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Bi-decadal variability in physico-biogeochemical characteristics of temperate coastal ecosystems: from large-scale to local drivers

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Abstract :

Coastal marine ecosystems, which play a crucial role in the biogeochemical and ecological functioning of the Earth, are highly sensitive to the combined effects of climate and human activities. Because of their location, coastal ecosystems are directly influenced by human activities, but it remains challenging to assess the spatial and temporal scales at which climate influences coastal ecosystems. We monitored 12 sampling stations, distributed in 8 ecosystems in France, over 2 decades for physico-biogeochemical parameters (temperature, salinity, concentrations of dissolved oxygen, nutrients and particulate material). The study encompasses a large diversity of temperate coastal ecosystems with respect to e.g. geomorphology, trophic status, tidal regime, river influence and turbidity. Time-series analysis coupled with standardised 3-mode principal component analyses, partial triadic analyses and correlations were used to assess bi-decadal variability and ecosystem trajectories, and to identify large-scale, regional and local drivers. Our results highlighted 2 abrupt changes in 2001 and 2005. The bi-decadal changes were related to changes in large-scale and regional climate, detected through proxies of temperature and atmospheric circulation, as well as through river discharge. Ecosystem trajectories tended to move towards an increase in temperature and salinity, and/or a decrease in chlorophyll a, nutrients and particulate matter. However, the magnitude of change, the year-to-year variability and the sensitivity to the 2001 and 2005 changes varied among the ecosystems. This study highlights the need for establishing long-term time series and combining data sets as well as undertaking multi-ecosystem and local studies to better understand the long-term variability of coastal ecosystems and its associated drivers.

Keywords : Long-term changes, Coastal ecosystems, Biogeochemistry, Climate change, Multivariate analysis, Monitoring programme

1. Introduction

Over the last decades, the rate and magnitude of changes in marine ecosystems have critically accelerated and coastal ecosystems — located at the interface between the ocean and the continent — are highly impacted by the combined effect of climate variability and direct anthropogenic pressures (Lima & Wethey 2012, Halpern et al. 2015, Lu et al. 2018). While coastal ecosystems represent 7% of the Earth surface, they play key roles in ecosystems functioning and shelter more than 50% of the marine biodiversity; they are also of high economic importance for the provisioning, regulating, habitat and cultural services that they provide to the human population (de Groot et al. 2012).

Over the twentieth century, the global nitrogen and phosphorus export from the continent has doubled (Beusen et al. 2016) as a consequence of human activities (Paerl 2009). Such changes in nutrient export have altered the global biogeochemical cycles with putative consequences on the increase — in rate and magnitude — of eutrophication episodes (Sinha et al. 2017). In the coming decades, the human fingerprint on coastal ecosystems is likely to increase as a result of fossil fuel combustion, the use of fertiliser and food production (Doney 2010).

Natural climate variability has also a strong influence on the physico-biogeochemical parameters in coastal ecosystems. At a local scale, an increase in sea surface temperature enhances water stratification, which in turn reduces the nutrient inputs from deep waters, and therefore the phytoplankton productivity (Doney 2006). In nutrient-poor ecosystems, such as the Mediterranean Sea, a rise in precipitation can induce phytoplankton blooms through atmospheric deposition (Durrieu de Madron et al. 2011). At a larger spatial scale, strong relationships have been detected between large-scale hydro-climate processes — such as the Northern Hemisphere Temperature (NHT) anomalies or the winter North Atlantic Oscillation (NAO) index — and changes in the physico-biogeochemical properties of coastal waters (Breton et al. 2006, Goberville et al. 2010).

The responses of coastal ecosystems — often characterised as complex and dynamic systems — to both climate and anthropogenic drivers usually occur in non-linear ways (Cloern et al. 2010, Chaalali et al. 2013). Moreover, ecosystems can respond in different ways to changes, they can switch to another equilibrium state or return to the state prior change (Scheffer & Carpenter 2003, Scheffer et al. 2009). Mounting evidence suggests that changes in the hydro-climate system can ramify through the food-web, from benthic to pelagic, from species to communities, and from terrestrial to coastal ecosystems. Such alterations can erode ecosystems resilience (Hughes 2000, Parmesan & Yohe 2003) and can trigger, in some cases, sudden, substantial and persistent changes in the state of ecosystems (Carpenter & Brock 2006). Another complex response is that large-scale processes do not directly influence coastal ecosystems variability but indirectly through a number of physical and chemical processes and pathways. In the Bay of Brest, the East Atlantic Pattern (EAP) has been related to salinity changes through its patent influence on precipitation patterns and river discharge (Tréguer et al. 2014). Identifying the relevant drivers of change in coastal ecosystems — and their temporal and spatial scales — and disentangling the effects of natural climate variability from the direct / indirect impacts of human activities, are essential to accurately project the future trajectories of changes in coastal ecosystems (Elahi et al. 2015).

While the influence of large-scale hydro-climatic processes can be detected on short time periods, such oceanic/atmospheric drivers have long cycles (NAO ~6/8 years, AMO ~60/80 years). In this context, long-term observation surveys are essential to unambiguously separate the main drivers of changes that can affect coastal ecosystems in order to better understand and anticipate possible alterations of biological and ecological systems as a result of global climate change (Hays et al. 2005). Among other coastal surveys the French monitoring programme SOMLIT (Service d’Observation en Milieu LIToral) has gathered, since 1997, a database of thirteen physical and biogeochemical parameters at twelve sites located along the English Channel, the Atlantic coast and the Mediterranean Sea (Cocquempot et al. 2019).

The sensitivity of these coastal ecosystems to climate variability is noticeable (Goberville et al. 2010). The authors showed a substantial impact of regional atmospheric and ocean circulation on changes in nutrient concentrations, particulate matters, salinity and chlorophyll-*a*, and highlighted that the regional climate variability was significantly correlated to large-scale hydro-climatological processes. Using a decade of observations, the authors also reported a major modification in the state of these coastal ecosystems in 2001. The present study updates their analysis using 20 years of observation and integrates local climate and rivers, as well as an investigation of ecosystem trajectories.

It was beyond the scope of the present study to detail the long-term changes in each parameter, at each sampling station (see. e.g. Talarmin et al. (2016) and Tréguer et al. (2014) for studies dedicated to particulate organic matter and to the westernmost stations, respectively). It was preferred to synthesize the data set in order to get an overview of the variability of the overall physico-biogeochemical characteristics of coastal ecosystems and finally to highlight the main messages. The objectives of the study are (1) to understand the main changes in the physico-biogeochemical characteristics of a panel of temperate ecosystems during a 20-year period (1997-2016), (2) to identify large-scale, regional and local drivers of change, and (3) to investigate changes in ecosystem trajectories.

2. Material and Methods

2.1. The coastal ecosystems and their sampling stations

Twelve stations belonging to eight contrasted ecosystems located along the French coast were considered (Fig. 1 and Table 1): (1) the eastern (Point C and Point L) and (2) western (Astan and Estacade) English Channel, (3) the Iroise Sea (Portzic, in the Channel of the Bay of Brest), (4) the Arcachon Bay (Eyrac), (5) the Gironde Estuary (pk30, pk52, and pk86), (6) the Bay of Banyuls (Sola), (7) the Bay of Marseille (Frioul) and (8) the Bay of Villefranche (Point B). In three ecosystems, two (eastern and western English Channel) and three stations (Gironde Estuary) were distributed along a continent-ocean gradient. The three stations located in the Gironde Estuary were referred to as ‘estuarine stations’, while the other nine stations as ‘marine stations’.

The diversity of the studied ecosystems (Table 1) relies on their geomorphological characteristics (estuary, ria, lagoon, bays and littoral ecosystems standing for semi-enclosed and open systems) with various bathymetric conditions (from less than 10 to 80 meters depth). These ecosystems have different tidal regimes (from micro- to mega-tidal regimes), show a large range of turbidity (the annual mean of suspended particulate matter ranged from less than 1 to more than 300 $mg.L^{-1}$) and different trophic status (from oligotrophic to eutrophic ecosystems); they also differ from their local climate conditions (e.g. annual air temperature mean ranges from 11 °C to 16 °C) and from their riverine influence: mean annual salinity varies from 2 to 38 and river flow ranges from a few to hundreds cubic meters per second (see Table 1). Thus, these ecosystems are representative of most of the coastal ecosystems encountered at mid-latitudes.

2.2 Physico-biogeochemical parameters

The physico-biogeochemical parameters were retrieved from the SOMLIT database, a long-term monitoring programme that uses a standardised sampling procedure since 1997. Samples were collected on a weekly (Bay of Brest) to monthly (Gironde Estuary) basis at high-tide in subsurface waters. A thoughtful description of the SOMLIT network can be found in Goberville et al. (2010), Liénart et al. (2017, 2018) and Coquempot et al. (2019).

Five nutrients (ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), orthophosphate (PO_4^{3-}) and silicic acid ($Si(OH)_4$), four particulate parameters (suspended particulate matter

(SPM), particulate organic carbon (POC), particulate organic nitrogen (PON), and chlorophyll-*a*), as well as water temperature, salinity and dissolved oxygen concentration were considered. These parameters were defined as Essential Ocean Variables by the Global Ocean Observing System because they are effective at addressing the ocean health and services (http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114). Water temperature has an impact on water stratification and in turn on the vertical mixing of the nutrients. Dissolved oxygen, directly influenced by the water temperature, is essential to the biological component. Chlorophyll-*a* biomass is a proxy of phytoplankton biomass and is controlled by temperature, light and nutrients. Nutrients, mainly delivered to the coastal ecosystems by the rivers and internal recycling, are essential to autotrophs but can lead to eutrophication episodes when in excess, which in turn can affect the whole ecosystem. Salinity is a proxy of riverine influence. Suspended particulate matter can be considered as a proxy of hydro and sediment dynamics (particle sinking and re-suspension, river load). Finally, POC and PON are useful variables to quantify the particulate organic matter.

Data providers are listed in Table 2.

2.3 Drivers of change

2.3.1 Large-scale climate

Five teleconnection indices were selected to examine the influence of large-scale hydro-climatic processes on coastal ecosystems of Western Europe: the Atlantic Multidecadal Oscillation (AMO), the winter North Atlantic Oscillation (NAO), the Northern Hemisphere Temperature anomalies (NHT), the Eastern Atlantic Pattern

(EAP) and the Arctic Oscillation (AO) (Table 2).

The AMO characterises the multidecadal ocean/atmosphere natural variability in temperatures, in a range of 0.4°C, in many oceanic regions of the North Atlantic, with a periodicity ranging from 60 to 80 years (Enfield et al. 2001). By investigating the influence of the AMO over the period 1997-2016, we focused on its positive (warm) phase, to assess the influence of a large-scale natural increase in sea surface temperature on coastal ecosystems of Western Europe. NHT anomalies are a proxy of the potential effect of climate change in the Northern Hemisphere, although this index also integrates hydro-climatic variability (Beaugrand & Reid 2003). The winter NAO index describes the basin-scale gradient of atmospheric pressures over the North Atlantic in winter. This oscillation has been correlated with a large range of physical processes such as the frequency and intensity of Atlantic storms and precipitation patterns (Hurrell 1995). The EAP is the second most prominent mode of low-frequency variability over the North Atlantic and is structurally similar to the NAO (Barnston & Livezey 1987). This pattern has a strong influence on Western Europe, negative values of the index being in phase with drought episodes over the Mediterranean region. The AO index is characterised by pressure anomalies of one sign in the Arctic and with the opposite anomalies centred about latitudes of 37-45°N (Givati & Rosenfeld 2013). During winter, it is one the main driver of intra-seasonal variability over the North Atlantic and Europe (Givati & Rosenfeld 2013) with strong consequences on Atlantic cyclones (Thompson & Wallace 1998). While its positive phase induces dry conditions in the Mediterranean, its negative phase is associated to extreme cold days in northern Europe (Thompson & Wallace 1998).

2.3.2. Regional and local climate

Six regional climatic parameters were selected to examine the influence of regional climate on coastal ecosystems of Western Europe: Sea Surface Temperature (SST), Sea Level Pressure (SLP), wind intensity and its zonal and meridional components (i.e. west-east and south-north components of the wind, respectively) and mean precipitation. Datasets are derived from reanalysis procedures and improved statistical methods have been applied to produce stable monthly reconstruction on a a 2.5° × 2.5° spatial grid, but on a 1° × 1° spatial grid for SST (see Betts et al. (1996), Kalnay et al. (1996) and Kistler et al. (2001) for further details on the methodology).

Five *in-situ*: air temperature, wind intensity (and its zonal and meridional components) and mean precipitation and one reconstructed parameter: short-wave irradiation (see Gelaro et al. (2017) for information on the method) were selected to examine the influence of local climate on coastal ecosystems (Table 2).

SST — and air temperature, to a lesser extent — has a direct impact on water stratification and nutrient supply rates (Sarmiento et al. 2004), and influence species' phenologies (Poloczanska et al. 2013). For example, the seasonal occurrence of phytoplankton and meroplankton, larval fishes and ichthyoplankton species advanced significantly over the last decades as a response to warming in the North Sea (e.g. plankton species; Edwards et al. 2004), in the English Channel (e.g. sprat and sardine; Reygondeau et al. 2015) and in the Mediterranean Sea (e.g. copepod species such as *Temora stylifera*; Mackas et al. 2012). Short-wave irradiation is the quantity of solar energy incoming from the sun to the ground/ocean and is used by phytoplankton species for photosynthesis. Atmospheric circulation (SLP and wind intensity) contributes to the horizontal and/or vertical mixing of nutrients and dissolved oxygen by its action on oceanic currents and therefore the mixing of river water and impact on the ocean-atmosphere coupling (Reid et al. 2003). Precipitation has both direct and indirect effects on coastal ecosystems. Its direct influence is observed on temperature, salinity and nutrient concentrations in raining periods, whereas its indirect impact appears through water run-off that contributes to river discharge. Precipitation can also influence phytoplankton communities (Delphy et al. 2018).

2.3.3 River discharge

Five parameters — selected for their availability over the whole period in all sites — were used to examine the influence of local river discharge to the coastal ecosystems: NH_4^+, NO_3^-, and PO_4^{3-}, suspended particulate matter and river flows (Table 2). Rivers flowing directly to, or known to influence, the studied ecosystems were selected. The selected monitored stations were located as close to the sea-side as possible, upstream the dynamic influence of the tide and with datasets available from 1997 to 2016. For coastal ecosystems influenced by more than one river, water discharge was weighted by the distance between the river mouth and the sampling station. Nutrient concentrations were weighted by considering the flow and the distance between the river mouth and the sampling station (see Liénart et al. 2018).

2.4 Numerical approach

2.4.1 Data pre-treatment

The SOMLIT provides quality codes associated to each data. Data flagged as false were discarded: only 3% of the original dataset was removed and therefore we used

97% of the samples. Time series were then regulated and standardised at a monthly basis using the spline method. The Kalman smoothing procedure was applied on the Eyrac dataset to prevent possible bias related to repeated missing values over the study period (Moritz & Bartz-Beielstein 2017). Following the method applied in Goberville et al. (2010), the seasonality was removed from the time series, except for the large-scale hydro-climate indices, using a simple moving average of order m = 6. Because the application of a moving average prevents from computing values for the first and last (m − 1) values of the sequence (Legendre & Legendre 1988), the first and last 6 months were removed from further analyses.

2.4.2 Statistical analyses

Analysis 1: Bi-decadal spatial and temporal changes in coastal ecosystems

Bi-decadal (1997–2016) changes in (1) the coastal physico-biogeochemical parameters, (2) regional and (3) local climate parameter, (4) river parameter concentrations and (5) river flows were assessed separately using 3-mode standardised principal component analyses (PCAs; Hohn 1993, Beaugrand et al. 2000, Goberville et al. 2010). Prior each PCA - and to overcome possible biases due to parameters with different units of measurement - all parameters were standardised (Jolliffe and Cadima, 2016). This statistical technique allows — in a single analysis — (1) to characterise temporal changes by the examination of the first principal components (PCs) and (2) to identify the parameters and sites (for coastal ecosystems) or the geographical cells (for gridded climate parameters) mainly influenced by the temporal patterns (associated normalised eigenvectors). Here, the first two principal components (PCs) were retained for further examination.

Analysis 2: Influence of environmental and climate drivers on coastal sites

The Pearson linear correlation coefficient was calculated to assess the relationships between the first two PCs obtained from the PCA applied on the physico-biogeochemical parameters and (1) the first two PCs calculated from the PCAs performed on environmental and climate drivers and (2) large-scale hydro-climatic indices. Probabilities were corrected to account for temporal autocorrelation using the Chatfield's (Chatfield 1996) modified Box-Jenkins' function (Box & Jenkins 1976) and by adjusting the degrees of freedom according to the method proposed by Chelton (1984). Because multiple testing may increase the type I error rate (i.e. rejection of a true null hypothesis), probabilities were adjusted following the Hochberg method (Hochberg 1988, Legendre & Legendre 1998).

Analysis 3: Identification of patterns of change among the twelve sampling sites

The Partial Triadic Analysis (PTA) method is a triadic analysis introduced in ecology by Thioulouse & Chessel (1987) that can be applied to the analysis of series of ecological tables containing the same variables and observations. While the PTA relies on the STATIS method (Escoufier 1973, L'Hermier des Plantes 1976, Escoufier 1980), the analysis is applied directly on the ecological tables rather than on the scalar product derived from the tables (Bertrand & Maumy, 2010). The PTA is a three-step procedure, namely the interstructure, the compromise and the intrastructure analyses (Lavit et al. 1994). As this technique has been fully described and applied elsewhere (e.g. Lavit et al. 1994, Thioulouse et al. 2004, Bertrand & Maumy, 2010, Mendes et al. 2010, Thabet et al. 2018), we refer the reader to this literature for a detailed mathematical description and only recall the main steps of calculation. First, a matrix of scalar products is calculated between the k different tables, the diagonalisation of the resulting matrix providing eigenvectors. The coefficients of the first eigenvectors are then used to weight the tables in the calculation of the compromise table (step 2). At this stage, a matrix of vector correlations (called ‘Rv’) can be applied to rescale the importance of the k ecological tables. The second step of the PTA consists in the analysis of the compromise, a fictitious table that results from the linear combination of the k initial tables (i.e. weighted mean of all the tables of the series, using the components of the first eigenvector of the interstructure as weights; Lavit et al. 1994, Mendes et al. 2010) in order to construct a mean table of maximum inertia with the aim of capturing the similarities among the k individual matrices. A principal component analysis is then performed on the mean table, the rows and columns of the individual matrices being projected onto the analysis as supplementary individuals and supplementary variables, respectively. Analysis of the compromise depicts the structures which are common to all the tables (Thioulouse et al. 2004, Bertrand & Maumy, 2010). Finally, the third step summarises the variability of the succession of tables in comparison to the common structure defined by the compromise (Mendes et al. 2010), the rows and columns of all the tables of the three-dimensional array being projected onto the factor map of the PCA of the compromise as additional elements (Thioulouse et al. 2004). The quality of the compromise can be established by dividing the first eigenvalue of the Rv coefficients by their sum and with the cos², an indicator of the representation of the information contained in each original table by the compromise. For each table, each row (column) is a point in the space of its p columns (its n rows) that can be projected as a supplementary individual onto the principal axes of compromise. The points can then be linked to study trajectories.

In our study, each table contains the values of all the physico-biogeochemical parameters at all the stations at a given (k) month; the compromise is the mean structure of the parameters during the study period. Year-to-year changes at each sampling station, i.e. its dynamic trajectory, can be studied while identifying the possible common temporal structures among stations.

All statistical analyses were performed using the R software (RCoreTeam 2020, R version 4.0.2) and the FactoMineR, ade4, pastecs and ggplot2 packages.

3. Results

3.1 Bi-decadal spatial and temporal changes in coastal ecosystems

Year-to-year variability in the first PC of the PCA performed on the physico-biogeochemical parameters (19.36% of the total variability; Fig. 2a) showed a gradual increase from 1997 to the end of 2001, followed by an overall decrease until 2016 revealing an abrupt change in 2001. Mapping of the first eigenvectors (Fig. 2b) revealed that PC1 was correlated to almost all the parameters and stations, but the temperature was poorly represented. Most of the correlations were positive, suggesting that the parameters mostly decreased from 2001 to 2016 (e.g. NO_3^- at all the English Channel and Atlantic stations), with the exception of salinity that increased at almost all the marine stations and in the upstream part of the Gironde Estuary where an overall increase in nutrients and particulate parameters was also detected.

Year-to-year variability in the second PC of the PCA (11.37% of the total variability; Fig. 2c) showed two periods of decrease from 1997 to 2001 and from 2005 to 2016, but an increase from 2001 to 2005 pointing out two abrupt changes in 2001 and 2005. Mapping of the second eigenvectors (Fig. 2d) revealed that PC2 was positively correlated to the nutrients whereas the salinity, water temperature and particulate parameters (SPM, POC, PON, chlorophyll-*a*) were negatively correlated at almost all the stations. The PC2 showed a clear opposition between the nutrients on the one hand and salinity, temperature and the particulate parameters on the other hand. Salinity and water temperature increased at most of the stations from 2006 onwards. The analysis also revealed that the water temperature was not highly related to the first two PCs (Figs. 2b and d).

3.2 Bi-decadal influence of the drivers

Results from correlation analyses between the first two principal components of the hydrological and biogeochemical variability along the French coast and the first two PCs of the PCAs performed on large-scale hydro-climatic indices, regional climate indices, and local drivers are presented in Fig. 3. In addition, temporal trends for which significant correlations were found are displayed in Fig. 4. Strong correlations ($r > 0.5$) were found between PC1 and PC2 of the physico-biogeochemical variability of the French coastal ecosystems and drivers of the three considered spatial scales: large, regional and local. The correlated drivers were either based on the air temperature or the atmospheric circulation. PC1 and/or PC2 were correlated to the NHT anomalies, to changes in wind intensity and direction, SLP and mean precipitation, and to the river nutrient concentrations and flow (Figs. 3 and 4). The coastal-ecosystem PCs and the correlated drivers exhibited not only a similar long-term trend but also a similar year-to-year variability (e.g. Figs. 4g and i).

Among the correlated drivers, the zonal wind PC2 influenced all the ecosystems (eigenvalues > 0.5), the SLP PC2 and mean precipitation PC2 influenced the eastern and western English Channel and the Iroise Sea (eigenvalues > 0.5), the wind intensity PC2 influenced the Arcachon Bay and Gironde Estuary (eigenvectors > 0.5) and the meridional wind PC2 influenced the three Mediterranean and the two Atlantic ecosystems (eigenvalues > 0.5). The eigenvalues maps are shown in Supplement I.

3.3 Inter- and intra-station variability

The PTA compromise explained 84% of the total variability of the original set of matrices. Between 80 and 95% of the information contained in each table was expressed in the compromise. The first two axes of the compromise expressed 72.47% and 19.58% of the total variability, respectively. By opposing the estuarine (nutrient-rich, particle-rich and low-salt water) and marine sampling stations (nutrient-poor, particle-poor and salty water), the position along the abscissa revealed a continent-ocean gradient (Figs. 5a, b), with a clear opposition between salinity on the one hand and nutrients (NO_3^-, $Si(OH)_4$ and PO_4^{3-}) and particulate matter (SPM, POC and PON) on the other hand. The downstream estuarine station (pk86) exhibited an intermediate behaviour. By opposing the Mediterranean stations (warm oligotrophic waters) and the stations located in the English Channel (cold eutrophic waters), the y-axis showed a gradient based on both the latitude and the trophic status. The Atlantic stations (oceanic and estuarine) had an intermediate position in the Euclidean space. The variability between the stations was more related to the salinity and the associated parameters than to latitude and trophic status (Figs. 5a, b). In contrast, the variability within the stations was more related to the latitude and trophic status (y-axis) than to the continent-ocean gradient (x-axis) (Fig. 5c), suggesting that this spatial organisation on the Euclidean plan can be related to a temperature effect. While the estuarine stations of the Gironde estuary showed an important variability, the stations located in the Iroise Sea and in the western part of the English Channel (Astan, Estacade and Portzic) showed relatively stable trajectories (Fig. 5c).

Over the period 1997–2016, year-to-year variability in the physico-biogeochemical parameters had gone roughly from the lower or the lower-left to the upper or upper-right hand side of the panel for most of the stations (Figs. 5d, e, g, h, k, n) which was associated with an overall increase in temperature, salinity and/or a decrease in chlorophyll-*a*, nutrients and particulate matter. Few stations exhibited opposite (Fig. 5l) or different (Figs. 5f, i, m, o) behaviours.

At stations such as Frioul (Fig. 5k), the trajectories were approximately linear, meaning that changes over the period 1997–2016 are quite constant without abrupt modifications. Frioul tended to be hotter and/or saltier and more oligotrophic. At other stations such as Point L (Fig. 5e), pronounced modification in the trajectories have been observed, after a period of stability: a seesaw to hotter and/or saltier conditions was detected, with less eutrophic waters. Some stations showed hysteresis-like behaviours as observed at Point B (Fig. 5l): a pseudo-cyclical variability was observed with two phases of cold, less salty and less oligotrophic waters interrupted by a period of warmer and more oligotrophic waters. Such variations occurred in a relatively small part of the Euclidean space, however, suggesting that modifications are less intense at the oceanic stations than at the estuarine stations. The two abrupt changes detected in 2001 and 2005 (Figs. 2a and c) were patent for most of the stations, as observed at pk86 (Fig. 5o) and Point B (Fig. 5l).

4. Discussion

4.1 Importance of long-term monitoring programmes to assess the influence of drivers on coastal ecosystems

Long-term monitoring programmes are precious tools for studying the long-term variability of coastal ecosystems (Hays et al. 2005). However, they are usually not long enough to provide any baseline of ecosystems which would be useful to disentangle the natural climate variability from anthropogenic-induced changes and to detect possible consequences on the ecosystem functioning. The need for long-term environmental and biological time series to assess the climate influence on coastal ecosystems is associated with the time span of the climatic processes. For example, while Fromentin & Planque (1996) attributed changes in the abundance of *Calanus Finmarchicus* to the NAO over the period 1962-1992, this relationship broke down from 1996, when one of the most extreme negative phases of the NAO was observed (Beaugrand 2012). By extending the study to five decades of observations, Beaugrand (2012) demonstrated that the correlation between the NAO and *C. finmarchicus* abundance was in fact modulated by the thermal regime of the North Sea, which in turn covaries positively with global temperature anomalies. However, examples of temporal patterns detected and confirmed using extended datasets also exist (e.g. Pimm & Redfearn 1988, Cloern & Jassby 2012).

Our study based on assessing changes in the physico-biogeochemical variability of the French coastal ecosystems confirms the results obtained by Goberville et al. (2010), and emphasises the importance of the abrupt episode observed in 2001, even when twenty years of observation are used instead of ten. This highlights the magnitude of this event, while confirming the main environmental and climate drivers, i.e. the influence of changes in atmospheric and oceanic patterns.

By combining marine long-term monitoring programmes with other biological, environmental, climatological, meteorological long-term time series, one can compare different ecosystems, while identifying local influences. For instance, Capuzzo et al. (2018) combined different data sets to estimate changes in primary production, zooplankton abundances, environmental conditions (SST and riverine) and large-scale hydro-climate processes, and to quantify pathways between these ecological compartments. By investigating a possible synchrony among patterns of changes, they showed that the decline in the primary production in the North Sea was induced by a decrease in riverine inputs and revealed patent consequences on higher trophic levels (Capuzzo et al. 2018).

In our study, combining several data sets allowed us to assess changes in coastal ecosystems and to investigate the drivers of these changes.

4.2 Abrupt changes in Western Europe coastal ecosystems: drivers of change and consequences

Abrupt changes in the late 90s / early 2000s have already been detected in physico-biogeochemical parameters, fish communities, local meteorology and sea surface temperature in the vicinity of the Gironde Estuary (Chaalali et al. 2013), for phytoplankton communities in the English Channel (Hernández Fariñas et al. 2014) and in the coastal Atlantic Ocean (David et al. 2012). The relationship between large-scale hydro-climatic indices and the coastal-ecosystem compartments has already been reported in the literature: the NAO was correlated to the abundance of plankton species in the English Channel (Beaugrand et al. 2000) and diatoms in southern Bight of the North Sea (Breton et al. 2006) and significant links between the AMO and phytoplankton blooms, plankton population and fish population have been detected at the global scale (Nye et al. 2014 and references therein).

According to Somavilla et al. (2016), an extreme winter mixing occurred in the mid-2000s potentially due to a particularly cold and dry winter in 2005 (Shein 2006, Somavilla et al. 2009) that had modified the Eastern North Atlantic Central Water (ENACW). These changes induced a modification of the ocean circulation, introducing northern saltier waters to lower latitudes, and altered regional climate conditions in the Northern Atlantic (Somavilla et al. 2016). The Atlantic Meridional Overturning Circulation (AMOC) also exhibited changes during the beginning of the twenty-first century. Chen & Tung (2018) reported that the transport of southern warm and saline water northward increased rapidly since 1999 and that the AMOC was decreasing from 2005 onward, confirming changes in circulation patterns in the north Atlantic. A decreasing AMOC could lower precipitation rates and therefore influence water runoff and river flows (Jackson et al. 2015). Goberville et al. (2010) found that the variability in coastal ecosystems was more related to changes in atmospheric circulation than in SST. The patent influence of atmospheric circulation that we detected over the period 1997-2016 corroborates previous results obtained from a decade of observation, while highlighting that the link between atmospheric circulation and rapid/major ecosystem changes (Goberville et al. 2010; Beaugrand et al. 2019) is stronger than when SST was considered. In addition, we found that the riverine influence was of high importance. Indeed, river parameter concentrations were the only driver correlated to the two PCs of the coastal ecosystems. These results are reliable: our data showed an increase in salinity over the study period along with correlations with atmospheric circulation and river discharge. The two abrupt changes detected circa 2001 and 2005 (Figs. 2a, c) can then be attributed to changes in wind intensity and sea level pressure at the regional scale and to changes in river parameter concentrations and river flow at the local scale (Fig. 4).

The consequences of such changes to coastal ecosystem functioning could be of various types. For example, changes in regional wind intensity and SLP modified water circulation dynamics (Somavilla et al. 2016), inducing saltier waters to the mid-latitudes in combination with decreasing precipitation and therefore a reduction in inputs from the continent: the flows of the main French rivers have decreased in the end of the twentieth century like in the Loire river (Ratmaya et al. 2019). In the literature, similar processes have been reported in the Patos Lagoon, Brazil (Cloern et al. 2016). In our ecosystems, the most convincing example is the “marinisation” observed in the Gironde estuary over the last decades (David et al. 2007). The increase in salinity in the estuary combined with lower SPM concentration, favoured the colonisation of this ecosystem by the invasive species *Acartia tonsa*. In other low-salinity ecosystems, especially in wetlands and lagoons, an increase in salinity can lead to a decrease in zooplankton abundance and a reduction in species richness (Schallenberg et al. 2003). Richirt et al. (2019) showed that changes in copepod abundance in the Arcachon Lagoon, one of the studied ecosystem, are governed by changes in physico-biogeochemical parameters, including salinity and SPM.

4.3 Ecosystem trajectories: common patterns and local differences

Among the trajectories of the oceanic coastal ecosystems studied in the present study, the general trend was towards warmer and saltier waters and/or less nutrient-rich waters. Similar trends were reported worldwide, such as in the Danish coastal ecosystems (Riemann et al. 2016), in the Chesapeake Bay (Harding et al. 2016) and in the Moreton Bay, Australia (Saeck et al. 2013). The two abrupt changes that we detected over the period 1997-2016 - and especially the 2001 event which may reflect a response to the global rise in ocean heat content (Levitus et al. 2009, Chaalali et al. 2013) - were associated with warmer, saltier and nutrient-poorer waters for most of the sampling sites, with ensuing consequences on the biological compartment: changes in dinoflagellate and zooplankton assemblages in the North Sea (Beaugrand et al. 2014; Goberville et al. 2014), and in fish abundances in the Gironde estuary *circa* 2001 (Chaalali et al. 2013); alterations in phytoplankton biomass (Somavilla et al. 2009) and copepod diversity (Richirt et al. 2019) in the mid-2000s in the Bay of Biscay. Despite this overall trend in the studied ecosystems and similar abiotic drivers of changes (Figs. 2 and 3), different responses of individual ecosystems were observed in terms of magnitude, timing and even direction of the trajectories. Local discrepancies from an overall pattern are common, especially in coastal ecosystems that can face strong local drivers as seen in relationships between dissolved inorganic nitrogen and chlorophyll-*a* (Lefebvre & Dezécache 2020). Furthermore, no overall common pattern may be found highlighting the role of local over global drivers in controlling the functioning of coastal ecosystems (Talarmin et al. 2016, Carstensen & Duarte 2019). These variations demonstrate the importance of taking into account local events to understand the direction and magnitude of the changes that occurred in coastal ecosystems over the recent decades.

For example, the trajectory at Eyrac goes from right to left (Fig. 5i), suggesting less saline and more nutrient-rich waters, whereas the overall trend was towards lower nutrient concentrations in the French coastal ecosystems (Fig. 2a). When analysed individually, nutrient concentrations in the Arcachon Bay increased since the late 1990s (Lheureux et al. unpub.). The two abrupt changes detected in 2001 and 2005 in the overall pattern (Figs. 2a, c) did not seem to have impacted the trajectory of the Arcachon Bay, but other abrupt changes occurred ca. five years later (see the right-hand side of panel i). In this ecosystem, the strong decline of the *Zostera noltii* seagrass meadow, which had accelerated between 2005 and 2007 (Plus et al. 2010), may explain the increase in nutrient over the study period (Lheureux et al. unpub.). Changes in zooplankton abundance and diversity were also reported in this ecosystem (Richirt et al. 2019).

The western English Channel tended to be warmer, but without changes regarding salinity or nutrient concentrations (Figs. 5f, g). The Iroise Sea showed an increase in both nutrient concentrations and temperature (Fig. 5h). Although these two ecosystems were geographically close with similar large-, regional- and local- scale climate influences, the Iroise Sea was under a greater influence of river discharge than the western English Channel (Charria et al. 2020). We also highlight that the abrupt change in 2001 was very obvious on the trajectories of the two stations located in the western English Channel (Astan and Estacade) but not in the Iroise

Sea (Portzic). Interestingly, it seems that this abrupt change prevented the western English Channel from shifting towards more nutrient-rich and less saline waters and may illustrate the resilience capacity of these ecosystems.

The English Channel ecosystems were more influenced by the 2001 event than other ecosystems, whereas a predominant abrupt change in the Mediterranean ecosystems occurred in 2005 (Fig. 5), which may have also impacted zooplankton abundances and assemblages in the Levantine Basin (Ouba et al. 2016). This difference is not due to riverine influence, since some stations are under the influence of rivers (Point C, Sola) and some are not (Astan, Estacade, Point B) in both the English Channel and the Mediterranean Sea. This can be explained by the patent influence of precipitation patterns over the English Channel. Whereas no correlation was detected between the EAP and the physico-biogeochemical properties of the studied ecosystems as a whole, EAP is known to significantly influence precipitation patterns over the English Channel (Casanueva et al. 2014). This relation between the EAP, precipitation patterns and river flows was highlighted by Tréguer et al. (2014) in the Bay of Brest and western English Channel. As the EAP entered in a positive phase at the beginning of the 2000s, it can be assumed the variability in the precipitation patterns played a role in the 2001 abrupt change in the English Channel.

The Gironde Estuary exhibited a large variability in the physico-biogeochemical characteristics over the two last decades compared to the marine ecosystems (Figs. 5c, m-o). This was expected since estuarine ecosystems, due to their location, face more pressures, especially from the continent, than marine coastal ecosystems. Estuarine stations were therefore segregated along the salinity-nutrient axis of the PTA compromise (Fig. 5b) rather than on the temperature axis.

Finally, it appears that more work at a local scale is needed in addition to multi-ecosystem studies in order to better understand the long-term variability of coastal ecosystems and its associated drivers. Thus, our analysis can be seen as a proof of concept that one must consider the environmental and ecological context of each site to better understand how external drivers can influence the functioning of such ecosystems.

5. Conclusion

Many complex ecosystems have a critical threshold at which the ecosystems can abruptly change from one state to another (Scheffer et al. 2009). Such thresholds can be detected using appropriate statistical analyses. It is difficult to understand how these abrupt changes are affecting the coastal ecosystems. Our study enables to point out the general patterns of changes in the physico-biogeochemical properties of coastal surface waters that occurred in temperate coastal ecosystems over the past 20 years. Such a multi-ecosystem approach has the great advantage to highlight overall patterns as well as discrepancies, and potentially to point out gradients and/or typology of ecosystems and ecosystem functioning (e.g. Liénart et al. 2017, 2018). Each ecosystem being influenced by climatic and river related drivers at different spatial and temporal scales, however, and because of the peculiarities of each ecosystem, we recommend to investigate changes also at a local scale. Local-scale studies should allow to deeply document subtle changes and to gather information about local ecological processes such as local changes in water circulation, quantification of the influence of the biology on remineralisation processes, impact of direct anthropogenic disturbances such as pollutions. Multi-ecosystems studies and local studies are complementary approaches to better understand the long-term variability of coastal ecosystems and associated drivers.

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Table 1: Characteristics of the studied ecosystems

Ecosystem	Type of ecosystem	Tidal regime (range in m)	Trophic status	Station	Depth at sampling station (m)	Catchment basin area (km^2)	Mean river flow ($m^3.s^{-1}$)	Distance from the river mouth (km)
Eastern English Channel	Littoral ecosystem	Megatidal (7.7)	Eutrophic	Point C Point L	21 50	96315	Canche (13) Somme (36) Seine (509)	20 40 212
Western English Channel	Littoral ecosystem	Megatidal (7.5)	Mesotrophic	Estacade Astan	11 60	612	Penzé (3)	13 10
Bay of Brest	Semi-enclosed ria	Megatidal (7.6)	Mesotrophic	Portzic	10	2709	Aulne (26) Elorn (6)	50 23
Arcachon Bay	Semi-enclosed lagoon	Mesotidal (4.2)	Mesotrophic	Eyrac	8	3754	Leyre (15)	15
Bay of Banyuls	Open bay	Microtidal (centimetric)	Oligotrophic	Sola	27	104200	Têt (7) Aude (29) Hérault (31) Rhône (1640)	33 86 93 212
Bay of Marseille	Open bay	Microtidal (centimetric)	Oligotrophic	Frioul	60	524	Huveaune (1)	7
Bay of Villefranche	Semi-enclosed bay	Microtidal (centimetric)	Oligotrophic	Point B	80	/*	/	/
Gironde Estuary	Estuary	Macrotidal (5)	Eutrophic	pk30 pk52 pk86	8 7 8	81793	Garonne (500) Dordogne (249)	9 26 61

* /: not availableTable 2: Summary of datasets

Parameters	Provider	Website
T, S, O, $NH_4^{+}{}_4^{+}$, $NO_3^{-}{}_3^{-}$, $NO_2^{-}{}_2^{-}$, $PO_4^{3-}{}_4^{3-}$, $Si(OH)_{44}$, POC, PON, SPM, Chla	SOMLIT	http://somlit-db.epoc.u-bordeaux1.fr/bdd.php?serie=ST
AMO	National Oceanic and Atmospheric Administration	www.esrl.noaa.gov/psd/data/timeseries/AMO/
NAO		www.climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based
EAP		www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml
AO		www.ncdc.noaa.gov/teleconnections/ao
NHT	Hadley Centre for Climate Prediction and Research	www.ncdc.noaa.gov/monitoring-references/faq/anomalies.php#anomalies
Gridded data (SST, SLP, Iwind, Uwind, Vwind, MP)	National Centers for Environmental Protection and National Center for Atmospheric Research	www.esrl.noaa.gov/psd/data/gridded
In-situ local climate (air temperature, Iwind, Uwind, Vwind, MP)	Meteo France	https://donneespubliques.meteofrance.fr/
Reconstructed local climate (GLO)	Modern-Era Restrospective Analysis for Research and Application Version 2	https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/
River flows	Banque Hydro	http://www.hydro.eaufrance.fr
Continental concentrations	Naïades, the French water agencies and Ecoflux	http://www.naiades.eaufrance.fr/acces-donnees#/physicochimie
		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

https://www-iuem.univ-brest.fr/ecoflux/observation/acces-aux-donnees

1

Fig 1: Localisation of the ecosystems and the twelve sampling stations used in this study. The four panels highlight where the sampling stations are located.

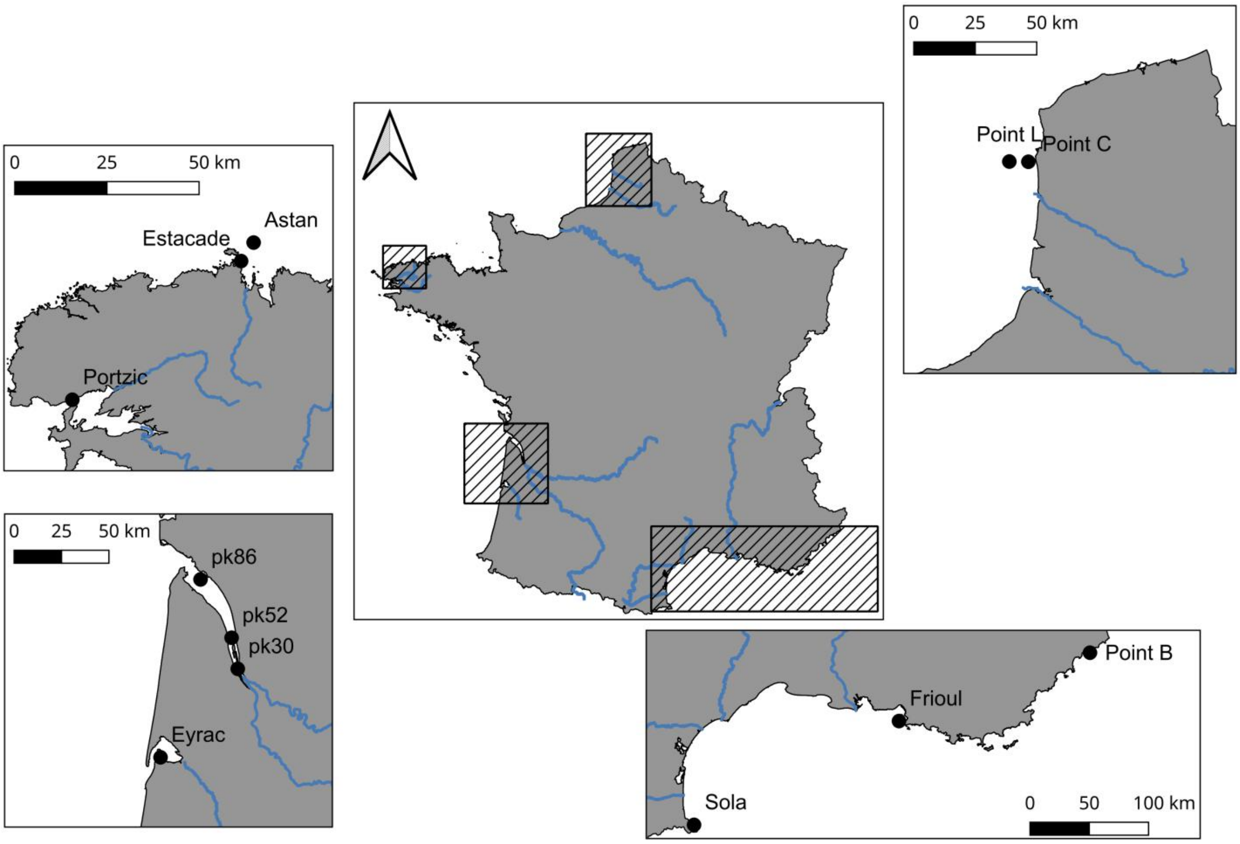


Fig 2: Principal Component Analysis (PCA) of the variability of the 12 coastal ecosystems stations from 1997 to 2016, a) and b) on the first and c) and d) on the second principal component (PC).

a) and c) are the parameters variability and b) and d) are the eigenvector correlation to the coastal ecosystems variability. Green cells are positive and significant correlation, red cells are negative and significant correlations and white cells are non-significant correlations. The stations were ordered from north to south along the English Channel and Atlantic Ocean coast and from west to east along the Mediterranean coast. The Gironde Estuary stations were on the right-hand side. T: Temperature; Sal: Salinity; dO_2 : dissolved oxygen; PO_4^{3-}: Orthophosphates; NH_4^+: Ammonium; NO_2^-: Nitrite; NO_3^-: Nitrate; $Si(OH)_4$: Silicic acid; POC: Particulate Organic Carbon; PON: Particulate Organic Nitrogen; SPM: Suspended Particulate Matter; Chla : Chlorophyll-*a*.

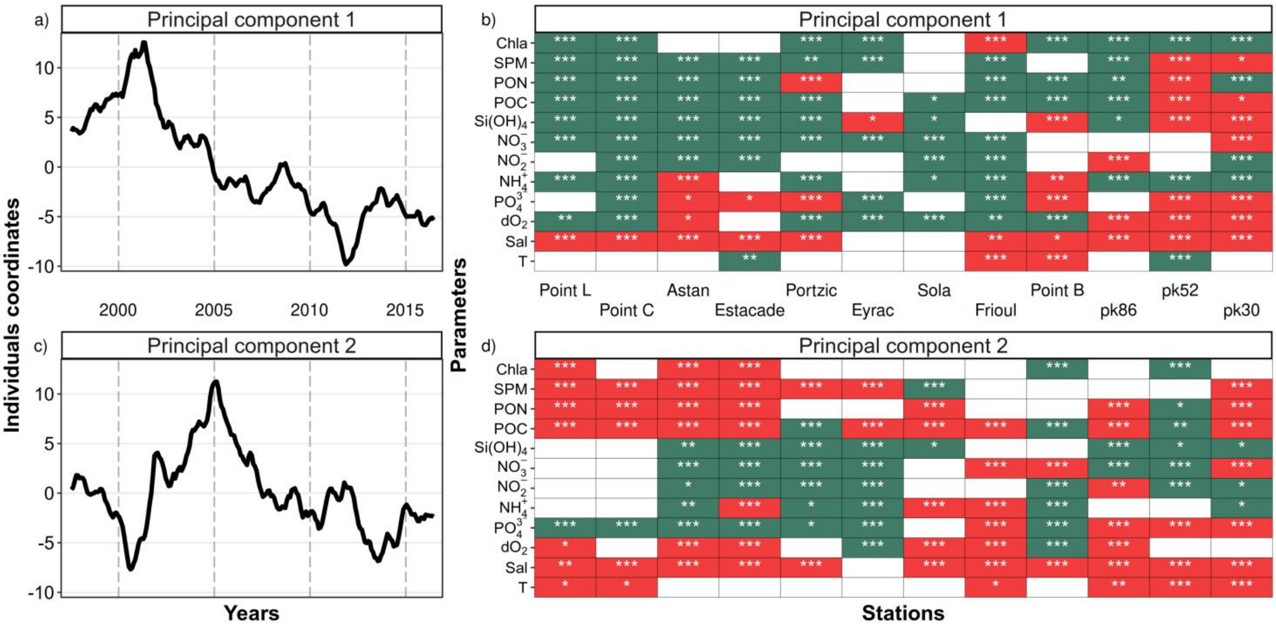


Fig 3: Correlations between the first two principal components (PCs) of the coastal ecosystems variability Principal Component Analysis (PCA) and the drivers of change. Coloured bars represented strong positive (green) and negative (red) correlations (r > 0.5), and white bars non-significant correlations. The probability was corrected to account for temporal autocorrelation following Pyper & Peterman (1998) and p values were adjusted to account for multiple testing following Hochberg (1988).

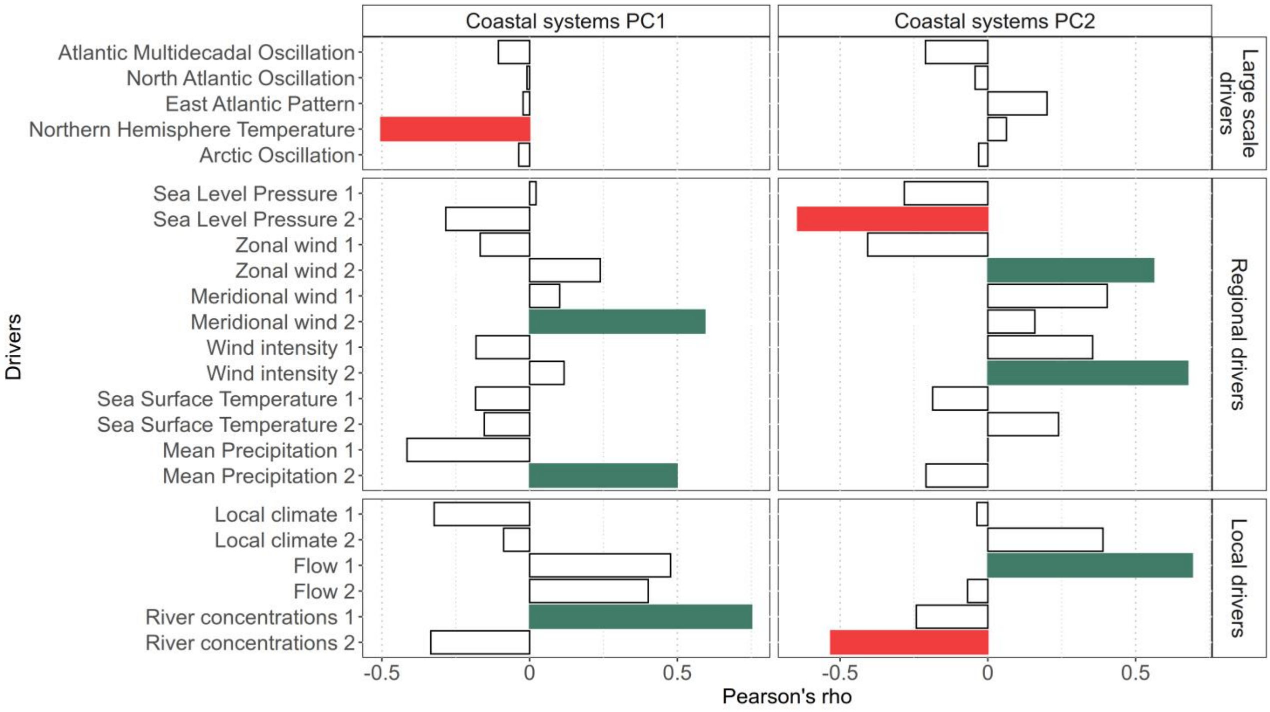


Fig 4: Year-to-year changes in the coastal ecosystems in relation to changes in the drivers. First (a-d) and second (e-i) principal components (in black) and correlated (r > 0.5) drivers (dotted blue line) When the correlation was negative, the driver was inverted (Inv).

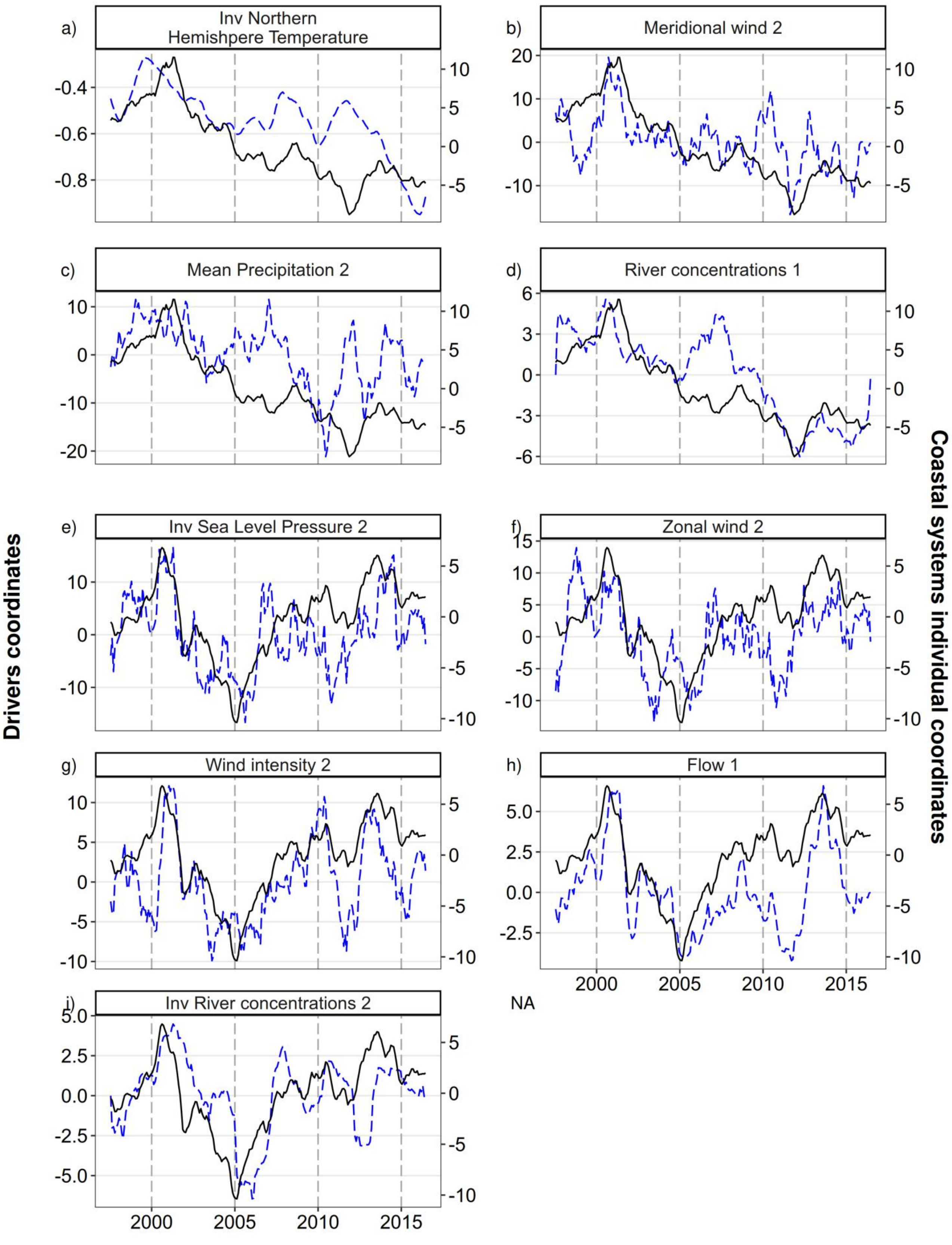
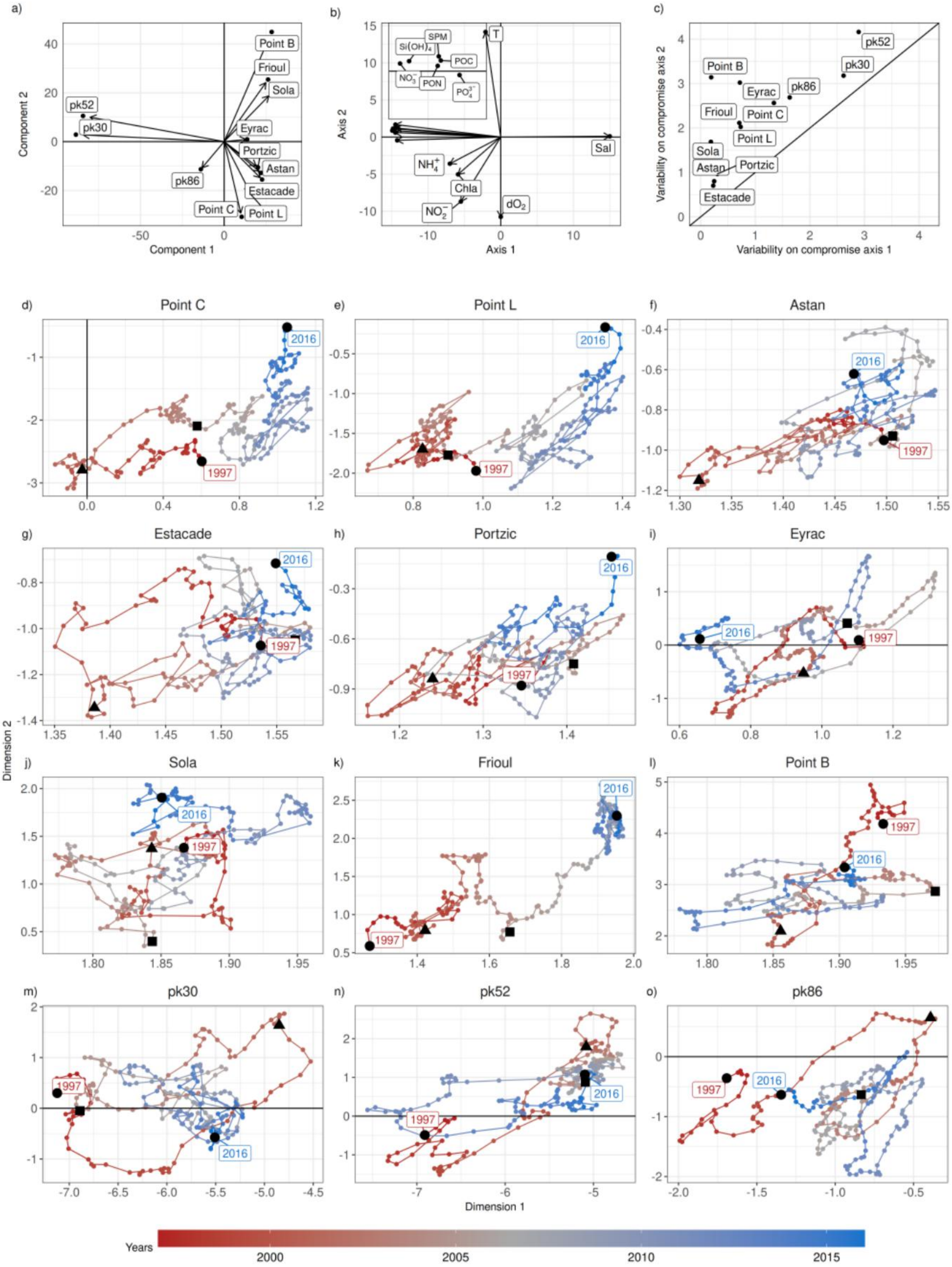

a)
Inv Northern Hemishpere Temperature
-0.4
-0.6
-0.8
10
5
0
-5
b)
Meridional wind 2
20
10
0
-10
10
5
0
-5
c)
Mean Precipitation 2
10
0
-10
-20
10
5
0
-5
d)
River concentrations 1
6
3
0
-3
-6
10
5
0
-5
e)
Inv Sea Level Pressure 2
10
0
-10
5
0
-5
-10
f)
Zonal wind 2
15
10
5
0
-5
-10
5
0
-5
-10
g)
Wind intensity 2
10
5
0
-5
-10
5
0
-5
-10
h)
Flow 1
5.0
2.5
0.0
-2.5
5
0
-5
-10
2000
2005
2010
2015
NA
i)
Inv River concentrations 2
5.0
2.5
0.0
-2.5
-5.0
5
0
-5
-10
2000
2005
2010
2015
Drivers coordinates
Coastal systems individual coordinates

Figure 5: Trajectories of the studied stations from 1997 (red) to 2016 (blue). a): Euclidean plot of the stations; b): compromise of the PTA analysis; c): variability of the trajectories among stations; d-o) trajectories of the stations.

The stations were ordered from north to south along the English Channel and Atlantic Ocean coast, and from west to east on the Mediterranean coast. The Gironde Estuary stations are located on the lower part of the figure. The black triangles represented the 2001 abrupt change and the black circles the 2005 abrupt change. T: Temperature; Sal: Salinity; dO_2 : dissolved oxygen; PO_4^{3-}: Orthophosphates; NH_4^+: Ammonium; NO_2^-: Nitrite; NO_3^-: Nitrate; $Si(OH)_4$: Silicic acid; POC: Particulate Organic Carbon; PON: Particulate Organic Nitrogen; SPM: Suspended Particulate M23,9atter; Chla : Chlorophyll-a


a)
Component 1
Component 2
Point B
Frioul
Sola
Eyrac
Portzic
Astan
Estacade
Point C
Point L
pk52
pk30
pk86
b)
Axis 1
Axis 2
T
SPM
$Si(OH)_4$
POC
NO_3^-
PON
PO_4^{3-}
Sal
NH_4^+
Chla
NO_2^-
dO_2
c)
Variability on compromise axis 1
Variability on compromise axis 2
pk52
pk30
pk86
Point B
Eyrac
Frioul
Point C
Point L
Sola
Astan
Portzic
Estacade
d)
Point C
e)
Point L
f)
Astan
g)
Estacade
h)
Portzic
i)
Eyrac
j)
Sola
k)
Frioul
l)
Point B
m)
pk30
n)
pk52
o)
pk86
1997
2016
Dimension 1
Dimension 2
Years
2000
2005
2010
2015