Decadal fluctuations in North Atlantic water inflow in the North Sea between 1958–2003: impacts on temperature and phytoplankton populations

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Abstract

The circulation of Atlantic water along the European continental slope, in particular the inflow into the North Sea, influences North Sea water characteristics with consequent changes in the environment affecting plankton community dynamics. The long-term effect of fluctuating oceanographic conditions on the North Sea pelagic ecosystem is assessed. It is shown that (i) there are similar regime shifts in the inflow through the northern North Sea and in Sea Surface Temperature, (ii) long-term phytoplankton trends are influenced by the inflow only in some North Sea regions, and (iii) the spatial variability in chemicophysical and biological parameters highlight the influence of smaller scale processes.

1. Introduction

As a semi-enclosed basin, the North Sea is characterised by a complex relationship between physical forcing (i.e. waves, tides and currents), water chemistry, suspended sediments, living organisms and human activities (Eisma 1987). The circulation of Atlantic water along the European continental slope, especially the inflow of Atlantic water into the North Sea, influences its water properties to a high degree (Mork 1981). Consequent changes in temperature, salinity and nutrient concentration strongly affect the biology and ecology of plankton communities.

The mean circulation of the North Sea is governed by two main branches: the inflowing Atlantic water and the outflowing Norwegian Coastal Current (Mork 1981). More specifically, two main Atlantic water masses flow into the North Sea through the northern North Sea and English Channel. The continental slope flow of Atlantic water enters the north-western North Sea through the Fair Isle Channel (Figure 1a) and along the east side of the Shetland Islands (Turrell et al. 1990), while a deeper northern inflow occurs either over the northern North Sea plateau or southwards along the Norwegian trench (Iversen et al. 2002). A smaller, warmer and more saline flow enters the North Sea from the south through the Straits of Dover (Figure 1a) and influences temperature and salinity distributions in the Southern Bight of the North Sea (Pingree 2005). The main outflow of North Sea water, the Norwegian coastal current (NCC), flows northwards along the west coast of Norway in the upper 50–100 m of the water column (Helland-Hansen & Nansen 1909, Ikeda et al. 1989). This current is a combination of wind-driven coastal water from the southern North Sea, saline water from the western North Sea and low-salinity water from the Baltic Sea outflow (Lee 1970).

Highly variable in both source and volume, the inflow of Atlantic water into the North Sea is strongly linked to climate variability, mainly through

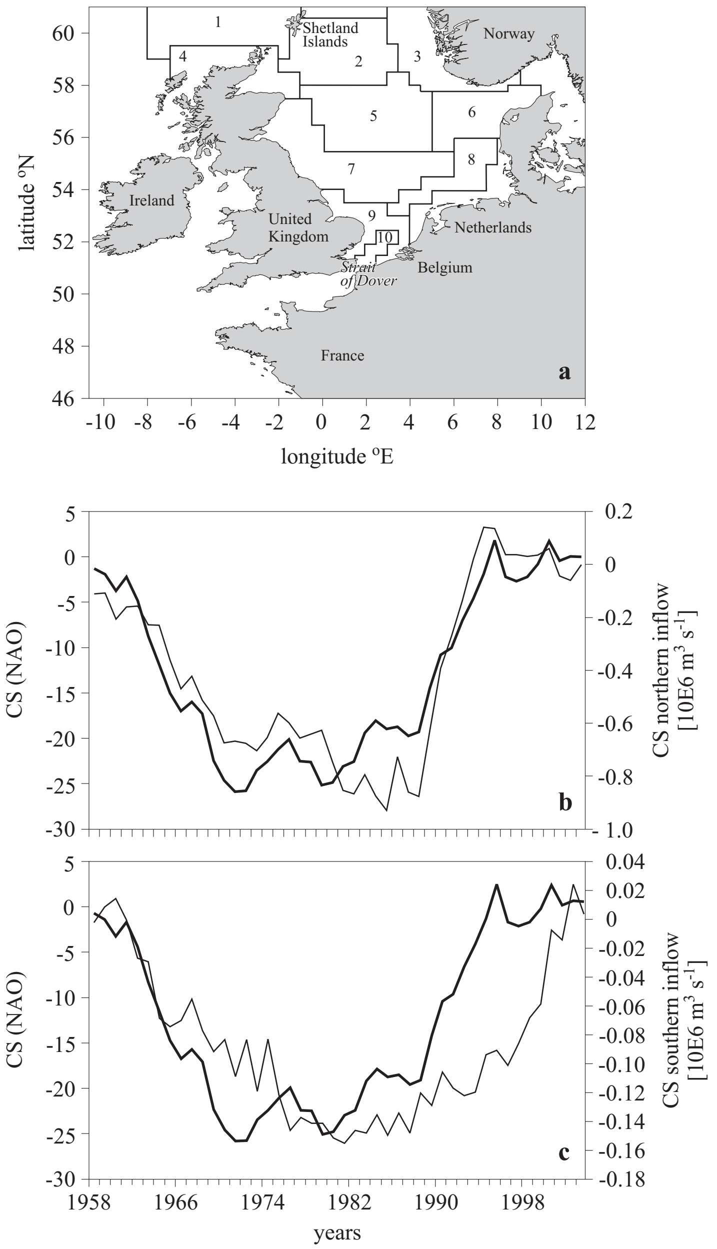

Figure 1. Study area divided into 10 regions (a) according to hydrodynamic (i.e. stratified, mixed and frontal) and bathymetric criteria. The fluctuations of the North Atlantic Oscillation (NAO) and (b) the northern inflow (i.e. through the Fair Isle Channel, along the east side of the Shetland Islands and along the Norwegian trench) and (c) southern inflow (i.e. via the Strait of Dover) over the period 1958 –2003 are illustrated by the cumulative sums (CS). The NAO is represented in black and the Atlantic inflows in grey

the North Atlantic Oscillation (Corten 1990). Atlantic inflow into the northwestern North Sea decreased during the 1960s and 1970s but increased in the 1980s (Corten 1990). However, the potential impact of long-term (1958–2003) fluctuations in the inflow of North Atlantic water on the chemicophysical properties of the North Sea and the temporal dynamics of phytoplankton communities has received only scant attention. In this context, the objectives of this paper were to assess (i) the long-term fluctuations of the two main sources of Atlantic water inflow into the North Sea (i.e. through the northern North Sea and Strait of Dover) over a 45-year period, (ii) the potential effect of those fluctuations on salinity, temperature and nutrient concentrations in the North Sea between 1958 and 2003, and (iii) the related long-term changes in North Sea phytoplankton in different regions of the North Sea.

2. Data and methods

2.1. The CPR sampling strategy

The Continuous Plankton Recorder (CPR) survey is an upper-layer plankton monitoring programme conducted at monthly intervals in the North Atlantic and the North Sea since 1931 (Warner & Hays 1994). Methods for counting and processing the sampled plankton organisms have been reviewed by Richardson et al. (2006). A visual estimate of the total phytoplankton biomass, known as the Phytoplankton Colour Index (PCI), is determined for each sample. The PCI is a relevant index of in situ chlorophyll concentration (Batten et al. 2003) and has been significantly correlated with Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Chl *a* estimates in different regions of the North Atlantic basin (Raitsos et al. 2005, Leterme & Pingree 2007). Diatom and dinoflagellate abundances are also taken into account in this study. To determine the overall trends in these two phytoplankton groups the abundances of every identified diatom or dinoflagellate species were grouped by summing the number of cells identified.

The study area (46°N–60°N; 12°W–12°E) was divided into 10 regions (Figure 1a) on the basis of hydrodynamic (i.e. stratified, mixed and frontal) and bathymetric criteria. The 106 607 samples available from 1958 to 2003 in the study area were used in the present work.

2.2. Chemicophysical and climatic data

Chemicophysical data were provided by ICES and the British Atmospheric Data Centre (http:/badc.nerc.ac.uk/home). ICES provided monthly salinities and nutrient concentrations (nitrate and phosphate) from 1958 to 2003. The British Atmospheric Data Centre supplied SST data that gave additional information likely to affect phytoplankton growth and abundance. The climatic index used in this study is the North Atlantic Oscillation (NAO) winter index (Hurrell 1995); this is based on the pressure difference between Lisbon, Portugal and Stykkisholmur, Iceland.

2.3. North Atlantic water inflow into the North Sea

The NORWegian ECOlogical Model System (NORWECOM) is a coupled 3D physical, chemical and biological model (Skogen & Søiland 1998), validated for the North Sea and the Skagerrak (Søiland & Skogen 2000). In the present study, a 20 x 20 km horizontal grid covering the whole shelf area from Portugal to Norway, including the North Sea, was used. Each simulation year was started on 15 December and model results were stored from 1 January to 31 December. The model was then re-initialised and run for the next year.

Based on the modelled current fields, average monthly transports through an east-west section from Utsira (Norway) to the Orkney Islands along 59°17′N (i.e. northern inflow) in the northern North Sea and a longitudinal section through the English Channel in the Dover Straits along 0°E (i.e. southern inflow) were computed from 1958 to 2003.

2.4. Statistical analysis

In each region, the estimates of phytoplankton biomass (PCI), phytoplankton abundance (total diatoms and total dinoflagellates), salinity and nutrients were averaged for every year over the period 1958–2003. The SST and the estimated northern and southern inflows from the Atlantic were also considered as yearly means.

The existence of long-term temporal trends within each of the ten North Sea regions (Figure 1a) were tested by calculating the Kendall coefficient of rank correlation τ for the physical and biological parameters and the x-axis values in order to detect the presence of an underlying trend. The cumulative sum method (Hays et al. 1993, Leterme et al. 2005, 2006) was used to detect changes as well as the intensity and duration of any variation in the value of a given parameter. The calculation involved subtracting a reference value (here the mean of the series) from the data; these residuals were then successively added, forming a cumulative function. Successive positive residuals produced an increasing slope, whereas successive negative residuals produced a decreasing slope. A succession of values similar to the mean showed no slope. As some data were missing from the salinity and nutrient time series, the cumulative sum analysis was applied only to SST, inflows and phytoplankton variables.

The associations between inflows of Atlantic water, climatic forcing (NAO), chemicophysical (SST, salinity and nutrient concentration) and biological parameters (PCI and phytoplankton groups) were tested by means of Spearman's rank correlation analysis. In addition, the relationship between the oceanic inflow and phytoplankton parameters was investigated by applying Spearman's correlation to cumulative sums of the variables. The same approach was applied to climatic forcing data such as NAO. However, as the cumulative sum method could not be performed on the chemicophysical parameters because of the missing data in the ICES database, Spearman's correlation analysis was not conducted between inflow of Atlantic water, and salinity and nutrient concentration. The analysis was only performed between inflow of Atlantic water and SST data.

3. Results and discussion

3.1. Long-term changes in the environment

Between 1958 and 2003, the inflow of Atlantic waters into the North Sea via the Strait of Dover (southern inflow) increased significantly (Kendall correlation, $p < 0.05$; Figure 2b). No significant long-term trend was identified in the northern inflow ($p < 0.05$; Figure 2a). However, a significant relationship was observed between NAO and the northern inflow (Spearman correlation, $p < 0.05$). The cumulative sums analysis revealed short-term trends within the long-term changes identified above. More specifically, the northern inflow was smaller than the long-term mean between 1958 and 1988, and between 1996 and 2003, but greater between 1989 and 1995 (Figure 1b). In contrast, the southern inflow was smaller than the long-term mean until 1981 and greater until 2003 (Figure 1c). This shows different shifts in the inflows of Atlantic waters into the northern and southern North Sea. The shift observed in the northern inflow in 1988 is consistent with previous work based on the inflow of North Atlantic plankton species into the North Sea (Corten 1999, Lindley & Batten 2002).

A significant relationship was found between the cumulative sums of NAO and both cumulative sums of northern inflow (Spearman correlation, $p < 0.05$, Figure 1b) and southern inflow (Spearman correlation, $p < 0.05$, Figure 1c). These results are related to the link between the wind regimes associated with the NAO phases and the wind-driven component of the oceanic inflows. Positive NAO phases are associated with south-westerly winds, which increase the flow of Atlantic water along the Continental slope and the inflow through the northern and southern North Sea (Figure 3a). In contrast, the negative NAO phases associated with south-easterly winds

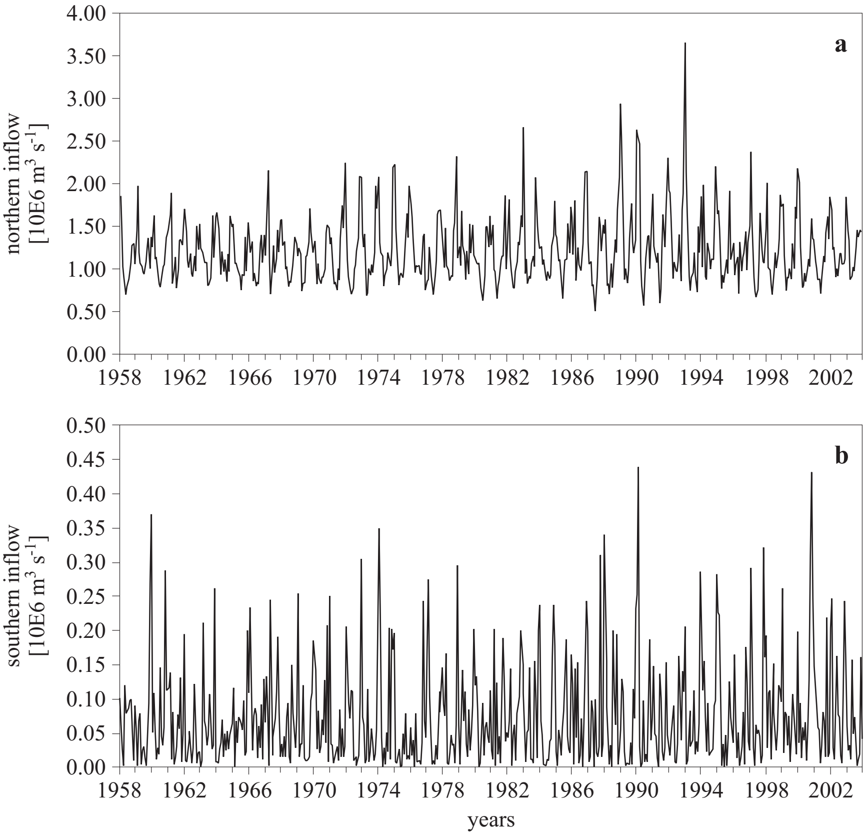

Figure 2. Fluctuations of (a) the northern inflow (i.e. through the Fair Isle Channel, along the east side of the Shetland Islands and along the Norwegian trench) and (b) southern inflow (i.e. via the Strait of Dover) over the period 1958 –2003

(Figure 3b), which are in quadrature with the south-westerly wind-driven northern inflow, result in less inflow under similar wind stress conditions (Pingree 2005).

There were also long-term changes in hydrologic parameters over the 1958–2003 period. Salinity increased long term in the north-western North Sea (Table 1), and a significant relationship was observed between salinity and the northern inflow in the north-central North Sea. This suggests that the salinity increase is linked to the inflow of more saline Atlantic waters into the North Sea (Corten & van de Kamp 1996). Salinity can also be influenced by other factors, e.g. evaporation, precipitation and river run-off, which were not taken into account in this study. Decadal changes have also been observed in nitrate and phosphate, with positive long-term trends in the southern North Sea. In the Southern Bight of the North Sea (i.e. regions

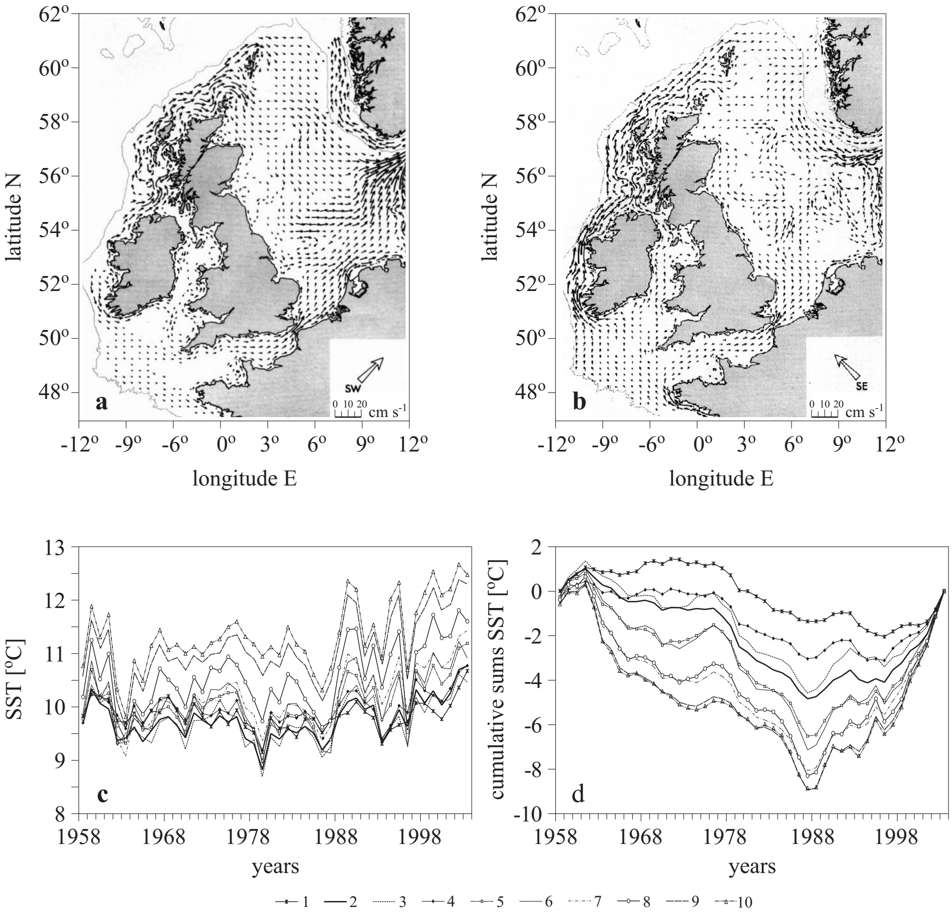

Figure 3. Wind-driven residual currents (cm s^{-1}) resulting from a uniform (a) south-west (positive phase NAO) and (b) south-east (negative phase NAO) wind stress of 1.6 dynes cm^{-2}; modified from Pingree & Griffiths (1980). The length of a current vector determines the strength of the current at its central point. The current arrows are slightly curved to conform to the direction of current flow. Over the period 1958 to 2003, (c) yearly means of Sea Surface Temperature (SST, °C) have increased, and (d) cumulative sums of Sea Surface Temperature show similar patterns in the whole North Sea; 1–10 – regions of the North Sea

8 and 9; Figure 1a), the increase in nutrients reflects the eutrophication (i.e. the increase in the rate of supply of organic matter; Nixon (1995)) reported in the area (Lancelot et al. 1997, Druon et al. 2004). The increase in nitrate and phosphate in the eastern North Sea could, however, also be related to the circulation dynamics of the North Sea, as nitrate is positively correlated to the southern inflow in this area. During positive NAO phases the increase in westerly winds is associated with an increase in the cyclonic

Table 1. Long-term trends inferred from the Kendall's coefficient rank correlation between time and yearly time series of Sea Surface Temperature (SST), salinity, nutrients, Phytoplankton Colour Index (PCI), dinoflagellates and diatoms in the 10 regions of the North Sea over the period 1958–2003

	Region									
	1	2	3	4	5	6	7	8	9	10
SST	–0.02	0.23*	0.20*	0.17	0.30*	0.26*	0.36*	0.32*	0.36*	0.33*
Salinity	–0.18	–0.14	–0.14	0.29*	–0.06	–0.07	–0.14	–0.14	–0.17	0.18
Nitrate	0.25*	0.22	0.02	0.05	–0.08	0.51*	0.07	0.32*	0.36*	–0.02
Phosphate	0.14	0.35*	–0.08	0.02	–0.07	0.34*	0.07	0.18	0.23*	0.11
PCI	0.03	0.04	0.15	0.20*	0.13	0.22*	0.13	0.08	0.11	–0.02
Dinoflagellates	–0.27*	0.05	0.41*	–0.28*	–0.14	–0.23*	–0.19	–0.17	–0.26*	–0.02
Diatoms	–0.42*	0.03	0.33*	–0.33*	–0.18	–0.24*	–0.25*	–0.07	–0.17	–0.10

*5% significance level.

circulation of the North Sea (Schrum 2001) enhancing the flow of southern waters towards the east. The increase in nutrients observed in the eastern North Sea would then reflect the flow of eutrophic waters from the Southern Bight towards the eastern North Sea.

Across most of the North Sea, long-term trends in SST were observed (Table 1, Figure 3c). The relationship between the inflow of Atlantic water and SST differed depending on the origin of the flow. Apart from the north-western and north-central North Sea (i.e. regions 1, 2 and 4; Figure 1a), there was a significant positive relationship between SST and the northern inflow (Spearman correlation, $p < 0.05$) and also the southern inflow in the Strait of Dover ($p < 0.05$). The cumulative sums of SST increased until 1962, slowly decreased until 1987, then increased again until 2003. The regime shifts observed in SST (Figure 3d) and the northern inflow occurred during the same period (1987–1988), which suggests that decadal fluctuations of SST in the North Sea are significantly influenced by oceanic inflows (Becker & Pauly 1996). In addition, the positive phases of NAO are associated with warmer atmospheric temperatures in northern Europe, which have also contributed to the increase in temperature of North Sea waters (Leterme et al. 2005).

3.2. Long-term fluctuations of phytoplankton in the North Sea: the importance of local processes

Between 1958 and 2003, decadal-scale changes were observed in the phytoplankton community (Table 1). These trends, however, were not consistent across the whole North Sea, indicating the importance of smaller spatial scale processes. In addition, the fluctuations observed in the PCI did not reflect those observed for diatoms and dinoflagellates. PCI increased in the north-western and eastern North Sea (Table 1), while diatoms and dinoflagellates both decreased in these regions and increased in the north-eastern North Sea. This indicates that even if the PCI has been significantly correlated to other phytoplankton biomass proxies (i.e. fluorescence and SeaWiFS Chl *a*) in various parts of the North Atlantic basin (Batten et al. 2003, Raitsos et al. 2005, Leterme & Pingree 2007), information at the taxon level are critical for a full assessment of any changes in phytoplankton dynamics.

Dinoflagellates and diatoms significantly increased in the north-eastern North Sea, where they were positively correlated with the northern inflow (Table 1). The increase in these two groups off the coast of Norway could be related to local hydroclimatic changes. In particular, the increase in precipitation and runoff associated with positive phases of NAO induced a long-term decreasing trend in salinity along the Norwegian coast (Sætre et al. 2003) that could explain the changes observed in that region. As the Norwegian Coastal Current (NCC) flow increased between 1958–2003 (Kendall correlation, $p < 0.05$), low-salinity water input from the Baltic, as well as the transport of freshwater discharged by rivers draining the continental areas, may have increased, causing more frequent stratification along the western coasts of Norway. This is supported by the freshening of North Sea waters and an increase in stratification west of 5°E between 1958 and 1998 (Beare et al. 2002). The increase in nutrient inputs associated with increased river discharge could have enhanced the growth of diatoms, whereas the increase in stratification could have enhanced the growth of dinoflagellates.

Significant decreases were also observed in diatoms and dinoflagellates in the north-western and eastern North Sea (Table 1). Negative correlations were observed between dinoflagellates and the two inflows in the north-western North Sea (Table 2), while diatoms were positively correlated with them in the north-eastern North Sea (Table 2). As the north-western area (i.e. regions 1 and 4; Figure 1a) is directly under the influence of the northern inflow, this area is the most representative of North Atlantic conditions. The lack of any significant long-term trend in the northern inflow suggests, however, that the changes observed in the diatoms and dinoflagellates in this area are not linked to the inflow. In addition, the changes observed in the eastern North Sea could be explained by the flow of water masses from the southern North Sea along the coasts of Denmark. During positive NAO phases, an increase in the cyclonic circulation of the North Sea was observed (Schrum 2001, see Figure 3a), i.e. the flow pattern shown in Figure 2a

Table 2. Spearman's rank correlation between the Cumulative Sums time series of Phytoplankton Colour Index (PCI), dinoflagellates, diatoms, and the Cumulative Sums time series of northern (N) and southern (S) inflows in the 10 regions of the North Sea over the period 1958–2003

		Region									
		1	2	3	4	5	6	7	8	9	10
PCI	N	0.44*	0.70*	0.59*	0.76*	0.56*	0.79*	0.75*	0.29*	–0.10	–0.24
	S	0.25	0.64*	0.29*	0.53*	0.49*	0.81*	0.56*	0.65*	0.21	–0.62*
Dinoflagellates	N	–0.68*	0.49*	0.76*	–0.51*	–0.16	–0.32*	–0.01	0.31*	–0.62*	–0.27
	S	–0.72*	–0.01	0.94*	–0.85*	0.13	–0.12	–0.28	–0.15	–0.94*	–0.28
Diatoms	N	–0.62*	0.42*	0.79*	–0.67*	–0.39*	–0.61*	–0.48*	–0.48*	–0.81*	–0.69*
	S	–0.36*	0.77*	0.89*	–0.76*	0.11	–0.20	–0.15	–0.33*	–0.69*	–0.63*

*5% significance level.

increases), enhancing the eastward flow of southern eutrophic waters. The increase in nutrients in the eastern North Sea could explain the changes observed in diatoms and dinoflagellates in this area.

4. Conclusions

Both inflows have an impact on the hydrologic characteristics (i.e. salinity and temperature) of the North Sea. However, they cannot explain all the fluctuations observed (i.e. changes in nutrient concentrations), which suggests that other global (e.g. changes in the cyclonic water circulation in the North Sea) or local (e.g. eutrophication) processes need to be considered. This paper therefore shows that the changes in the PCI did not reflect the changes observed in the diatom and dinoflagellate groups, highlighting the importance of using information at the taxon level in order to fully assess the changes in phytoplankton. Finally, the long-term trends and spatial variability observed in the chemicophysical and biological parameters were not consistent across the whole North Sea, which demonstrates the significance of processes occurring at smaller spatial scales.

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