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ORIGINAL RESEARCH ARTICLE

Water type quantification in the Skagerrak, the Kattegat and off the Jutland west coast

Trond Kristiansen [a], Eyvind Aas [b,*]

[a] *Institute of Marine Research, Bergen, Norway*
[b] *Department of Geosciences, University of Oslo, Oslo, Norway*

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KEYWORDS
German Bight;
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Summary An extensive data series of salinity, nutrients and coloured dissolved organic material (CDOM) was collected in the Skagerrak, the northern part of the Kattegat and off the Jutland west coast in April each year during the period 1996—2000, by the Institute of Marine Research in Norway. In this month, after the spring bloom, German Bight Water differs from its surrounding waters by a higher nitrate content and higher nitrate/phosphate and nitrate/silicate ratios. The spreading of this water type into the Skagerrak is of special interest with regard to toxic algal blooms. The quantification of the spatial distributions of the different water types required the development of a new algorithm for the area containing the Norwegian Coastal Current, while an earlier Danish algorithm was applied for the rest of the area. From the upper 50 m a total of 2227 observations of salinity and CDOM content have been used to calculate the mean concentration of water from the German Bight, the North Sea (Atlantic water), the Baltic Sea and Norwegian rivers. The Atlantic Water was the dominant water type, with a mean concentration of 79%, German Bight Water constituted 11%, Baltic Water 8%, and Norwegian River Water 2%. At the surface the mean percentages of these water types were found to be 68%, 15%, 15%, and 3%, respectively. Within the northern part of the Skagerrak, closer to the Norwegian coast, the surface waters were estimated to consist of 74% Atlantic Water, 20% Baltic Water, and 7% Norwegian River Water. The analysis indicates that the content of German Bight Water in this part is less than 5%.

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* Corresponding author at: Department of Geosciences, University of Oslo, Gaustadalléen 21, N-0315 Oslo, Norway.
Tel.: +47 22855808; fax: +47 22855269.
E-mail address: eyvind.aas@geo.uio.no (E. Aas).
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1. Introduction

Skagerrak is heavily influenced by both the Baltic and the North Sea. About 70% of the water entering the North Sea is assumed to pass through this area (ICES, 1983), and many of the hydrographical events taking place in the North Sea will be reflected in the Skagerrak. The general circulation in the area is cyclonic (Fig. 1), and the distribution of the water masses is mainly regulated by the in- and outflow of water in the North Sea. The steep bottom topography characterised by the deep Norwegian Trench is of special importance for the steering and mixing of the water masses (Danielssen et al., 1997; Rodhe, 1996; Svansson, 1975). In addition there is a large freshwater supply to the Skagerrak from the Baltic, the Kattegat, local rivers and continental river discharge to the southern North Sea (Gustavsson and Stigebrandt, 1996). The Jutland Coastal Current appears to constitute a link between the eutrophicated waters of the southern North Sea and the waters of the Skagerrak and Kattegat, and according to Aarup et al. (1996a) its transport may be in the range of 0.01—0.02 Sv. The average total transport of the basic cyclonic circulation in the Skagerrak has been estimated to 0.5—1 Sv (Rodhe, 1987, 1992, 1996). The distribution of the relatively fresh surface waters in the Skagerrak is strongly influenced by varying weather conditions, and local wind conditions may block as well as increase the usual pattern of surface circulation (Aure and Sætre, 1981). The surface waters mainly follow the general circulation.

Eutrophication by anthropogenic nutrients has been identified as an issue of concern for the Skagerrak/Kattegat area (Anon., 1993; North Sea Task Force, 1993). In late April 1988, just after the spring bloom, a cruise was carried out by the Institute of Marine Research in the Skagerrak, the Kattegat and along the western Danish North Sea coast to investigate the environmental conditions and anomalous nutrient concentrations related to the large fresh water runoff from the German rivers and the Baltic at that time of the year (Aure et al., 1998). High nitrate concentrations were found in the surface waters of the inner Skagerrak and the Kattegat, resulting in high NO_3:PO_4 and NO_3:SiO_4 ratios as both phosphate and silicate were near the detection limits. In the beginning of May 1988, in connection with weak winds, a well defined surface layer with high temperatures and low salinities and high nitrate concentrations and nitrate/phosphate ratios (Dahl et al., 2005), a harmful bloom of the prymnesiophyte flagellate *Chysochromulina polylepis* occurred in a large part of the Skagerrak and in the entire area of Kattegat (Dahl et al., 1989; Lindahl and Dahl, 1990). This bloom killed a large number of marine species in the upper 20 m of the sublittoral zone along most of the Norwegian Skagerrak coast (Edvardsen et al., 1988; Granéli et al., 1993; Johannessen and Gjøsæter, 1990; Underdal et al., 1989), in addition to 800 tonnes of farmed fish (Skjoldal and Dundas, 1991). Possible long-term effects and recovery in the ecosystem caused by this event have been evaluated by Gjøsæter et al. (2000). Minor blooms of *Chysochromulina polylepis* were since detected in 1994 and 1995. In 1998, 2000 and 2001 harmful algal blooms caused by *Chattonella* spp. occurred in the area. The bloom of 1998 resulted in a loss of 350 tonnes of farmed salmon in addition to some wild fish

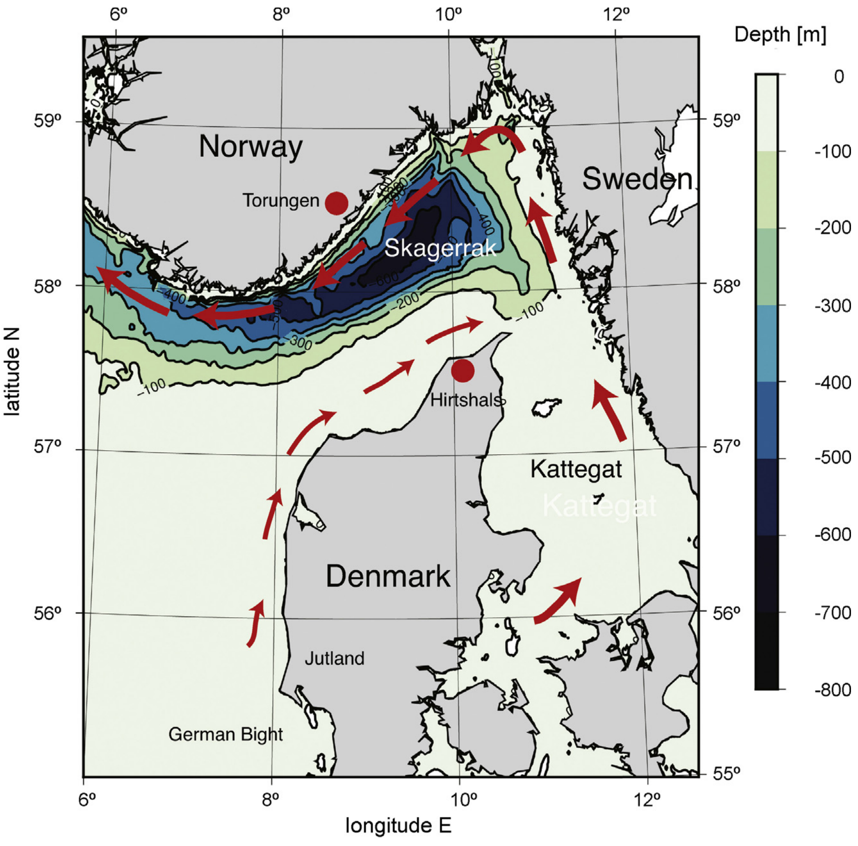

Figure 1 Currents off the Jutland west coast and in the Skagerrak and the Kattegat.

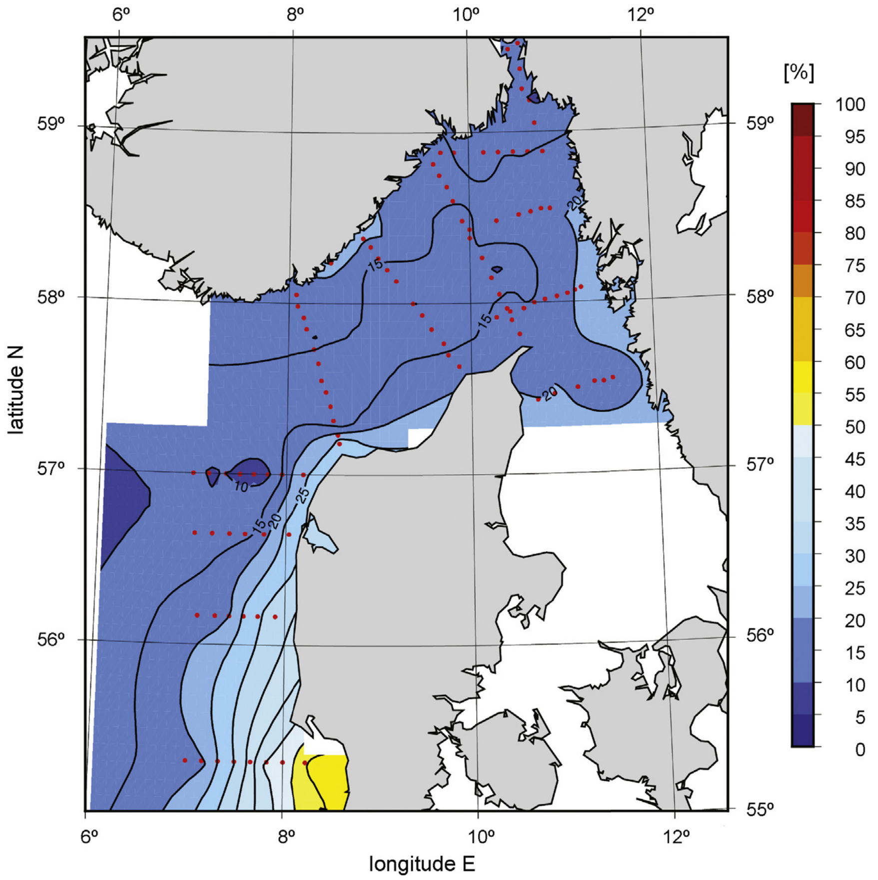

Figure 2 Surface distribution of the percentage of German Bight Water in April 1996, according to the Danish algorithm.

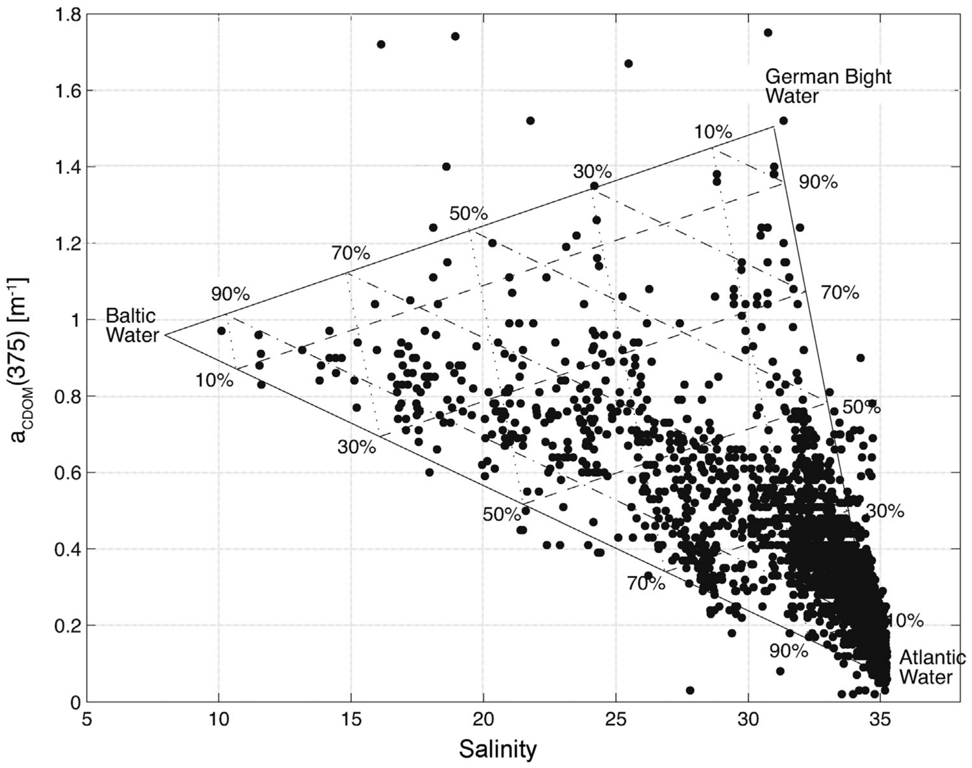

Figure 3 CDOM absorption coefficient $a_{CDOM}(375)$ versus salinity in April for all years 1996—2000 and all depths (3454 data points) from the entire area of investigation, with the Danish triangle of water types.

along the Danish and Norwegian coasts, and the bloom of 2001 caused a loss of about 1100 tonnes of farmed salmon.

Occurrence of extremely high nitrate concentrations transported with the Jutland Coastal Current from the German Bight was thought to provide favourable conditions for harmful algal blooms in the area (Aure et al., 2001; Dahl et al., 2005). The monitoring cruise started in 1988 by the Institute of Marine Research has since been repeated in April every year to document and assess the spring environmental conditions and the possibility for harmful blooms. Salinity and nutrient observations provide good indications of the width of the Jutland Coastal Current along the Danish west coast and therefore an indication of the highly annually varying volume transports into the Skagerrak caused by this current. From 1996 to 2000 the content of CDOM (Chromophoric Dissolved Organic Matter or Coloured Dissolved Organic Material), originally termed Gelbstoff (yellow substance) by Kalle (1938)), was also sampled in the entire area to investigate whether this parameter would be a suitable tracer for the water masses of the Jutland Coastal Current and for quantification of their inter-annual variations.

For references to the pioneer works on CDOM, leading up to the algorithms applied here, see Højerslev et al. (1996) and references therein. Other relevant studies of the CDOM content in this area has been presented by Aarup et al. (1996b), Ferrari and Dowell (1998), Højerslev and Aas (1998, 2001), Kopelevich et al. (1989), Kowalczuk (1999), Kowalczuk and Kaczmarek (1996), Kowalczuk et al. (2005, 2006, 2010), Lundgren (1976), Stedmon et al. (2000, 2010), and Warnock et al. (1999).

Table 1 Water types of the algorithms and their properties.

Water type	Salinity	$a_{CDOM}(375)$ [m^{-1}]
Atlantic Water	35.3	0.05
Baltic Water	8.0	0.96
German Bight Water	31.0	1.50
Norwegian River Water	0.0	7.00

2. Material and methods

2.1. Data

The data presented in this article were collected onboard r/v G.M. Dannevig in the last half of April until May each year from 1996 to 2000 in the Skagerrak, the northern part of the Kattegat and along the Danish North Sea coast. The area covered during the cruises is indicated by dots in Fig. 2, but was in some of the years reduced due to bad weather conditions or technical problems. The cruise dates were (yy.mm.dd): 1996.04.15–1996.05.04, 1997.04.16–1997.05.05,

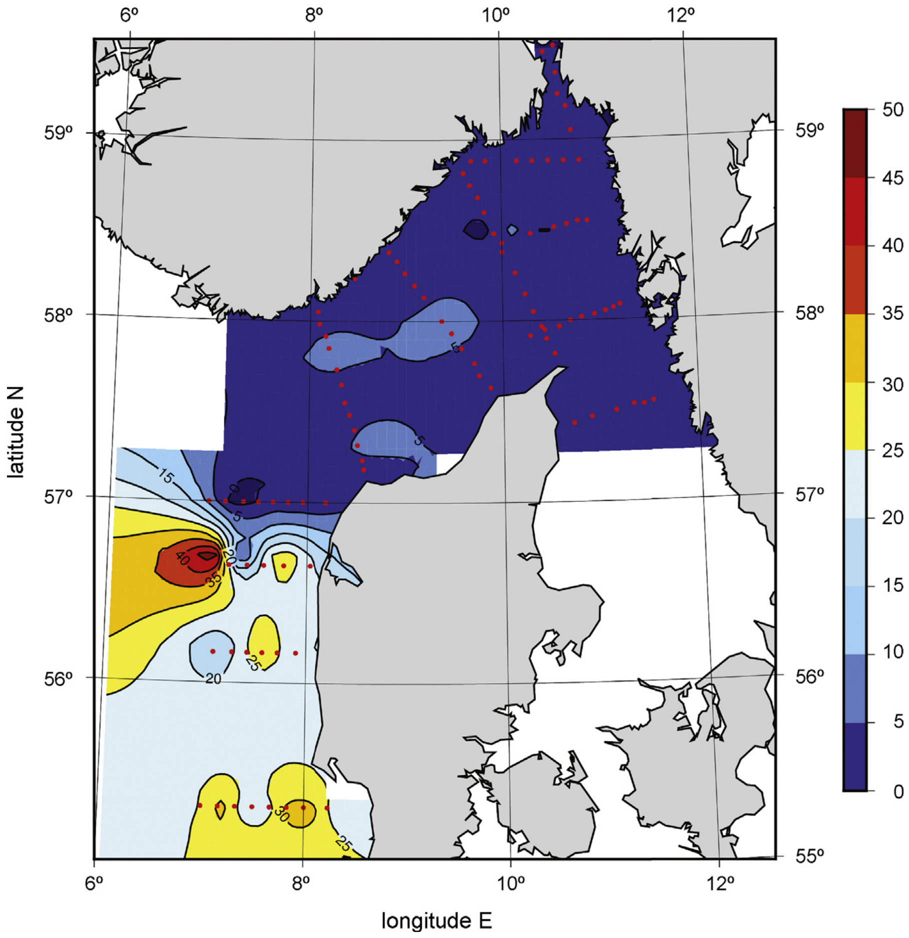

Figure 4 Surface distribution of the NO_3/SiO_4 ratio in April 1996.

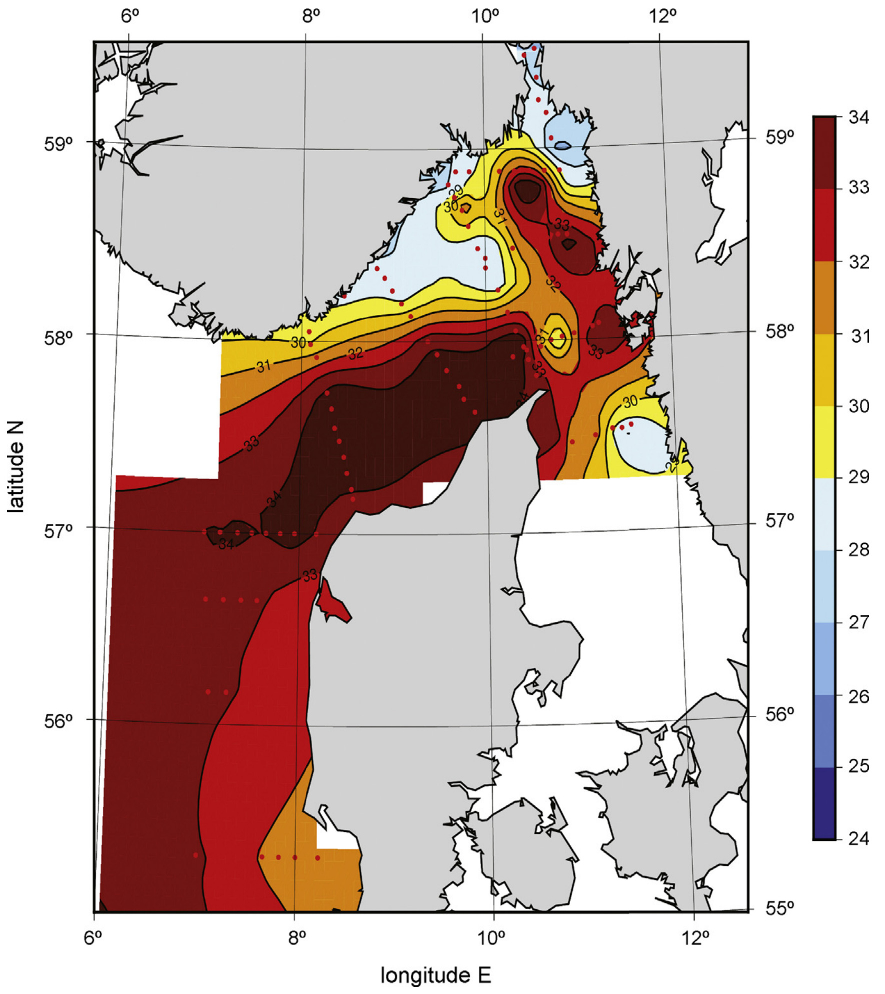

Figure 5 Surface distribution of salinity in April 1996.

1998.04.08–1998.04.27, 1999.04.15–1999.05.02 and 2000.04.15–2000.04.30. The April cruises were continued through the years, but recordings of CDOM ended in 2000. The contribution of these cruises to the environmental monitoring of these areas have been described by Mork et al. (2012). The hydrographic data can be obtained at the ICES Data Centre, the World Ocean Database or the Norwegian Marine Data Centre: http://www.imr.no/forskning/faggrupper/norsk_marint_datasenter_nmd/en

Salinity was determined by CTD (Neil Brown), and water was sampled at standard depths (0–5–10–20–30–50–75–100–150–200–300–400–500–600 m), except in the shallower Kattegat where the samples were taken at every 5 m down to a depth of 30 m. Inorganic nutrients were analysed by standard methods onboard using an auto-analyser. The content of CDOM, expressed by $a_{CDOM}(375)$, the optical absorption coefficient at 375 nm of a filtered water sample relative to a pure water reference, was measured at

Table 2 Influence of four water types on the estimates by the Danish and Norwegian algorithms. The water types are Atlantic Water (AW), Baltic Water (BW), German Bight Water (GW) and Norwegian River Water (NW). $a_{CDOM,x}$ and S_x are the resulting values of the CDOM absorption coefficient and salinity, respectively.

Input						Danish algorithm			Norwegian algorithm		
AW	BW	GW	NW	$a_{CDOM,x}$	S_x	AW	BW	GW	AW	BW	NW
[%]				[m^{-1}]		[%]			[%]		
84	8	8	0	0.24	32.8	84	8	8	91	7	2
84	8	7	1	0.29	32.5	80	9	11	90	7	3
84	8	6	2	0.35	32.2	76	9	15	89	7	3
84	8	4	4	0.46	31.5	68	10	22	88	7	5
84	8	2	6	0.57	30.9	60	12	29	86	8	6
84	8	1	7	0.62	30.6	56	12	32	85	8	7
84	8	0	8	0.68	30.3	52	13	35	84	8	8

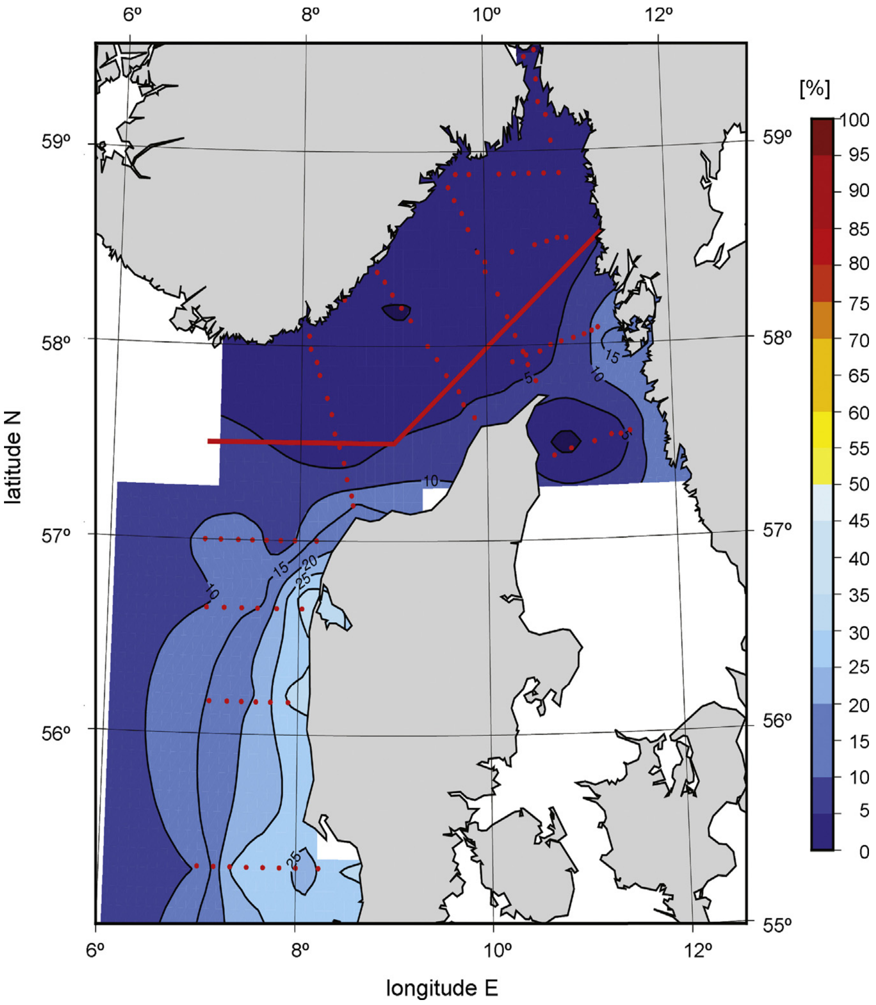

Figure 6 Surface distribution of the percentage of German Bight Water (southern part) and Norwegian River Water (northern part) in April 1996, according to the Danish and Norwegian algorithms.

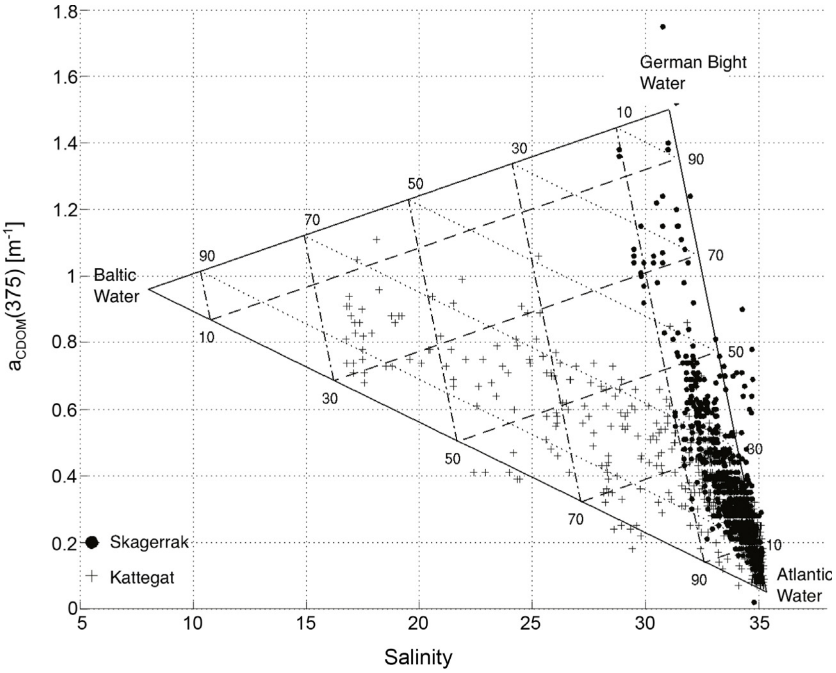

Figure 7 CDOM content versus salinity in April for all years 1996–2000 and all depths (1548 data points) from the Kattegat, the southern part of the Skagerrak and off the Jutland west coast, with the Danish triangle of water types.

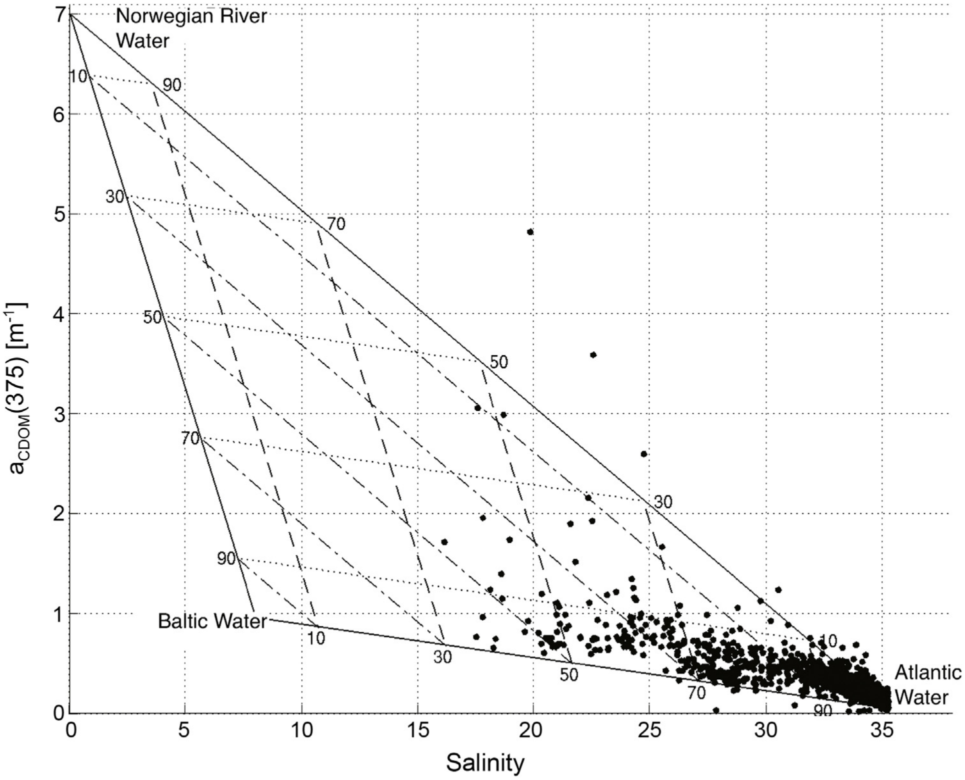

Figure 8 CDOM content versus salinity in April for all years 1996—2000 and all depths (1906 data points) from the northern part of the Skagerrak, with the Norwegian triangle of water types.

every station using a Shimadzu UV-VIS 1201 spectrophotometer with a 10 cm long cuvette. In order to correct for possible residual particles, a baseline correction was applied, based on the value at 750 nm. The reference was a sample from a Millipore water purification system. In the present study only the observations of salinity, CDOM, nitrate, and nitrate/silicate and nitrate/phosphate ratios will be discussed. From a total of 3454 observations of salinity

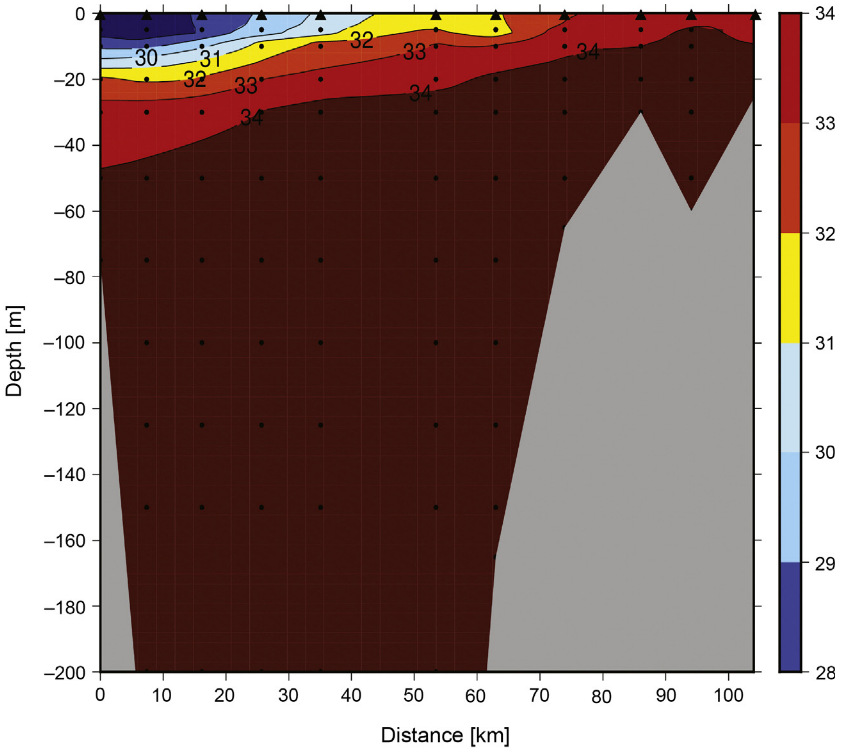

Figure 9 Mean vertical distribution of salinity in the section Torungen—Hirtshals, based on the observations in April 1996—2000.

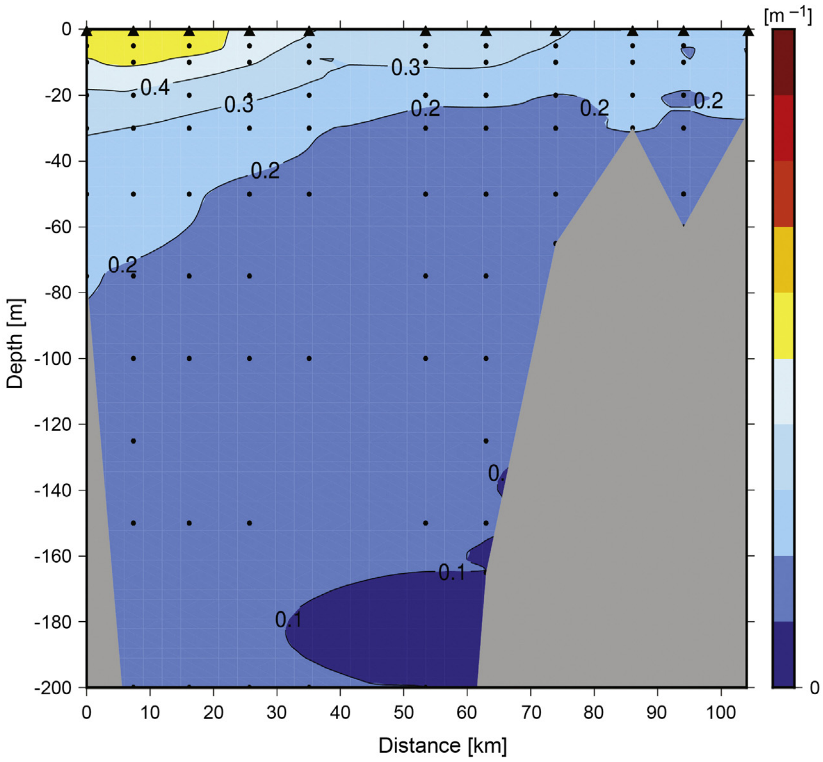

Figure 10 Mean vertical distribution of the CDOM absorption coefficient $a_{CDOM}(375)$ [m^{-1}] in the section Torungen—Hirtshals, based on the observations in April 1996—2000.

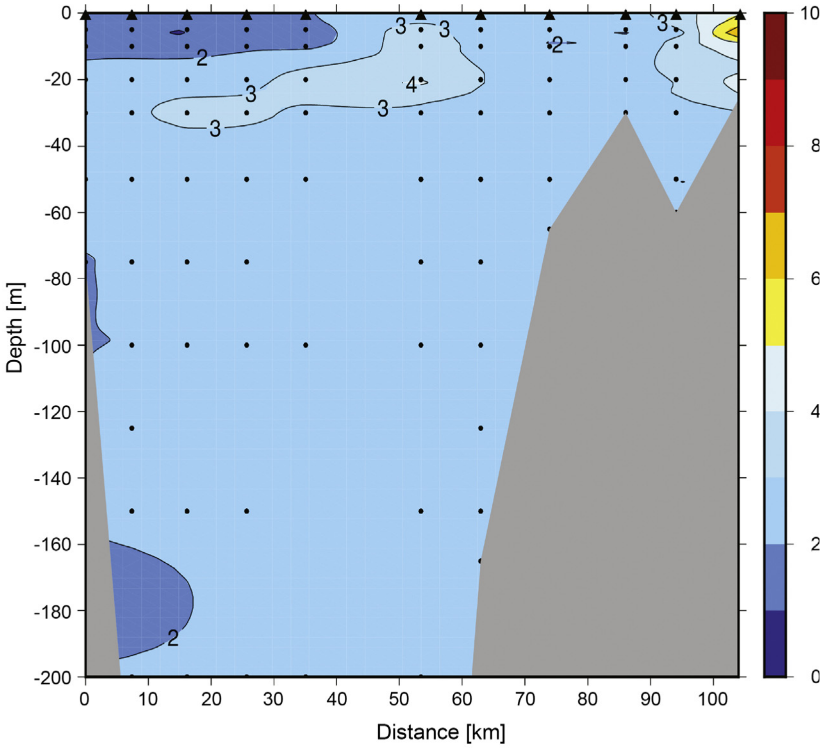

Figure 11 Mean vertical distribution of the NO_3/SiO_4 ratio in the section Torungen—Hirtshals, based on the observations in April 1996—2000.

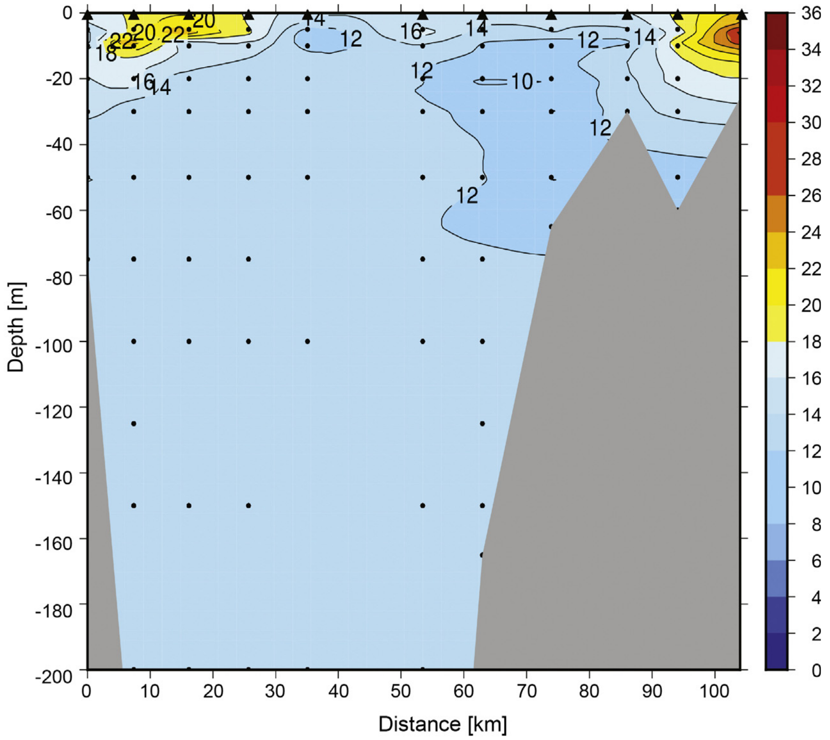

Figure 12 Mean vertical distribution of the NO_3/PO_4 ratio in the section Torungen—Hirtshals, based on the observations in April 1996—2000.

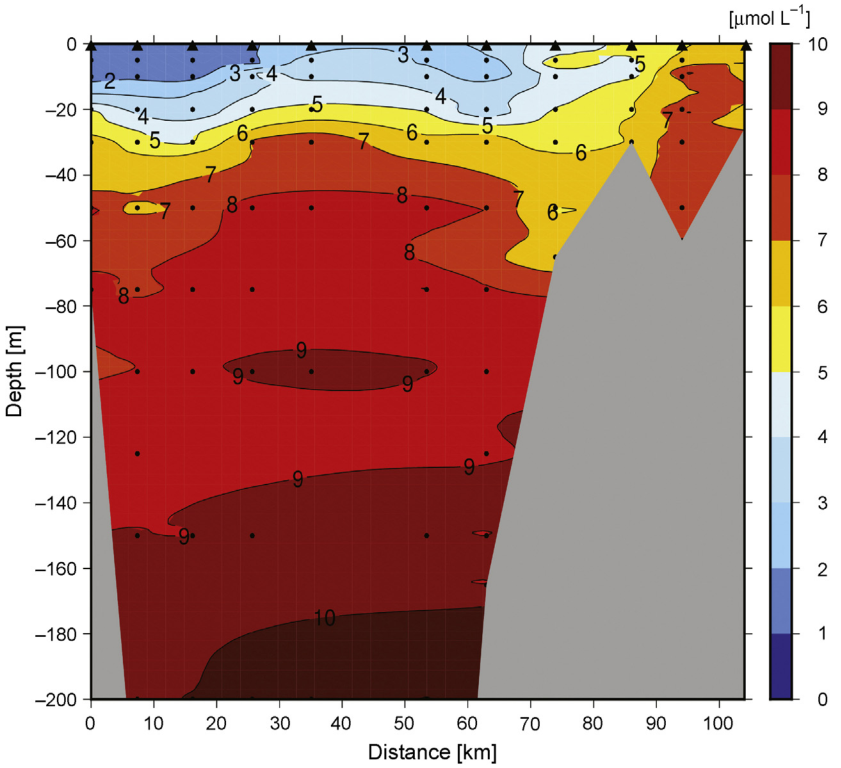

Figure 13 Mean vertical distribution of the NO_3 content [μmol L^{-1}] in the section Torungen—Hirtshals, based on the observations in April 1996—2000.

and CDOM content a smaller number of 2227 have been used to quantify the spatial distributions of water from the German Bight, the Baltic, the North Sea (Atlantic water) and Norwegian rivers within the upper 50 m.

2.2. The Danish algorithm

The water masses of the Skagerrak and the Kattegat are typically a mixture of three or four dominant water types. The algorithm presented by Højerslev et al. (1996) determines the different percentages of three water types at a given location and depth, provided the salinity and CDOM content at this depth are known. In addition the method requires some knowledge of the local hydrography and of the water types most likely to be found.

The quantification of the contents of the three water types is based on the assumption that volume, salinity and CDOM content of a water sample are conservative properties. The concentration of CDOM is expressed by the absorption coefficient $a_{CDOM}(375)$ at 375 nm. The simple algebraic relationships between relative volumes, salinities and absorption coefficients for a water sample can be written as:

$$q_B + q_A + q_G = 1, \tag{1}$$

$$S_A q_A + S_B q_B + S_G q_G = S_x, \tag{2}$$

$$a_{CDOM,A} q_A + a_{CDOM,B} q_B + a_{CDOM,G} q_G = a_{CDOM,x}. \tag{3}$$

The symbols are defined as:

q_A: relative volume of Atlantic (North Sea) Water Type,

q_B: relative volume of Baltic Water Type,

q_G: relative volume of German Bight Water Type,

S_A: salinity of the Atlantic Water Type,

S_B: salinity of the Baltic Water Type,

S_G: salinity of the German Bight Water Type,

S_x: observed salinity,

$a_{CDOM,A}$: CDOM absorption coefficient of the Atlantic Water Type,

$a_{CDOM,B}$: CDOM absorption coefficient of the Baltic Water Type,

$a_{CDOM,G}$: CDOM absorption coefficient of the German Bight Water Type,

$a_{CDOM,x}$: observed CDOM absorption coefficient.

From these equations the three relative volumes can be expressed as functions of the observed salinity and absorption coefficient.

$$\begin{aligned} q_G = &(S_x(a_{CDOM,B} - a_{CDOM,A}) + S_B(a_{CDOM,A} - a_{CDOM,x}) \\ &+ S_A(a_{CDOM,x} - a_{CDOM,B}))/(S_B(a_{CDOM,A} - a_{CDOM,G}) \\ &+ S_A(a_{CDOM,G} - a_{CDOM,B}) + S_G(a_{CDOM,B} - a_{CDOM,A})), \end{aligned} \tag{4}$$

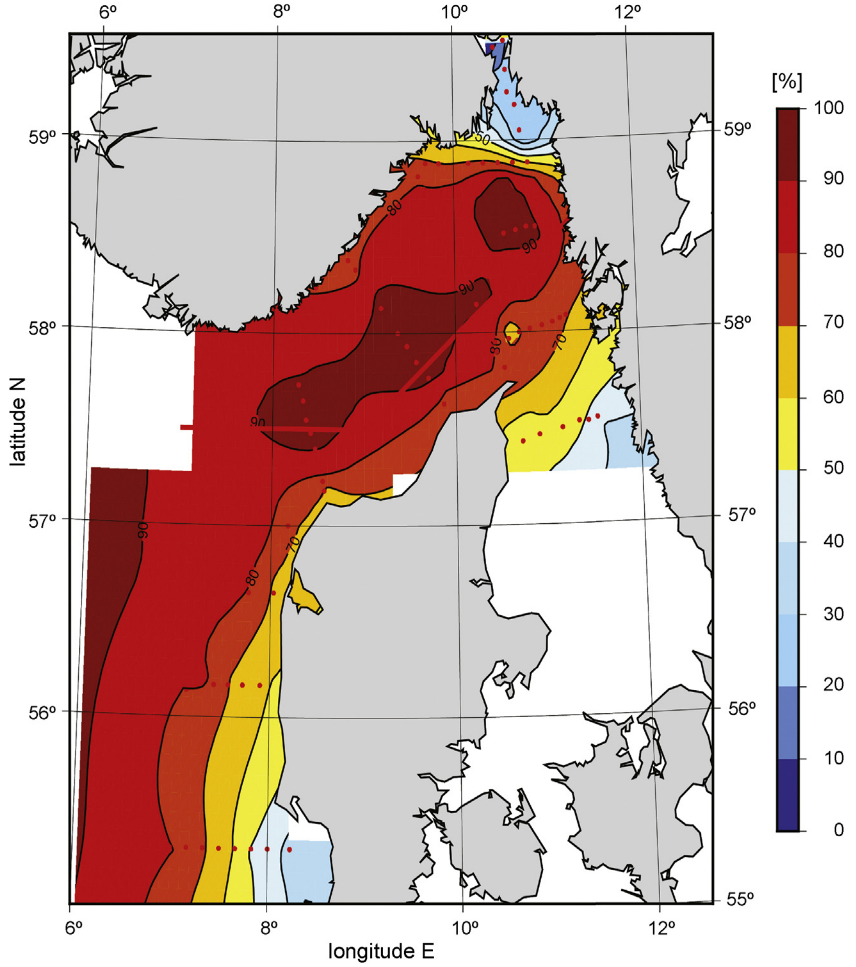

Figure 14 Mean surface distribution of the percentage of Atlantic Water, according to the Danish and Norwegian algorithms, based on the observations in April 1996—2000.

$$q_A = \left(\frac{S_x - S_B}{S_A - S_B}\right) - \left(\frac{S_G - S_B}{S_A - S_B}\right) q_G, \tag{5}$$

$$q_B = (1 - q_G - q_A). \tag{6}$$

The salinities and absorption coefficients of the water types used in this algorithm are presented in Table 1. They are close to the values used by Højerslev et al. (1996), who used the absorption coefficient at 380 nm. The spectral slope of a_{CDOM} was not recorded during the cruises analysed in this paper, but its values in the Baltic—North Sea transition zone have been discussed by Stedmon et al. (2000, 2010), Højerslev and Aas (2001) and Kowalczuk et al. (2005, 2006, 2010).

2.3. The Norwegian algorithm

When the algorithm of Højerslev et al. (1996) was applied to our data, it was successful in determining reasonable values for the content of water from the German Bight in the Kattegat, the southern part of the Skagerrak and off the Jutland west coast. The model assumes that the observed water masses are composed of three dominant water types, but these water types are not necessarily the same in the northern part of the Skagerrak. Closer to the Norwegian coast the algorithm often produced local maxima of German Bight Water in the surface layer. An example from 1996 of such maxima is shown in Fig. 2. The content of German Bight Water is gradually reduced from 65—25% along the Danish west coast. In the Skagerrak it is further reduced to less than 15%, before some local maxima of 20% appear outside the Swedish and Norwegian Skagerrak coasts. When we plotted the observations from all years 1996—2000 into an a_{CDOM}—S diagram (Fig. 3), we saw that several points were lying above the triangle constituted by the three water types, indicating that another water type was present, with a higher content of CDOM and a lower salinity than the German Bight Water.

Here it should be noted that another characteristic of the German Bight and its river runoffs is the local nitrate/silicate ratios. When the units of the nitrate and silicate contents are μmol L^{-1}, the ratios typically range from 20—400 (Rydberg and Andersson 2003, pers. comm.), which is two orders of magnitude greater than in the Norwegian coastal waters, where typical NO_3/SiO_4 ratios lie in the range 0—5. When we compared the mentioned maxima of German Bight Water (Fig. 2) to the corresponding horizontal distributions of the NO_3/SiO_4 ratio (Fig. 4), no similar maxima were found, but the salinity distribution (Fig. 5) showed local minima.

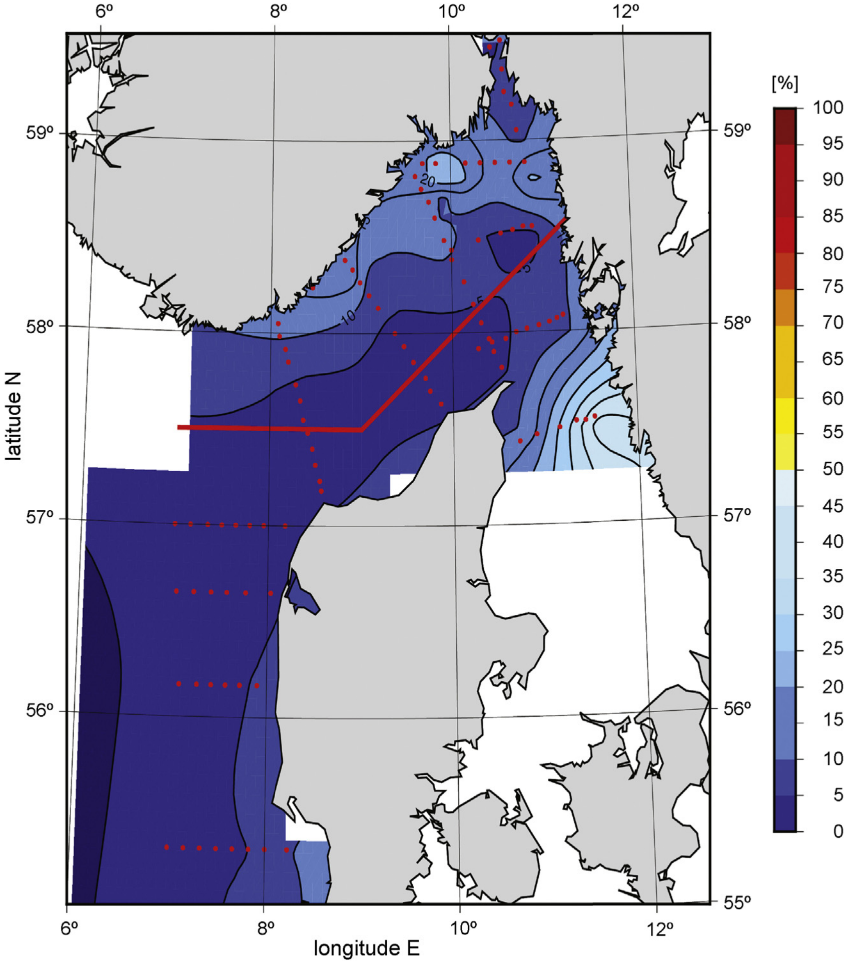

Figure 15 Mean surface distribution of the percentage of Baltic Water, based on the Danish and Norwegian algorithms, based on the observations in April 1996—2000.

Although neither nitrate nor silicate concentrations can be regarded as conservative properties of a water volume, this still indicates that the apparent maxima of German Bight Water more likely were due to CDOM-rich runoffs from Norwegian rivers. It is also noteworthy that the Danish algorithm was not based on data from these parts of the Skagerrak.

In order to obtain more reliable results closer to the Norwegian coast, a new algorithm for these areas was developed. The water masses of the Norwegian Coastal Current seem to be dominated by waters from the North Sea and the Baltic Current together with fjord water and river runoff from Norway, the latter defining a new water type that in this report has been termed Norwegian River Water. The properties of this water type have mainly been determined from measurements in the Glomma estuary, but also from measurements in the Drams River and the Skien River (Aas 1995; Korsbø 1999, Dept. Geophys., Univ. Oslo, unpublished internal reports). All three are major rivers, supplying freshwater to the Northern Skagerrak. The properties of the Norwegian River Water are presented in Table 1. The mathematical expressions for the Norwegian and Danish algorithms are similar, except that the Norwegian River Water has substituted the German Bight Water. An algorithm distinguishing between four water types would require recordings of four conservative and characteristic properties, and this fourth property remains to be found.

At this point it should be noted that the concentrations of water type, estimated by the Danish and Norwegian algorithms, are tentative, because errors will occur when more than the three assumed water types are present, as illustrated by the seven rows of numbers in Table 2. If a water volume in the middle of Skagerrak consists of 84% Atlantic Water and 8% Baltic Water, as shown by the first and second column and the seven rows of Table 2, and the contents of German Bight Water and Norwegian River Water vary in the ranges 8—0% and 0—8%, respectively, shown by the third and fourth column, the CDOM content and salinity will vary as shown by the fifth and sixth column. The percentages of the different water types estimated by the Danish and Norwegian algorithms are then presented in columns seven to twelve.

In this example the Danish algorithm clearly produces the greatest deviations from the true percentages of water types. The influence of Norwegian River Water on the Danish algorithm is to under- and overestimate the contents of Atlantic Water and German Bight Water by up to 30%, while the errors of Baltic Water are smaller, up to 5%. The

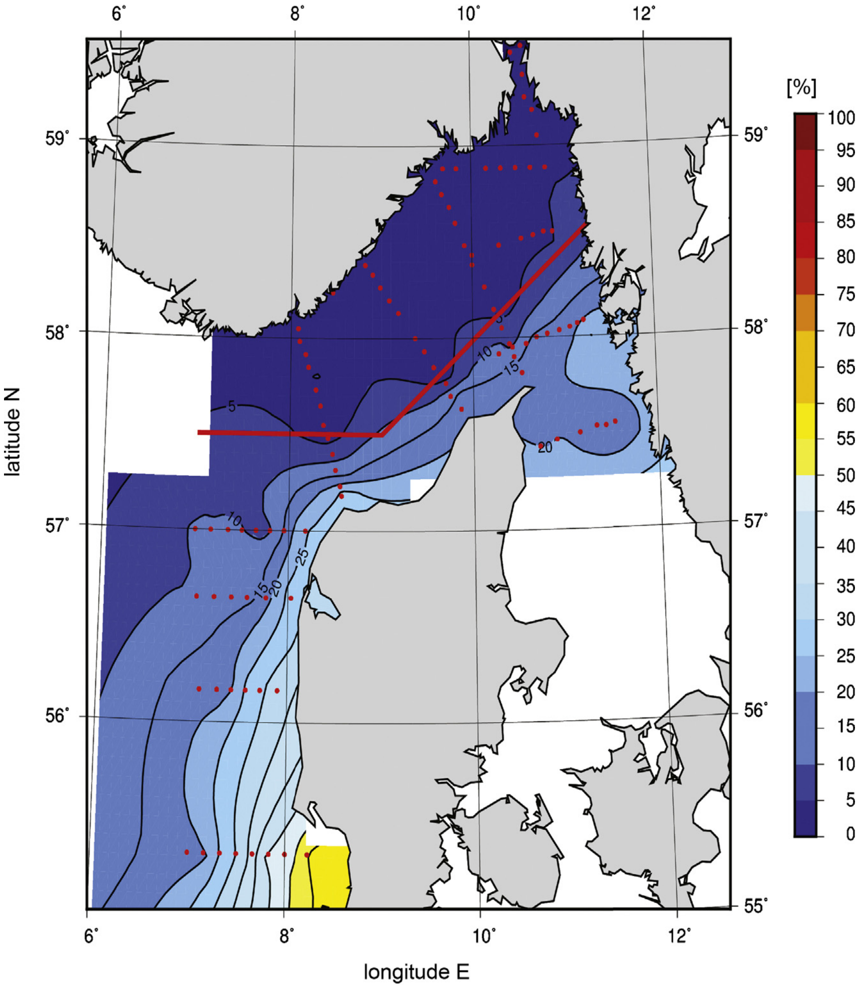

Figure 16 Mean surface distribution of the percentages of German Bight Water (southern part) and Norwegian River Water (northern part), according to the Danish and Norwegian algorithms, based on the observations in April 1996—2000.

Norwegian algorithm is less influenced by the presence of German Bight Water; Atlantic Water is overestimated by up to 7%, while the errors of Baltic Water and Norwegian River Water are up to 1% and 2%, respectively. More specifically the table also tells us that in the Danish half of the Skagerrak, where the content of Norwegian River water probably is much less than 1%, due to the circulation pattern (Fig. 1), the under- and overestimates of Atlantic Water and German Bight Water by the Danish algorithm are likely to be much less than 4% (first and second data row in table). In the Norwegian half of the Skagerrak, if the content of German Bight Water is less than 4%, the overestimate of Atlantic Water by the Norwegian algorithm will also be less than 4% (fourth to seventh data row in table). We find that these errors can be accepted.

The Norwegian algorithm was used in the northern part of the Skagerrak, and the Danish algorithm in the southern part, off the Jutland west coast and in the Kattegat. The line separating the two areas is shown in Fig. 6. Fig. 2 presented the distribution of water from the German Bight according to the Danish algorithm, and Fig. 6 shows the new situation when both algorithms are applied. The former a_{CDOM}—S diagram (Fig. 3) has been substituted by two new ones, Figs. 7 and 8, where most of the observations now fall inside the triangles. In Section 3.1.1 we will determine how deep down in the water column the two algorithms should be applied.

3. Results and discussion

3.1. Average conditions

Mean values for salinity, $a_{CDOM}(375)$, NO_3/SiO_4, NO_3/PO_4 and NO_3 in April have been calculated for the five-year period 1996—2000. The values used in Figs. 9—21 are arithmetic means for each point of observation. A vertical section Torungen—Hirtshals with the distribution of the mean values (Figs. 9—13) will be discussed in Section 3.1.1. The horizontal distributions at the surface of observed and calculated mean properties (Figs. 14—21) will be presented in Section 3.1.2. Finally, the average conditions within the upper 50 m will be commented upon in Section 3.1.3. From the last two sets of mean values new integrated means for the surface and for the upper 50 m have been calculated and presented in Table 3.

3.1.1. The Torungen—Hirtshals section

The vertical distribution of properties in the section from the Norwegian lighthouse Torungen to the Danish seaport Hirtshals (Fig. 1) demonstrates that most of the variation takes place within the upper 50 m. Salinity has its minimum in the Norwegian Coastal Current (upper left corner in Fig. 9), while the CDOM content obtains its maximum in this part of the section (Fig. 10). Below 50 m both

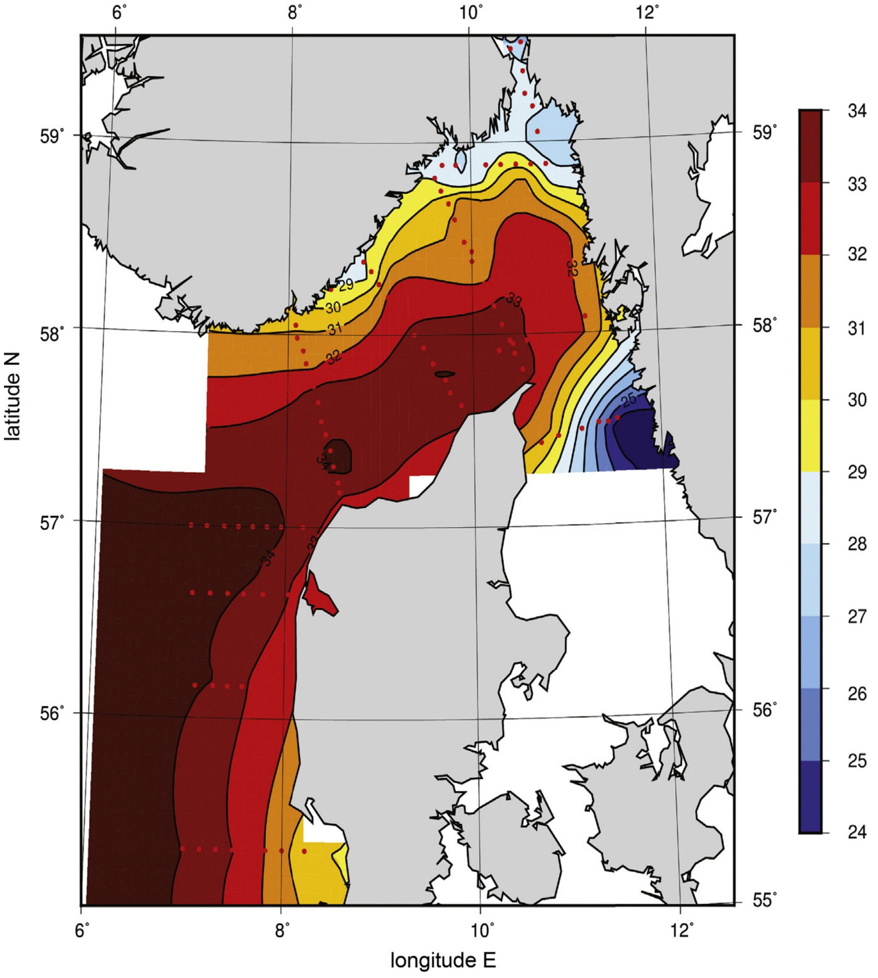

Figure 17 Mean surface distribution of salinity, based on the observations in April 1996—2000.

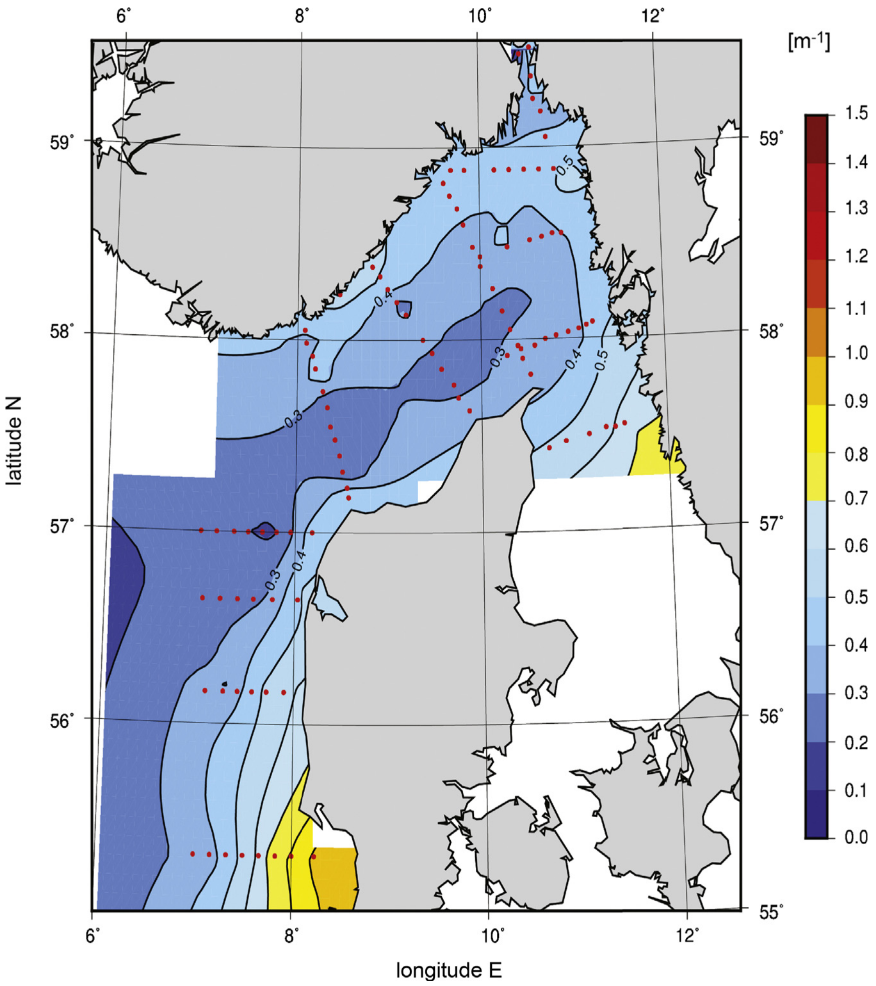

Figure 18 Mean surface distribution of the CDOM absorption coefficient $a_{CDOM}(375)$ [m^{-1}], based on the observations in April 1996—2000.

properties show very little variation. The NO_3/PO_4 ratio exhibits maxima in the surface layer close to the Danish and Norwegian coasts, and little variation below 50 m (Fig. 11). The NO_3/SiO_4 ratio on the other hand remains practically constant with depth (Fig. 12), while the nitrate concentration decreases gradually from about 10 μmol L^{-1} at 200 m to 8 μmol L^{-1} at 50 m, and then decreases more rapidly to 2 μmol L^{-1} at the surface (Fig. 13). Our overall conclusion becomes that while there seems to be clearly different water types in the upper 50 m, conditions below this depth are more homogeneous. Although turbulent vertical diffusion may transport German Bight Water and Norwegian River Water from the surface to the layer below 50 m, the validity of the two algorithms at the lower depths is open to question. Accordingly we have restricted the use of the algorithms to the upper 50 m.

3.1.2. Surface distribution

Fig. 14 presents the mean surface distribution of Atlantic Water. This is clearly the dominant water type in the surface layer of the Skagerrak, with contents in the range 50—90%. The mean content of Baltic Water in the surface is above 45% in the Kattegat, and its concentration is then gradually reduced down to less than 5% when the water is diluted in the Skagerrak (Fig. 15).

The isolines in Fig. 16 show surface contents up to 55% of German Bight Water, and up to 5% of Norwegian River Water. Around the line representing the border between the areas where the two different algorithms have been applied, the content of German Bight Water is between 5% and 10%. North of this border the content is then likely to be less than 5% due to dilution, and our conclusion becomes that its mean concentration will probably also be smaller than 5% in the Norwegian Coastal Current. Here it should be noted that this conclusion differs from the result of Aure et al. (1998), who found from observations of salinity and nitrate that the Skagerrak surface water off Arendal contained 21% of German Bight Water in March—April, based on the years 1980—1995.

At the surface north of the algorithm line the arithmetic mean values of the different water types are Atlantic Water 74%, Baltic Water 20%, and Norwegian River Water 7% (Table 3). For the entire area of investigation the mean surface concentrations become Atlantic Water 68%, German Bight Water 15%, Baltic Water 15%, and Norwegian River Water 3% (Table 3). According to the discussion in Section 2.2 the uncertainties of the Atlantic Water and German Bight Water estimates are probably less than 4%, while the uncertainties of Baltic Water and Norwegian River Water may be 1—2%.

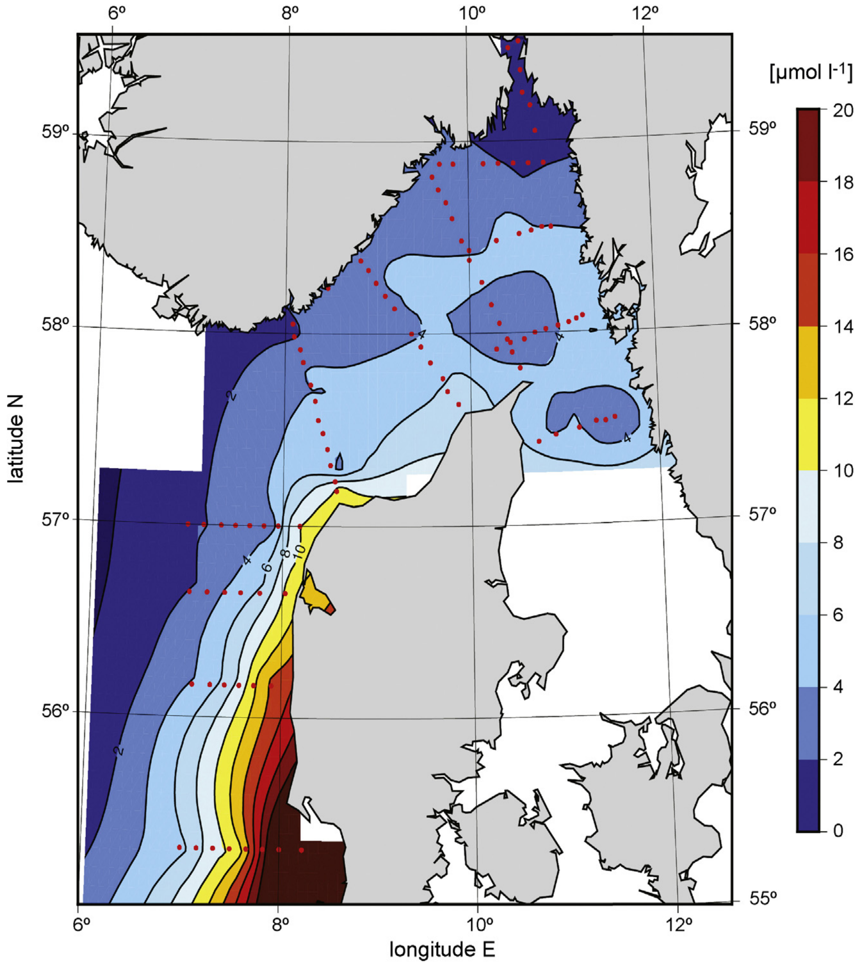

Figure 19 Mean surface distribution of the NO_3 content [μmol L^{-1}], based on the observations in April 1996–2000.

Fig. 17 presents the mean surface salinities, ranging from less than 30 in the Kattegat to more than 34 in the Skagerrak. The values of $a_y(375)$ exhibit local maxima of more than 0.7 m^{-1} in the Kattegat and in the German Bight (Fig. 18). The mean surface content of nitrate amounts to more than 15 μmol L^{-1} in the German Bight (Fig. 19), and this area also exhibits the highest values of the NO_3/SiO_4 and NO_3/PO_4 ratios, being up to 35 and 50, respectively (Figs. 20 and 21). The mean surface values of these ratios for the entire area are 7 and 51, respectively (Table 3).

Stedmon et al. (2010) used observations of salinity and CDOM content (absorption coefficient at 300 nm) with a three-component water type model to estimate the relative volumes of Atlantic Waters, German Bight Waters and Baltic Waters in the Baltic–North Sea transition region, between 6°E and 14°E. In the Skagerrak their observations extended to

Table 3 Mean values and rms deviations of the investigated quantities, *n* is the number of observations.

	Northern area surface *n* = 185		Total area surface *n* = 443		Total area upper 50 m *n* = 2227	
	Mean	rms	Mean	rms	Mean	rms
Atlantic Water [%]	74	16	68	18	79	16
Baltic Water [%]	20	16	15	13	8	10
German Bight Water [%]			15	8	11	7
Norwegian River Water [%]	7	9	3	4	1.7	1.8
Salinity	27.2	4.6	29.4	3.6	31.9	3.1
$a_{CDOM}(375)$ [m^{-1}]	0.69	0.57	0.59	0.42	0.42	0.27
NO_3 [μmol L^{-1}]	2.4	3.0	4.5	5.3	5.3	5.4
NO_3/SiO_4	1.2	1.9	7.0	10.5	6.4	8.8
NO_3/PO_4	55	128	51	91	37	63

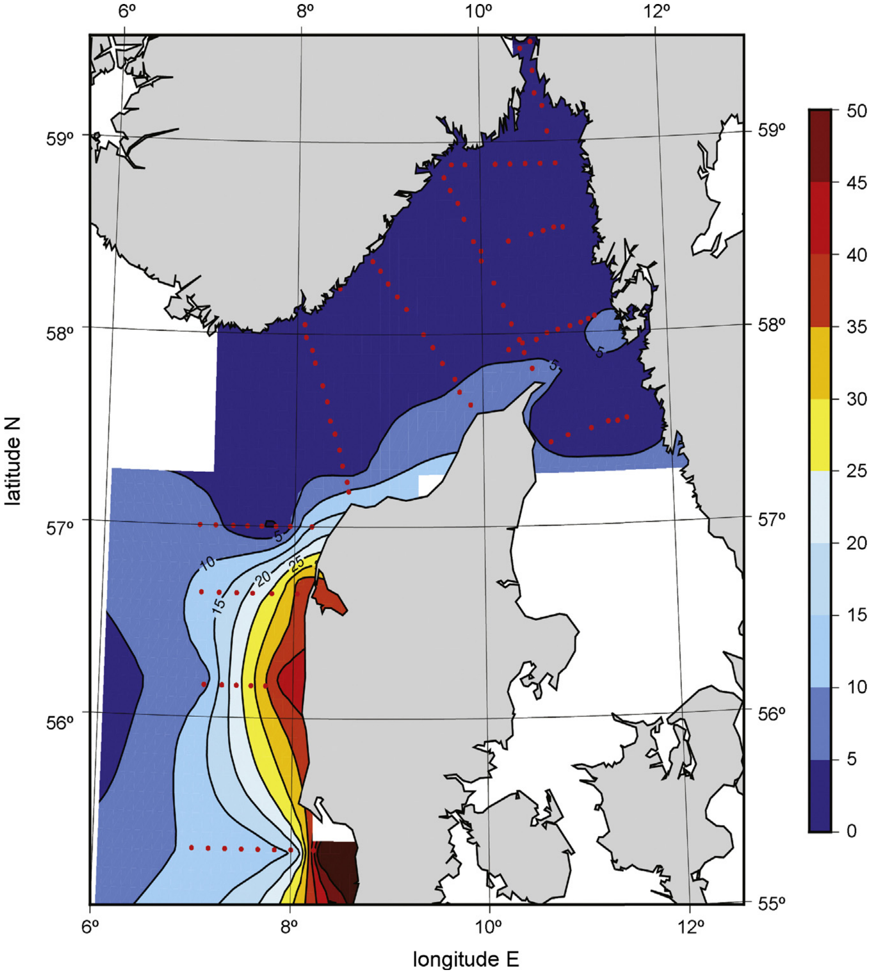

Figure 20 Mean surface distribution of the NO_3/SiO_4 ratio, based on the observations in April 1996—2000.

a little more than halfway between Denmark and Norway. Their distributions of Atlantic and Baltic Waters resemble our results in Figs. 14 and 15, while the content of German Bight Water is more like our distribution in Fig. 2, with values up to 20% in the northern part of the Skagerrak.

3.1.3. Upper 50 m

Figs. 9—13 showed that there were vertical gradients above 50 m depth, in contrast to the more homogeneous conditions below. Accordingly those properties that have their vertical maxima at the surface, will obtain smaller mean values when all depths within the upper 50 m are taken together. These properties are Baltic Water (8%), German Bight Water (11%), Norwegian River Water (2%), $a_y(375)$ (0.42 m^{-1}), and the NO_3/SiO_4 (6.4) and NO_3/PO_4 (37) ratios. The properties with minima at the surface obtain greater mean values for the upper 50 m. These properties are Atlantic Water (79%), salinity (31.9) and nitrate (5.3 $\mu mol\ L^{-1}$).

3.2. Annual variations

We shall not discuss all the details of the annual variations in our data set, but only mention two of its manifestations. During the years of investigation the salinity distribution showed that the amount of water from the German Bight brought by the Jutland Coastal Current along the Danish west coast and into the Skagerrak varied to a large extent. In both 1996 and 1997 the salinity along the Danish Skagerrak coast was higher than in the years after. In 1996 and 1997 the amount of nitrate in the German Bight water at the southernmost section on the Danish North Sea coast was extremely low, while in the years 1998 and 1999 high amounts of nitrate were spreading from this area and up along the Danish west coast and into the Skagerrak. The great difference in the nitrate concentrations from year to year at the southernmost section is assumed to be due to variation in runoff and flooding on the continent, brought from the German Bight with the Jutland Coastal Current.

The considerable annual variation of the surface percentages of German Bight Water and Norwegian River Water is illustrated in Table 3 by the root-mean-square deviations from the mean values, being of the same order of magnitude as the mean values themselves. In the table some of the rms deviations are greater than the corresponding mean values, implying a very unsymmetrical distribution of observations around the mean value.

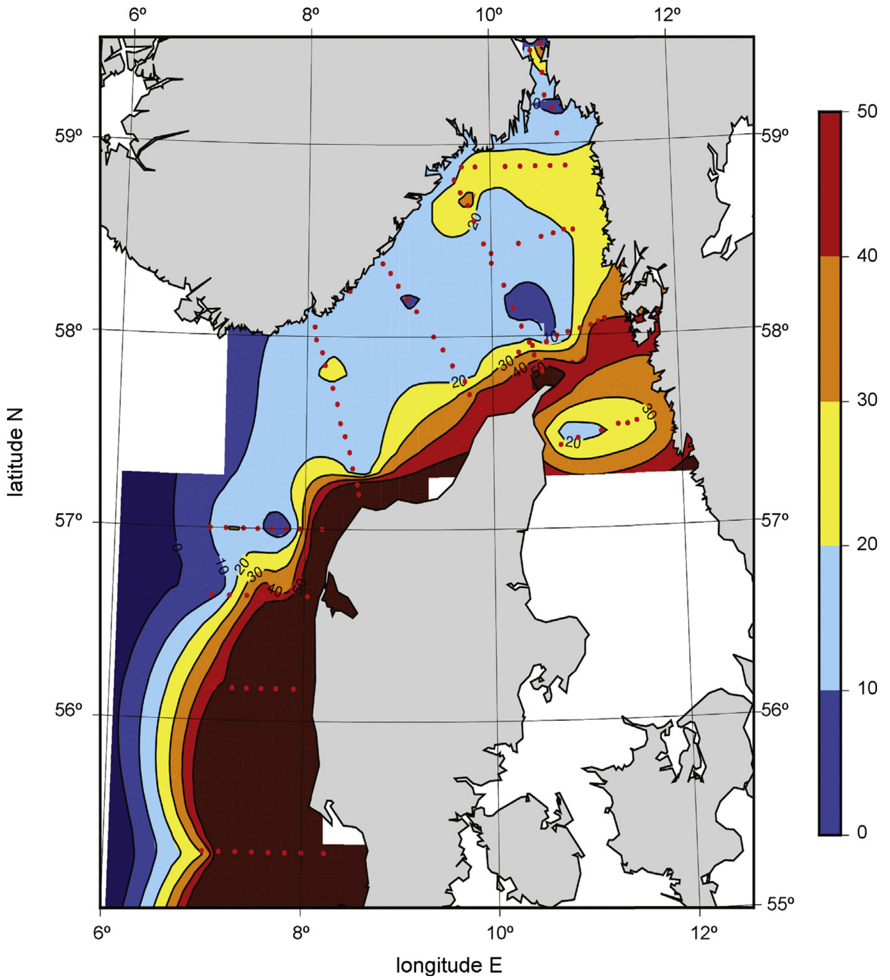

Figure 21 Mean surface distribution of the NO_3/PO_4 ratio, based on the observations in April 1996—2000.

4. Summary and conclusions

Initiated by a number of toxic algal blooms occurring along the Norwegian Skagerrak coast a series of cruises were carried out in the 5-year period 1996—2000. The central issue was to determine if nutrient-rich water from the German Bight could be the cause of these blooms. By using an algorithm for water mass analysis developed by Højerslev et al. (1996), reasonable results were obtained in the Kattegat, off the Jutland west coast and in the southern part of the Skagerrak. However, close to the Norwegian coast in the Skagerrak the apparent distribution of German Bight Water became improbable, yielding local maxima outside the fjords. Consequently an alternative algorithm, with Norwegian River Water type substituted for the German Bight Water type, was constructed for these parts. The border between the areas for the two algorithms (the line in Fig. 6) is approximately consistent with the limits of the Danish area of investigation.

The result of our analysis in Table 3 is that north of the borderline the mean surface contents of Atlantic Water, Baltic Water and Norwegian River Water are 74%, 20% and 7%, respectively. Since this result is based on the assumption that German Bight Water is not one of the three water types of the applied algorithm, these numbers may of course be questioned, but our analysis also indicates that the mean content of German Bight Water in this current, regardless of the applied algorithm, will be less than 5%. For the entire area of investigation the mean surface contents become Atlantic Water 68%, German Bight Water 15%, Baltic Water 15%, and Norwegian River Water 3%. For all depths within the upper 50 m taken together the Atlantic Water constitutes 79%, German Bight Water 11%, Baltic Water 8%, and Norwegian River Water 2%. The values in Table 3 are arithmetic means, and their uncertainties have been estimated to be less than 4% for the Atlantic and German Bight Waters, and 1—2% or less for the Baltic and Norwegian River Waters.

In conclusion, within our investigated area Atlantic Water is the dominant water type (70—80%), while the contents of German Bight Water and Baltic Water are an order of magnitude smaller. The content of Norwegian River Water is on average smaller than the content of Baltic Water by a factor of 3—5 (Figs. 14—16, Table 3).

We hope the present analysis may serve as a contribution to further investigations of the mixing of water types in this area.

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