Communications

Optical water types of the Nordic Seas and adjacent areas

doi:10.5697/oc.55-2.471
OCEANOLOGIA, 55 (2), 2013.
pp. 471–482.

KEYWORDS
Arctic Sea
Baltic Sea
Barents Sea
Nordic Seas
Optical classification

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Received 11 February 2013, revised 26 March 2013, accepted 8 April 2013.

Abstract

A new map of Jerlov's optical water types in the Nordic Seas and adjacent waters at 139 locations, as well as a table with statistical and geographical properties of the vertical attenuation coefficient of downward irradiance at 475 nm, are presented.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

The data analysis is based on 715 recordings at different stations, at latitudes between 54° and 82°N, and longitudes between 31°W and 49°E, obtained by different authors from May 1954 to August 2003. The results show that the Atlantic and Polar waters are typically of oceanic type II–III, although during algal blooms the optical conditions may change to coastal types 1, 3 and 5, which are also the most frequent types found in coastal areas.

The Nordic Seas constitute a transition area for Atlantic and Polar waters, entering and leaving the Arctic Sea. The heat budget of the currents represents an important part of the global climate system and also influences local weather conditions. In order to model the penetration of daylight into the waters and the resultant heating, information about the optical properties of the surface layer is needed. Several of the oceanographic models commonly used in meteorology have Jerlov's optical classification system for sea water as one of the inputs. The Regional Ocean Modeling System (ROMS), for instance, uses algorithms suggested by Paulson & Simpson (1977), and these algorithms are based on Jerlov's optical water types. The map (Figure 1) and Tables 1–2 presenting Jerlov's optical water types in the Nordic Seas may then provide useful input to such models.

The classification of optical water types was originally (Jerlov 1951) based on the vertical attenuation in the sea of spectral downward irradiance. The clearest ocean water type was denoted by Roman number I, and the less transparent ocean types by numbers II and III. Coastal water types were identified by Arabic numbers 1–9. Later on Jerlov added the oceanic water types IA and IB between I and II (Jerlov 1964), and still later he reduced the description of the coastal water types to 1, 3 and 5 (Jerlov 1978). The vertical attenuation of spectrally integrated quantities like the quanta irradiance (350–700 nm) and the total energy irradiance (300–2500 nm) can also be used to identify the water types (Jerlov 1968, 1976, 1978).

In Jerlov's map of the world ocean (Jerlov 1976) the Nordic Seas were characterized by three points of water type III, while in the map of the Atlantic by Rutkovskaya et al. (1982) the range was from II to the coastal types. Over the years we have observed a great diversity of optical water types in these areas (Aas & Berge 1976, Højerslev 1986, Højerslev & Aas 1991, Aas & Høkedal 1996, Aas et al. 2002), and in the present work we will briefly add some new information on the variation and distribution of these types.

Jerlov (1968, 1976, 1978) pointed out how the vertical attenuation coefficient of downward irradiance at 465 nm was a basic parameter in his optical classification of sea water. In 1974 he also described how irradiance measurements at this wavelength could be used to estimate the quanta irradiance (Jerlov 1974a). At that time very few marine-optical instruments were commercially available, but a simple and cheap instrument, consisting of a selenium photovoltaic cell provided with Schott broadband filters 2 mm BG12 + 2 mm GG5 + an opal glass, would produce a vertical profile that was practically identical to the true vertical profile of downward irradiance at 465 nm. Since such instruments supplied our data base up to 1993, we have chosen the mean vertical attenuation coefficient K of downward irradiance at 465 or 475 nm within the upper 20 m as a reference quantity for the optical water types. The difference between K(465 nm) and K(475 nm) is negligible in this context. It may be added that Pelevin & Rutkovskaya (1977) chose K(500) as the reference for their optical classification, and that Morel & Højerslev discovered that the best correlation between quanta and spectral irradiance was not obtained at 465 or 475 nm, but at 500 nm (Morel & Højerslev 1979, Højerslev 1986). Austin & Petzold (1986, 1990) related K at different wavelengths to K(490 nm).

In the original presentation (Jerlov 1951) the vertical attenuation of the oceanic water types referred to a zenith sun, while the solar zenith angle was supposed to be 45° for the coastal water types. However, according to our observations the influence of the solar angle on K is rather small. In the clear waters of the Western Mediterranean it was found that although the downward irradiance varied during the day, the depths of the 50%, 10% and 1% levels of irradiance and thus the values of K remained practically constant (Højerslev 1974a); similar results were obtained at the Fladen Ground in the North Sea (Højerslev 1982, 1986). In the turbid Oslofjord the mean vertical attenuation coefficient in the 0–10 m layer seemed to be independent of the solar angle (Nielsen & Aas 1977). Consequently no corrections for solar altitude have been made for our area of investigation, where the sun never reaches the zenith.

A survey of the applied data material is presented in Table 1. The material has been sorted by area and latitude, starting in the Arctic Sea north of Svalbard and ending in the Baltic Sea. Direct observations of K(465 nm) or K(475 nm) were made by the authors of references b), c), f), i), m), n) and partly by d). Observations by d) of spectral irradiance at other wavelengths were converted to coefficients at 475 nm by comparing them to observed spectra within the same area. K(530 nm) was recorded by e), and the values were converted to 475 nm by comparing them to Jerlov's spectra for the different optical types. Recordings of K(526 nm) by g) and of K(490 nm) by j) and o) were converted to 475 nm in the same way. The conversion of UV-B irradiance at 310 nm depends on the water type. The

Table 1. N is the number of recordings, K is the vertical attenuation coefficient of downward irradiance at 465 or 475 nm in 10^{-3} m^{-1}, SD is the standard deviation

Latitude	Longitude	Area	Period	N	$K_{\mathrm{mean}} \pm \mathrm{SD}$	K_{min}	K_{max}	Data
82°	7°E–13°E	Arctic Sea	Sept.–Oct. 1979	6	156 ± 40	117	223	a
79°	33°E-48°E	King Charles Land	August 1993	4	99 ± 46	61	164	b
78°–79°	25°E–32°E	King Charles Land	August 1991	14	105 ± 38	64	200	c
71°–78°	11°E–49°E	Barents Sea	May–June 1973	8	242 ± 143	79	464	d
72°–76°	41°E–42°E	Barents Sea	Aug.–Sept. 1998	4	64 ± 23	46	96	e
70°–72°	32°E–43°E	Barents Sea	July 1955	3	100 ± 14	88	116	d
75°–79°	14°W–2°E	Fram Strait	August 1991	11	123 ± 22	96	181	c
74°–79°	14°W–10°E	Fram Strait	August 1993	9	112 ± 55	59	195	b
75°	3°E	Greenland Sea	April–May 1993	1	39			f
70°–75°	14°W–5°E	Greenland Sea	May–June 1958	9	128 ± 55	63	233	d
70°–74°	6°W–0°E	Greenland Sea	May–June 1954	4	124–70	68	219	d
71°	14°W–13°W	Greenland Sea	June 1962	2	424	351	496	d
72°	17°E	Norwegian Sea	July–August 1993	1	210			f
70°–72°	7°E–10°E	Norwegian Sea	June 1954	2	318	214	421	d
70°–71°	8°E–15°E	Norwegian Sea	May–June 1958	2	76	66	85	d
65°–67°	6°E–9°E	Norwegian Sea	March 1955	3	75 ± 6	63	83	d
62°–65°	8°W-2°E	Norwegian Sea	April–May 1971	3	74 ± 12	60	83	d
66°–69°	17°W–13°W	North of Iceland	May–June 1962	14	220 ± 145	61	516	d
65°–68°	31°W–21°W	West of Iceland	May–June 1976	24	198 ± 130	39	580	g
64°–65°	14°W–12°W	East of Iceland	Aug.–Sept. 1973	7	164 ± 28	110	190	h
60°–62°	10°W–2°W	Faroe Islands	July 1978	15	139 ± 58	98	300	a
66°–69°	2°E–10°E	Norw. Coast. Curr.	May 1958	3	108 ± 55	62	169	d
64°–69°	7°E–15°E	Norw. Coast. Curr.	May 1969	8	137 ± 52	97	253	i
63°–66°	5°E–10°E	Norw. Coast. Curr.	April 1968	3	186 ± 59	128	246	i
62°–64°	4°E–10°E	Norw. Coast. Curr.	April 1971	2	198	143	253	d
62°–63°	4°E–6°E	Norw. Coast. Curr.	March 1955	2	426	391	461	d
62°–63°	6°E–7°E	Norw. Coast. Curr.	March 1967	3	112 ± 18	94	129	i

Table 1. (*continued*)

Latitude	Longitude	Area	Period	N	$K_{\text{mean}} \pm \text{SD}$	K_{min}	K_{max}	Data
61°–63°	2°E–6°E	Norw. Coast. Curr.	May 2002	9	115 ± 47	66	198	j
59°	1°E	Fladen Ground	March–June 1976	98	162 ± 84	60	370	k
58°–59°	0°E–1°E	Fladen Ground	August 1975	23	76 ± 19	53	140	l
54°–55°	7°E–8°E	German Bight	Aug.–Sept. 1979	45	477 ± 235	135	1200	a
59°	10°E–11°E	Skagerrak	May–August 2003	5	244 ± 113	153	436	j
58°–59°	11°E	Skagerrak	March–April 1979	24	126 ± 26	75	155	a
57°–59°	8°E–11°E	Skagerrak	May–August 2002	19	287 ± 158	139	733	j
57°–58°	7°E–12°E	Skagerrak-Kattegat	Feb.–Nov. 1990–92	257	243 ± 115	72	842	m
56°–58°	11°E–12°E	Kattegat	June 2002	4	168 ± 57	105	231	j
56°–57°	11°E–12°E	Kattegat	May 1979	48	220 ± 80	140	300	a
56°	11°E	Great Belt	August 1976	1	370			a
56°	13°E–17°E	Sound, Baltic Sea	Sept.–Nov. 1977	2	278	125	430	a
55°–59°	15°E–18°E	Baltic Sea	May 1973	4	279 ± 30	236	308	n
59°	18°E	Baltic Sea	June–July 2001	9	406 ± 24	371	454	o

a) Højerslev unpublished; b) Aas & Høkedal 1996; c) Høkedal 1993; d) Aas & Berge 1976; e) Burenkov et al. 2001a,b, Burenkov personal communication; f) Dallokken et al. 1994; h) Højerslev & Lundgren 1977; i) Aas 1969; j) Sorensen unpublished; k) Højerslev 1982; l) Højerslev 1977; m) Aarup et al. 1996a,b; n) Højerslev 1974b; o) Kratzer et al. 2003.

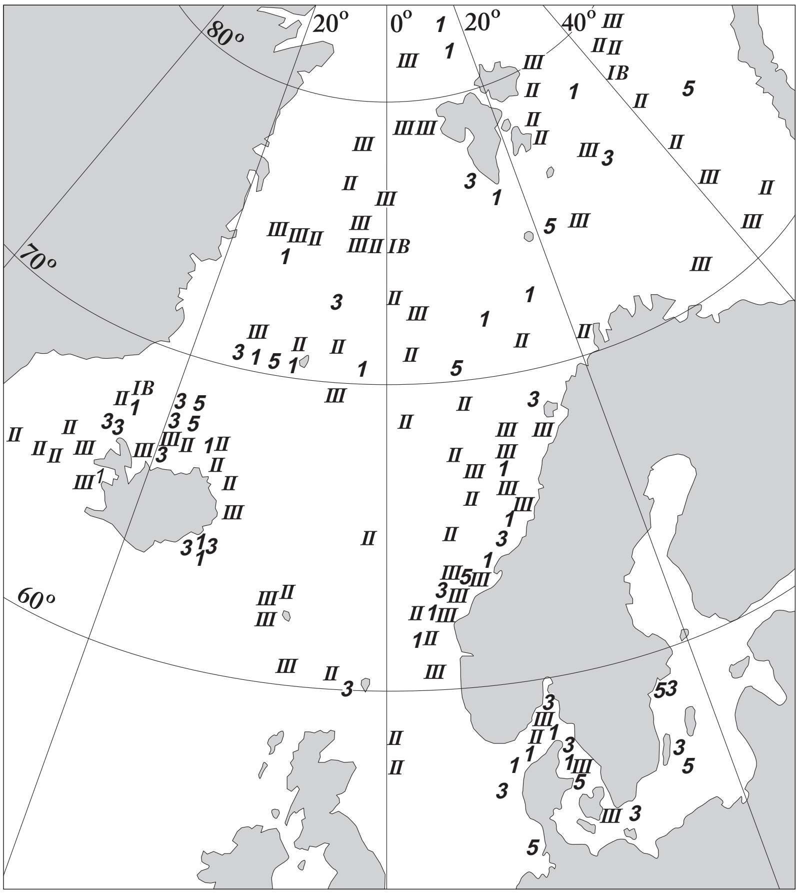

Figure 1. Optical water types in the Nordic Seas and adjacent waters, based on Jerlov's optical classification

relationship between K(310 nm) and salinity in North European coastal waters was commented upon by Aas & Højerslev (2001). Højerslev & Aas (1991) found a linear relationship between K(310 nm) and K(465 nm) for sea waters with a low content of yellow substance, and the relationship differed from Jerlov's optical classification. Consequently, observations of K(310) by a) in Atlantic and Polar waters where K(310 nm) 0.4 m^{-1} were converted by using this relationship, while Jerlov's classification was used in the Skagerrak-Baltic area where K(310 nm) > 0.4 m^{-1}. Finally quanta irradiance was observed by h), k) and l), and their results were converted to K(475 nm) by using Jerlov's figures and tables (1976, 1978). The conversion of K(475 nm) to optical water types is shown by Table 2. The depth ranges for which the K values were calculated, differ, being e.g. 0–5 m, 0–10 m and 0–20 m, depending on signal strength and weather conditions.

The data material is based on 715 recordings at different stations, located at latitudes between 54° and 82°N, and longitudes between 31°W and 49°E. The temporal span is from May 1954 to August 2003. Although the data are not evenly distributed either in season or space, they still provide a very useful picture of the optical conditions, as we shall see.

Figure 1 presents the optical water types at 139 locations. Some of the numbers represent mean values at the location, because the stations are too close to be separated. We see that out in the open sea the most abundant water types are the oceanic types II–III, although coastal types from 1 to 5 occur frequently. These coastal types are not real coastal waters with high contents of yellow substance and inorganic particles; they are caused by algal blooms reducing the transparency of the oceanic water to the coastal range. Dallkken et al. (1995) showed how pre-bloom, bloom and post-bloom values of K(475 nm) at a station in the Greenland Sea (75°N, 3°E) changed from 0.040 m^{-1} to 0.241 m^{-1} and back to 0.052 m^{-1}, corresponding to water types IB, 3 and II. True coastal types are for instance found in the waters of the Baltic, Kattegat and Skagerrak and their continuation in the Norwegian Coastal Current.

Table 2 demonstrates that the choice of optical water type is likely to have a significant influence on the modelled daylight heating of the surface layer. The total energy irradiance (300–2500 nm) will be reduced to 1% of its surface value at depth 23–35 m when the water type is III, and at twice this depth, 53–67 m, when the type is IB. The same doubling applies to the 10% depths of these water types.

Rutkovskaya et al. (1982) presented a map of the different water types in the Atlantic Ocean, based on Pelevin's optical index m (Pelevin & Rutkov-

Table 2. Classification of optical water types from the vertical attenuation coefficient K at 475 nm for the depth range 0–20 m, and the corresponding 10% and 1% depths of the total energy irradiance (300–2500 nm), Z_E

Water type	K(475 nm) [10^{-3} m^{-1}]		Z_E(10%) [m]		Z_E(1%) [m]	
	Centre	Range	Centre	Range	Centre	Range
ocean water I	20	<24	33	>30	86	>80
ocean water IA	27	24–31	27	24–30	74	67–80
ocean water IB	34	31–48	20	17–24	60	53–67
ocean water II	63	48–90	14	11–17	45	35–53
ocean water III	116	90–144	8.3	7.6–11	25	23–35
coastal water 1	171	144–231	7.0	5.9–7.6	22	18–23
coastal water 3	291	231–360	4.8	4.0–5.9	14	12–18
coastal water 5	428	>360	3.2	<4.0	9.0	<12

skaya 1977, Pelevin & Rostovtseva 2001). This index is related to K(500 nm) by $K(500\text{ nm}) = 0.023m$, where K is in units of m^{-1}. In the Nordic Seas the range of m is from 2.5 to > 10, corresponding to a range of K(500 nm) from 0.058 m^{-1} to $> 0.230\ \text{m}^{-1}$, or K(475 nm) from 0.076 m^{-1} to $> 0.265\ \text{m}^{-1}$. According to Table 2 the latter values correspond to the Jerlov range from oceanic II to the coastal types, which is in agreement with the diversity shown by Figure 1. The map by Koprova et al. (2010) of the same area, based on the same data, contains isolines separating the different water types. For the North Atlantic Current they find Pelevin type 4, corresponding to Jerlov type II, for the East Greenland Current and Irminger Current they find Pelevin type 6, corresponding to Jerlov III, while the area north of Iceland has the Pelevin type 7 or the Jerlov range from III to the coastal types. The Norwegian coastal water belongs to Jerlov type III. These results are consistent with Figure 1, although the figure presents a much greater diversity. Simonot & Le Treut (1986) constructed a map of Jerlov's optical water types for the world ocean, extending to the borders of the Nordic Seas. For the area around Iceland and the Faroe Islands they obtained the water type II, and in the North Sea they found water type III, consistent with Figure 1 and Table 1. Pierson et al. (2008) reported K(490 nm) values from 0.33 to 0.91 m^{-1} in the Baltic, corresponding to coastal water types 5–9, which are less transparent than the Baltic recordings shown in Figure 1 and Table 1. These observations are probably representative of more fjord-like conditions.

Figure 1 presents an overall picture of the optical water types in the Nordic Seas, obtained during seagoing expeditions, mostly in the summer season. A better data base would consist of mean values and standard deviations for each month through the year. Unfortunately, however, oceanographic cruises are expensive and resources are meagre. Remote sensing represents an alternative method. Jerlov (1974b) introduced a colour index, defined as the ratio between blue (450 nm) and green (520 nm) radiances from the nadir, just beneath the surface. This colour index can be related to the quanta irradiance, and thus to the optical water types (Jerlov 1974b, Højerslev & Jerlov 1977, Højerslev 1986). The basic product in the remote sensing of ocean colour is the water-leaving radiance at different channels, and thus these radiances can be used to construct colour indices and identify optical water types. Austin & Petzold (1981) presented algorithms for K(490 nm) and K(520 nm) as a function of the ratio of water-leaving radiances at 443 and 550 nm. They also found that the ratio between radiances at 443 and 550 nm was correlated to the similar ratio 443/520 nm and 443/670 nm, while Burenkov et al. (2001b) found a correlation between K(490 nm) and the ratio 510/555 nm. The long-term trends in the chlorophyll content of the world ocean, based on such methods, were analysed by Antoine et al. (2003, 2005). NASA has published monthly climatology maps as well as daily maps of $K(490\text{ nm})$ (http://oceancolor.gsfc.nasa.gov/), thus providing an opportunity to estimate the standard deviations of $K(490\text{ nm})$.

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