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Decrease in water clarity of the southern and central North Sea during the 20th century

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Abstract

Light in the marine environment is a key environmental variable coupling physics to marine biogeochemistry and ecology. Weak light penetration reduces light available for photosynthesis, changing energy fluxes through the marine food web. Based on published and unpublished data, this study shows that the central and southern North Sea has become significantly less clear over the second half of the 20th century. In particular, in the different regions and seasons investigated, the average Secchi depth pre-1950 decreased between 25% and 75% compared to the average Secchi depth post-1950. Consequently, in summer pre-1950, most (74%) of the sea floor in the permanently mixed area off East Anglia was within the photic zone. For the last 25+ years, changes in water clarity were more likely driven by an increase in the concentration of suspended sediments, rather than phytoplankton. We suggest that a combination of causes have contributed to this increase in suspended sediments such as changes in sea-bed communities and in weather patterns, decreased sink of sediments in estuaries, and increased coastal erosion. A predicted future increase in storminess (Beniston *et al.*, 2007; Kovats *et al.*, 2014) could enhance the concentration of suspended sediments in the water column and consequently lead to a further decrease in clarity, with potential impacts on phytoplankton production, CO_2 fluxes, and fishery production.

Keywords: chlorophyll, coastal seas, long-term changes, North Sea, Secchi disk, suspended particulate materials, water clarity

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Introduction

Coastal seas, such as the North Sea, have undergone considerable changes in the past century due to human exploitation of resources, transformation of habitats, and pollution (Lotze *et al.*, 2006). In particular, the North Sea is under pressure from a wide range of activities from fishing to hydrocarbons extraction (McGlade, 2002). Anthropogenic pressures on these highly productive coastal ecosystems have caused changes such as the loss of vital habitats (e.g., marshes and intertidal mudflats), and the reduction in area of structurally complex seabed features (Reise, 2005; Airoldi & Beck, 2007). Some of these changes have affected the level of clarity of the water column and the depth of sunlight penetration.

Underwater light availability is a key environmental variable, coupling physics to marine biogeochemistry and ecology. The rate at which nutrients are converted into phytoplankton biomass via primary production is directly proportional to the quantity of light received (Cole & Cloern, 1987). Hence, the potential for algal blooms, important for eutrophication assessment, is lower for regions where the water column is mostly turbid (Foden *et al.*, 2010). Underwater light also modulates processes at higher levels of the food web, affecting fish and crustacean catchability (Tulp *et al.*, 2012), fish feeding behavior (Macy *et al.*, 1998), predator–prey relationships (Meager *et al.*, 2006), and the success of tactile predators (e.g., jellyfish) vs. visual predators (e.g., fish; Eiane *et al.*, 1999).

The amount of light, measured as photosynthetically available radiation (PAR), in the water column is the result of absorption and scattering of photons by optically active components, that is, phytoplankton and non-living detritus, inorganic suspended particulate material or SPM, colored dissolved organic materials (CDOM), and water itself (Sathyendranath, 2000). A simple and widely used measurement of water clarity is given by the depth of disappearance of the Secchi disk (referred to as Secchi depth, Z_{SD}).

Long-term time series of Secchi depth measurements indicate that coastal seas (Fleming-Lehtinen &

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Laamanen, 2012), bays (Kemp *et al*., 2005), and fjords (Aksnes *et al*., 2009) have shown a decrease in clarity, or darkening, of the water column. There is evidence that the North Sea has experienced changes in its light climate over the 20th century (Dupont & Aksnes, 2013). Thanks to published and previously unpublished data, with this study, we investigated the magnitude of this change, as well as possible causes and implications for the marine environment. For the last 25+ years, we also discuss what may have been driving the change in water clarity (i.e., phytoplankton or total SPM).

Materials and methods

Secchi depth

To study the long-term changes in water clarity of the southern and central North Sea, all available estimates of Secchi depth from ICES (Aarup dataset; http://ocean.ices.dk/Project/SECCHI/), the World Ocean Database (NOAA; http://www.nodc.noaa.gov/OC5/WOD/pr_wod.html), the Dutch Demersal Fish Survey (provided by Dr. Ingrid Tulp), and Cefas (UK; unpublished) were collated. When collection time was known, measurements collected outside the interval 8:00–19:00 were not used. Observations collected in the same day and at the same location were averaged. Observations from different datasources were checked and compared to eliminate possible duplicates. To our knowledge, there is no evidence that a visor was used when recording Secchi depths used in this study; therefore, no correction was applied for this (see Fleming-Lehtinen & Laamanen, 2012, for details).

Chlorophyll and SPM concentrations

Measurements of chlorophyll concentration (determined using standard fluorimetric technique) and total SPM concentration (organic and inorganic) from gravimetric analysis, for the upper 20 m of the water column, were collated from ICES, the NERC North Sea Project, and Cefas. For SPM, observations from WaterBase (RIKZ; http://live.waterbase.nl/waterbase_wns.cfm?taal=nl) and from the North-West European Shelf Programme (NOWESP; van Leussen *et al*., 1996) were also used. Chlorophyll and SPM observations were combined with measurements of chlorophyll (from calibrated fluorescence; Greenwood *et al*., 2010) and SPM (from calibrated backscatter; Greenwood *et al*., 2010) from SmartBuoys (http://cefasmapping.defra.gov.uk/Smartbuoy/Map).

Observations collected in the same day and at the same location were averaged, as well as observations from different depths in the upper 20 m of the water column.

Spatial and temporal correlations of data were investigated with semi-variograms (Cressie, 1991) using the software R (R Development Core Team, 2014; http://www.r-project.org/). In particular, for measurements from SmartBuoy, semi-variograms were prepared for both chlorophyll and SPM measurements, according to Heffernan *et al.* (2010), after de-trending the dataset (using a kernel smoother with band width of 20 days), and standardization of the variance of observations. The latter was carried out by dividing the residuals by the localized standard deviation from a kernel smoothing (15-day bandwidth) of the de-trended residuals. Chlorophyll and SPM values were natural log-transformed to reduce variability and to make easier the application of the kernel smoother.

The semi-variogram analysis indicated that data collected from SmartBuoy was temporally correlated with a range of approximately 7 days (data not shown). As a result, SmartBuoy measurements of calibrated chlorophyll and SPM were averaged weekly.

Data from different datasources were checked and compared to eliminate possible duplicates. Measurements of CDOM have been carried out sporadically; therefore, they were not included in this study.

Hydrodynamic regions

Due to the variable spatial distribution and temporal frequency of data, observations (>6 nautical miles from the coast and up to 57°N) were divided into five hydrodynamic regions (Fig. 1), with homogenous stratification and SPM regimes. In particular, the five regions were identified based on the length of mixing and stratification periods (van Leeuwen *et al.* submitted; see also Capuzzo *et al*., 2013).

The East Anglia Plume polygon was created based on MODIS-derived maps of mean non-algal suspended particulate matter concentration, greater than 10 mg l^{-1}, for the North Sea during January 2002–2012. Mean monthly maps were generated by averaging daily maps of non-algal suspended particulate matter, for the month of January provided by Ifremer (Brest, France; ftp://ftp.ifremer.fr; Gohin *et al*., 2005).

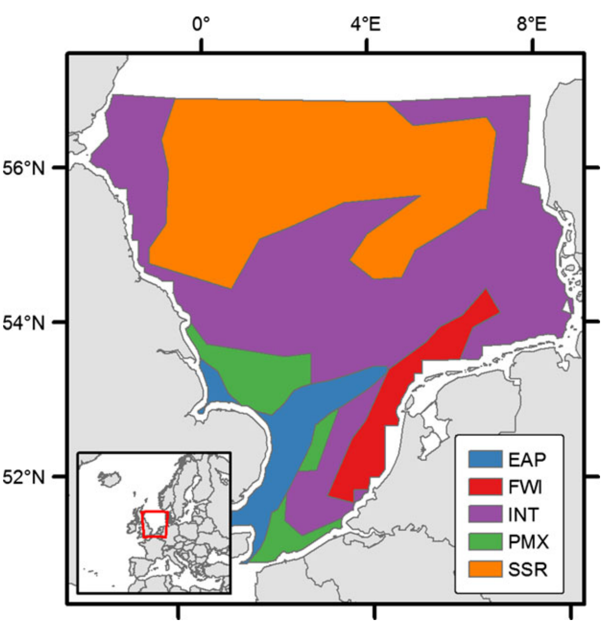

Fig. 1 Study area and hydrodynamic regions. EAP, East Anglia Plume; FWI, freshwater influence; INT, intermediate; PMX, permanently mixed; SSR, seasonally stratified.

Observations (Secchi depth, chlorophyll, SPM concentration) were grouped and analyzed accordingly to these regions.

Data analysis

Mean estimates of Secchi depth (Z_{SD}) pre- and post-1950 were calculated by averaging all available observations of Z_{SD}, collected before and after 1950, respectively, by hydrodynamic region and by season. Mean Z_{SD} pre- and post-1950 were then compared (by region and season) using a nonparametric randomization test (Manly, 1998) in R, under the null hypothesis of no difference in mean Z_{SD} pre- and post-1950. The year 1950 was chosen assuming that major changes in the benthic communities of the North Sea and in the fishing effort took place after the 1950s (although demersal trawling started from the late 19th century; Callaway *et al.*, 2007), but also because the 1950s and 1960s correspond to a gap in the dataset.

Mean depth of the photic zone (i.e., the depth at which PAR is reduced to 1% of its surface value) pre- and post-1950 ($Z_{eu\text{-}pre}$ and $Z_{eu\text{-}post}$, respectively) was calculated according to Eqn (1).

$$Z_{eu-pre} = 4.605/K_{d-pre} \text{ and } Z_{eu-post} = 4.605/K_{d-post} \quad (1)$$

where $K_{d\text{-}pre}$ and $K_{d\text{-}post}$ were calculated transforming all available observations of Secchi depth into estimates of K_d (light attenuation coefficient) using Eqn (2) (from Devlin *et al.*, 2008; for UK coastal and offshore waters) and then calculating the mean values of K_d for all estimates pre-1950 and post-1950, respectively.

$$\ln(K_d) = -0.010 - 0.861\ln(Z_{SD}) \quad (2)$$

Results

Available measurements of Secchi depth (Z_{SD}) for the southern and central North Sea started in 1903, with the bulk of observations being collected from the 1970s (Fig. S1). Time series of SPM observations started in the late 1980s (Fig. S2), while chlorophyll concentration measurements were collected from the mid-1970s (Fig. S3).

For most regions and seasons, there were more Z_{SD} observations post-1950, with the exception of the permanently mixed (PMX) region in spring–autumn and the East Anglia Plume (EAP) region in all seasons (Table 1). More Z_{SD} observations were collected in summer compared to winter for all regions, both pre- and post-1950 (Table 1).

The annual mean Z_{SD} showed a statistically significant decrease in the second half of the 20th century in all regions (Fig. 2) and in all seasons (Table 1), except for the freshwater influence (FWI) and EAP regions in winter (due to lack of data) and for the FWI in summer,

Table 1 Comparison of mean Z_{SD} pre- and post-1950 by hydrodynamic region and season

		<1950 Z_{SD}			≥1950 Z_{SD}						
Region	Season	Mean	SD	*N*	Mean	SD	*N*	$N_{<1950}/N_{>1950}$	Change (m)	Change (%)	*P*-value
EAP	Summer	7.69	3.22	84	5.52	1.06	45	1.87	−2.16	−28.1	<0.001
EAP	Winter	3.73	1.79	69	–	–	0	–	–	–	–
EAP	Spring/Aut	3.72	1.51	71	1.1	0.82	43	1.65	−2.61	−70.3	<0.001
INT	Summer	11.75	4.34	64	5	2.62	1803	0.04	−6.76	−57.5	<0.001
INT	Winter	5.97	1.95	19	3.60	2.07	188	0.10	−2.38	−39.8	<0.001
INT	Spring/Aut	7.74	3.54	55	4.81	2.55	906	0.06	−2.93	−37.9	<0.001
PMX	Summer	8.53	4.06	24	3.27	2.22	57	0.42	−5.26	−61.7	<0.001
PMX	Winter	6.55	2.3	7	1.66	0.93	15	0.47	−4.89	−74.7	<0.001
PMX	Spring/Aut	8.12	2	23	2.70	2.41	19	1.21	−5.41	−66.7	<0.001
FWI	Summer	6.62	3.77	11	5.17	2.61	384	0.03	−1.45	−22	0.073
FWI	Winter	–	–	0	3.7	2.6	52	–	–	–	–
FWI	Spring/Aut	9.24	1.65	7	4.02	1.95	145	0.05	−5.22	−56.5	<0.001
SSR	Summer	14.07	3.72	37	10.61	3.56	63	0.59	−3.46	−24.6	<0.001
SSR	Winter	12	5.48	8	4.11	1.3	17	0.47	−7.89	−65.8	<0.001
SSR	Spring/Aut	12.58	4.37	34	7.97	3.03	40	0.85	−4.61	−36.6	<0.001
ALL	Summer	9.98	4.53	220	5.14	2.79	2352	0.09	−4.84	−48.5	<0.001
ALL	Winter	4.98	3.23	103	3.54	2.14	272	0.38	−1.44	−28.9	<0.001
ALL	Spring/Aut	7.2	4.29	190	4.64	2.65	1153	0.16	−2.56	−35.5	<0.001

Mean Z_{SD} (m^{-1}), standard deviation (SD), number of observations (*N*), ratio of observations ($N_{<1950}/N_{>1950}$), change in Z_{SD} (as m and as percentage), and *P*-values of the comparison between mean Z_{SD} pre-1950 and post-1950. All available estimates of Secchi depth were used for this comparison, using a nonparametric randomization test.

Winter = November, December, January, and February; summer = May, June, July, and August; spring–autumn = March, April, September, and October; EAP, East Anglia Plume; FWI, freshwater influence; INT, intermediate; PMX, permanently mixed; SSR, seasonally stratified.

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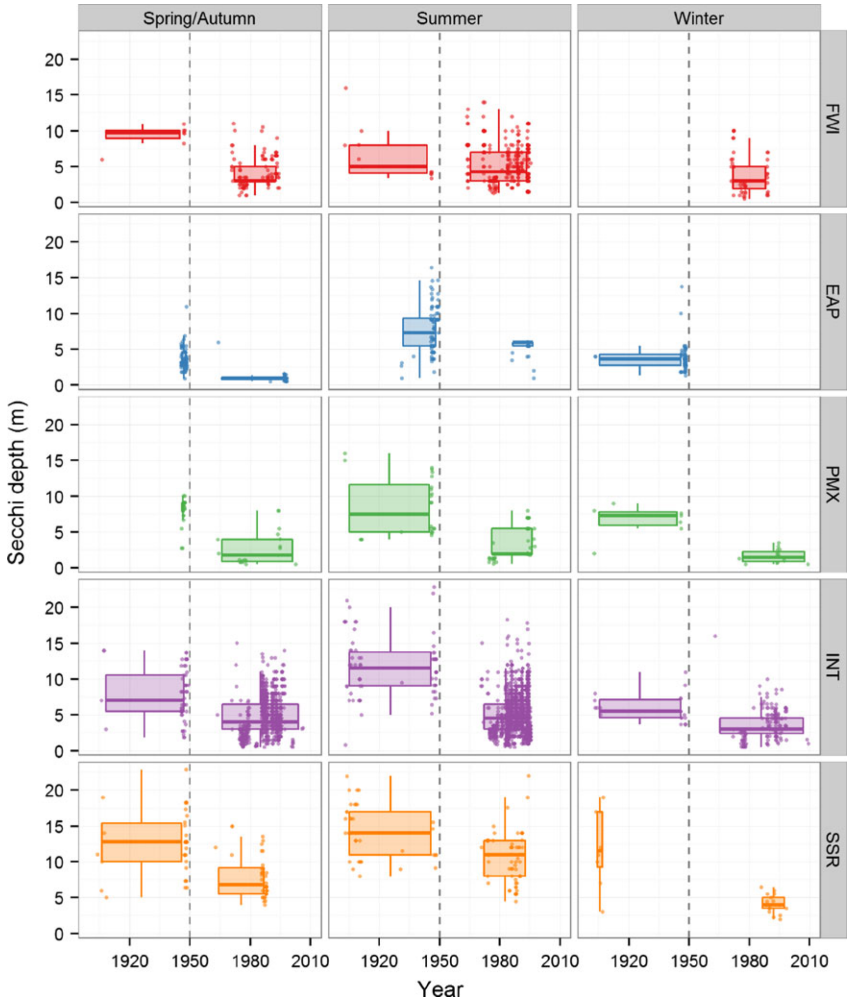

Fig. 2 Observations of Secchi depth (m) for each hydrodynamic region and season. Points indicate individual observations of Secchi depth. Box plots show the median and the inter-quartile range of observations of Secchi depth pre- and post-1950. Abbreviations for hydrodynamic regions as in Fig. 1.

indicating a reduction in water clarity. In particular, comparing the average Z_{SD} pre-1950 with the average Z_{SD} post-1950 (Table 1; Fig. 2), the decrease in clarity was the largest (in meters) at the seasonally stratified region (SSR; 7.9 m in winter), and at the PMX region, in terms of percentage (74.7% in winter).

Focusing on the depth of 1% surface light for the permanently mixed and East Anglia Plume regions, PMX + EAP (for which the highest number of observations pre-1950 was available), the mean Z_{eu} (pre- and post-1950) in summer (May to August inclusive) was compared with the depth of the water column (Fig. 3). The mean value of the depth of the photic zone during summer pre-1950 was 37 m, and this decreased to 20 m post-1950. With the exclusion of the deep area off East Anglia, in summer pre-1950, most (74%) of the sea floor in these two hydrodynamic regions was within the photic zone (Fig. 3).

Plots of the seasonal mean values of total SPM from 1988 (Fig. 4a and Table S1) show that SPM has significantly increased (P-value < 0.05) in the EAP region (in all seasons), INT region (in spring/autumn and winter), and in the seasonally stratified region, SSR (in summer). At the same time, similar plots of mean seasonal values of chlorophyll concentration for the same period (Fig. 4b and Table S1) did not show statistically significant trends (P-value > 0.05), except for the PMX region in winter (increase) and the INT region in summer (decrease).

Discussion

Centennial time series of Secchi depth (Z_{SD}) observations provide unique insight on long-term changes in the light climate of water bodies. Measurement of Z_{SD} is rather simple (determination of the disappearance

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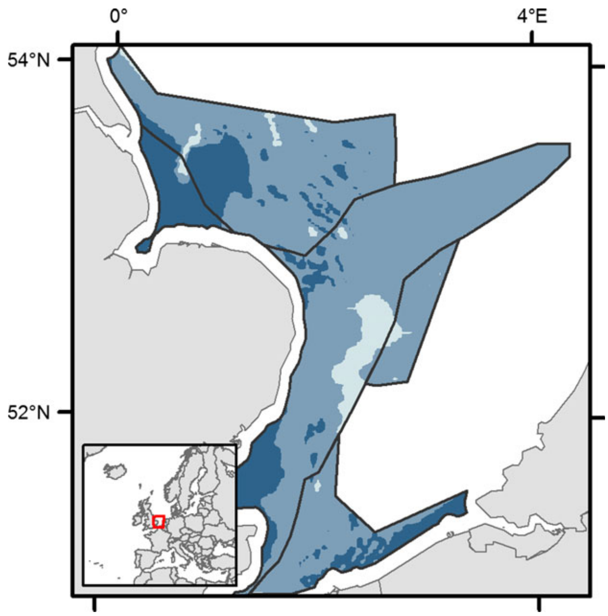

Fig. 3 Comparison of sea floor area within photic zone pre- and post-1950 for PMX and EAP during summer (May–August). The dark areas indicate part of the sea floor which were in the photic zone in summer pre-1950 and in post-1950; lighter areas used to be within the photic zone in summer pre-1950 but not in post-1950; very light areas of sea floor were not in the photic zone in summer pre-1950 nor in post-1950.

depth of a white disk in the water), and some environmental factors during the measurement (e.g., solar zenith, roughness of the sea surface, bathymetry) as well as some characteristics of the disk (diameter, reflectance of the paint) can affect the resulting value of Z_{SD} (see, for example, Preisendorfer, 1986; Dupont & Aksnes, 2013; Philippart *et al.*, 2013).

The study by Philippart *et al.* (2013), on Z_{SD} measurements of the western Wadden Sea, provides a useful indication of the magnitude of the error associated with the measurements carried out with disks of different size and reflectance. In particular, the authors reported that a change in Secchi disk diameter from 30 to 22 cm caused a lowering of Z_{SD} of 7%, while a change in reflectance from 0.95 to 0.7 caused a lowering of 3% (Philippart *et al.*, 2013). In the same study, the authors highlighted that measurements carried out at sunrise or sunset (instead of noon) would underestimate Z_{SD} between 3% and 16% (at the winter solstice and summer solstice, respectively; Philippart *et al.*, 2013). Z_{SD} observations used in this study were screened to remove potentially biased values (see Materials and Methods) and were spatially aggregated based on similar hydrodynamic conditions; however, other details (e.g., the size and reflectance of the disks used) were not known. The observed reduction in Z_{SD} between pre- and post-1950, in the different regions and seasons, varied between 25% and 75% (Table 1). Therefore, it could be argued that even if a change in size and reflectance of the disks have occurred (similar to the example given by Philippart *et al.*, 2013), the associated bias in the measurements would have been substantially smaller than the changes between pre- and post-1950 observed in this study.

The reduction in Z_{SD} between pre- and post-1950 for all regions combined (1.4–4.8 m; see Table 1) was comparable to the reduction estimated by Dupont & Aksnes (2013) for the coastal and offshore waters of the North Sea (1.8 ± 0.3 and 5.2 ± 0.9 m, respectively), and with the reduction observed during summer in the coastal Baltic Sea (1.2–4 m; Fleming-Lehtinen & Laamanen, 2012). Dupont & Aksnes (2013) observed that the strongest reduction in Z_{SD} occurred in offshore waters of the North Sea. Because of different spatial and temporal aggregations of data, it is not possible to directly compare Dupont and Aksnes outcome with results from this study. In fact while the offshore SSR region showed the strongest reduction in m of Z_{SD} (7.9 m; Table 1), the coastal PMX region was affected by the highest percentage reduction (75%; Table 1).

The mean values of $Z_{eu\text{-}pre}$ (37 m) for PMX+EAP regions was comparable with estimates for a site north of the Dogger Bank in 2007, classified as clear offshore water (Capuzzo *et al.*, 2013). This suggests, therefore, that, in the first half of the past century, the presently turbid waters of the southern North Sea were clearer and comparable with the present-day waters of the northern North Sea.

The impact of the changes in clarity can be better understood by considering the mean depth of the photic zone, compared to the depth of the water column, during summer for the PMX and EAP regions (Fig. 3). Benthic primary production, an important component of the total primary production in shallow coastal environments, is sustained by the penetration of sufficient light to the sea floor (Gattuso *et al.*, 2006). It is likely that a biofilm of microphytobenthic algae would be able to colonize the seafloor surface in the EAP and PMX regions pre-1950, as it has been observed in an area of the North Sea with similar water depth and light climate (the Dogger Bank area; Reiss *et al.*, 2007). Microphytobenthos would have contributed to the stability of the surface layer of sediments (Madsen *et al.*, 1993), thereby reducing resuspension, and would have been an important food source for both benthic deposit and suspension feeders, thus affecting benthic production (Miller *et al.*, 1996).

Records of benthic macrofauna (Frid *et al.*, 2000; Rumohr & Kujawski, 2000; Callaway *et al.*, 2007) and

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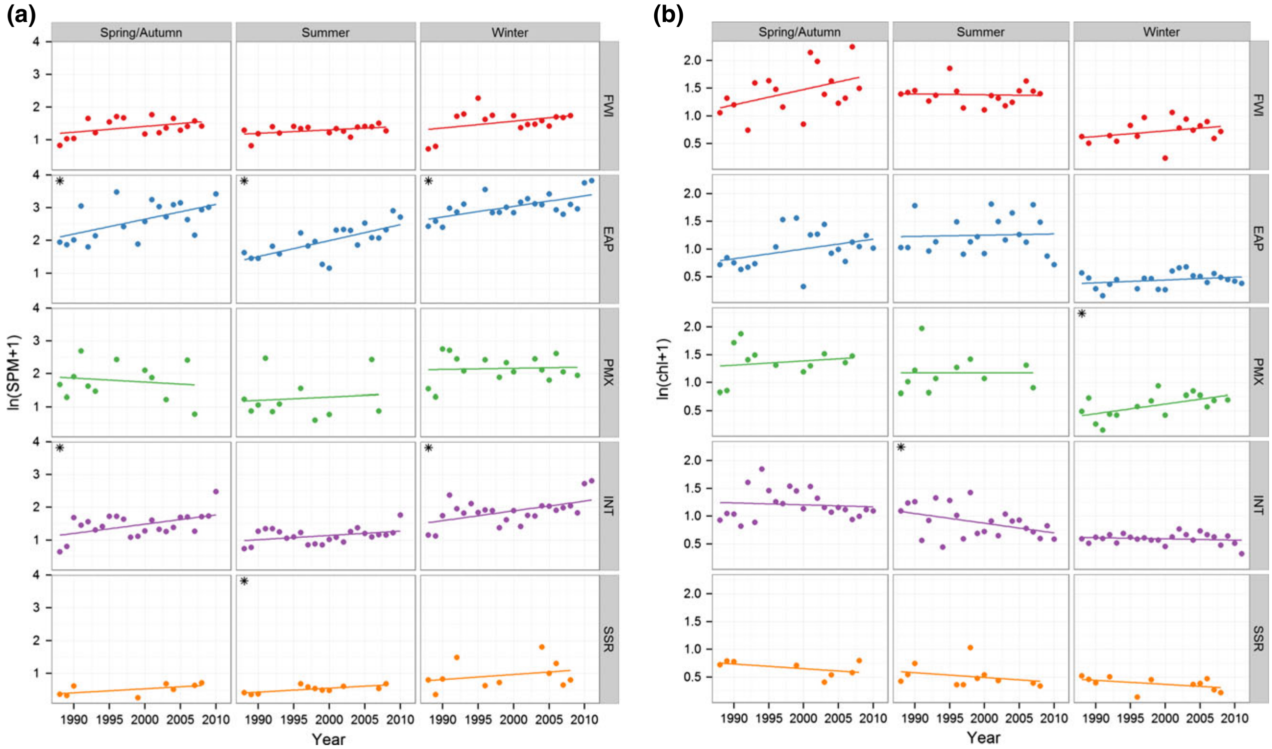

Fig. 4 Mean seasonal SPM (a) and chlorophyll (b) concentrations from 1988 to 2011, with trend line, for each hydrodynamic region. Linear model coefficients and *P*-values of each regression line are given in Table S1. Statistically significant regressions (*P*-value < 0.05) are indicated with a star (*). FWI, freshwater influence; EAP, East Anglia Plume; PMX, permanently mixed; INT, intermediate; SSR, seasonally stratified.

of fish stomach contents (Frid & Hall, 1999) show that during the first half of the 1900s, the North Sea floor was colonized by a different benthic community compared to the one observed from the 1980s. The former community was characterized by slow-growing, long-lived species, including large mollusk bivalves (Callaway *et al.*, 2007). There is also evidence that, up to the late 1800s and early 1900s, extensive oyster beds were present along the British, Belgian, and Dutch coastlines and in the central North Sea (Olsen, 1883; de Vooys *et al.*, 2004; Houziaux *et al.*, 2011). In a similar way to that observed in Chesapeake Bay in the USA (Newell, 1988), we could expect that in the shallow waters of the southern North Sea, this diverse bivalve community would have regularly filtered the water column, helping to maintain the water column clear.

The changes in the benthic community structure of the North Sea during the 1900s have been linked to the intensification of beam trawling (Frid *et al.*, 2000; Rumohr & Kujawski, 2000; Callaway *et al.*, 2007). Particularly in the southern and central North Sea (Callaway *et al.*, 2007), the exploitation of demersal fish intensified from the 1960s; the fishing effort continued to increase up to 1995, largely due to beam trawlers (Jennings *et al.*, 1999). Trawling, and in particular beam trawling, has many ecosystem consequences (Hall, 1994; Jennings *et al.*, 1999). In this case, it is likely that the trawling activity contributed to the changes in clarity of the southern North Sea indirectly, by altering the community of bottom filter feeders and, directly, by disturbance and resuspension of the bottom sediments. However, it is important to keep in mind that trawling was also carried out during the first half of the 1900s, when the water column was clearer.

Assuming the reduction in clarity during the second half of the 20th century was due to an increase in the concentration of suspended sediments, causes other than trawling could have led to this increase. The amount of suspended sediments in the water column is affected by resuspension and transport of bottom sediments by the action of tide, currents, and waves. Therefore, changes in weather patterns (e.g., wind intensity and/or direction) could have had effects on sediment concentration through changes in the hydrodynamic of the water column (Fettweis *et al.*, 2012). In fact, SPM concentration in winter in the southern North Sea is

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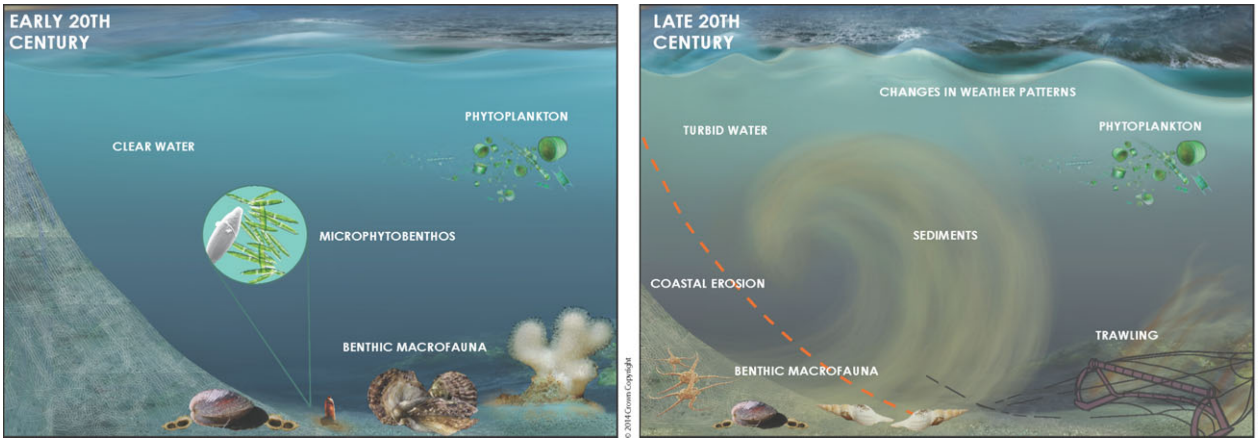

Fig. 5 Decrease in water clarity of the southern and central North Sea during the 20th century and possible causes. The water column was clearer in the early 20th century, and the sea floor was colonized by a benthic community including oysters (*Ostrea edulis*), and potentially microphytobenthos. During the second half of the 20th century, water clarity of the southern and central North Sea decreased. For the last 25+ years, this was likely driven by a higher concentration of suspended materials in the water column. Possible causes of this increase in suspended materials could be changes in the benthic community, increased trawling effort, changes in weather pattern and coastal erosion (figure by Bayliss-Brown G).

correlated with the North Atlantic Oscillation (NAO) index (Fettweis *et al.*, 2012). Interestingly, west-south-westerly winds over the North Sea during winter months have intensified from the period 1958–1967 to 1968–1997 (Siegismund & Schrum, 2001). In addition to bottom erosion and resuspension, coastal erosion is the major source of suspended sediments in the southern North Sea (Fettweis *et al.*, 2012). In the 1960s, and particularly 1970s, a phase of marked erosion of salt marshes of the Greater Thames estuary occurred, caused by human activities (construction of embankment and land claim) and by changes in wind and wave patterns (van der Wal & Pye, 2004). Salt marshes are important sinks for sediments (Roman & Nordstrom, 1996), and loss of these areas, due to erosion and/or reclamation, prevents the deposition of thousands of tonnes of sediments per year (see example of the Welwick Marsh in the Humber estuary; Andrews *et al.*, 2008). Finally, disposal grounds of dredged materials and navigation channels are another source of fine-grain sediments that can be resuspended during storms (Fettweis *et al.*, 2010).

The major reduction in water clarity could also have been caused by an increase in phytoplankton and/or CDOM. Inputs of dissolved inorganic nutrients from European rivers in the North Sea peaked in the early 1980s (Pätsch & Radach, 1997). The Marsdiep time series (Wadden Sea) showed that, as in coastal waters, the increase in nutrients was followed by an increase in phytoplankton and primary production (Cadée & Hegeman, 2002). Model simulations (Gröger *et al.*, 2013) suggest that an enhancement of production due to nutrients enrichment occurred also in the southern and central North Sea. Phytoplankton growth and degradation releases CDOM (Astoreca *et al.*, 2009); therefore, it would be reasonable to assume that an increase in phytoplankton biomass was also associated with an increase in CDOM. The importance of CDOM concentration, increased as result of higher precipitations and ‘brownification’ of rivers, in affecting the underwater light attenuation has also been highlighted by Dupont & Aksnes (2013).

Observations of chlorophyll and SPM for the southern and central North Sea were collected regularly only from the late 1980s, while measurements of CDOM were collected only more recently and sporadically. Thus, it is not possible to discern and quantify the contribution of the different optically active components to the change in water clarity of the North Sea. Analyses of SPM and chlorophyll concentration values for the last 25+ years (Fig. 4, and Table S1) suggest that where a significant increase in the total SPM occurred, this was mainly driven by the inorganic component, rather than the organic (i.e., phytoplankton).

The lack of a trend in chlorophyll concentration is in contrast with the observations estimated from the Phytoplankton Colour Index of the Continuous Plankton Recorder, suggesting that an increase in phytoplankton has occurred in the North Sea since the late 1980s (McQuatters-Gollop *et al.*, 2007; Raitsos *et al.*, 2014). The different conclusion could be explained by taking into account the different spatial aggregation of observations adopted in this and the previous studies (McQuatters-Gollop *et al.*, 2007; Raitsos *et al.*, 2014) and/or the different methods adopted for estimating chlorophyll concentration (i.e., calibrated scale of silk

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'greenness' vs. standard fluorimetric technique and calibrated fluorescence, used in this study).

Our study highlights the magnitude of the reduction in underwater light availability that occurred from the second half of the 20th century in the southern and central North Sea. We suggest this was the result of a combination of causes, including decrease in sea-bed integrity, increased trawling effort, windiness, and coastal erosion (Fig. 5). For the last 25+ years, the variability in the light climate was more likely driven by inorganic SPM, rather than phytoplankton, although no information is available on the changes in CDOM concentration.

Recent climate change model scenarios suggest that, during the course of this century, winter storms may increase (Beniston *et al.*, 2007; Kovats *et al.*, 2014). If this scenario proves correct, sediment resuspension and bottom and coastal erosion could be enhanced in the future, leading to higher concentrations of inorganic suspended solids in the water column. The implication of a further decrease in water clarity may not be limited to phytoplankton production and fisheries (e.g., Eiane *et al.*, 1999; Meager *et al.*, 2006; Tulp *et al.*, 2012) but could also extend to affecting CO_2 and heat fluxes. It has been observed that during summer and autumn, the trophic balance of the southern North Sea is net heterotrophic (gross primary production < community respiration), with its shallow and well-mixed waters acting as a source of CO_2 to the atmosphere (Thomas *et al.*, 2005). A reduction in light availability in this area of the North Sea, as a result of reduced clarity, could shift the trophic balance even more toward heterotrophy and consequently enhance the carbon dioxide flux from water to air.

Furthermore, in highly turbid coastal seas, heating by solar radiation is restricted to the near-surface layer (Oschlies, 2004) with potential for the resultant trapped heat to cause regional 'hot-spots' of anomalously rapid sea surface warming (Löptien & Meier, 2011). Since the 1980s, the surface temperature of the southern North Sea has been increasing at between 0.2 and 0.4 °C decade^{-1} (Dye *et al.*, 2013). This is not only one of the highest rates observed in UK coastal waters but also high on a global scale. This increase has been attributed to global warming and to natural variability (Dye *et al.*, 2013). However, the marked reduction in water clarity that occurred in the second half of the 20th century in the southern North Sea could have enhanced the surface heating rate and therefore the increase in temperature.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Spatial/temporal distribution, and number of observations of Secchi depth by datasource.
Figure S2. Spatial/temporal distribution, and number of observations of SPM concentration by datasource.
Figure S3. Spatial/temporal distribution, and number of observations of chlorophyll concentration by datasource.
Table S1. Summary of linear regression models of chlorophyll and SPM concentrations by hydrodynamic region and season.

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