Transparency of the North Sea and Baltic Sea – a Secchi depth data mining study

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Abstract

This paper presents the results of a Secchi depth data mining study for the North Sea – Baltic Sea region. 40,829 measurements of Secchi depth were compiled from the area as a result of this study. 4.3% of the observations were found in the international data centers [ICES Oceanographic Data Center in Denmark and the World Ocean Data Center A (WDC–A) in the USA], while 95.7% of the data was provided by individuals and ocean research institutions from the surrounding North Sea and Baltic Sea countries. Inquiries made at the World Ocean Data Center B (WDC–B) in Russia suggested that there could be significant additional holdings in that archive but, unfortunately, no data could be made available. The earliest Secchi depth measurement retrieved in this study dates back to 1902 for the Baltic Sea, while the bulk of the measurements were gathered after 1970. The spatial distribution of Secchi depth measurements in the North Sea is very uneven with surprisingly large sampling gaps in the Western North Sea. Quarterly and annual Secchi depth maps with a 0.5°×0.5° spatial resolution are provided for the transition area between the North Sea and the Baltic Sea (4°E–16°E, 53°N–60°N).

1. Introduction

The depth of the euphotic zone, Z_e, is defined as the depth where daylight downwelling photosynthetically available radiation (PAR) is reduced to 1% of the value measured just below the sea surface. Z_e is an important parameter for many oceanographic studies and is used in physical and biological modelling. In those contexts, climatologies of state variables are often used to provide initial conditions for the models or as a base line against which to compare observations or modelling results. Maps of Z_e are also useful for masking/correcting satellite colour imagery for bottom effects or for outlining areas suitable for airborne laser bathymetry mapping.

Until the late 1980s direct determination of Z_e through PAR measurements were only carried out at a few laboratories on a routine basis as a part of hydrographic casts. Although PAR sensors are now more widespread, Z_e data are still relatively scarce.

The Secchi depth measurement, named after the Italian Jesuit priest and astronomer Angelo Secchi, provides an indirect method of determining the depth of the euphotic zone. This measurement is carried out by lowering a white disc (which today typically has a diameter that is between 30 cm and 100 cm) into the water until it disappears from view. The depth at which the disc disappears is called the 'Secchi depth'. Angelo Secchi's experiments were carried out in the Gulf of Gaeta in 1865 with a number of discs, some of which were coloured, that measured between 43 cm and 237 cm in diameter (Secchi 1866). Secchi should, however, only be credited for his systematic experiments. The very first Secchi experiments (with red and white discs) were carried out in 1815 in the Pacific by the Estonian Otto von Kotzebue on the vessel Rurik (Krümmel 1886).

From a Secchi depth measurement, SD, Z_e can be calculated as

$$Z_e = m \times SD, \tag{1}$$

where $m \sim 2$ (Højerslev 1978, 1986). The beam attenuation coefficient, c, can be calculated from the relation

$$c \times SD \sim 6, \tag{2}$$

as given by Højerslev (1978, 1986). From c, the concentration of suspended matter, P, can also be derived.

Although Secchi depth measurements can be affected by a number of factors that can cause small systematic shifts in the readings, [see, for instance Sandén & Håkansson (1996) for a discussion of the importance of these factors], and hence may not be the most optimal method for determining the depth of the euphotic zone, Secchi depth measurements are, nevertheless, more plentiful both on a spatial and temporal scale than Z_e, c and P

observations. Therefore, maps and time series of Secchi depth measurements provide a potential alternative for establishing vicarious climatologies for the above parameters.

The first global map of Z_e was established by Jerlov (1968). He subsequently extended it [Jerlov (1976) and Jerlov (1978)]. Jerlov's maps are based on spectral downward irradiance measurements and quanta-irradiance (PAR) measurements. Owing to the relatively few measurements, the maps are not contoured and contain a rather coarse, discrete classification of the global oceans.

Several authors have established regional and global transparency maps from Secchi depth measurements. Dickson (1972) produced a transparency chart for the Atlantic between latitudes 15°S and 60°N based on 5,060 measurements. Arnone (1985) established a 1°×1° Secchi depth atlas based on about 23 000 measurements for the world's coastal zones between 40°S and 40°N. Lewis et al. (1988) established global climatological mean fields of ocean transparency based on about 120,000 measurements. For all three of these studies the bulk of the measurements were retrieved from WDC–A. Voitov (1983) also provided global contour maps of Secchi disc depth (summer and winter). These, however, were based upon an estimated 300 000–320 000 observations for the global oceans held by Voitov's group at the P. P. Shirshov Institute in Moscow, Russia.

For meso- and small-scale studies the climatological maps provided in the above mentioned studies are rather coarse. Furthermore, vast numbers of Secchi depth measurements from the world's coastal regions are not included in the international databases.

In the North Sea and the Baltic Sea, Secchi depth measurements have been collected since at least 1902. Few Secchi depth measurements, however, are available from the international data centers (i.e. the ICES Oceanographic Data Center or the WDC–A). For the Southern North Sea, Visser (1970) determined average Secchi depth and standard deviation for a 0.5°×0.5° box grid. Relatively little data was available at the time of his study (725 observations in total). Visser particularly noted the scarcity of data in the central and northern parts of the North Sea. To date this is the only study that has attempted to collate Secchi depth data from multiple sources in the North Sea. Vast numbers of Secchi depth measurements have been gathered since 1970 but no attempt has been made to pool these observations, most likely because they are not available from any central or distributed archive. This study is a first attempt to (1) mine out Secchi depth measurements from the North Sea and the Baltic Sea; and (2) establish a Secchi depth climatology for the transition zone between the North Sea and the Baltic Sea.

2. Materials and methods

Secchi depth measurements for the North Sea/Baltic Sea were collected from existing international archives including the ICES Oceanographic Data Center, the WDC–A and WDC–B, literature, and institutes that measure Secchi depth on a routine basis. The data search was carried out in part by the use of the database of Reports of Oceanographic Cruises and Oceanographic Programmes (ROSCOP) maintained by ICES. This meta database, which provides a low level inventory for tracking oceanographic cruise data, can be searched by criteria such as time, location, ship name, country, data type code, etc. Unfortunately, a data type code for Secchi measurements does not exist in the ROSCOP database. In some instances it is recorded under the ROSCOP Data Type Code 'H16 (Transparency – e.g. transmissometer)'. In other instances, Secchi depth measurements are recorded under the ROSCOP Data Type Code 'H17 [Optics (e.g. underwater light levels)]'. And in yet other instances Secchi depth measurements are only mentioned in a field for additional comments.

Despite the limited reporting of Secchi depth measurements, the ROSCOP database helped to pinpoint cruises and/or studies in which the measurements might have been gathered. Subsequently, approximately 100 individuals and institutions in the surrounding countries of the North Sea and Baltic Sea were questioned about the availability of Secchi depth measurements in the region. Nearly all of the parties that had data contributed it freely in digital or hard copy form.

The above search identified data sets that could not be included in this report. For instance, in the former Soviet Union, the Secchi depth measurement became part of the standard measurement suite on hydrographic stations in the 1930s, resulting in a significant increase in the number of observations (Voitov 1983). But few of these are available. As mentioned earlier, Voitov (1983) claimed to have a database of 300 000–320 000 Secchi measurements from the global oceans – twice the number held at WDC–A in 1999 when this present study was initiated. Voitov passed away several years ago and further information regarding his database could unfortunately not be found (Koepelevich, personal communication). Based on inquiries to the WDC–B, it is estimated that about 30 000 observations in digital form for the Baltic Sea and 20 000–30 000 observations in paper form for the North Sea are in their archives (WDC–B, pers. comm.). Through the Global Oceanographic Data Archaeology and Rescue (GODAR) project sponsored by the Intergovernmental Oceanographic Commission of UNESCO an attempt was made to include this data; however, WDC–B could not get the necessary permission to release it. The only data available from the former Soviet Union came from the few holdings in the WDC–A.

3. Results and discussion

40,829 Secchi depth measurements from the North Sea/Baltic Sea area were retrieved during the study. 4.3% of the observations were found in the international data centers (ICES Oceanographic Data center and the WDC–A), while 95.7% of the data was provided by individuals and national oceanographic institutions. The data was quality controlled with respect to date, time, location, and observation outliers.

Figure 1 shows a scatter plot of the gathered Secchi depth measurements with colour-coding that represents the actual observation values. The high turbidity areas (i.e. Southern North Sea, the German Bight, outside the Oslo Fjord, and the Gulf of Riga) show up clearly. A gradual change in Secchi depth can be observed between the clear water in the northern North Sea and the more brackish northern Baltic Sea. This pattern is qualitatively consistent with what can be observed in satellite ocean colour imagery of the area (Holligan et al. 1989).

Tables 1, 2 and 3 provide some further insights into the spatial and temporal distribution of the Secchi depth measurements. The spatial distribution is very uneven. It is particularly puzzling to find so few observations in the Western North Sea since a vast number of UK physical and biological observations have been gathered in that region (see for instance http://www.ices.dk/ocean/maps/maps.htm) which could have included Secchi depth measurements. However, several ocean scientists from the UK with detailed knowledge about sampling programs since 1945 have confirmed that Secchi depth measurements were not carried out (J. Steele, J. Ramster, D. Cushing; pers. comm.). Inquiries with the British Oceanographic Datacenter (L. Rickards, pers. comm.) and the UK Hydrographic Office (pers. comm.) did not reveal any additional UK observations beyond the few held by the WDC–A.

Approximately 68% of the Secchi depth measurements have been collected in the months April through September. The temporal distribution of the observations shows that the bulk of the observations have been gathered after 1970. This increase is probably a result of the establishment and expansion of water quality monitoring programs by many nations and enhanced record keeping through the introduction of computers. It is also noted that the Secchi depth measurement technique still appears to be widely used, despite the fact that PAR sensors have become cheaper and have been introduced at several oceanographic institutions. The fact that a Secchi depth measurement usually works and is simple to carry out still has much appeal.

Figure 2 shows the mean Secchi depth for the transitional zone of the North Sea – Baltic Sea, where the sampling density is highest (Table 2).

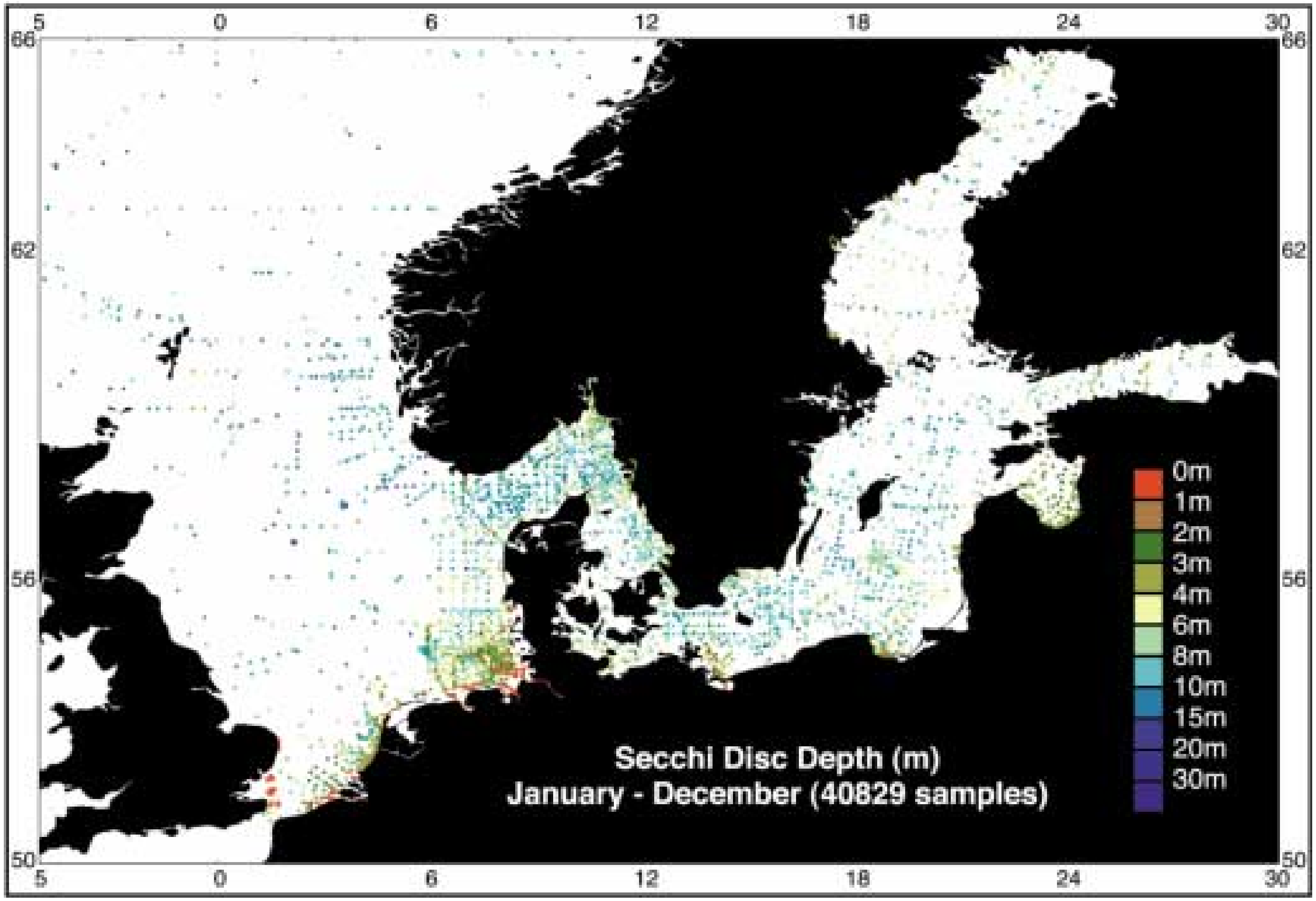

Fig. 1. Scatter plot of all Secchi depth measurements in the database. The values have been colour coded according to the scale shown

Table 1. Number of Secchi depth measurements for the larger North Sea west of 4°E grouped according to year and country origin of observation

Country	Years												Grand Total
	1900–1904	1905–1909	1910–1914	1955–1959	1960–1964	1965–1969	1970–1974	1975–1979	1980–1984	1985–1989	1990–1994	1995–1999	
Belgium	10												10
FRG	8	29	2							24	16		79
Norway							60	25					85
The Netherlands	6		18		46		166	1011	17	49	380	43	1736
UK									1	11	1	125	138
USSR				48	7	75	96	13	29	8			276
Grand Total	24	29	20	48	53	75	322	1049	47	92	397	168	2324

Table 2. Number of Secchi depth measurements for the transition zone between the Baltic Sea and the North Sea (53°N ≤ latitude ≤ 60°N; 4°E ≤ longitude ≤ 16°E) grouped according to year and country origin of observation

Country	Years												Grand Total
	1900–1904	1905–1909	1910–1914	1955–1959	1960–1964	1965–1969	1970–1974	1975–1979	1980–1984	1985–1989	1990–1994	1995–1999	
Denmark			1		91	332	94	113	199	711	2267	1159	4967
Estonia									18	1			19
Finland							10	35					45
FRG	50	220	58				114	59	512	1099	1068	124	3304
GDR									97	314	125		536
Latvia												1	1
Norway							62	40	19	255	1240	1018	2634
Poland				45	240	97	143	23	8	133	328	74	1091
Sweden						93	585	1033	1193	2723	3498	2281	11406
The Netherlands	1		6		2		12	226	8	128	321	32	736
UK									1	15		1	17
USSR				15			15			2	10		42
Grand Total	51	220	65	60	333	522	1035	1529	2055	5381	8857	4690	24798

Table 3. Number of Secchi depth measurements in the Baltic Sea east of 16°E grouped according to year and country origin of observation

Country	Years																	Grand Total
	1900–1904	1905–1909	1910–1914	1915–1919	1920–1924	1925–1929	1930–1934	1935–1939	1955–1959	1960–1964	1965–1969	1970–1974	1975–1979	1980–1984	1985–1989	1990–1994	1995–1999	
Denmark															21	10		31
Estonia														76				76
Finland		298	157	20	150	191	251	112			5	258	318	19	29			1808
FRG	8	60	4									34		127		17	5	255
GDR														43	403	19		465
Latvia																384	620	1004
Poland									194	513	308	260	122	279	595	322	340	2933
Sweden											73	143	1299	1489	1274	1425	1274	6977
The Neth.												1						1
USSR		20							124			13						157
Grand Total	8	378	161	20	150	191	251	112	318	513	386	709	1739	2033	2322	2177	2239	13707

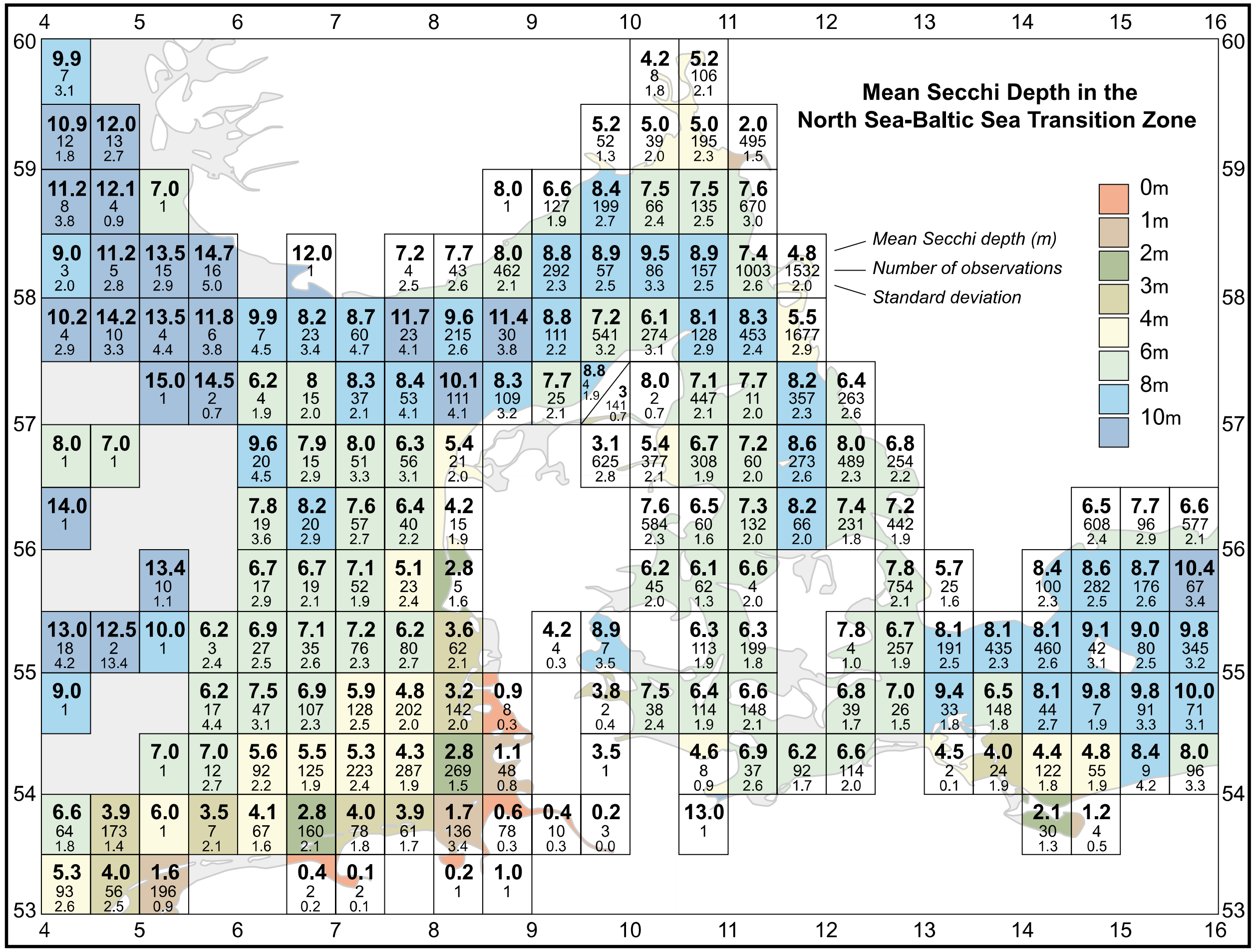

Fig. 2. Mean Secchi depth (top number), number of observations (middle number) and standard deviation (bottom number) for $0.5^{o} \times 0.5^{o}$ squares for the transitional zone of the North Sea – Baltic Sea

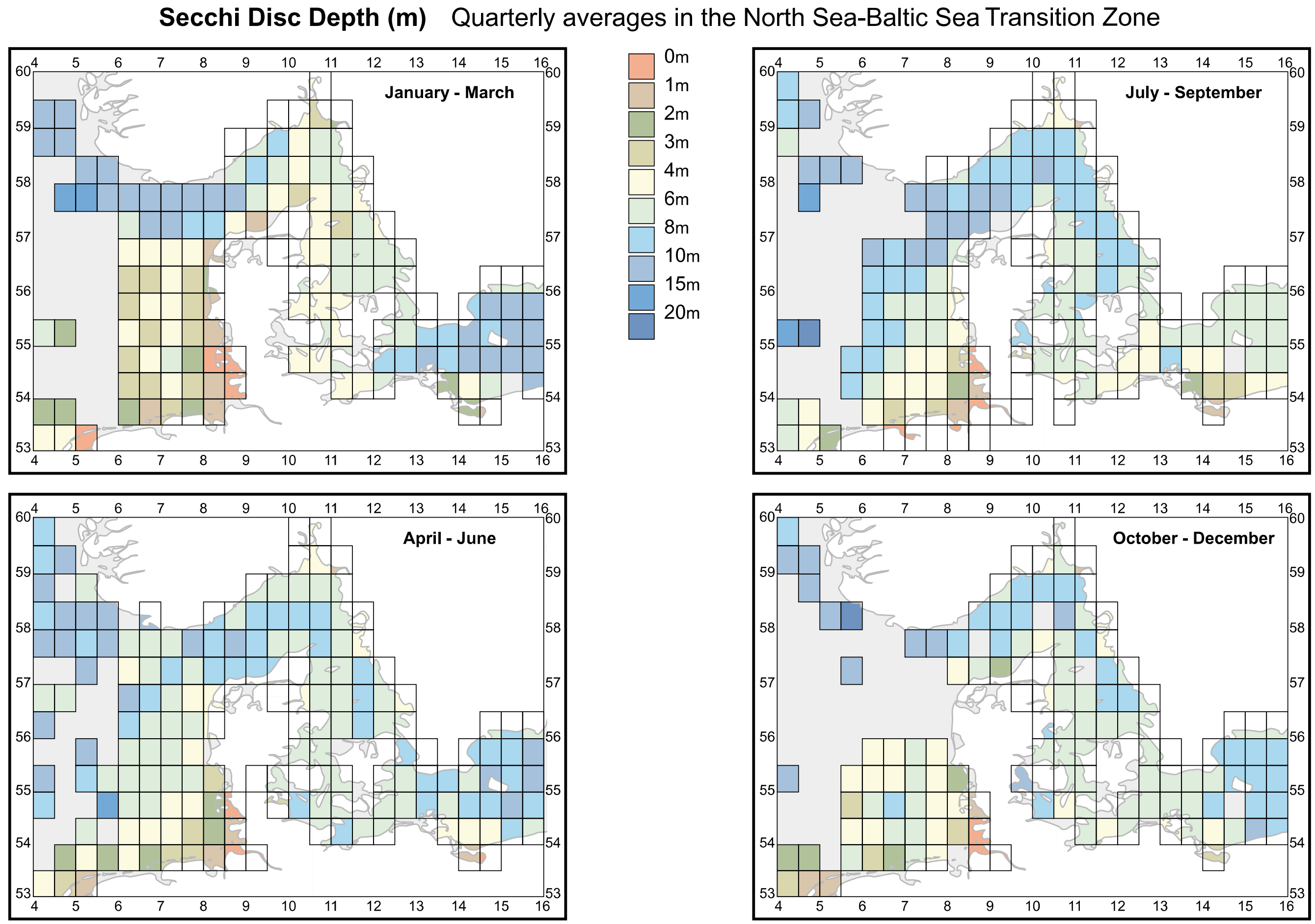

Fig. 3. Quarterly mean Secchi depth maps for the transitional zone of the North Sea – Baltic Sea

The average, the number of observations, and the standard deviation were calculated for each 0.5×0.5 degree square in which observations are contained.

In the Southern Bight and German Bight, low average Secchi depth values are seen. This may be due to stronger tides in the Southern North Sea. Somewhat higher Secchi depth variation is observed in the North Eastern North Sea and the Skagerrak than in the Western Baltic and the Kattegat. This reflects the more dynamic environment due to the Atlantic inflow and blocking/outburst events of the Norwegian Coastal Current (Aure & Sætre 1981). A slight east-west gradient in Secchi depth can be observed accross the Kattegat. The gradient is located in the eastern Kattegat and associated with the more pronounced stratification found here and perhaps intruision of clear deep water to the surface layer. Otherwise, the Kattegat appears optically rather homogeneous on the latitudinal scale. The relatively high Secchi depth in the Western Baltic Proper is also noteworthy.

Figure 2 cover over some seasonal variablity. In Fig. 3 quarterly averaged Secchi depth maps for the zone of the North Sea – Baltic Sea are shown. [There is not a sufficient number of observations available to provide monthly maps]. Sea state and biological production impacts the derived Secchi depth fields. In the shallow areas in the eastern North Sea reduced Secchi depth is clearly observed in the first quarter as the seasonal stratification has typically not yet developed. In the Kattegat and northern part of the Skagerrak the spring bloom normally starts in March. It starts approximately 2–4 weeks later in the eastern part of the North Sea due to a later onset of the seasonal thermocline in this area. In the western Baltic the spring bloom normally starts in the second half of April. Minor fall blooms are typically also observed in August–September for the area.

It may be possible to produce similar transparency climatologies from satellite ocean colour data. However, frequent cloud cover and uncertainties in the atmospheric correction scheme and the in-water algorithms for coastal waters pose some limitations. The climatologies as shown in Figs. 2 and 3 can thus be of some use in the calibration and validation of satellite ocean colour products for the area, and could provide an *in situ* climatology for comparison with a satellite derived climatology.

Comparison with Z_e observations

Jerlov (1978) introduced an optical classification scheme for natural waters based on their transmission capability of PAR. The classification was developed from a global set of about 200 PAR profiles of which many had been gathered in Scandinavian waters. Jerlov classified waters into 10 types (five oceanic types denoted by Roman numerals I, IA, IB, II and III; and five coastal types denoted by Arabic numerals 1, 3, 5, 7 and 9), and tabulated characteristic values for transmission and attenuation of PAR for different depths for each water type. According to Jerlov's data and classification, the Northern North Sea (on average) is between type II and type III (equivalent to Z_e having a value of 31 m to 55 m), the Skagerrak belongs to type 1 (equivalent to Z_e having a value of 27 m) and the Baltic Proper to type 3 (equivalent to Z_e having a value of 19 m).

Using the relation (1) between Z_e and SD on the characteristic Jerlov water type Z_e-values, it is possible to convert them to roughly equivalent Secchi depth values for the water types. Comparing these values with the climatology (Fig. 2), the Western Baltic Proper and the Kattegat belong to Jerlov water type 3. In the open waters west of Norway watertype III is mostly seen. The open Skagerrak waters lie somewhere between type 1 and type 3. The Southern North Sea was not represented in Jerlov's data set. However, PAR measurements in the inner German Bight (Højerslev, pers. comm.) show that it is coastal type 7 (equivalent to Z_e having a value of about 8 m). This is consistent with the climatological values for that region.

Final remarks

40 829 Secchi depth measurements from the North Sea/Baltic Sea area have been retrieved. Despite the size of the database there are surprisingly large spatial gaps, particularly in the Western North Sea. This gap is surprising and suggests a difference between ocean scientists in the UK and on the European continent in the acceptance of the Secchi disc.

Only about 4% of the assembled data was retrieved from the international oceanographic repository archives, while approximately 96% came from individual scientists and national oceanographic institutions. Since small and meso scale ocean measurements are often interpreted in a larger scale setting, supplementary products extending outside of a study region are often required. Relying on individual scientists and oceanographic institutions rather than international or national oceanographic data centers for the collation of data raises concern about (1) the timeliness in which such data can be assembled, and (2) the long-term preservation of such measurements. Ultimately, one must question how to protect the investment in the research and observing activities, which in most countries are largely provided through public funds. These amounts are by no means small. Levitus et al. (1998) have outlined an economic justification for maintaining archives of historical oceanographic data. In their analysis they assumed an average operating cost of US $ 16,000 per day for a medium sized research vessel with the capability of sampling 10 shallow stations a day.

While Secchi depth measurements generally play a secondary role in marine observation programs, time and experience have shown that one can never obtain enough sea observations; everything can eventually be used. In that context, this study illustrates that Secchi depth measurements are very useful when there are sufficient numbers of them in a region and/or when they are available over an extended time period. As such, this may be the real value of appropriate archiving management of Secchi depth measurements.

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The Secchi depth data collected for this study has been assembled for the benefit of humankind and the public good. Toward this end the assembled data has been turned over to the ICES Oceanographic Data Center which will manage and maintain the database. It is this author's hope that the database will be augmented with additional historical data and new measurements.

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