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Centennial changes in water clarity of the Baltic Sea and the North Sea☆

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A R T I C L E I N F O

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A B S T R A C T

Secchi depth is a valuable proxy for detecting long term changes in the water clarity of oceanic and coastal ecosystems. We analyse approximately 40 000 observations, which are available from ICES, from the Baltic Sea and the North Sea in the 20th century. Our results suggest pronounced effects of bottom depth and distance to coast on Secchi depth, and we account for this topographical effect in an assessment of the long term change in water clarity. Our results suggest a centennial Secchi depth shoaling of 3.2 ± 0.2 and 5.8 ± 0.6 m in areas that are shallower and deeper than 100 m in the Baltic Sea. For the North Sea the corresponding numbers were 1.8 ± 0.3 and 5.2 ± 0.9 m. We discuss potential ecosystem effects involving pronounced reductions in photic habitats and reduced visibility for visual predators. We suggest that the role of long term variations in colour dissolved organic matter (CDOM) on the transparency in the Baltic Sea and North Sea deserves future attention.

1. Introduction

Secchi depth, the depth at which a white disc disappears from sight when lowered in water, has been measured for more than a century. It is a valuable proxy for detecting long term changes in the water clarity of oceanic and coastal ecosystems (e.g. Falkowski and Wilson, 1992; Sandèn and Håkansson, 1996; Aksnes, 2007). Secchi depth (S, m) is perhaps best known as an indirect measure of phytoplankton biomass, productivity (Lewis and Kuring, 1988; Boyce et al., 2010) and eutrophication (Henriksen, 2009), but is basically a proxy of optical properties (Preisendorfer, 1986):

$$S = \frac{\Gamma}{K + c} \tag{1}$$

where K (m^{-1}) is the attenuation of downwelling irradiance, c (m^{-1}) the beam attenuation coefficient, and Γ is termed the coupling constant. Its value is typically 8–9, but varies with several factors such as disk size and painting, the observer, and properties of the water such as reflectance (Preisendorfer, 1986; Davies-Colley and Vant, 1988).

A change in Secchi depth is commonly reported as the change in metres. It should be noted, however, that since K and c relate inversely to Secchi depth (Eq. (1)), changes in the reciprocal Secchi depths are of interest from an ecological as well as an optical point of view. In this context it is useful to note that a reduction in Secchi depth from 2 to 1 m requires 45 times larger increase in $c + K$ than the "same" 1 m change from 10 to 9 m Secchi depth. Organisms are affected in many different ways by the optical environment (Kirk, 2011; Johnsen, 2012) and optical changes are likely to affect, not only the photoautotrophs, but all organisms utilizing light in one or another way. E.g. evidence suggest that changes in water clarity has a direct effect on fish production, abundance, and migration in aquatic environments (Lester et al., 2004; Aksnes, 2007; Karlsson et al., 2009; Kaartvedt et al., 2012). Changes in the competitive relationship between tactile (e.g. jellyfish) and visual predators (e.g. fish) have been connected to changes in the optical environment (Eiane et al., 1997; Sørnes and Aksnes, 2004; Haraldsson et al., 2012). Thus long records of Secchi depth are potentially valuable, not only as a proxy for phytoplankton and primary production, but also as an important habitat characteristic for all organisms that are affected by the optical environment. Generally, increased K implies shoaling and narrowing of vertical habitats, such as the euphotic zone, of organisms having certain requirements for light intensity (Kirk, 2011). Increased c implies decreased visibility for visual hunters such as fishes (Aksnes and Utne, 1997; Johnsen, 2012). Thus

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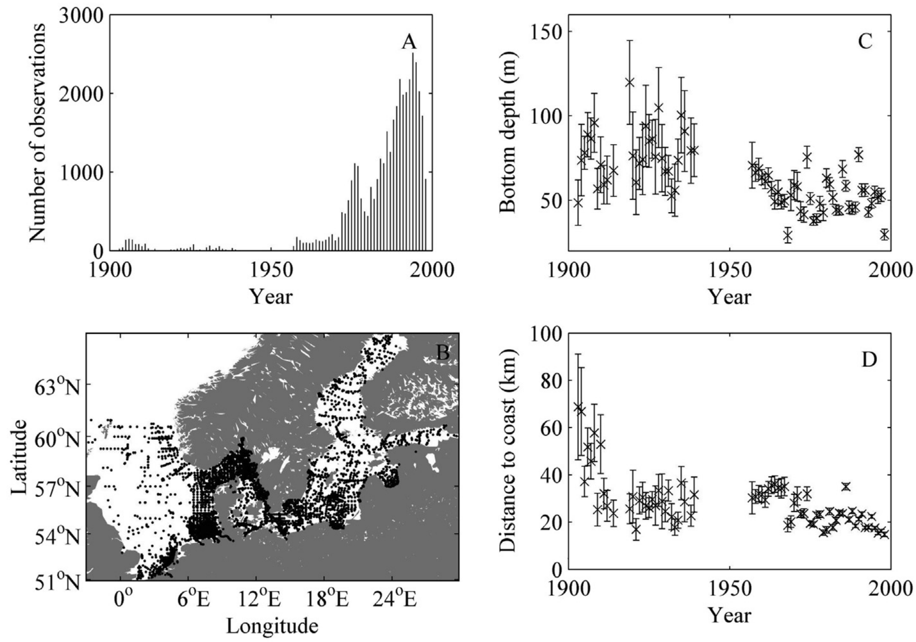

Fig. 1. The number of Secchi disc observations per year (A) and their geographical distribution (B). Annual average of the bottom depth (C) and of the distance to the coast (D) of the Secchi depth locations as a function of time. Note that the bars represent 95% c.i. of the means and not the span of the underlying observations.

effects of changes in Secchi depth on organisms can be categorized in terms of *c* and *K* effects (Irigoien et al. 2013).

Here we investigate changes in the Secchi depth of the North Sea and the Baltic Sea from more than 40 000 records that was compiled by Aarup (2002). These observations are from the period 1903–1998. Some of these observations have been utilized in previous studies of long term changes in the Baltic Sea. For the North Sea, however, we are not aware of previous studies that extend further back in time than 1970. The data set used in the analysis of Sandèn and Håkansson, 1996 included 3952 observations from the Baltic Sea and they obtained a Secchi depth shoaling rate of ~0.05 m yr^{-1}. Fleming-Lehtinen and Laamanen (2012) report shoaling rates, which was based on observations from the summer season in open water, on the range 0.01–0.04 m yr^{-1} in different sub regions of the Baltic Sea. They excluded the coastal waters and noted that these waters need a detailed analysis on their own. This is achieved in the present study by adding two attributes to the data base of Aarup (2002); the distance to coast and bottom depth for each Secchi observation.

Seasonality is commonly considered to be an import source of variation in Secchi depth. But factors like distance to coast and bottom depth are also strong predictors for Secchi depth (e.g. Aksnes et al., 2007). Such topographical effects also appear in climatologies for the Baltic Sea and the North Sea (Aarup, 2002; Doron et al., 2011). Here we estimate how Secchi depth is affected by bottom depth and distance to coast and use this to map temporal changes in water clarity in the coastal as well as in the open waters of the Baltic Sea and the North Sea. Finally, we discuss potential ecosystem effects that involve reduced photic habitats and visibility associated with the centennial change in Secchi depth of the Baltic Sea and the North Sea.

2. Materials and methods

2.1. The data set

The Secchi depth observations compiled by Aarup (2002) are available at ICES (http://www.ices.dk/ocean/project/secchi/). This database contains 40 829 Secchi depth observations made in the period from 1903 to 1998 and covers the geographic area from −5°E to 55°E and from 50°N to 66°N. Information on the position (latitude, longitude) and the time of observation are provided for each record, but no records of bottom depth are included.

We checked the dataset and removed duplicate records. Observations made the same day at the same location, but at a different hour, were averaged to represent that day. The Secchi disk observations are irregularly distributed in time (Fig. 1A) and space (Fig. 1B) with a prominent lack of observations in the period 1940–1957 (Fig. 1A).

We estimated the bottom depth and the shortest distance to the coast by use of the NOAA internet accessible databases (http://www.ngdc.noaa.gov/). The one arc-minute global relief model ETOPO1 (Amante and Eakins, 2009) was used to estimate the bottom depth, and the shoreline database (Wessel and Smith, 1996) to calculate the shortest distance between a Secchi depth station and the coast (mapping package m_map for Matlab MathWorks©). Fig. 1C and D show that the Secchi observations have, on average, been taken in shallower areas, as well as closer to the coast, in the later than in the early years. Bottom depth was positively correlated with distance to coast, but the association was surprisingly low. In a linear regression (not shown) only 10% of the variation in bottom depths could be accounted for by the variation in distance to coast.

We defined North Sea observations as those obtained between 51°N and 61°N and between −3.5°E and 13°E, and Baltic Sea observations as those obtained between 50°N and 66°N and between 13°E and 30°E.

2.2. Statistical analyses

First we used a non-parametric Wilcoxon test to estimate the temporal change in Secchi depth by comparing the median Secchi depth of the early (before 1940) and the late period (after 1957). This comparison was based on pairwise observations made at approximately the same location, i.e. within a distance of 0.25 latitudinal degrees. Secchi depth observations of the same time period from one such location were averaged so that we were left with only one Secchi depth for the early period and one Secchi

Table 1
The Wilcoxon test for differences in the Secchi depths of the early and the late period (see Methods). The number of pairs is given by n, and the p-values refer to the test of the null hypothesis: There is no significant difference between the Secchi depth of the early and the late period. The variation of the 30 repeated random selections (see Methods) is indicated by the 95% confidence interval given in parentheses. The early and late periods for the Baltic Sea are 1905–1940 and 1957–1999 for locations deeper than 100 m (marked deep), and 1903–1940 and 1957–1999 for locations shallower than 100 m (marked shallow). For the North Sea these are 1904–1909 and 1968–1999 (deep) and 1903–1913 and 1962–1999 (shallow than). The column "Years between periods" are the differences between the midyear of the two time periods. The absolute change is $S2 - S1$, while the proportional change is $100\% \times (S2 - S1)/S1$, where $S1$ and $S2$ are the median Secchi depths of the early and late period respectively.

Area	p	Median Secchi depth (m)		n	Years between periods	Absolute change (m)	Proportional change (%)
		Early period	Late period				
Baltic Sea deep	<0.001	10.3	6.8 (6.8, 6.9)	90	55.5	−3.5 (−3.6, −3.5)	−34
Baltic Sea shallow	<0.001	9.5	6.0 (6.0, 6.0)	203	59.5	−3.5 (−3.5, −3.5)	−37
North Sea deep	<0.05	13.2	9.8 (9.8, 10)	19	77.0	−3.4 (−3.4, −3.2)	−26
North Sea shallow	<0.001	10.0	6.4 (6.2, 6.5)	90	72.5	−3.6 (−3.8, −3.5)	−36

depth for the late period. Since there are much more observations in the late than the early period, observations in the late period were randomly sampled and compared with the observations of the same grid cell in the early period. We used the non-parametric sign test for paired samples with the null hypothesis that there was no difference between the Secchi depth (median) of the early and the late period. The random pairing and subsequent test were repeated 30 times.

We consider the geographic (Fig. 1B) coverage of the data set to be better than the temporal coverage (Fig. 1A) and estimated the topographical before the temporal effect. The topographical effect, i.e. the effects of bottom depth (B, m) and distance to coast (D, km) on Secchi depth (S, m), were estimated by multiple linear regression analysis according to the model; $S = a + bB + dD$. Here, a (m) corresponds to a (theoretical) Secchi depth at $B = 0$ m and $D = 0$ km while b (m m^{-1}) and d (m km^{-1}) are the effects of bottom depth and distance to coast respectively. These effects were estimated by fitting the model to the observed Secchi observation (S_{obs}). The residuals, i.e. $S_R = S_{obs} - S$, from this model corresponds to the Secchi depth after removal of the topographical effects. We tested whether these residuals contained a temporal effect by the use of a second regression analysis, $S_R = e + ft$, where t (yr) is time, f (yr^{-1}) is the temporal effect, and e (m) is the residual Secchi depth at $t = 0$ (which corresponds to 1903). We also included the two interaction terms between bottom depth and time, and distance to coast and time. These were minor or statistically insignificant and are not reported.

An alternative way to estimate the temporal effect is to enter all three effects (i.e. distance to coast, bottom depth and time) simultaneously in a multiple regression analysis. This procedure provided estimates of the temporal effect that were, at most, 13% higher than the estimates obtained by the stepwise procedure explained above. We have reported the results of the stepwise procedure as we consider this procedure to be more conservative according to the null hypothesis of no change in Secchi depth.

3. Results

3.1. Temporal changes in Secchi depth according to the Wilcoxon test

First we note that the pairwise comparisons made in this test were based on the location of the Secchi observations of the first period only (see Methods), and therefore the result was not affected by the change towards shallower and more coastal locations over time as seen in Fig. 1C and D.

We separated the observations for the Baltic Sea and the North Sea, but also for areas deeper and shallower than 100 m. The null hypothesis; there is no difference between Secchi depths in the early and the late period, was rejected for all four subsets (Table 1). According to this test the decline in median Secchi depth between the two periods was 3.4–3.6 m for the four subdivisions of the data set (Table 1). This shoaling occurred over a time period that corresponds to the difference between the midpoints of the two periods ranging from 55.5 to 77 years (Table 1). As will be discussed below it is also of interest to look at the proportional change in Secchi depth (i.e. the change divided by the initial value). According to the Wilcoxon test the Secchi depth was reduced with 26–36% over the reported time periods in Table 1. The proportional change was somewhat higher in the shallow than the deep areas because the initial Secchi depth was shallower in shallow areas.

3.2. The topographical effect on Secchi depth

Secchi depth deepens with bottom depth (Fig. 2A) and distance to coast (Fig. 2B). The two effects appear similar for the Baltic Sea and the North Sea. Both effects were statistically significant ($p < 0.01$) in seven out of eight cases (Table 2). The correlation, although not particularly strong (see Methods), between the two predictors complicates interpretation of their relative contribution to the variation in Secchi depths. The standardized regression coefficient (β in Table 2), however, suggests that distance to coast is most influential on Secchi depth (0.018–0.034 m km^{-1}) in the deeper areas (>100 m), while bottom depth appears most influential (0.040–0.063 m m^{-1}) in the shallow areas (<100 m).

The seasonal variation in Secchi depth is not very pronounced (Fig. 2C) which is consistent with the findings of Fleming-Lehtinen and Laamanen (2012) that variation in phytoplankton did not account for a very large proportion of the variation in Secchi depth of the Baltic Sea. The seasonality appears to be even less pronounced in the North Sea (Fig. 2C). Here, storm action has the potential to significantly increase resuspension of bottom sediments over the large shallow areas during winter (Thompson et al., 2011). This might have contributed to the shallow Secchi depth that appears for the North Sea in the winter months (Fig. 2C). We also note that the estimated effect of bottom depth, 0.063 m m^{-1} (Table 2) is strongest for the shallow (<100 m) North Sea, and it might be speculated whether the strong bottom depth effect reflects increased resuspension of bottom sediments in shallow areas.

3.3. Temporal changes in Secchi depth according to the regression analysis

If all Secchi depth observations for the Baltic and the North Sea are combined, an overall centennial decline in the mean Secchi depth of 4.6 ± 0.2 m is indicated (upper line in Fig. 3). Part of this decline, however, is due to the topographical effect, i.e. the change towards shallower and more coastal locations over time (Fig. 1C and D). After subtraction of the topographical effects (see Methods), the

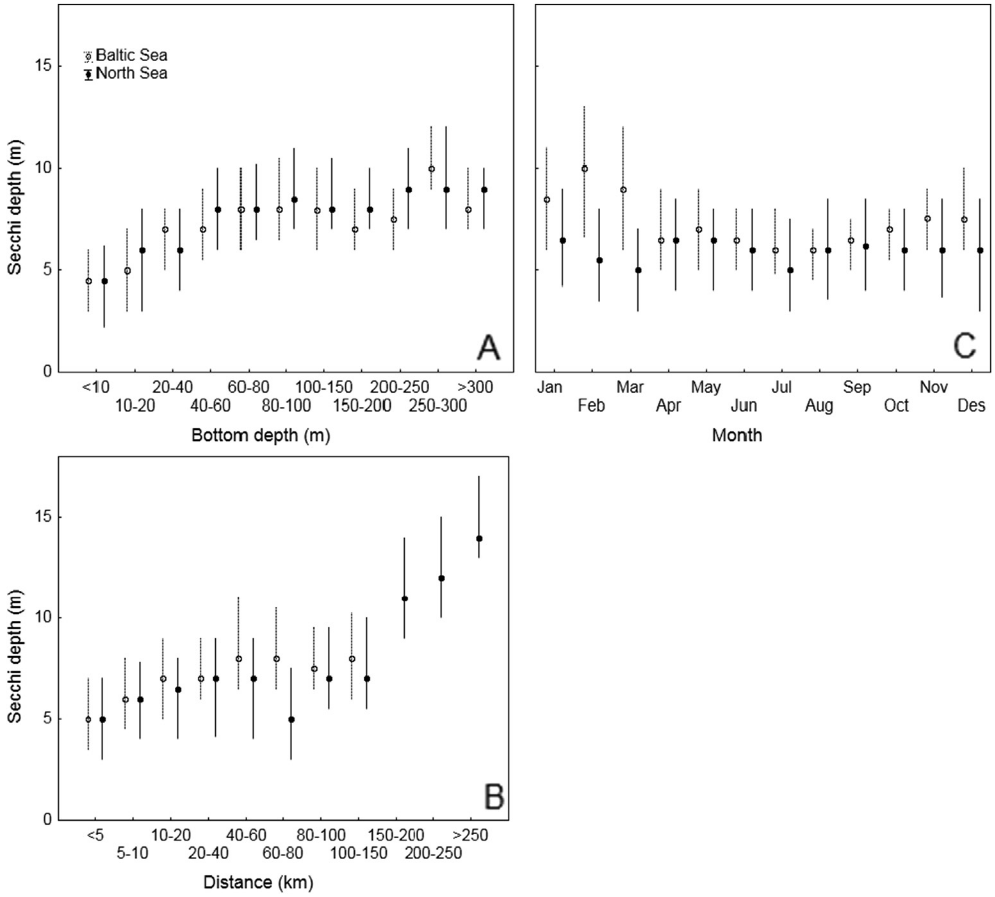

Fig. 2. Median Secchi depth and quartiles as a function of bottom depth (A), distance to coast (B), and month (C) for the Baltic Sea and the North Sea.

overall Baltic Sea and North Sea centennial decline corresponds to 3.1 ± 0.2 m (lower line in Fig. 3) which is in close agreement with the results of the Wilcoxon test. This decline, however, spanned from 1.8 to 5.8 m when the observations were divided into the Baltic Sea, the North Sea, and into deep (>100 m) and shallow (<100 m) areas (Table 3, Fig. 4). The largest centennial declines were indicated for the deep areas of the Baltic Sea (5.8 ± 0.6 m) and the North Sea (5.2 ± 0.9 m). The declines for the shallow areas were 3.2 ± 0.2 m for the Baltic Sea and 1.8 ± 0.3 m for the North Sea (Table 3).

If the regression model for the topographical effects is combined with that of the temporal effect (see Methods), we obtain a predictor for the Secchi depth as a continuous function of bottom depth, distance to coast, and time; $S_{pred} = (a + e) + bB + dD + ft$. The estimates of a, b and d are given in Table 2 and of e and f in Table 3. This combined model was used to provide a geographical map of the Secchi depth decline (Fig. 5). The largest shoaling rates are generally far from the coast, but a notable exception is seen along the coast of Norway. Here the large Secchi depth shoaling coincides with the large bottom depths of the Norwegian Trench.

4. Discussion

For the North Sea, we are not aware of studies on Secchi depth that extend further back in time than 1970. Both the Wilcoxon test (Table 1), and the changes in residual Secchi depth (Table 3 and

Table 2
Effects of bottom depth (B, m) and distance to coast (D, m) on Secchi depth. The effects were estimated according to the multiple regression model: $S = a + bB + dD$. The estimated values of a (m), b (m m^{-1}), and d (m km^{-1}) are given in the column "Coefficient". The β is the regression coefficient that is obtained when all variables are standardized to a mean of 0 and a standard deviation of 1. This coefficient compares the relative contribution of each independent variable (bottom depth and distance to coast) in the prediction of the dependent variable (Secchi depth). Deep and Shallow refer to locations with bottom depth larger and shallower than 100 m respectively.

Effect	Baltic Sea			North Sea		
	Deep (n = 3223)			Deep (n = 1788)		
	β	Coefficient	p	β	Coefficient	p
Intercept (a)		7.00	<0.001		7.31	<0.001
Bottom depth (b)	0.06	0.003	<0.001	0.04	0.001	0.07
Distance to coast (d)	0.16	0.018	<0.001	0.27	0.034	<0.001
	Shallow (n = 13935)			Shallow (n = 19941)		
Intercept (a)		4.98	<0.001		4.42	<0.001
Bottom depth (b)	0.33	0.040	<0.001	0.41	0.063	<0.001
Distance to coast (d)	0.08	0.013	<0.001	0.02	0.003	<0.01

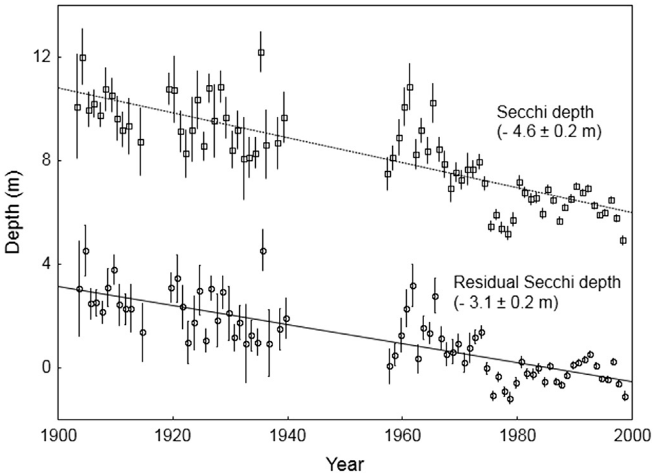

Fig. 3. Centennial trends before (Secchi depth) and after (residual Secchi depth) subtraction of the topographical effects (see text) for all observations in the Baltic Sea and the North Sea. The data points are annual means (95% c.i.). The trend lines and the indicated slopes were estimated by linear regression.

Fig. 4), suggest that the centennial change of the North Sea is comparable to that of the Baltic Sea. The pronounced lack of observations in the North Sea in the period from 1913 to 1962, however, makes this interpretation uncertain. McQuatters-Gollop et al. (2007) observed the shallowest Secchi depth in the late 1970's. This minimum also appears as a notable drop in the residual Secchi depth (i.e. after removal of the topographical effect) in the North Sea (Fig. 4). Our results, however, suggest that the Secchi deepening, which took place after the minimum in the 1970's, did not return to the Secchi depths recorded at the beginning of the century (Fig. 4).

Sandèn and Håkansson (1996) obtained a long term Secchi depth shoaling rate of ~0.05 m yr^{-1} for the Baltic Sea while Fleming-Lehtinen and Laamanen (2012) reported shoaling rates on the range 0.01–0.04 m yr^{-1} in different sub regions of the Baltic Sea (their Table 1). Our results (Table 3 and Fig. 5) are consistent with the estimates of these previous studies, but suggest that the Secchi depth shoaling of a location is severely affected by the topography (i.e. the bottom depth and distance to coast). Our results suggest that the change of location towards shallower areas (Fig. 1C) and towards the coast (Fig. 1D) over time causes overestimation of the temporal shoaling rate unless the observations are corrected for the "change of location effect" (Fig. 3). For the entire dataset the overestimation corresponds to a surplus of 1.5 m, or 37%, compared to the shoaling rate obtained after removal of the topographical effects (i.e. the residual Secchi depth in Fig. 3).

Distance to coast has previously been reported as strong predictor of Secchi depth and shoaling rates off the coast of California (Aksnes et al., 2007; Aksnes and Ohman, 2009) and an important implication of this was noted: A certain absolute change in Secchi depth at an inshore location is generally caused by a larger change in $c + K$ than the same absolute change at an offshore location. This is because 1) the Secchi depth of the offshore location is likely to be deeper than at the inshore location (as seen in Fig. 2A and B); and 2) as seen from Eq. (1) and exemplified in the Introduction; a 1 m change in a shallow Secchi depth requires much larger change in $c + K$ than a deep Secchi depth. Thus although our results suggest that the absolute centennial change in Secchi depth has been larger at far from coast than close to coast, this cannot be interpreted as if the change in the underlying optical properties has been largest away from coast.

The Secchi observations used in our study originate from many sources (Aarup, 2002), and the observations are affected by methodological changes concerning the disc as well as natural changes in the water reflectance that affects the coupling constant of Eq. (1). This prohibits assessments of changes in c and K. Nevertheless, since these properties have large ecological implications (Kirk, 2011; Johnsen, 2012; Irigoien et al., 2013) and they scale with the reciprocal Secchi depth, we find it useful to discuss potential ecosystem effects with reference to them.

4.1. Potential ecosystem effects associated with Secchi depth shoaling

4.1.1. The K-effect and photic habitat reduction

An organism, which is characterized by having a preferred or required range of light intensity, will have a vertical photic habitat (H, m) of $H = k_1/K$, where k_1 is determined by the upper and lower light preference thresholds of the organism (Fig. 6A). For the euphotic zone, which is often defined as the layer between the surface (100% light) and the depth of 1% light penetration (Kirk, 2011), this expression becomes $H = 4.6/K$ since ln(100%/1%) = 4.6. Thus, because Secchi depth also relates reciprocally to K (Eq. (1)), H tends to be proportional to the Secchi depth, i.e. $H \propto S$. From this, we expect that the vertical euphotic habitat loss of the Baltic Sea and the North Sea correspond to the proportional change in Secchi depth. Consequently, the Wilcoxon test (last column of Table 1) suggests that the euphotic habitat has been reduced with 26–37% from the early to the late period (i.e. over a period of 55.5–77 years, Table 1). Depending on location somewhat larger losses are indicated with the regression model. E.g. if 20 m bottom depth at a distance of 1 km are inserted in the model for the shallow Baltic Sea (Table 3), a centennial euphotic habitat loss of 44% is indicated.

A linear relationship between the vertical macroalgae habitat and the Secchi depth of Danish coastal waters has indeed been observed (e.g. Nielsen et al., 2002). For the outer Oslofjord, in the

Table 3
Temporal change in residual Secchi depth (S_R) estimated by regression analysis (see Methods). The estimated values of the intercept and the temporal change, f, are given with 95% c.i. in the column "Coefficient". Note that the temporal change is here given as m yr^{-1} and that the centennial change referred to in the text equals this quantity multiplied with 100 years. Deep and Shallow refer to locations with bottom depth larger and shallower than 100 m respectively.

Effect	Baltic Sea			North Sea		
	Deep (n = 3223)			Deep (n = 1788)		
	Coefficient	c.i.	p	Coefficient	c.i.	p
Intercept (e)	3.69	0.31	<0.001	4.46	0.77	<0.001
Temporal change (f)	−0.058	0.006	<0.001	−0.052	0.009	<0.001
	Shallow (n = 13935)			Shallow (n = 19941)		
Intercept (e)	2.69	0.20	<0.001	1.71	0.28	<0.001
Temporal change (f)	−0.032	0.002	<0.001	−0.018	0.003	<0.001

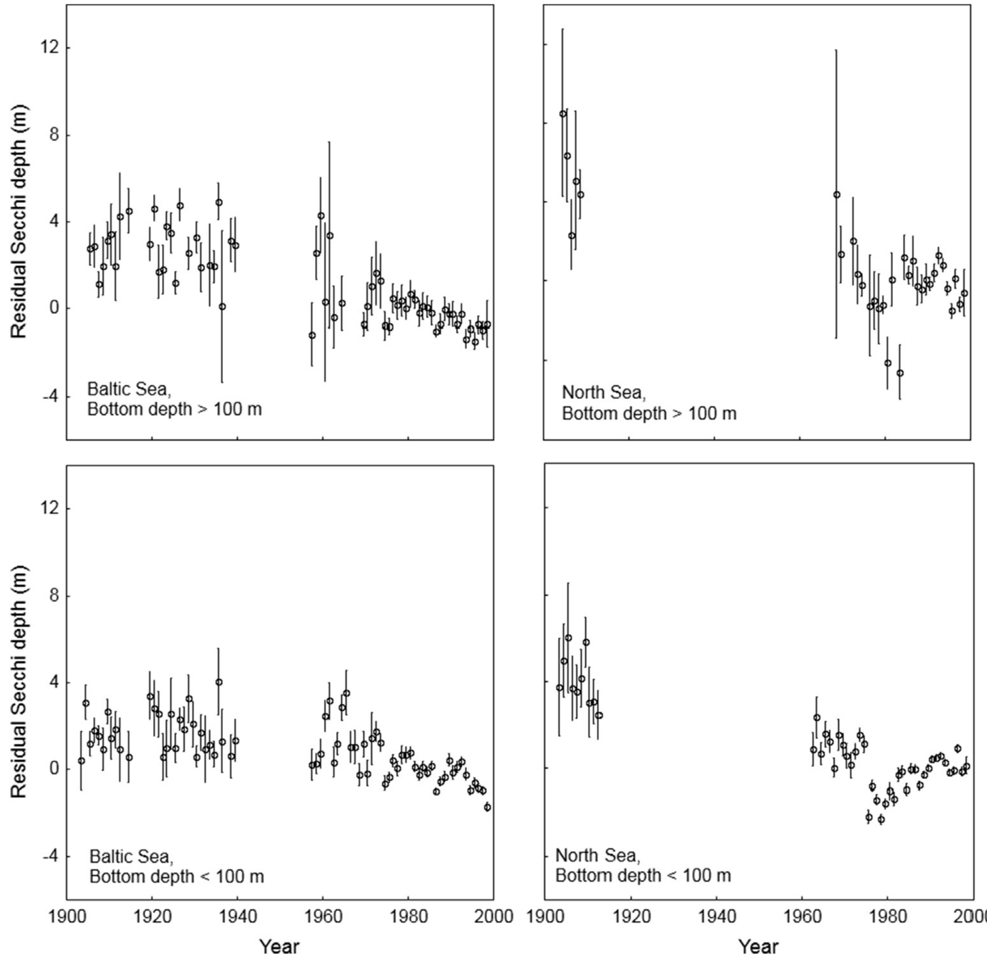

Fig. 4. Residual Secchi depth (i.e. after removal of the topographical effects) as a function of time for four subdivisions of the data set. The data points are annual means (95% c.i.). Estimates of temporal changes are given in Table 3.

Skagerrak area of the North Sea, Rueness and Fredriksen (1991) reported that the lower depth limit of a number of common algal species on average had become 30–40% shallower in the period from around 1950 and up to 1989 (fig. 3 in Rueness and Fredriksen, 1991). E.g. the lower depth limit of the kelp *Laminaria saccharina* shoaled from 25 to 15 m. Further reduction of this species along the coast of southern Norway has been reported (Moy et al., 2008) and is currently of great concern (Frigstad et al., 2013). Kautsky et al. (1986) found that the lower depth limit of *Fucus vesiculosus* in the Baltic Sea had moved upwards from 11.5 m in 1943/44 to 8.5 m in 1984. This corresponds to a vertical habitat loss of 26%. Our Secchi derived estimates of euphotic habitat losses appear consistent with the results of macroalgae studies.

Euphotic zone shoaling, as expressed by Secchi depth shoaling, implies that the phytoplankton biomass and nutricline becomes shallower and narrower (Urtizberea et al., 2013). For the California Current System this effect corresponded to 3–4 mnitracline shoaling for each metre of Secchi depth shoaling (Aksnes et al., 2007). If this applies to the Baltic Sea and the North Sea, a centennial 10–15 m nutricline shoaling is indicated. In stagnant hypoxic water masses, such as in the Baltic Sea, where photosynthesis is a source for dissolved oxygen at depth, oxycline shoaling is also a likely effect of euphotic zone shoaling. The analysis of Urtizberea et al. (2013) suggests that increased CDOM concentration of costal and oceanic water causes symptoms that are similar to those of eutrophication also in cases where production and nutrient supplies are unchanged.

4.1.2. The c-effect and decreased visibility

While the light intensity is important to the photoautotrophs, water clarity also has direct effects on organisms that utilize vision in their search for prey (Fig. 6B). The sighting distance (r) of a visual predator can be expressed $r = k_2/c$, where k_2 is determined by the inherent contrast of the prey and contrast threshold of the predator (Johnsen, 2012). The prey detection rate tends to be proportional to r^2 (Aksnes and Utne, 1997) and therefore also to $1/c^2$. Since c is here squared, the potential loss in visual feeding ability is much more sensitive to a change in c than a photic habitat is to the same relative change in K. Evidence of visual constraints on fish stocks have been provided elsewhere (Lester et al., 2004; Aksnes, 2007), but also for the Baltic Sea some evidence suggest that increasing visual constraints in the Baltic Sea have affected the competitive relationship between tactile (jellyfish) and visual (fish) predators (Haraldsson et al., 2012).

4.2. CDOM – a role in the Secchi depth shoaling?

Based on a proxy relationship between Secchi depth and chlorophyll, Sandèn and Håkansson (1996) found that a 0.05 m yr^{-1} Secchi depth shoaling in the Baltic Sea corresponded to a 1% yr^{-1}

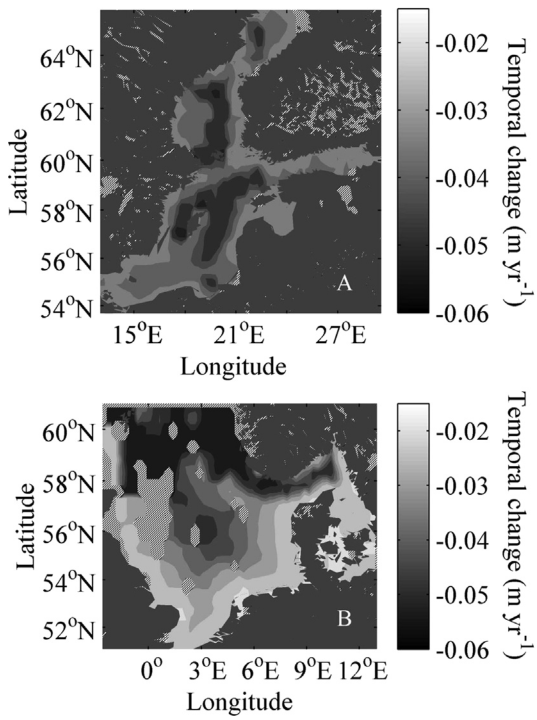

Fig. 5. Map of the long term Secchi depth shoaling rate (m yr^{-1}) for the Baltic Sea (A) and the North Sea (B) according to the estimated effects of bottom depth, distance to coast (see text).

rise in chlorophyll. They cautioned, however, that this estimate was unreliable due to substantial uncertainty regarding the assumed proxy and the effect of humic substances (CDOM) that might have changed in the 20th century. Chlorophyll, or phytoplankton, alone is indeed known to be a poor predictor for light attenuation in many coastal waters and often the effect of variation in CDOM appears much more important than chlorophyll (Branco and Kremer, 2005; Kowalczuk et al., 2006). Since terrestrial CDOM is transported with freshwater that are mixed conservatively with seawater in the coastal zone (Kowalczuk et al., 2006), absorption of light is inversely related to salinity (Aarup et al., 1996; Højerslev et al., 1996; Kowalczuk et al., 2005). Salinity therefore appears to be an efficient proxy for light absorption, attenuation, and thereby for Secchi depth. The brackish surface water of the Baltic Sea, with salinity less than 10 over large areas, contains more freshwater than water of oceanic origin. Consequently, from an optical point of view, the Baltic Sea is exceptional because of its brackish nature and its high concentration of terrestrial CDOM compared to other seas (Kratzer et al., 2003; Kowalczuk et al., 2005). Thus it is not surprising that the seasonal signal is relatively weak (Fig. 2C), and that Fleming-Lehtinen and Laamanen (2012) found that phytoplankton to a little degree affected the Secchi depth in the Baltic Sea.

Furthermore, an analysis of the Helgoland Roads time series revealed a deepening in Secchi depth from about 3.5 to 4.5 m over the period 1975–2005 (Wiltshire et al., 2008) that could not be explained by changes in algal density. Also, McQuatters-Gollop et al. (2007) noted that the shallow Secchi depth of the North Sea in the late 1970s's (see also Fig. 4) coincided with low, and not high, chlorophyll values in both the open and the coastal North Sea. What is described as a regime shift in the North Sea in the 1980's was characterized by increased chlorophyll concentrations that coincided with a deepening of the Secchi depth and increased inflow of salty oceanic water (McQuatters-Gollop et al., 2007). Given the inverse relationship between CDOM light absorption and salinity in the North Sea (Aarup et al., 1996; Højerslev et al., 1996), it might be hypothesized that the annual and decadal variation in CDOM concentrations, through its effect on light penetration, affected the state and regime shift of the North Sea in the 1980's. To what extent the centennial change in Secchi depth has been affected by changes in the CDOM content, however, is unclear.

For the Norwegian Coastal Water (NCW), which partly originates from the outflowing Baltic Sea water, evidence suggests that freshening, which has been linked to increased precipitation in Northern Europe, has contributed to a long term increase in the non-chlorophyll light attenuation of the NCW since the 1930's (Aksnes et al., 2009). In addition to increased CDOM loads as a consequence of increased precipitation, increased brownification (Roulet and Moore, 2006; Larsen et al., 2011; Frigstad et al., 2013) is an another concern. Brownification results from higher CDOM concentrations in streams and lakes. This phenomenon is probably linked to climatic driven changes in the terrestrial vegetation. A severe increase in CDOM concentration is predicted in Scandinavian freshwater sources in the coming years (Larsen et al., 2011). In that case this load ultimately ends up in the Baltic and the North Sea. Thus we suggest that the role of variation in CDOM, and its

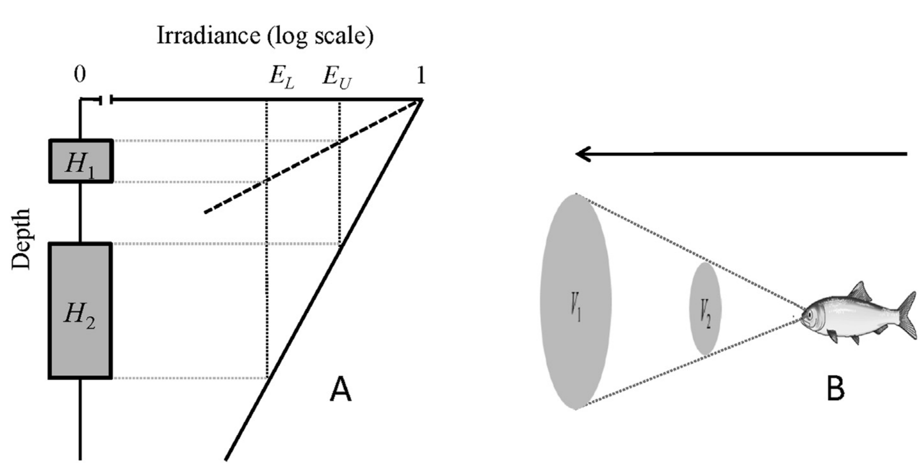

Fig. 6. The *K*- and *c*-effects on light sensitive organisms. Secchi depth shoaling is associated with increase in *c* and *K* (see Eq. (1)) A: An increase in the attenuation of downwelling irradiance from K_2 (solid line) to K_1 (broken line) shallows and narrows the habitat from H_2 to H_1 for an organism with a preference for a certain range of illumination. This range is here indicated by an upper (E_U) and a lower (E_L) irradiance level. B: An increase in the beam attenuation coefficient (*c*) reduces the visual area from V_1 to V_2 for a cruising predator.

effect on the water clarity and on the Baltic Sea and North Sea ecosystems, deserve future attention.

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