact on the coastal systems variability. Human impact had influenced both the climatological (i.e. through greenhouse gases emissions) and the continental forcings (i.e. through land use and run-off). Finally, there is a difference between the variability of the different systems, even though this variability seemed to be due to the characteristics of the system. Indeed, most of the studied systems were influenced by the same forcings whereas their responses differed. Major differences exist between the catchment areas used. The Leyre catchment area is mainly composed of forest while the Aulne and Elorn catchment areas are composed of agricultural lands (European Union, 2012). Therefore, local forcings do not have the same influences.

The PLS models supported the hypotheses that it is the characteristics of a systems that mostly determines its year-to-year variability as in the Arcachon Bay where the local meteorology is the predominant influencing factor.

An interesting pursuit of this work would be to add the phytoplankton year-to-year variability in the models. The biogeochemical variability could therefore be interpreted as an indicator of the systems variability (as in this study) and as another factor influencing the systems variability onto the phytoplankton compartment. To do so, we suggest to study the functions assured by the phytoplankton community in a system. The traits already reported in the literature as well as traits compiled from a large phytoplankton database would be useful to determine the role of the present phytoplankton communities in a system.

Adding the phytoplankton to the models might enable to give a better estimation of the interaction occurring in the ecosystems. Indeed, phytoplankton is at the base of the trophic web, so changes in their community might affect all the living organisms and thus human societies. Moreover, they assure important roles in the ecosystems so adding them to the model might give information on what functions are assured in a given ecosystem and how these functions might be impacted by the forcings.

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ANNEX 1

Catchment areas

Table 3: Land use (%) in the considered catchment areas. Data was previously balanced for a better approximation

CATCHMENT BASIN PER ECOSYSTEM	ARTIFICIAL LANDS (%)	AGRICULTURAL LANDS (%)	FOREST AND SEMI-NATURAL LANDS (%)	WETLANDS (%)	WATER SURFACES (%)
EASTERN ENGLISH CHANEL	6.75	74.42	17.61	0.64	0.58
WESTERN ENGLISH CHANEL	7.68	71.57	17.56	2.58	0.21
BREST BAY	6.20	73.84	17.39	1.11	1.46
ARCACHON BAY	4.41	12.10	79.96	1.40	2.17
BANYULS BAY	4.91	37.96	55.69	0.26	1.17
MARSEILLE BAY	23.75	12.02	64.23	0	0
VILLEFRANCHE BAY	/	/	/	/	/
GIRONDE ESTUARY	3.00	57.74	38.58	0.13	0.56

River flows were counterbalanced by the distance from the sampling site to the river rmouth

$$Q_w = \frac{\frac{Q_1}{d_1} + \cdots + \frac{Q_n}{d_n}}{\frac{1}{d_1} + \cdots + \frac{1}{d_n}}$$

Where Q_w was the weighted flow at a given site, Q_n the river n flow and d_n the distance between the river n mouth and the influenced sampling site.

Biogeochemical loads were weighted by the distance and by the river flow

$$[x] = \frac{\frac{Q_1 \times [x]_1}{d_1} + \cdots + \frac{Q_n \times [x]_n}{d_n}}{\frac{Q_1}{d_1} + \cdots + \frac{Q_n}{d_n}}$$

Where Qi_w was the weighted input of a given parameter at a given site, Q_n the river n flow, d_n the distance between the river n mouth and the influenced sampling site and $[x]_n$ the concentration of element x measured in river n.

ANNEX II

Wind meridional and zonal intensities calculation

A mathematical circle was built from the meteorological wind rose with

- 0° = 0°N
- 90° = 90°E
- 180° = 180°S
- 270° = 270°W

Moreover, a wind direction in meteorology is actually the provenance of the wind, therefore the sign “– “was added to respect the trigonometrical properties. The equation is modulo 2π.

$$Vwind = -\cos\left(\frac{direction\ (°) \times \pi}{180}\right) \times Iwind$$

$$Uwind = -\sin\left(\frac{direction\ (°) \times \pi}{180}\right) \times Iwind$$

KEYWORDS / ABSTRACT / RÉSUMÉ

Keywords: coastal systems, long-term variability, local and climate-driven changes, SOMLIT, 3-mode PCAs, Partial least Squares models.

Coastal systems are facing different forcings that are affecting their functioning and their year-to-year variability. Climatological drivers through the direct action of the temperature and the mechanical action of the atmospheric circulation modify the coastal systems functioning. In addition, continental forcings (river flows and riverine concentrations) most of the time acting in synergy with the climatological forcings, are disrupting the nutrient cycles and the nutrient availability. These forcings are natural but are enhanced by human activities especially for the last 50 years. However, it is difficult to separate global from local infleunce. Here we show the influence of both climatological and continental forcings on the coastal systems year-to-year variability. Our results suggest that the climatological forcings are responsible for a shift that occurred at the beginning of the years 2000s. Continental forcings acted in parallel but remained mostly the same or decreased a little over the 20-year studied period. In addition, we showed that the coastal systems response to the forcings depended on their geomorphological and physical characteristics and on their local forcings because no difference in the global climatological forcings where showed. We anticipate our study to be a starting point toward a broader study of the cosatal systems year-to-year variability and their forcings. The Partial Least Square models are actually good tools to study the direct and indirect action of the climatological forcings onto the systems variability.

Les écosystèmes côtiers font face à de nombreux forçages affectant leur fonctionnement et leur évolution au cours du temps. Les forçages climatologiques, au travers de l'action direct de la température et de l'action mécanique de la circulation atmosphérique modifient le fonctionnement des écosystèmes côtiers. De plus, les forçages continentaux (débits de fluviaux et leurs concentrations) agissent la plupart du temps en synergie avec les forçages climatologiques, modifient les cycles des nutriments et leur disponibilité. Ces forçages sont d'origine naturelle mais sont amplifiés par les activités humaines, notamment au cours des 50 dernières années. Cependant, il est difficile de séparer l'impact des forçages globaux des forçages locaux sur le fonctionnement des écosystèmes. Dans cette étude, nous montrons l'influence des forçages climatologiques et continentaux sur la variabilité interannuelle des écosystèmes côtiers. Nos résultats suggèrent que les forçages climatologiques sont responsables du shift du début des années 2000. Les forçages continentaux ont agi en parallèle mais sont restés relativement constant voire ont diminué au cours des 20 ans étudiés. De plus, nous avons montré que les écosystèmes côtiers répondent aux forçages en fonction de leurs propriétés géomorphologiques et physiques et des forçages locaux associés car pas de différences de forçages climatologiques globaux ne sont constatées entre les différents systèmes. Nous pensons que cette étude permettra d'étudier les écosystèmes côtiers de façon plus complète en prenant en compte plus de paramètres forçant. Les modèles de type somme des moindres carrés sont de bon outils pour étudier les effets directs et indirectes des forçages climatologiques sur les écosystèmes côtiers.