G Model
ECOIND-780; No. of Pages 11
ARTICLE IN PRESS

Ecological Indicators xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Evaluation of coastal perturbations: A new mathematical procedure to detect changes in the reference state of coastal systems

Eric Goberville[a,b,*], Grégory Beaugrand[c], Benoit Sautour[b], Paul Tréguer[d]

[a] Laboratoire d'Océanologie et de Géosciences, UMR CNRS 8187 (LOG), 28 avenue Foch, 62930 Wimereux, France
[b] Université Bordeaux I – Laboratoire d'Océanographie Biologique UMR CNRS 5805, Rue du Pr Jolyet, 33120 Arcachon, France
[c] Centre National de la Recherche Scientifique, Université des Sciences et Technologies de Lille – Lille 1, Laboratoire d'Océanologie et de Géosciences, UMR CNRS 8187 (LOG), 28 avenue Foch, 62930 Wimereux, France
[d] Institut Universitaire Européen de la Mer UMS CNRS 3113, Université Européenne de Bretagne, Technopole Brest-Iroise, Place Nicolas Copernic, 29280 Plouzané, France

ARTICLE INFO

Article history:
Received 6 December 2010
Received in revised form 7 February 2011
Accepted 10 February 2011

Keywords:
Coastal systems
Monitoring
SOMLIT
Climate change
Anthropogenic nutrient enrichment

ABSTRACT

The pressure exerted by human activities on living systems has become so intense that it is inspiring the inception of a global network of monitoring of the biosphere and the use of robust statistical procedures to detect potential changes. Here, we propose a new multivariate non-parametric procedure, based on the Mahalanobis generalised distance and a simplification of the multiple response permutation procedure to identify rapidly changes in any natural systems. The procedure can be virtually coupled on all monitoring programmes and is not influenced by missing data, a common feature found in many ecological databases. In France, physical, chemical and biological variability of coastal waters have been monitored since 1997 by the SOMLIT Network. Applied to this data set, this technique enabled a first quantification of the impacts of human disturbance through changes in the concentration of nutrients. Our results revealed how climate may interact with anthropogenic pressure to alter coastal marine systems and suggest a synergism between nutrient enrichment, human activities and local climatic conditions. Indeed some effects of climate (e.g. insolation duration – increase in duration of daylight) may attenuate the fertility of coastal systems, while some others (e.g. precipitation) amplify the human signals.

1. Introduction

Human impacts occur on a variety of temporal and spatial scales (Dobson et al., 1997), but in more recent time, particularly during the last century, anthropogenic activities have exerted huge pressures on living systems, causing alterations in the structure and functioning of all types of systems (Halpern et al., 2008). Concurrently, many studies have shown that climate variability could strongly affect both marine and terrestrial (agricultural) systems (Attrill and Power, 2002; Donner and Kucharik, 2003; Ghil, 2002; Parry et al., 2007). This influence has been well-documented for coastal systems of Western Europe where concomitant changes in the state of the coastal environment and both regional climate and large-scale hydro-climatic indices such as the Atlantic Multidecadal Oscillation ("AMO") or the North Atlantic Oscillation ("NAO") have been observed (Goberville et al., 2010). Current global warming represents a further pressure, which could exacerbate the human fingerprint on both marine and terrestrial systems (Alley et al., 2003).

About 50% of the population lives within 60 km of the shoreline (Kremer et al., 2004). Coastal systems are being impacted by fragmentation or destruction of habitat (Sherman and Duda, 1999; Cloern, 2001), invasion of exotic species (Steneck, 1998; Edwards et al., 2001) and overexploitation of marine resources (e.g. Pauly et al., 1998; Pauly, 2003), resulting in major alterations of marine ecosystems (Omori et al., 1994; Frank et al., 2005). Transfer of pollutants from continents provides 80% of all marine pollution and contamination (e.g. Norse, 1993; Kremer et al., 2004). Human activities (e.g. agriculture, sewage and urban development) contribute to alter nutrient concentrations resulting in dramatic disruptions of coastal and estuarine systems (Cloern, 2001; Selman et al., 2008). An increase in nutrients (i.e. over-fertilisation) can have profound effects on the biological productivity and the health of ecosystems (North Sea Task Force, 1993; Cloern, 2001) and lead to toxic or harmful algal blooms (Anderson et al., 2002), anoxia or hypoxia (Diaz, 2001) and shifts in species dominance (e.g. an increase in non-siliceous species as a result of a raise in nitrate, ammonium and/or phosphate, Richardson et al., 1997).

The worldwide accumulation of evidence of the alteration of marine systems has led policymakers (e.g. National Research Coun-

* Corresponding author at: Laboratoire d'Océanologie et de Géosciences, UMR CNRS 8187 (LOG), Station Marine de Wimereux, 28 avenue Foch, 62930 Wimereux, France.
E-mail address: e.goberville@epoc.u-bordeaux1.fr (E. Goberville).

1470-160X/$ – see front matter © 2011 Published by Elsevier Ltd.
doi:10.1016/j.ecolind.2011.02.002

cil) and scientists (e.g. Institut National des Sciences de l'Univers) to encourage the implementation of monitoring projects. For example, French marine coastal ecosystems have been monitored since 1997 by a programme called SOMLIT ("Service d'Observation en Milieu LITtoral"). This network of observations has gathered together a database of physical, chemical and biological parameters at 12 sites around France on a bi-monthly basis since 1997 (i.e. 12 years of sampling in 2008). However, while data are accumulating, classical mathematical procedures as moving averages, cumulative sums or standardised principal component analyses (PCA) generally fail to detect and quantify rapid modifications in ecosystem state. These procedures mainly allow the detection of long-term changes in these systems. For example, long time series were required to apply PCA in order to isolate the most important modes of variability in the dataset (Hare and Mantua, 2000) and to identify abrupt changes in patterns of variability. This limitation explain why abrupt shifts observed in several large marine ecosystems have been detected at least 10 years after they had actually occurred (e.g. the recognition of the regime shifts in 1977 and 1989 in the North Pacific Ocean by Hare and Mantua (2000); the detection of a regime shift in the North Sea circa 1988 by Reid et al. (2001)). A current challenge is to be able to detect rapidly major shifts in the state of coastal systems because of their biological, social and economical consequences (Beaugrand et al., 2008).

Both the management and conservation of coastal systems require a substantial knowledge on their current dynamic equilibrium (Kremer et al., 2004). However, one of the main problems scientists face when monitoring a living system is the absence of a reference state against which fluctuations can be detected. This limitation makes it difficult to determine the extent to which marine systems are being impacted by human activities or natural environmental fluctuations. This restriction does not exist in statistical quality control because the engineer uses a training set to have an idea on the natural variability of the process under control (Montgomery, 1991).

Establishing a reference state, i.e. quantifying the actual state of an ecosystem and its natural variability, is a prerequisite to better identify potential effects of disturbances (Binet, 1997). The concept of reference state is increasingly used in ecology to describe the "standard" against which the current state of a system can be compared (Zonneveld, 1983; Dziock et al., 2006). Therefore, it is crucial to account for the natural variability of the system based on (1) the spectrum of natural variability in terms of structure, composition and ecosystem function (Kaufmann et al., 1994; Swanson et al., 1994; Kaufmann, 1998; Moore et al., 1999), (2) a reference against which to assess changes in ecosystem, and (3) a criterion to estimate the achievement of management and/or restoration plans (Christensen et al., 1996). Because of the multiple significance of the notion of "reference state", the concept is highly debated: situation of the system at a given period, the best current conditions, conditions in the absence of human disturbance or alteration (i.e. a pristine, unpolluted, or anthropogenically undisturbed state; Hughes, 1995, Davies and Jackson, 2006). For these multiple reasons, reference states are considered as "relative" because they depend on both conditions determined for their design and the spatial and temporal scales considered as well as the monitored parameters. In order to deal with this conundrum, we chose to use the term of "relative reference state" in our study.

Here, we use data from SOMLIT to present a new numerical procedure that enables (1) the identification of a relative reference state against which changes in marine coastal systems can be instantaneously detected and (2) the quantification of the anthropogenic nutrient enrichment in nitrates and phosphates on coastal systems. Our study reveals how climate may interact with anthropogenic pressures to alter coastal marine systems.

2. Materials and methods

2.1. Data

2.1.1. Environmental data

Our analysis on coastal marine systems was based on data collected by the French sampling programme SOMLIT, which has coordinated activities of marine laboratories along the French coasts since 1997. Seven marine stations are currently monitored under this programme, at 12 sampling sites representing all seas surrounding France such as the English Channel, the Atlantic Ocean and the Mediterranean Sea marine stations. Coastal systems studied by this project have distinctive hydro-climatic characteristics ranging from the weak-tidal Mediterranean Sea (e.g. Marseille) to the mega-tidal English Channel (e.g. Wimereux) (Fig. 1). More details on the monitoring programme can be found in Goberville et al. (2010). In this study, we focussed on three parameters, temperature, nitrate and phosphate concentrations, collected from 1997 onwards on a bi-monthly basis (i.e. twice a month) in the twelve sites along the French coast (Fig. 1).

We used the large-scale data set of the World Ocean Atlas 2005 (WOA05) (Locarnini et al., 2006) to create a reference matrix of temperature, nitrate and phosphate concentrations against which SOMLIT data were tested. Monthly surface climatology data of these three parameters were organized on a virtual grid of 1° longitude and 1° latitude for the whole Northern Hemisphere (Antonov et al., 2006; Garcia et al., 2006a; Garcia et al., 2006b).

To evaluate the impact of river discharge on coastal marine systems, data on monthly mean river discharge were used. These data originated from the project HYDRO (Ministère de l'Ecologie et du Développement Durable; http://www.hydro.eaufrance.fr/).

2.1.2. Climatological data

Data on insolation duration, provided by Meteo-France (http://france.meteofrance.com), were also used to examine the potential influence of local environmental conditions, resulting from climate variability on a larger scale, on the level of nutrients regulated by primary production. Insolation duration and river discharge were normalised so that their interval of variation ranged between 0 and 1 and the difference between insolation duration and river discharge was then calculated. To our knowledge, while studies about the impact of insolation duration or/and river discharge existed, both influences had never been directly interconnected within an index. The advantage of the index was related to its design that was very intuitive. The index described easily and rapidly the hydro-climatological context that influenced the system. A negative value therefore indicated that river discharge was higher than insolation duration, and a positive value reflected the opposite. Negative values, prevalence of wettest periods, are expected to increase nitrate and phosphate loadings from terrestrial runoff to coastal waters while positive values, exhibiting driest and sunniest periods, tend to decrease nutrient concentrations. We used exclusively these local hydro-climatological parameters because of their potential and more direct influence on the state of coastal systems in comparison to other indices of large-scale variability such as the NAO. The influence of large-scale hydroclimatic variability (e.g. NAO, AMO) or direct spatial and temporal fluctuations in climate (sea level pressure, precipitation, atmospheric circulation and temperature) were recently quantified on French coastal systems (Goberville et al., 2010).

2.2. Rationale and description of the new numerical procedure

2.2.1. Step 1: identification of a relative reference state

In our study, we were interested in monitoring the state of the French coastal systems based on the concentration of

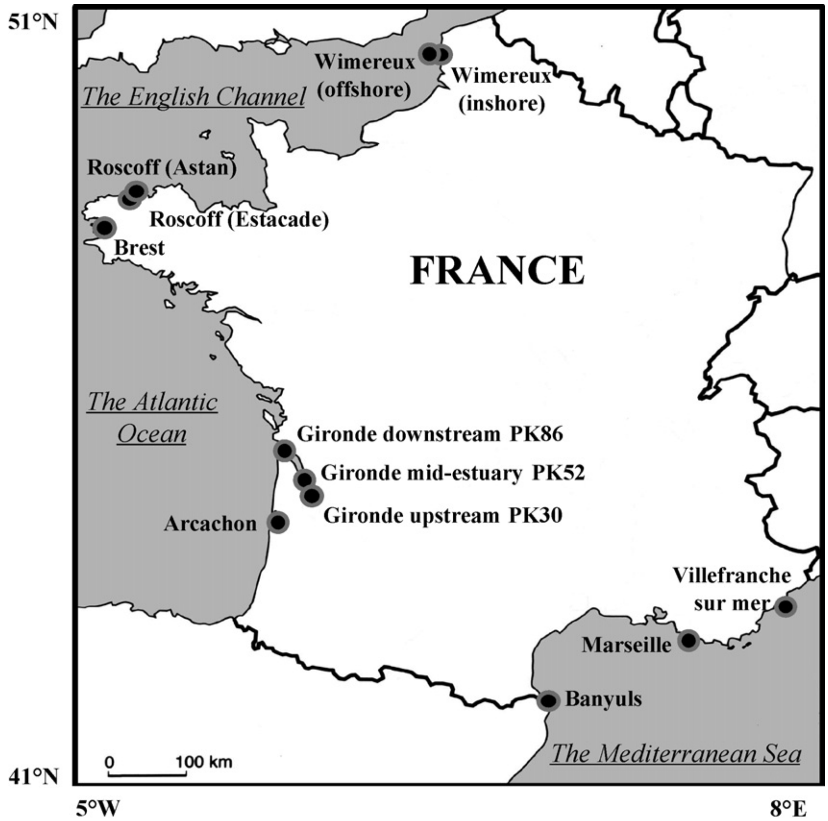

Fig. 1. Location of SOMLIT sites.

nitrate, phosphate and temperature. Taken together, both nitrate and phosphate are indicative of anthropogenic activities (Cloern, 2001; Selman et al., 2008). We could not use the annual ratio nitrate:phosphate = 16 as a reference (Redfield, 1934) because this ratio varies strongly in space and time (Justic et al., 1995).

For a given month, each geographical cell of 1° longitude × 1° latitude for the World Ocean Database 2005 data (matrix $\mathbf{X}_{n,p}$; n observations and p variables) was tested against all SOMLIT samplings (matrix $\mathbf{Y}_{m,p}$; m observations and p variables). The number of variables p was equal to 3 (sea-surface temperature, nitrate and phosphate concentrations). To calculate the distance between each geographic cell and each group of observations (SOMLIT site for a given month), $\mathbf{Z}_{n+1,p}$ was created for each observation of the matrix $\mathbf{Y}_{m,p}$ (SOMLIT; m observations and p variables) to be tested against $\mathbf{X}_{n,p}$ (each geographical cell of the World Ocean Database 2005 data; n observations and p variables). For the first observation, the following matrix was constructed:

$$\mathbf{Z}_{n+1,p} = \begin{bmatrix} \boldsymbol{y}_{1,1} & \boldsymbol{y}_{1,2} & \boldsymbol{y}_{1,3} \\ x1,1 & x1,2 & x1,3 \\ . & . & . \\ . & . & . \\ xn,1 & xn,2 & xn,3 \end{bmatrix} \quad (1)$$

With $x_{i,j}$, the observations in matrix $\mathbf{X}$ and $y_{i,j}$, an observation of matrix $\mathbf{Y}$. The building of matrix $\mathbf{Z}$ is repeated m times, corresponding to the m observations of $\mathbf{Y}$.

We used the Mahalanobis generalised distance (Mahalanobis, 1936) because it has the advantage to be independent of the scales of the descriptors but also to take into consideration the covariance (or the correlation) among descriptors (Ibañez, 1981). To calculate the Mahalanobis generalised distance between each observation of the environment y_i ($1 \le i \le m$) and all observations of the reference matrix x_j ($1 \le j \le n$), we used a particular form of the generalised distance, giving the distance between any observation and the centroid of a unique group (Ibañez, 1981):

$$D^2_{z_1}, z_{n,p} = k'R^{-1}k \quad (2)$$

With $\mathbf{R}_{p,p}$ the correlation matrix of the table $\mathbf{Z}_{n,p}$, $\mathbf{k}_{1,p}$ is the vector of the differences (of length p) between the average value of the p variables in table $\mathbf{Z}_{n,p}$ and the values of the p variables of the site (or geographical cells) to be compared. Then, the average observed distance ε_0 is calculated as follows:

$$\varepsilon_0 = \frac{\sum_{1=1}^{n} D_i}{n} \quad (3)$$

With n, the total number of Mahalanobis generalised distances, equal to the number of observations in the training set $\mathbf{X}$ (Beaugrand et al., 2011).

Probability of the generalised Mahalanobis distance was then estimated using a simplified version of the multiple response permutation procedure (MRPP; Mielke et al., 1981) recently adapted to compare a single site to a group (Beaugrand and Helaouët, 2008). The mean Mahalanobis generalised distance is tested by replacing each observation of $\mathbf{X}$ by y in $\mathbf{Z}$ from row 2 to $n+1$. The number of maximum permutations is equal to n. After each permutation, the mean Mahalanobis generalised distance ε_s is recalculated, with $1 \le s \le n$. A probability (called 'proM' latter in the text) can be assessed by looking at the number of times a simulated mean Mahalanobis generalised distance is found to be superior or equal to the observed mean Mahalanobis generalised distance between the observation and the reference matrix $\mathbf{X}$ (Beaugrand et al., 2011).

$$\text{proM} = \frac{q\varepsilon_s \ge \varepsilon_0}{n} \quad (4)$$

where the probability proM is the number of times the simulated mean Mahalanobis generalised distance was found superior

Please cite this article in press as: Goberville, E., et al., Evaluation of coastal perturbations: A new mathematical procedure to detect changes in the reference state of coastal systems. Ecol. Indicat. (2011), doi:10.1016/j.ecolind.2011.02.002

or equal to the observed mean distance. When proM = 1, the observation statistically belongs to the centroïd of the relative reference state. When proM = 0, the observation has conditions in sea surface temperature, nitrate and phosphate concentrations outside the relative reference state. Applying the procedure to each observation of $\mathbf{Y}_{m,p}$ leads to a matrix $\mathbf{P}_{m,1}$ of probability.

We kept the geographical cells of the World Ocean Database when the probability proM was superior or equal to 0.1. This indicates that all World Ocean Database chosen cells were not significantly different from the SOMLIT site for a given month. According to Beaugrand et al. (2011), the resolution R of the probability of each observation to belong to the relative reference state was defined as:

$$R = \frac{1}{m} \tag{5}$$

With m the number of observations in $\mathbf{Y}$. In our study, for each site and a given month, m = 12 years (monitored period from 1997 to 2008) and the limit resolution was R = 0.083. As R was determined to 0.1, we were above the resolution limit.

The procedure was repeated for all SOMLIT sites (12) and all months (12), giving a total of 144 reference matrices (Table 1). We therefore stress that the reference state should be seen as a relative reference state against which the equilibrium of the system can be evaluated.

2.2.2. Step 2: representation of the relative reference state

The position of the relative reference state was calculated for each station and each month in an Euclidian space of two dimensions, the first dimension being represented by the phosphate concentration and the second dimension being represented by the nitrate concentration. Probabilities were calculated using the generalised Mahalanobis distance tested by the simplified MRPP on each reference matrix (i.e. World Ocean Database geographical cells kept when *proM* ≥ to 0.1) obtained from the previous step 1. The position of the relative reference state was indicated in this space by high probabilities.

2.2.3. Step 3: representation of the probability of each year for a given site and month

To determine the position of coastal marine systems on the grid of probability, the procedure described in step 1 was repeated. The probability of each year of the period 1997–2008 was calculated for a given month and site by calculating the generalised Mahalanobis distance and its probability. These probabilities were then superimposed on the Euclidian space for the given month and site. The distance between a given year and the centre of high probabilities was directly given by the probability of the year (see Fig. 2a and b).

2.3. Synthesis of the results

The probabilities were calculated for each site at both monthly and year-to-year scales. Firstly, for each site, probabilities were represented on contour diagrams where years were plotted as a function of months (Fig. 3a–i). Then, probabilities were represented on a contour diagram where sites were plotted as a function of months (Fig. 4a) or years (Fig. 4b). Sites were sorted by applying a principal component analysis (PCA) on two tables: (1) 9 sites × 12 months and (2) 9 sites × 12 years. The sorting was used to facilitate the reading of the contour diagram.

Another type of synthesis of the results was undertaken using boxplots representing the median, the first and third quartiles and the range (i.e. minimum and maximum; see Table 3) of probabilities for each site (Tukey, 1977). This analysis was performed to summarise the influence of anthropogenic nutrient enrichment for each site (Fig. 4c).

Table 1
Number of observations selected from the World Ocean Database 2005 in each relative reference state after application of the first step of the procedure for each month and each site. Sites were ordered from north to south and estuarine sites placed at the end of the table.

	Wimereux (offshore)	Wimereux (inshore)	Roscoff (offshore)	Roscoff (inshore)	Brest	Arcachon	Villefranche-sur-Mer	Marseille	Banyuls	Gironde downstream (pk86)	Gironde midestuary (pk52)	Gironde upstream (pk30)
January	2740	1851	553	753	319	2543	186	7370	231	2003	261	31
February	758	13529	279	1386	82	9369	89	4002	906	0	0	0
March	1294	3713	86	1786	82	2400	191	8286	14	2303	1076	363
April	250	43	464	877	1673	958	173	3030	24	0	0	0
May	2525	3633	858	333	80	2503	10436	978	29	2429	0	875
June	460	2341	190	112	350	1230	9965	17136	1503	11362	201	154
July	621	2115	147	626	1670	12438	9229	4689	1048	3807	0	0
August	1760	3815	430	400	240	3138	9134	12150	386	6650	0	0
September	1503	1123	51	192	533	2881	10950	6940	104	1661	0	0
October	8323	1644	138	305	897	2328	2143	4737	433	2387	10677	25
November	2461	1101	2110	679	1157	1923	106	1248	148	2133	0	2969
December	12811	808	351	661	948	437	201	2155	215	0	0	0

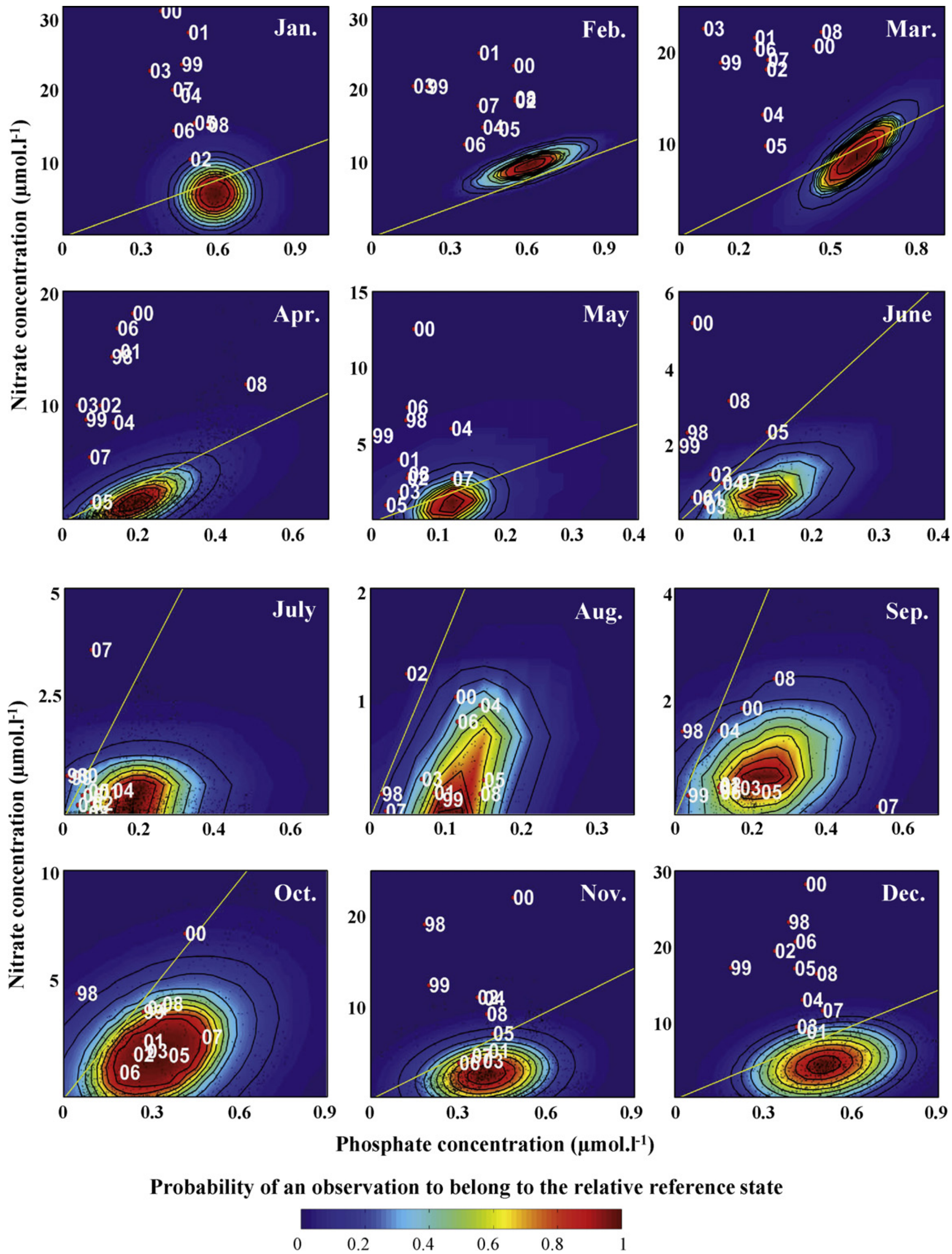

Fig. 2. Representation of the relative reference states and probability that an observation belongs to the relative reference states of each year for a given month from January (Jan.) to December (Dec.): example of Brest. The position of the reference states was calculated in an Euclidian space of two dimensions, the first dimension (x) being represented by the phosphate concentration and the second dimension (y) being represented by the nitrate concentration. Probability that an observation belongs to the relative reference states of each year (from 1997 to 2008) was calculated and superimposed on the Euclidian space for the given month. The distance between a given year and the centroïd of high probabilities was directly given by the probability of the year. The yellow line represents the Redfield ratio (N:P = 16) (For interpretation of references to color, in this figure legend, the reader the referred to the web version of this article.).

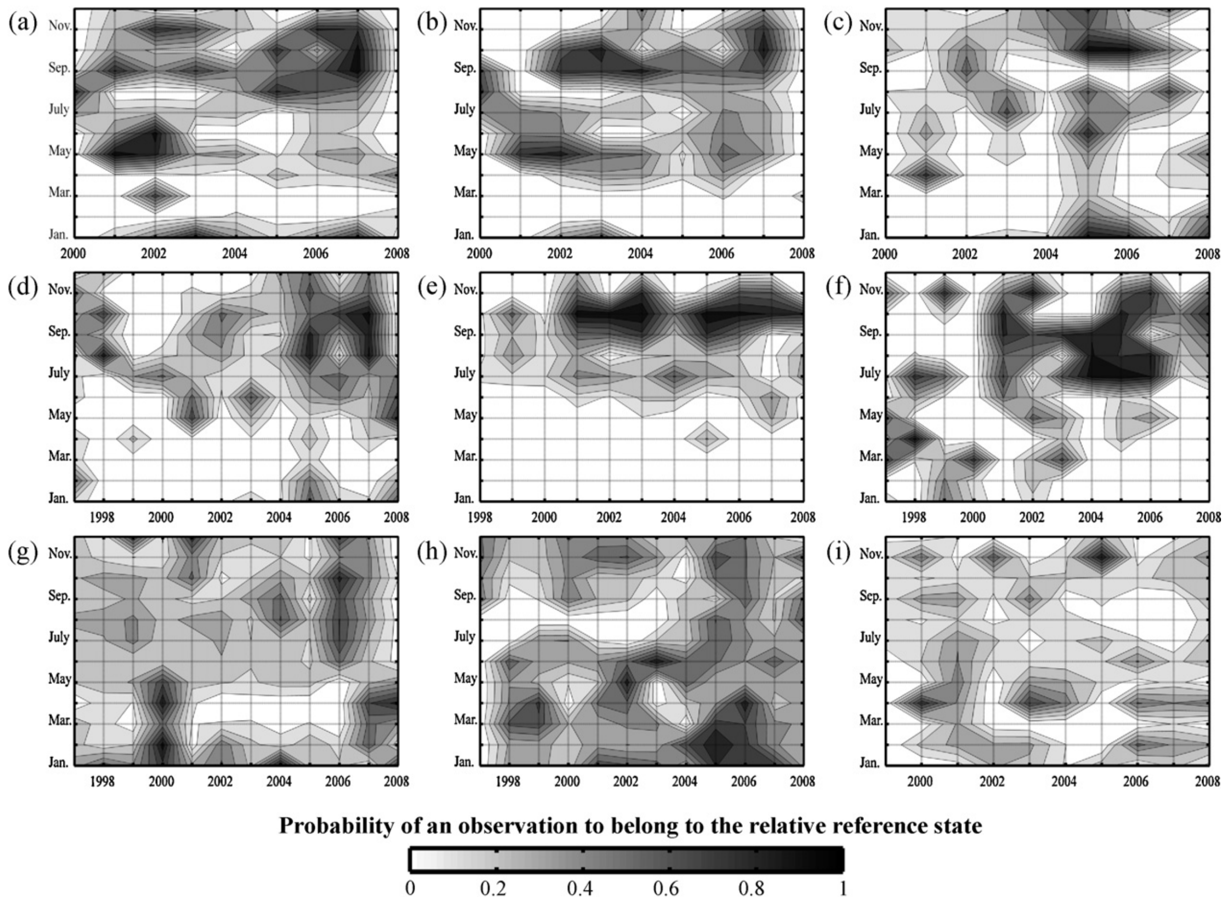

Fig. 3. Year-to-year changes in the influence of the anthropogenic nutrient enrichment with respect to nitrate and phosphate concentrations in each SOMLIT site (except for the Gironde estuary). Contour diagrams show the monthly changes in the probability that an observation belongs to the relative reference state as a function of years. Sites were ordered from north to south. (a) Wimereux (offshore); (b) Wimereux (inshore); (c) Roscoff Astan; (d) Roscoff Estacade; (e) Brest; (f) Arcachon; (g) Villefranche-sur-Mer; (h) Marseille; (i) Banyuls. The level of grey is related to the probability of an observation to belong to the relative reference state.

2.4. Influence of climate on the state of coastal systems: example of Brest and Marseille

To evaluate the potential influence of climate on the year-to-year changes in the state of French coastal systems, we focused on the two sites Brest and Marseille. These sites were chosen for their distinct hydrodynamic features and freshwater loading (Goberville et al., 2010). Year-to-year fluctuations in the probability of the two sites were examined for the period 1997–2008. A simple order-6 moving average was used to remove the effect of seasonality (Legendre and Legendre, 1998).

Correlation analyses were performed between the probabilities and the difference between normalised insolation duration and normalised river discharge (see Data). Probabilities were calculated after accounting for temporal autocorrelation by adjusting the degrees of freedom using the modified Box-Jenkins autocorrelation function (Chelton, 1984; Box and Jenkins, 1976). Cross-correlation analyses were also performed to search for any potential lags. To assess the probability of the cross-correlogram, we adjusted the degrees of freedom of each lag, accounting for temporal autocorrelation.

3. Results

3.1. Identification of relative reference state: example of Brest

In Brest, our new procedure identified the relative reference state (i.e. probability > 0.05) inferred from nitrate and phosphate concentrations particularly close to the Redfield ratio in winter but slightly below the ratio for other months of the year (Fig. 2). We recall here that the probability is a measure of the distance between the observation and the centroïd of the relative reference state. While the relative reference state expanded in winter, it strongly contracted in summer. Years, reported on the scatter plots (Fig. 2), were far from the relative reference state during winter months. Years were closer to the relative reference state in spring and most years but 2007 belonged to the relative reference state in summer. In autumn, some years started to differ significantly to the relative reference state (e.g. 1998–2000, 2002, 2004 in November; Fig. 3e). Results suggested that nutrient (nitrate and phosphate) concentrations were closer to the relative reference state for recent observations.

3.2. General analysis

The probability of each observation belonging to the relative reference state was therefore calculated for all sites, months and years (Figs. 3 and 4). Overall on a monthly basis, the probability of an observation belonging to the relative reference state was low in winter and early spring for all Atlantic sites and Villefranche-sur-Mer (Figs. 3 and 4a). The highest probabilities were reached for these sites in summer and the beginning of autumn. In Marseille and Banyuls, probabilities remained high for all months of the year.

On a year-to-year basis, probabilities of each observation to belong to the relative reference state increased through time for

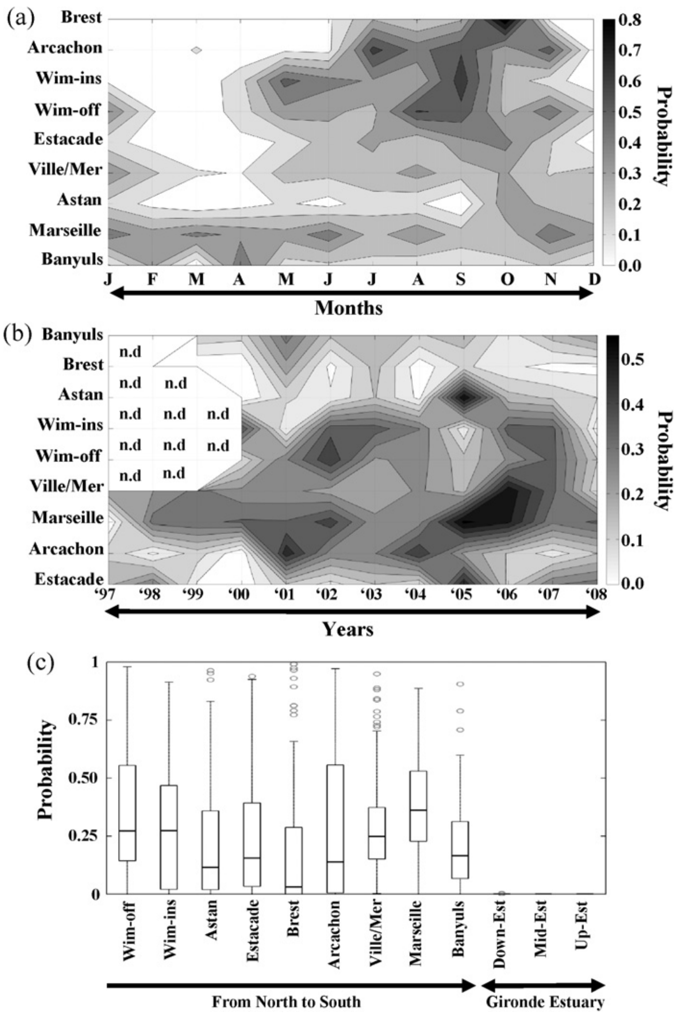

Fig. 4. Synthesis of the influence of anthropogenic nutrient enrichment with respect to nitrate and phosphate concentrations in each SOMLIT site. (a) Contour diagram showing the spatial changes in the probability that an observation belongs to the relative reference states as function of months. (b) Contour diagram showing the spatial changes in the probability that an observation belongs to the relative reference states as function of years. (c) Quantification of the influence of anthropogenic nutrient enrichment using a boxplot diagram. Sites were ordered from north to south and estuarine sites positioned following along the abscissa. Wim-off: Wimereux (offshore); Wim-ins: Wimereux (inshore); Astan: Roscoff Astan; Estacade: Roscoff Estacade; Brest; Arcachon; Ville/Mer: Villefranche-sur-Mer; Marseille; Banyuls; Down-Est: Gironde downstream PK86; Mid-Est: Gironde mid-estuary PK52; Up-Est: Gironde upstream PK30.

all sites during the period 1997–2008 (Figs. 3 and 4b). Two periods of high probability occurred in 2001 and 2005–2006. This positive trend was however not observed in Banyuls and Villefranche-sur-Mer.

Using a boxplot diagram, we quantified the influence of anthropogenic nutrient enrichment with respect to nitrate and phosphate concentrations for each SOMLIT site (Fig. 4c). The sites that have the highest probabilities of belonging to the relative reference state were Marseille followed by Wimereux and to a lesser extent Villefranche-sur-Mer and Banyuls. Sites that were characterised by the lowest probabilities were sites of the Gironde estuary, followed by sites of the Celtic Sea and to a lesser extent Arcachon. The null values observed at the Gironde estuary can be explained by the fact that observations from the three monitored sites were always significantly different from the relative reference states.

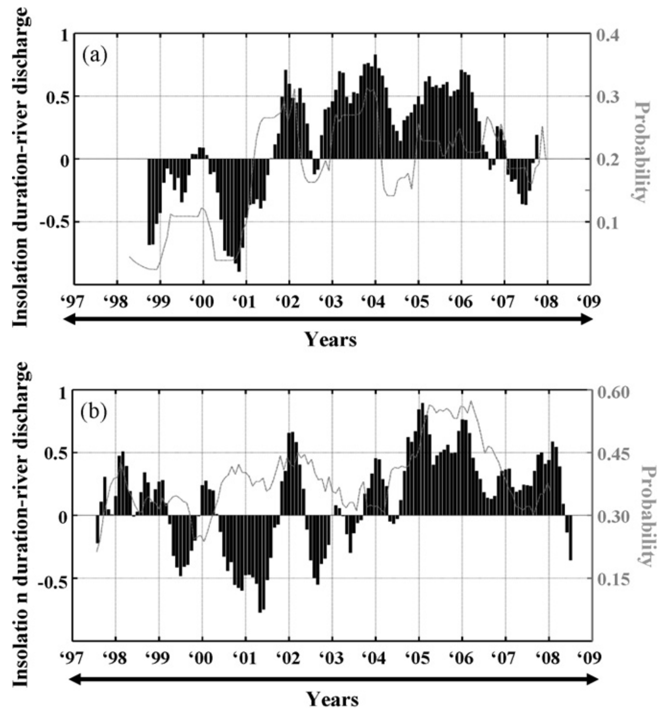

Fig. 5. Year-to-year changes in the probability that an observation belongs to the relative reference states in relation to local hydro-climatological conditions (difference between normalised insolation duration and normalised river discharge). (a) Year-to-year changes in the probability that an observation belongs to the relative reference states in Brest. (b) Year-to-year changes in the probability that an observation belongs to the relative reference states in Marseille. Individual bars represent year-to-year changes in the value of the local hydroclimatological index (between −1 and 1, difference between normalised insolation duration and normalised river discharge; see methods).

3.3. Influence of climate on the state of coastal systems: example of Brest and Marseille

The year-to-year changes in the probability in relation to local hydro-climatological factors (here, normalised insolation duration and normalised river discharge) were studied in the two contrasting sites: Brest and Marseille. The two systems differed by their nitrate and phosphate concentrations (Fig. 2 versus supplementary Fig. 1), Brest (e.g. mean nitrate concentration = 23.7 μmol l^{-1}, phosphate concentration = 0.43 μmol l^{-1} in January and a Redfield ratio nitrate:phosphate = 55; see Table 2) being richer in nutrient than Marseille (e.g. mean nitrate concentration = 1.6 μmol l^{-1}, phosphate concentration = 0.20 μmol l^{-1} in January and a Redfield ratio nitrate:phosphate = 8; see Table 2).

The examination of year-to-year changes in the probability that the site belongs to the relative reference state in Brest revealed the presence of three periods: 1998–2000 characterised by lower probability; 2002–2006 identified by higher probabilities; 2007–2008 distinguished by lower probabilities remaining in general higher than probabilities observed during the first period (Fig. 5a). Correlation analyses were calculated to test whether year-to-year changes in the probabilities in Brest were related to the influence in local hydro-climatological conditions (i.e. the difference between normalised insolation and normalised river discharge). There was a positive and significant relationship between probabilities and this hydro-climatological index ($r = 0.732$, $p = 0.01$; probability after correcting for autocorrelation).

The examination of year-to-year changes in probabilities in Marseille revealed a continued increase in the probability up to 2006 followed by a reduction to the present (Fig. 5b). Correlation between year-to-year changes in the probabilities and the differ-

Table 2
Mean nitrate and phosphate concentrations (in $\mu mol\, l^{-1}$) and Redfield ratio for the period 1997–2008 for each month and both Brest and Marseille sampling sites.

		January	February	March	April	May	June	July	August	September	October	November	December
Brest	Mean nitrate concentration (in fimol l^{-1})	23.65	22.11	18.71	10.98	4.93	1.81	0.83	0.51	0.94	3.29	10.06	16.89
	Mean phosphate concentration (in fimol l^{-1})	0.43	0.40	0.27	0.14	0.06	0.05	0.06	0.09	0.17	0.29	0.35	0.41
	Redfield ratio	54.49	55.90	70.50	77.65	89.11	37.05	14.56	5.59	5.42	11.44	28.83	41.65
Marseille	Mean nitrate concentration (in fimol l^{-1})	1.47	1.56	1.56	0.99	0.59	0.33	0.45	0.61	0.61	0.70	0.68	0.85
	Mean phosphate concentration (in fimol l^{-1})	0.26	0.24	0.28	0.36	0.10	0.23	0.23	0.11	0.10	0.10	0.13	0.11
	Redfield ratio	5.55	6.42	5.64	2.78	6.07	1.41	1.98	5.69	6.14	7.13	5.40	7.62

ence between normalised insolation duration and normalised river discharge was low and not significant ($r = 0.271$, $p = 0.33$; probability corrected for autocorrelation).

Cross-correlation analyses were also applied between year-to-year changes of the probabilities and the difference between normalised insolation duration and normalised river discharge for the two studied cases with a moving window of 12 months. Examination of the two cross-correlograms (not shown here) indicated that no lag existed between the year-to-year changes in probabilities and the influence in local hydro-climatological conditions.

4. Discussion

Both the last and current century have been periods of rapid and pronounced environmental changes (Omori et al., 1994). The recent awareness that the oceanic biodiversity is vulnerable to human threats such as exploitation, eutrophication, habitat destruction, pollution and species introduction (Halpern et al., 2008) has reinforced to the development of ecological monitoring. As a result, global monitoring has become part of many long-term scientific strategies (Pereira and Cooper, 2006). Long-term monitoring enables us to establish a baseline against which perturbations can be better identified (Southward, 1995). However, what is less obvious in the literature devoted to this subject is the equally important issue on developing new numerical procedures, adapted to the specificity of sampling of the marine biosphere. The majority of monitoring programmes (such as SOMLIT), suffers from lack of background and the presence in the time series of many missing data that prevent the use of conventional time series analyses (Goberville et al., 2010). Indeed, few marine monitoring programmes exist with a full coverage in space and time, except the California Cooperative Oceanic Fisheries and Investigations (CalCOFI) (Chelton et al., 1982) and Continuous Plankton Recorder (CPR) (Reid et al., 2003).

Some methods have been designed for evaluating the status of coastal waters focusing on different issues such as impacts on human health and/or ecosystem function (Borja and Dauer, 2008). Nevertheless, past efforts to identify changes in marine coastal systems used either coarse categorical or perhaps too specific numerical tools (Vander Schaaf et al., 2006; Ban and Alder, 2008; Halpern et al., 2008). Furthermore, few classical statistical techniques are able to identify and detect abrupt or progressive modifications in nutrient concentrations. While most of the algorithms cannot cope with missing values and associated biases (e.g. weighted or simple moving average, moving median, principal component analysis), our technique is insensitive to missing data and is not influenced by the temporal autocorrelation. The technique uses a relative reference state determined empirically or alternatively fixed by expert knowledge, against which each observation is then tested. There is no limitation on the number of variables although a too high number may increase the risk of multicollinearity when the Mahalanobis distance is calculated.

We show how the new numerical procedure can be implemented on a regular basis with a data set (here SOMLIT) to provide a rapid evaluation of the state of the system. This technique can easily be transposed to any data sets or parameters be it marine or terrestrial. Here, the structured framework provides a way of quantifying the changes in human-induced nutrient enrichment of French coast. The new numerical procedure presented in our study suggests that coastal systems of West Europe located between 42°N and 51°N of latitude have been altered by nutrient enrichment during the period 1997–2008 and that this perturbation has been modulated by climatic variability. Cloern (2001) stressed that one prominent mode of disturbance has resulted from human activities that mobilise the nutrient elements through land clearing, production and applications of fertilizer (e.g. Nixon, 1995). As a result of these activities, the mobilisation of nitrates and phosphates has accelerated in coastal waters and nutrient enrichment of coastal ecosystems has become a serious environmental issue (Selman et al., 2008).

Two potential caveats must be considered before interpreting our results. Firstly, the reference state was too conservative because they were directly based on ocean concentration of nitrate and phosphate and therefore did not incorporate the natural difference in the biogeochemical cycling of nitrate and phosphate in fresh and marine waters despite selecting offshore regions with the same thermal regime than studied SOMLIT sites. We therefore repeat that the reference state should be seen as a relative reference state against which the dynamic regime of the system can be evaluated. Secondly, in agreement with recent studies (e.g. Cloern, 2001; Billen and Garnier, 2007; Ludwig et al., 2009), we chose to only focus on both nitrate and phosphate concentrations to examine the current states of coastal systems, putting forward the alteration of some biogeochemical cycles in West Europe during the period 1997–2008. Despite these possible caveats, a reliable anthropogenic disturbance on coastal marine systems of West Europe was detected and results suggest that in some areas (e.g. Brest), the anthropogenic influence acts synergistically with climatic variability.

In spite of the pronounced spatial and temporal heterogeneity in the probability (Figs. 3 and 4), our technique revealed that all areas monitored by SOMLIT were affected to some extent by nutrient enrichment. Understanding the intensity in which each site was affected can aid in prioritisation of the management for specific locations (Halpern et al., 2007). Our technique provides a way to quantify the respective influence of human activities on coastal systems. It is also evident from our results that while winter is a period of increase in nutrient concentrations due to higher river runoff and decrease in primary production, summer is characterised by a minor nutrient enrichment caused by the reduction in precipitation and the action of photosynthetic organisms in both the terrestrial and marine realms. Since the twelve monitored sites have specific hydrographic characteristics (Goberville et al., 2010) the range of the values of the coastal nutrient enrichment (and the associated anthropogenic forcing) could therefore be largely attributed to the local peculiarities of a given coastal zone (i.e. particular morphology, hydrology and meteorology; Billen et al., 1991; Billen and Garnier, 2007; Halpern et al., 2007). Sites with lower coastal nutrient enrichment were more characteristic of oligotrophic conditions (except for Wimereux) as illustrated by the study site Marseille (Lefèvre et al., 1997). Conversely, Brest, the most disturbed site, showed emergence of eutrophic conditions related to nutrient enrichment more pronounced from autumn to winter (Le Pape et al., 1996).

Even if the range of variability in both nitrate and phosphate concentrations was the same through time, the highest values of nitrate reported on the scatter plots were further from the relative reference state than those of phosphate (Fig. 2). The large difference observed in the probability between Brest (lower probability) and Wimereux (higher probability) can be explained by the three-fold increase in nitrate concentration measured from the site of the Celtic Sea to the Channel during winter (Ragueneau et al., 1996). This large difference is mainly related to the high seasonal allochthonous inputs from the two nutrient-rich rivers, the Aulne River with a mean annual specific flux of 5000 kg km^{-2} yr^{-1} N and the Elorn River with a mean annual specific flux of 7200 kg km^{-2} yr^{-1} N (Aurousseau, 2001). Inlets in nutrients from the plumes of Loire River also extend to the Brest site (e.g. inputs in nitrates are diluted between 100 and 200 times for an average flow; Dussauze and Ménesguen, 2008).

The importance of local features was especially obvious for Brest and Marseille. By their location, the two sites presented dissimilar continental influences. Brest is located in a semi-enclosed ecosystem influenced by the Aulne and Elorn Rivers (Ragueneau et al., 1996), and six smaller other rivers (Ménesguen and Cugier, 2006). The sampling site in Brest was thereby directly influenced by the watershed (e.g. the programme ECOFLUX). Therefore, the strong correlation between year-to-year changes in probabilities and the hydro-climatological index could be explained by the direct freshwater inputs that carried nutrients from the continent. Instead, when the index was positive, nutrient loadings were lower, resulting in less turbid coastal waters. In addition, the relaxation of vertical mixing during neap tides was possible, condition required before phytoplankton was able to use nutrients originating from freshwater inputs (Ragueneau et al., 1996). The nutrient enrichment could thus be mitigated by biological activities.

Conversely, the site in Marseille is located in the north-western basin of the oligotrophic Mediterranean Sea (Lefèvre et al., 1997), with weak tidal forcing. While the River Rhône influences strongly freshwater inputs (Ludwig et al., 2009), Marseille, due to the influence of Coriolis force on Liguro-Provencal current circulation (i.e. flowing in a roughly NE-SW direction; Font et al., 1988) is less impacted. Its western location from the river mouth of the Rhone River makes it more protected from the freshwater inputs of this river (Ludwig et al., 2009) and as a consequence the sampling site was rarely impacted by nutrient enrichment. Furthermore, nitrate pollution does not appear to represent a major problem in the Mediterranean rivers (e.g. 1.44 mg l^{-1} of N for the Rhone River; Ludwig et al., 2009) as opposed to the North Sea coastal systems (e.g. between 3 and 6-fold of N pollution in the Netherlands; Crouzet et al., 1999). Finally, contrary to Brest, year-to-year changes in probabilities in Marseille were not linked with insolation duration. A potential explanation, but not verified in our study, was that the stimulation of primary production by local rivers was too brief to be observed (Guizien et al., 2007).

Human activities that modify riverine hydrology and riverine material fluxes to the coastal zone have increased in both scale and rate of change over the last 200 years (Le Tissier et al., 2006). However, our findings reveal that climate can modulate the anthropogenic nutrient enrichment of systems at the land-sea interface. Even so, two antagonist effects are shown. The first occurs through the effect of precipitation on river discharges, which amplify the influence of human activities on marine nutrient concentrations (Vermaat et al., 2008; Ludwig et al., 2009). As reported in the North Sea (Vermaat et al., 2008) or in the Mississippi basin (Donner et al., 2002), our results showed that the balance between storage of nutrients or their leaching co-vary strongly with direct freshwater inputs and insolation duration in Brest (positive relationship between probabilities and the hydro-climatological index, Fig. 5a). The minimum of the probabilities observed in the mid 2000s, during the more negative values of the difference, corresponded to the exceptionally rainy year 2000 (with a maximum annual specific flux of 9500 kg km^{-2} yr^{-1} N for the Elorn River; Aurousseau, 2001). This nutrient delivery was therefore influenced by precipitation (Scavia et al., 2002); themselves related to atmospheric circulation changes (Harley et al., 2006; Goberville et al., 2010). Hydrological alteration related to climate change may perturb the water cycle (Huntington, 2006). Some authors suggested that the global runoff increases by 4% when global temperature rises by 1 °C (Labat et al., 2004). The second effect of climate modulation on marine nutrient concentrations occurs when insolation increases, since insolation reduces the level of nutrient concentrations by its stimulatory influence on primary production (Valiela, 1995).

Our findings showed that the link between direct anthropogenic forcing and climate change is complex and that these interactions vary in space and time. The strong correlation detected between the probabilities and our hydro-climatological index (normalised insolation duration – normalised river discharge) in Brest did not hold in Marseille (Fig. 5). Year-to-year variability in probabilities in Marseille was not correlated with the hydro-climatological index. This result supports the low anthropogenic influence and is indicative of a non-impacted river discharge site. The two contrasting sites suggest that anthropogenic over-nutrient enrichment might be difficult to evaluate and anticipate because of local particularities of coastal zones (Breton et al., 2006), the high nonlinearity of the hydrological cycle response to climate change (Labat et al., 2004) and/or the potentially nonlinear response of coastal systems to local climatic variability (Mysterud et al., 2001; Breton et al., 2006).

Both multiple and pronounced alterations of natural systems of the planet have recently triggered reflections on the inception of a global network of monitoring (Pereira and Cooper, 2006; Richardson and Poloczanska, 2008). However, it is as important to develop new statistical procedures to detect, as soon as data become available, potential alteration of natural systems. Furthermore, the procedure enabled the quantification of the anthropogenic influence on marine nutrient concentrations even if it remains difficult to decipher the actual human impacts from the background of natural biogeochemical cycling variability. Our findings provide evidence that climate can interact with human activities in a different way, depending upon the local geoclimatology of the sites. These interactions can amplify the anthropogenic influence through the effect of precipitation on river runoff or attenuate it through the effect of insolation (and probably temperature) on both marine and terrestrial primary production. This confounding result might impede the anticipation of the effect of global change on coastal systems.

Acknowledgements

We thank the National Institute for the Sciences of the Universe and the whole SOMLIT team: technicians, researchers, captains and crews who have contributed to the collection of the SOMLIT samples since 1997. Thanks you also to Dr. I. Rombouts for reading and correcting the manuscript and

S. Lenoir for his precious advices. Database is available on Internet site: http://www.insu.cnrs.fr/co/services-nationaux-labellises/ocean-atmosphere-climat/surveillance-ocean/somlit-service-d-observatio. This project was funded by a French grant BDI-CNRS.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolind.2011.02.002.

References

Alley, R.B., Marotzke, J., Nordhaus, W.D., Overpeck, J.T., Peteet, D.M., Pielke, R.A., Pierrehumbert, R.T., Rhines, P.B., Stocker, T.F., Talley, L.D., Wallace, J.M., 2003. Abrupt climate change. Science 299, 2005–2010, doi: 10.1126/science.1081056.

Anderson, D.M., Glibert, P.M., Burkholder, J.M., 2002. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries Coasts 25, 704–726, doi: 10.1007/BF02804901.

Antonov, J.I., Locarnini, R.A., Boyer, T.P., Mishonov, A.V., Garcia, H.E., t;In >S Levitus, S.</In>, 2006. In World Ocean Atlas 2005, vol. 2: Salinity ,. NOAA Atlas NESDIS 62, US Government Printing Office, Washington, DC, 182 pp.

Attrill, M.J., Power, M., 2002. Climatic influence on a marine fish assemblage. Nature 471, 275–278.

Aurousseau, P., 2001. Les flux d'azote et de phosphore provenant des bassins versants de la rade de Brest. Comparaison avec la Bretagne. Océanis 27, 137–161.

Ban, N., Alder, J., 2008. How wild is the ocean? Assessing the intensity of anthropogenic marine activities in British Columbia, Canada. Aquat. Conserv.: Mar. Freshwat. Ecosyst. 18, 55–85, doi: 10.1002/aqc.816.

Beaugrand, G., Edwards, M., Brander, K., Luczak, C., Ibanez, F., 2008. Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic. Ecol. Lett. 11, 1157–1168, doi: 10.1111/j.1461-0248.2008.01218.x.

Beaugrand, G., Helaouët, P., 2008. Simple procedures to assess and compare the ecological niche of species. Mar. Ecol. Prog. Ser. 363, 29–37, doi: 10.3354/meps07402.

Beaugrand, G., Lenoir, S., Ibanez, F., Manté, C., 2011. A new model to assess the probability of occurrence of a species based on presence-only data. Mar. Ecol. Prog. Ser., doi:10.3354/meps08939, in press.

Billen, G., Garnier, J., 2007. River basin nutrient delivery to the coastal sea: assessing its potential to sustain new production of non-siliceous algae. Mar. Chem. 106, 148–160, doi: 10.1016/j.marchem.2006.12.017.

Billen, G., Lancelot, C., Meybeck, M., 1991. N, P, and Si retention along the aquatic continuum from land to ocean. In: Mantoura, R.F.C., Martin, J.-M., Wollast, R. (Eds.), Ocean Margin Processes in Global Change. John Wiley and Sons, pp. 19–44.

Binet, D., 1997. Menace anthropique et évolution climatique – Nécessité d'une stratégie pour évaluer le changement dans les écosystèmes. In: Dauvin, J.C. (Ed.), Les biocénoses marines et littorales françaises des côtes Atlantique, Manche et Mer du Nord, synthèse, menaces et perspectives, pp. 267–286. Laboratoire de Biologie des Invertébrés Marins et Malacogie – Service du Patrimoine naturel/IEGB/MNHN, Paris. 376 pp.

Borja, A., Dauer, D.M., 2008. Assessing the environmental quality status in estuarine and coastal systems: comparing methodologies and indices. Ecol. Indic. 8, 331–337, doi: 10.1016/j.ecolind.2007.05.004.

Box, G.E.P., Jenkins, G.W., 1976. Time Series Analysis: Forecasting and Control. Holden-Day, San Francisco.

Breton, E., Rousseau, V., Parent, J., Ozer, J., Lancelot, C., 2006. Hydroclimatic modulation of diatom/*Phaeocystis* blooms in nutrient-enriched Belgian coastal waters (North Sea). Limnol. Oceanogr. 51, 1401–1409.

Chelton, D.B., 1984. Commentary: short-term climatic variability in the northeast Pacific Ocean. In: Pearcy, W. (Ed.), The influence of Ocean Conditions on the Production of Salmonids in the North Pacific. Oregon State University Press, Corvallis, pp. 87–99.

Chelton, D.B., Bernal, P.A., McGowan, J.A., 1982. Large-scale interannual physical and biological interaction in the California Current. J. Mar. Res. 40, 1095–1125.

Christensen, N.L., Bartuska, A.M., Brown, J.H., Carpenter, S., D'Antonio, C., Francis, R., Franklin, J.F., MacMahon, J.A., Noss, R.F., Parsons, D.J., 1996. The report of the Ecological Society of America committee on the scientific basis for ecosystem management. Ecol. Appl. 6, 665–691.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Prog. Ser. 210, 223–253.

Crouzet, P., Nixon, S., Laffon, L., Bogestrand, J., Lallana, C., Izzo, G., Bak, J., 1999. Nutrients in European ecosystems. Environmental Assessment Report 4. European Environmental Agency, Copenhagen, Denmark, 123 pp.

Davies, S.P., Jackson, S.K., 2006. The biological condition gradient: a descriptive model for interpreting change in aquatic ecosystems. Ecol. Appl. 16, 1251–1266.

Diaz, R.J., 2001. Overview of hypoxia around the world. J. Environ. Qual. 30, 275–281.

Dobson, A.P., Bradshaw, A.D., Baker, A.J.M., 1997. Hopes for the future: restoration ecology and conservation biology. Science 277, 515–522.

Donner, S.D., Coe, M.T., Lenters, J.D., Twine, T.E., Foley, J.A., 2002. Modeling the impact of hydrological changes on nitrate transport in the Mississippi River Basin from 1955 to 1994. Global Biogeochem. Cycles 16, 1043, doi: 10.1029/2001GB001396.

Donner, S.D., Kucharik, C.J., 2003. Evaluating the impacts of land management and climate variability on crop production and nitrate export across the Upper Mississippi Basin. Global Biogeochem. Cycles 17, 1085, doi: 10.1029/2001GB001808.

Dussauze, M., Ménesguen, A., 2008. Simulation de l'effet sur l'eutrophisation côtière bretonne de 3 scénarios de réduction des teneurs en nitrate et phosphate de chaque bassin versant breton et de la Loire. Ifremer, 160 pp.

Dziock, F., Henle, K., Foeckler, F., Follner, K., Sholz, M., 2006. Biological indicator systems in Floodplains – a review. Int. Rev. Hydrobiol. 91, 271–291.

Edwards, M., John, A.W.G., Johns, D.G., Reid, P.C., 2001. Case history and persistence of the non-indigenous diatom Coscinodiscus wailesii in the north-east Atlantic. J. Mar. Biol. Assoc. UK. 81, 207–211.

Font, J., Salat, J., Tintoré, J., 1988. Permanent features of the circulation in the Catalan Sea. Oceanolog. Acta 9, 51–57.

Frank, K.T., Petrie, B., Choi, J.S., Leggett, W.C., 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science 308, 1621–1623 (doi: 10.1126/science.1113075).

Garcia, H.E., Locarnini, R.A., Boyer, T.P., Antonov, J.I., 2006a. In: Levitus, S. (Ed.), In World Ocean Atlas 2005, vol. 3: Dissolved Oxygen, Apparent Oxygen Utilization, and Oxygen Saturation. NOAA Atlas NESDIS 63, US Government Printing Office, Washington, DC, 342 pp.

Garcia, H.E., Locarnini, R.A., Boyer, T.P., Antonov, J.I., 2006b. In: Levitus, S. (Ed.), In World Ocean Atlas 2005 Volume 4: Nutrients (Phosphate, Nitrate, Silicate). NOAA Atlas NESDIS 64, US Government Printing Office, Washington, DC, 396 pp.

Ghil, M., 2002. Natural climate variability. In: Munn, T., Perry, J. (Eds.), Encyclopedia of Global Environmental Change, vol. 1. John Wley & Sons, New-York, pp. 544–549.

Goberville, E., Beaugrand, G., Sautour, B., Tréguer, P., SOMLIT Team, 2010. Climate-driven changes in coastal marine systems of Western Europe. Mar. Ecol. Prog. Ser. 408, 129–147, doi: 10.3354/meps08564.

Guizien, K., Charles, F., Lantoine, F., Naudin, J., 2007. Nearshore dynamics of nutrients and chlorophyll during Mediterranean-type flash-floods. Aquat. Living Resour. 20, 3–14.

Halpern, B.S., Selkoe, K.A., Micheli, F., Kappel, C.V., 2007. Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. Conserv. Biol. 21, 1301–1315, doi: 10.1111/j.1523-1739.2007.00752.x.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952, doi: 10.1126/science.1149345.

Hare, S.R., Mantua, N.J., 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Prog. Oceanogr. 47, 103–145.

Harley, C.D.G., Hughes, A.R., Hultgren, K.M., Miner, B.G., Sorte, C.J.B., Thornber, C.S., Rodriguez, L.F., Tomanek, L., Williams, S.L., 2006. The impacts of climate change in coastal marine systems. Ecol. Lett. 9, 228–241, doi: 10.1111/j.1461-0248.2005.00871.x.

Hughes, R.M., 1995. Defining acceptable biological status by comparing with reference conditions. In: Davis, W., Simon, T. (Eds.), Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making. CRC Press, Lewis, Boca Raton, FL, USA, pp. 31–47.

Huntington, T.G., 2006. Evidence for intensification of the global water cycle: review and synthesis. J. Hydrol. 319, 83–95, doi: 10.1016/j.jhydrol.2005.07.003.

Ibañez, F., 1981. Immediate detection of heterogeneities in continuous multivariate, oceanographic recordings. Application to time series analysis of changes in the bay of Villefranche sur Mer. Limnol. Oceanogr. 26, 336–349.

Justic, D., Rabalais, N.N., Turner, R.E., 1995. Stoichiometric nutrient balance and origin of coastal eutrophication. Mar. Pollut. Bull. 30, 41–46.

Kaufmann, M.R., 1998. Forest reference conditions for ecosystem management in the Sacramento Mountains, New Mexico. Rocky Mountain Research Station, Fort Collins, CO, USA.

Kaufmann, M.R., Graham, R.T., Boyce, D.A., Moir, W.H., Perry, L., Reynolds, R.T., Bassett, R.L., Mehlhop, P., Edminster, C.B., Block, W.M., 1994. An ecological basis for ecosystem management. U.S. Forest Service General Technical Report RM-GTR-246, Rocky Mountain Research Station, Fort Collins, CO, USA.

Kremer, H.H., Le Tissier, M.D.A., Burbridge, P.R., Talaue-McManus, L., Rabalais, N.N., Parslow, J., Crossland, C.J., Young, W., 2004. Land-Ocean Interactions in the Coastal Zone: Science Plan and Implementation Strategy. International Geosphere-Biosphere Programme Report 51/International Human Dimensions Programme on Global Environmental Change Report 18. Stockholm: IGBP Secretariat. 60 pp.

Labat, D., Godderis, Y., Probst, J.L., Guyot, J.L., 2004. Evidence for global runoff increase related to climate warming. Adv. Water Res. 27, 631–642, doi: 10.1016/j.advwatres.2004.02.020.

Le Tissier, M.D.A., Buddemeier, R., Parslow, J., Swaney, D.P., Crossland, C.J., Smith, S.V., Whyte, H.A.Y., Dennison, W.C., Hills, J.M., Kremer, H.H., 2006. The role of the coastal ocean in the disturbed and undisturbed nutrient and carbon cycles – a management perspective. LOICZ, Geesthacht, Germany.

Le Pape, O., Del Amo, Y., Ménesguen, A., Aminot, A., Quéguiner, B., Tréguer, P., 1996. Resistance of a coastal ecosystem to increasing eutrophic conditions: the Bay of Brest (France), a semi-enclosed zone of Western Europe. Cont. Shelf Res. 16, 1885–1907.

Lefèvre, D., Minas, H.J., Minas, M., Robinson, C., Williams, P.J., Le, B., Woodward, E.M.S., 1997. Review of gross community production, primary production, net community production and dark community respiration in the Gulf of Lions. Deep Sea Res. Part II 44, 801–819.

Please cite this article in press as: Goberville, E., et al., Evaluation of coastal perturbations: A new mathematical procedure to detect changes in the reference state of coastal systems. Ecol. Indicat. (2011), doi:10.1016/j.ecolind.2011.02.002

Legendre, L., Legendre, P., 1998. Numerical Ecology, second ed. English. Elsevier, Amsterdam, 853 pp.
Locarnini, R.A., Mishonov, A.V., Antonov, J.I., Boyer, T.P., Garcia, H.E., 2006. In: Levitus, S. (Ed.), In World Ocean Atlas 2005, vol. 1: Temperature. NOAA Atlas NESDIS 61, US Government Printing Office, Washington, DC, 182 pp.
Ludwig, W., Dumont, E., Meybeck, M., Heusser, S., 2009. River discharges of water and nutrients to the Mediterranean and Black Sea: major drivers for ecosystem changes during past and future decades? Prog. Oceanogr. 80, 199–217, doi:10.1016/j.pocean.2009.02.001.
Mahalanobis, P.C., 1936. On the generalized distance in statistics. Proceedings National Institute of Sciences of India 2, 49–55.
Ménesguen, A., Cugier, P., 2006. A new numerical technique for tracking chemical species in a multisource, coastal ecosystem applied to nitrogen causing Ulva blooms in the Bay of Brest (France). Limnol. Oceanogr. 51, 591–601.
Mielke, P.W., Berry, K.J., Brier, G.W., 1981. Application of multi-response permutation procedures for examining seasonal changes in monthly mean sea-level pressure patterns. Mon. Weather Rev. 109, 120–126.
Montgomery, D.C., 1991. Introduction to Statistical Quality Control. John Wiley and Sons, Inc., New York.
Moore, M.M., Covington, W.W., Fulé, P.Z., 1999. Reference conditions and ecological restoration: a southwestern ponderosa pine perspective. Ecol. Appl. 9, 1266–1277.
Mysterud, A., Stenseth, N.C., Yoccoz, N.G., Langvatn, R., Steinhelm, G., 2001. Nonlinear effects of large-scale climatic variability on wild and domestic herbivores. Nature 410, 1096–1099.
Nixon, S., 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia 41, 199–219.
Norse, E.A., 1993. Global Marine Biological Diversity: A Strategy for Building Conservation into Decision Making. Island Press, Washington, DC.
North Sea Task Force, 1993. North Sea quality status report. Oslo and Paris Commissions, London. Olsen and Olsen, Fredensborg.
Omori, M., Van Der Spoel, S., Norman, C.P., 1994. Impact of human activities on pelagic biogeography. Prog. Oceanogr. 34, 211–219.
Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., 2007. Climate Change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
Pauly, D., 2003. Ecosystem impacts of the world's marine fisheries. Global Change NewsLetter 55, 21–23.
Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres, T.J., 1998. Fishing down marine food webs. Science 279, 860–863, doi: 10.1126/science.279.5352.860.
Pereira, H.M., Cooper, D.H., 2006. Towards the global monitoring of biodiversity change. Trends Ecol. Evol. 21, 123–129, doi:10.1016/j.tree.2005.10.015.
Ragueneau, O., Quéguiner, B., Tréguer, P., 1996. Contrast in biological responses to tidally-induced vertical mixing for two macrotidal ecosystems of Western Europe. Estuarine Coastal Shelf Sci. 42, 645–665.
Redfield, A.C., 1934. On the proportions of organic derivatives in sea water and their relation to the composition of plankton. In: Daniel, R.J. (Ed.), James Johnstone Memorial Volume. University Press of Liverpool, Liverpool, pp. 177–192.
Reid, P.C., Borges, M., Svenden, E., 2001. A regime shift in the North Sea circa 1988 linked to changes in the North Sea horse mackerel fishery. Fish. Res. 50, 163–171.
Reid, P.C., Colebrook, J.M., Matthews, J.B.L., Aiken, J., Barnard, R., Batten, S.D., Beaugrand, G., Buckland, C., Edwards, M., Finlayson, J., Gregory, L., Halliday, N., John, A.W.G., Johns, D., Johnson, A.D., Jonas, T., Lindley, J.A., Nyman, J., Pritchard, P., Richardson, A.J., Saxby, R.E., Sidey, J., Smith, M.A., Stevens, D.P., Tranter, P., Walne, A., Wootton, M., Wotton, C.O.M., Wright, J.C., 2003. The Continuous Plankton Recorder: concepts and history, from plankton indicator to undulating recorders. Prog. Oceanogr. 58, 117–173, doi: 10.1016/j.pocean.2003.08.002.
Richardson, A.J., Poloczanska, E.S., 2008. Under-resourced, under threat. Science 320, 1294–1295, doi: 10.1126/science.1156129.
Richardson, K., 1997. Harmful or exceptional phytoplankton blooms in the marine ecosystem. In: Blaxter, J.H.S., Southward, A.J. (Eds.), Advances in Marine Biology. Academic Press, pp. 301–385.
Scavia, D., Field, J.C., Boesch, D.F., Buddemeier, R.W., Burkett, V., Cayan, D.R., Fogarty, M., Harwell, M., Howarth, R.W., Mason, C., Reed, D.J., Royer, T.C., Sallenger, A.H., Titus, J.G., 2002. Climate change impacts on U.S. coastal and marine ecosystems. Estuaries 25, 149–164.
Selman, M., Greenhalgh, S., Diaz, R., Sugg, Z., 2008. Eutrophication and hypoxia in coastal areas: a global assessment of the state of knowledge. Water Quality: Eutrophication and Hypoxia 1.
Sherman, K., Duda, A.M., 1999. An ecosystem approach to global assessment and management of coastal waters. Mar. Ecol. Progr. Ser. 190, 271–287.
Southward, A.J., 1995. The importance of long time-series in understanding the variability of natural systems. Helgol. Mar. Res. 49, 329–333.
Swanson, F.J., Jones, J.A., Wallin, D.O., Cissel, J.H., 1994. Natural variability-implications for ecosystem management. In: Jensen, M.E., Bourgeron, P.S. (Eds.), Ecosystem Management: Principles and Applications, Vol. II. Eastside Forest Ecosystem Health Assessment. U.S. Forest Service, General Technical Report PNW-GTR-318, Pacific Northwest Research Station, Portland, Oregon, USA, pp. 80–94.
Steneck, R.S., 1998. Human influences on coastal ecosystems: does overfishing create trophic cascades? Trends Ecol. Evol. 13, 429–430.
Tukey, J.W., 1977. Exploratory Data Analysis. Addison-Wesley Series in Behavioral Science: Quantitative Methods. Reading, Massachusetts.
Valiela, I., 1995. Marine Ecological Processes, second ed. Springer-Verlag, New York, USA, 546 pp.
Vander Schaaf, D., Wilhere, G., Ferdaña, Z., Popper, K., Schindel, M., Skidmore, P., Rolph, D., Iachetti, P., Kittel, G., Crawford, R., Pickering, D., Christy, J., 2006. A conservation assessment of the Pacific Northwest coast ecoregion: the nature conservancy of Canada, Victoria, BC, and Washington Department of Fish and Wildlife, Olympia, WA, 2006.
Vermaat, J.E., McQuatters-Gollop, A., Eleveld, M.A., Gilbert, A.J., 2008. Past, present and future nutrient loads of the North Sea: causes and consequences. Estuarine Coastal Shelf Sci. 80, 53–59, doi: 10.1016/j.ecss.2008.07.005.
Zonneveld, I.S., 1983. Principles of bio-indication. Environ. Monit. Assess. 3, 207–217.