Penetration of ultraviolet B, blue and quanta irradiance into Svalbard waters

EYVIND AAS and JO HØKEDAL

Aas, E. & Høkedal, J. 1996: Penetration of ultraviolet B, blue and quanta irradiance into Svalbard waters. *Polar Research 15 (2)*, 127–138.

Observations from August 1991 and 1993 of downward UV-B, blue and quanta irradiances, and of colour indices and Secchi disc depths in the Greenland Sea and the northern part of the Barents Sea, are presented. The UV-B irradiance (306 nm) is on average reduced to 10% of its surface value at 5 metres depth, and to 1% at 10 m. Blue irradiance (465 nm) is reduced to 10% at 21 m, and to 1% at 41 m. The integrated quanta irradiance obtains the same reductions at 16 m and 35 m, respectively. These penetration depths correspond to Ocean Water Type III in Jerlov's classification. They are about twice the values of May–June 1973 observed by Aas & Berge, but they are half the values observed in September 1979 by Højerslev. This variability may partly be seasonal, caused by the hydrological and light-climate cycles. The UV-B transparency of the Svalbard waters seems to be influenced by yellow substance from different freshwater run-offs, and there is probably no single relation between salinity and yellow substance content in this region. Statistical relations between the quanta irradiance and the colour index, the Secchi disc depth and the blue irradiance differ from one region to another, and from year to year.

Eyvind Aas and Jo Høkedal, Department of Geophysics, University of Oslo, P.O. Box 1022 Blindern, N-0315 Oslo, Norway.

Solar ultraviolet radiation is generally divided into three spectral ranges: (1) the extremely harmful UV-C radiation (200–280 nm) which is absorbed almost entirely by the Earth's atmosphere, (2) the DNA-damaging UV-B radiation (280–315 nm) which is strongly absorbed by the atmospheric ozone, and (3) the both damaging and repairing UV-A radiation (315–400 nm) which is only weakly absorbed by the ozone. The observed depletion of polar ozone in the Southern and Northern hemispheres (Fahey 1995) is assumed to lead to increased doses of UV-B radiation at the Earth's surface (McKenzie 1995; Taalas et al. 1995; Zerefos 1995), and this has brought new focus on the impact of UV-B radiation on aquatic life. The amounts of ultraviolet radiation at different depths in the sea may be estimated if the corresponding vertical attenuation coefficient for the surface layer is known (Zeng et al. 1993). Unfortunately very little systematic mapping of such optical properties has been made. Jerlov (1976) has published a figure which shows the regional distribution of optical water types for the world oceans between 70°S and 70°N. A similar map has been presented for the Secchi disc depth by Shifrin (1988), while Simonot & Le Treut (1986) combine several types of optical observations to produce regional distributions of optical water types, Secchi disc depths, and vertical attenuation coefficients for blue light (465 nm). None of these maps are suited to predicting the penetration of ultraviolet radiation into the sea, except perhaps for the clearest ocean waters, and none of them extend beyond 70°N.

For the Svalbard area north of 75°N some irradiance observations in the sea have been published (Aas & Berge 1976; Højerslev 1980; Højerslev & Aas 1991), and a few observations have been made in Svalbard fjords (Halldal & Halldal 1973; Høkedal 1993).

Højerslev & Aas (1991) found that for North Atlantic surface waters with a salinity above 35.0 psu, the best fit between the vertical attenuation coefficients K at 310 and 465 nm was obtained by the line

$$K(310) = [0.078\ m^{-1}] + 1.04\ K(465). \qquad (1)$$

It was also found that in the waters around Svalbard with salinities below 35.0 psu, the optical observations deviated from this relation. Although it could be presumed that the deviations were due to yellow substance brought into the sea by freshwater run-off, evidence for this hypothesis was lacking.

In 1991 different optical measurements were made in the Greenland and northern Barents seas in collaboration with the Norwegian Polar Institute and the Norwegian Institute for Water Research (Høkedal 1993). The main purposes of the project were to survey the vertical attenuation of UV-B and blue irradiance in this region and to study the influence of the freshwater content on the UV-B attenuation.

This paper presents the results of the project. Additional measurements made in 1993 have been included. As a useful by-product, relations between the integrated quanta irradiance and the blue irradiance, the colour index and the Secchi disc depth were obtained and are compared with similar results from the surrounding areas.

Instruments

One integrating and two single-channel irradiance meters were applied: a quanta irradiance meter manufactured by LI-COR, Inc., Nebraska, a UV-B meter from Dansk Havteknik a/s, Copenhagen, and a blue irradiance meter from the Department of Physical Oceanography at the Niels Bohr Institute, University of Copenhagen.

The underwater sensor LI-192S(B) measures integrated quanta irradiance in the range 400–700 nm (photosynthetically active or available radiation, PAR). The properties of this instrument have been described by Roemer & Hoagland (1981).

The sensor of the UV-B meter consists of a quartz diffusor and window, an interference filter, and a photomultiplier. Its spectral sensitivity peak lies at 306 nm and the band width at half peak value is 10 nm.

The blue irradiance meter has an opal glass, the standard filter combination BG12 + GG5 from Schott, a glass window and a photovoltaic cell. The sensitivity peak lies at about 465 nm, and the band width is 30 nm.

Details of the construction of the two single-channel instruments and of their calibrations with regard to linearity, cosine and immersion effects and spectral sensitivity have been presented elsewhere (Høkedal & Aas 1994). All three irradiance meters were calibrated against certified standard lamps.

The colour index meter, manufactured by Dansk Havteknik a/s, Copenhagen, consists of a sensor that "looks" down into the sea and measures the ratio between the upward scattered blue (446 nm) and bluegreen (514 nm) radiances (Jerlov 1974a). The spectral band widths at the two wavelengths are about 17 nm. The method of calibration has been described by Aas (1993, 1994).

A standard white Secchi disc with a diameter of about 30 cm was applied. Salinity and temperature were measured with a CTD Mark III sensor from Neil Brown.

Methods and errors of measurement

A deck model of the quanta meter served as a reference during all the irradiance measurements. It has been observed for green irradiance in coastal waters (Aas 1969) that the deviations from a linear relation between irradiance in air and irradiance at 2 m depth normally are less than 20%, but that in special cases (low sun and uneven cloudiness) they may amount to 70%. From observations during clear sky conditions in the Mediterranean Sea, it was concluded that blue irradiance at 10 m depth varied in the range from 48% to 66% of the surface value for solar elevations in the range 10°–70° (Højerslev 1974a). This corresponds to a relative variation of ±16% from the mean value. At 50 m depth the relative variation became ±20%. Similarly the relative variation of blue irradiance at 60 m depth below sea ice in the Arctic Ocean was observed to be only ±2% for irradiance fluctuations in air of about 70% (Smith 1973).

From the 60 m long ship R/V Lance, measurements were made using a bar to keep the irradiance meters at a distance of 5 m from the shipside, 10 m aft of the bow. The side of the ship nearest to the instrument bar reached about 4 m above sea level and 5 m below. The resulting influence of the ship on the calculated vertical attenuation coefficient of downward irradiance, K, was estimated to be of magnitude 0.01–0.025 m^{-1} (Høkedal 1993). Because most of the values obtained for K were greater than 0.1 m^{-1}, it was then assumed that the ship's influence could be ignored.

Joseph (1949) and Aas & Berge (1976) have demonstrated earlier that the signal from the blue irradiance meter is proportional to the downward irradiance at 465 nm (Fig. 1).

Unfortunately it is far more difficult to measure irradiance in the UV-B range. If the ratio between

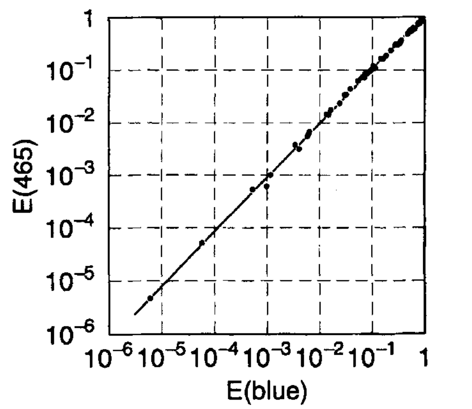

Fig. 1. Narrow band irradiance $E(465)$ at 465 nm as a function of the broad band irradiance E(blue) recorded with Schott filter BG12 + GG5, based on eight optical stations from the Norwegian Sea between the surface and a depth of 50 m. Both irradiances are normalised against their surface values (Aas & Berge 1976).

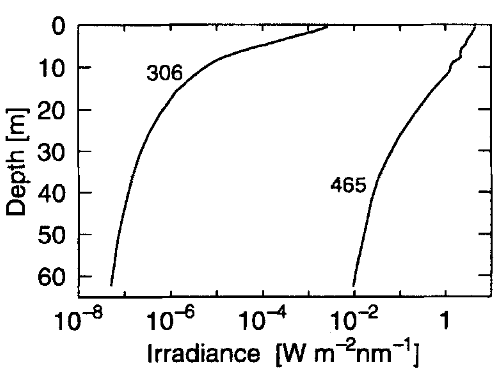

Fig. 2. Irradiance at 465 nm (right curve) and uncorrected irradiance at 306 nm (left curve) as functions of depth, at a station in the central Greenland Sea (75.0°N, 10.0°W, 1720 GMT, solar altitude 9°, 15 August 1991) (Høkedal & Aas 1994).

the blue and UV-B irradiances increases strongly with increasing depth, even a very small sensitivity to blue light in the UV-B instrument may make significant or dominating contributions to the signal (Højerslev 1978). For example the observed irradiance curves at 306 and 465 nm in Fig. 2 tend to become parallel from a certain depth on. The obvious explanation is that the UV-B instrument has a "light leakage" in the blue part of the spectrum. The leakage is quantified by the almost constant ratio τ between the irradiances E in the depth range where the two curves are approximately parallel:

$$\tau \approx \frac{E(306)}{E(465)}. \qquad (2)$$

At all depths z the "true" UV-B irradiance may then be calculated from the observed irradiances by

$$E(306,z)_{\text{true}} \approx E(306,z)_{\text{obs}} - \tau E(465),z)_{\text{obs}}. \qquad (3)$$

The observations were rejected when the correction given by the last term of eq. (3) amounted to 50% or more of the observed value. This is demonstrated in Fig. 3 which presents the UV-B irradiance of Fig. 2 after the corrections have been made. The ratio τ, which depends on the shape of the spectral irradiance distribution, varied from one station to another (Høkedal & Aas 1994).

The colour index was recorded by lowering the instrument over the rail. It was observed that the distance between ship and instrument had no significant effect on the colour index. The measurements were restricted to solar altitudes above 15°, where the index is practically independent of the sun's position (Højerslev 1974b; Jerlov 1974a). Overcast conditions will increase the index by about 10% (Jerlov 1974a). Most of the observations of the colour index were made with an overcast sky and have been suitably adjusted.

Results

Observations of the vertical irradiance attenuation

During August 1991 irradiance was measured at 29 stations in the Greenland Sea and in the northern part of the Barents Sea, and in August 1993 at 23 stations in the same area. The solar altitude was less than 30° at all stations, and often less than 20°. The positions were chosen for hydrographical rather than optical reasons.

At most of the stations the upper layer acted both as a thermo- and a halocline, from the surface or from a few metres depth down to the lower boundary at 10–20 m. Many stations also featured a dicotherm at this boundary (Fig. 3), which is a characteristic of vertical temperature profiles at high latitudes. The observed salinities

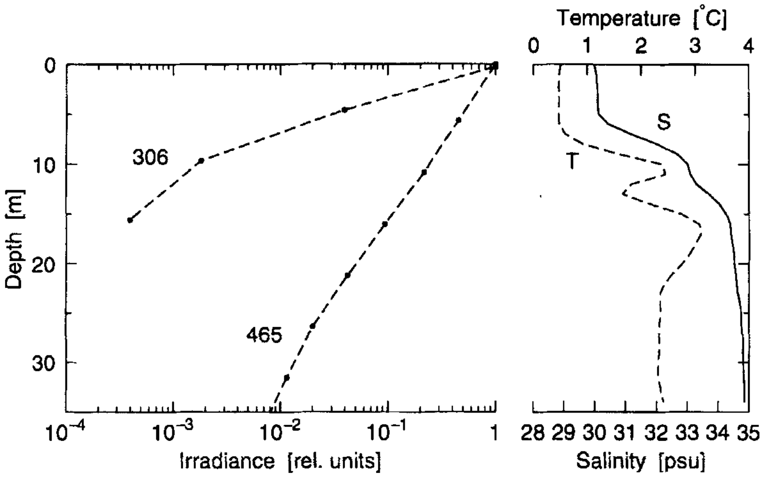

Fig. 3. Downward irradiances at 306 nm (corrected) and 465 nm, and temperature T and salinity S as functions of depth at the same station as in Fig. 2.

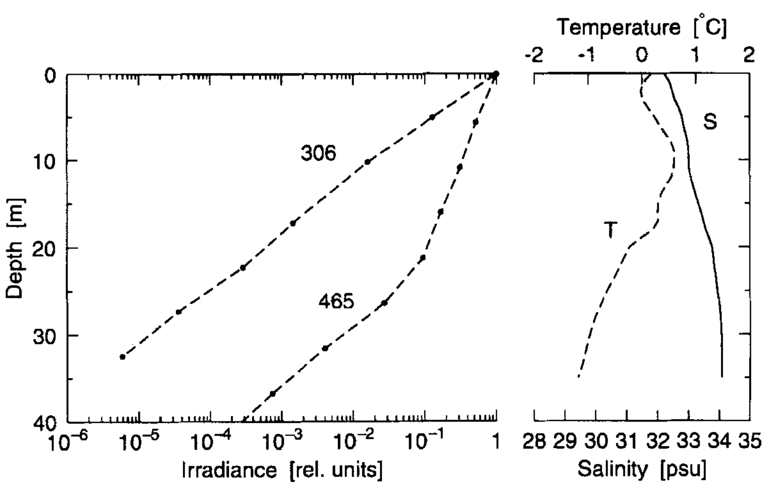

Fig. 4. Downward irradiances at 306 and 465 nm, and temperature T and salinity S as functions of depth at a station in the northern Barents Sea (75.8°N, 28.6°E, 1745 GMT, solar altitude 13°, 2 August 1991).

at the depths where the irradiance was measured varied in the range from 25.4 to 34.6 psu. At a typical station the vertical attenuation decreased with increasing depth (Fig. 3). At some stations, however, a distinct two-layer structure was observed in the vertical attenuation, with the boundary at 20–40 m depth (Fig. 4). The characteristic feature of the lower layer was a larger attenuation than in the layer above. Most probably this was caused by an internal maximum in particle concentration. Such maxima have been observed in Svalbard waters for the scattering coefficient (Kullenberg 1984; Kullenberg & Xu 1986) and the mass concentration of suspended particles (Forsberg 1983).

The present observations demonstrate that the irradiance will penetrate deeper in the central part of the Greenland Sea than in the more peripheral areas (Figs. 5–8). No clear pattern can be distinguished in the northern Barents Sea.

The statistical mean values ± the standard deviations for the depths $Z_{306}(10\%)$ and $Z_{306}(1\%)$ (Figs. 5–6), where the UV-B irradiance is reduced to 10% and 1% of its surface value, are 5 ± 2 m and 10 ± 3 m, respectively.

The corresponding depths for the blue irradiance, $Z_{465}(10\%)$ (Fig. 7) and $Z_{465}(1\%)$, are 21 ± 7 m and 41 ± 20 m. The last depth is partly based on extrapolated values.

The mean value and standard deviation of the 10% depths of integrated quanta irradiance, $Z_Q(10\%)$ (Fig. 8), become 16 ± 5 m. The depth

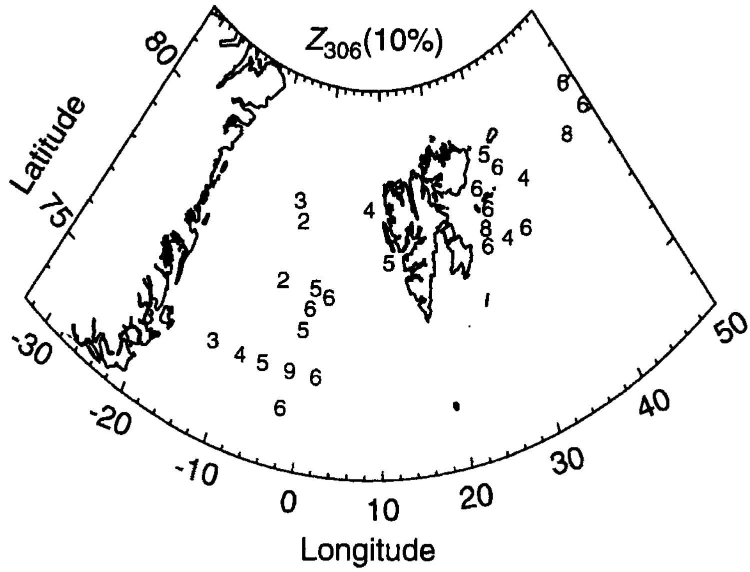

Fig. 5. Distribution in August 1991 and 1993 of the depths $Z_{306}(10\%)$ where the downward UV-B irradiance is reduced to 10% of its surface value. The depths represent one single station or the average of two or three closely situated stations.

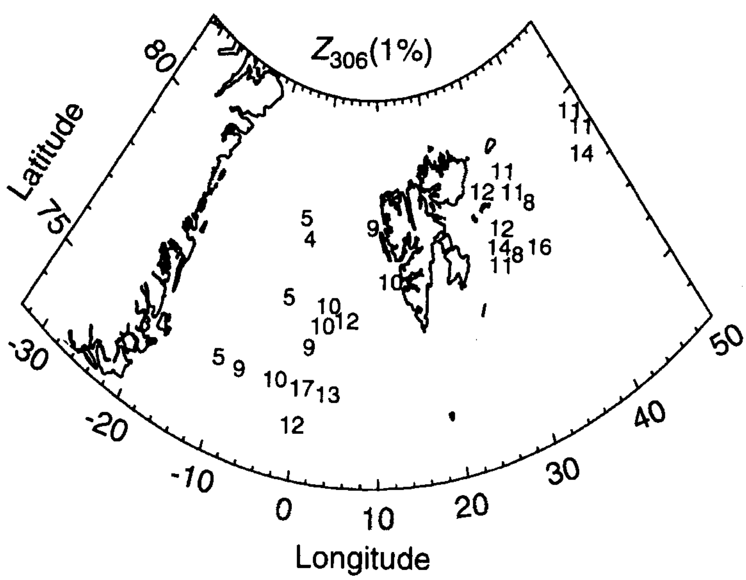

Fig. 6. Distribution in August 1991 and 1993 of the depths $Z_{306}(1\%)$ where the downward UV-B irradiance is reduced to 1% of its surface value.

$Z_Q(1\%)$ was not measured at all of our stations, but linear correlation based on 12 stations in 1991 gives for this quantity the approximation

$$Z_Q(1\%) \approx [3\ m] + 2Z_Q(10\%) \qquad (4)$$

with correlation coefficient $r = 0.74$. The mean value of $Z_Q(1\%)$ may then in our case be estimated to be about 35 m. The mean values of $Z_{465}(1\%)$ and $Z_Q(1\%)$ both correspond to Water Type *III* in Jerlov's optical classification of ocean water (e.g. Jerlov 1976).

The $Z(0.1\%)$ depths were usually not measured for the UV-B, blue and quanta irradiances, either because the signals became too small or because the underwater cables were too short. However, $Z_{306}(0.1\%)$ may be obtained as a crude estimate from the presented values of $Z_{306}(10\%)$ and $Z_{306}(1\%)$ by the assumption that semilogarithmic

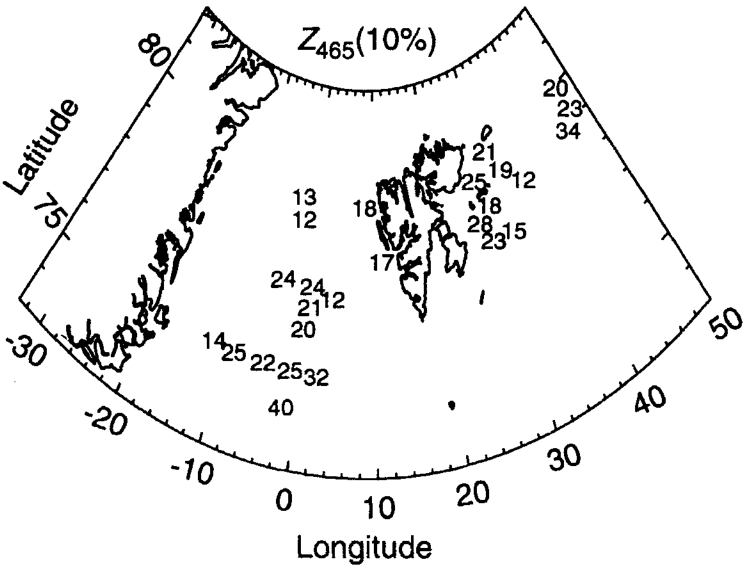

Fig. 7. Distribution in August 1991 and 1993 of the 10% depth for downward blue irradiance, $Z_{465}(10\%)$.

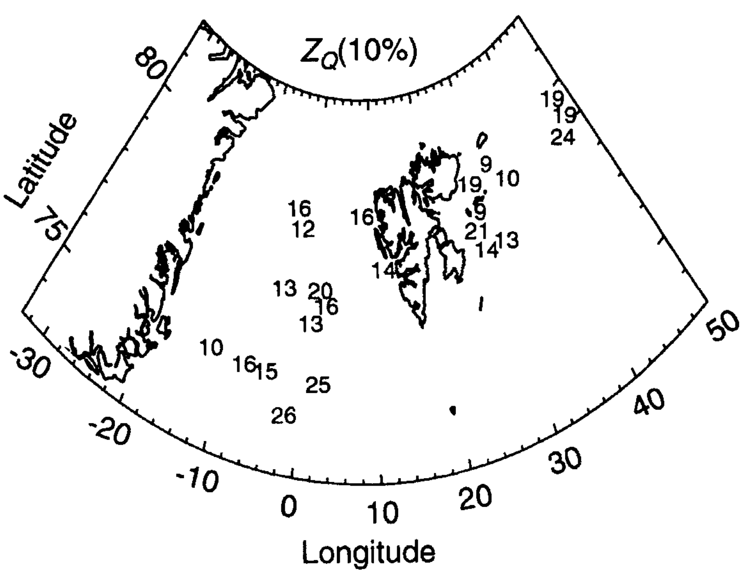

Fig. 8. Distribution in August 1991 and 1993 of the 10% depth for downward integrated quanta irradiance, $Z_Q(10\%)$.

plots of $E(306)$ versus z become straight lines below $Z_{306}(10\%)$:

$$\begin{aligned} Z_{306}(0.1\%) &\approx Z_{306}(10\%) + 2(Z_{306}(1\%) \\ &- Z_{306}(10\%)) = 2Z_{306}(1\%) - Z_{306}(10\%). \end{aligned} \tag{5}$$

This estimate works best in optically homogeneous water.

Influence of freshwater on the UV-B attenuation

If we plot our observed values of $K(306)$ from the Svalbard area as a function of the corresponding $K(465)$ values, the points will not lie on the line described by eq. (1), but they will form a diffuse cloud, situated above the line. This means that Svalbard waters contain optical components

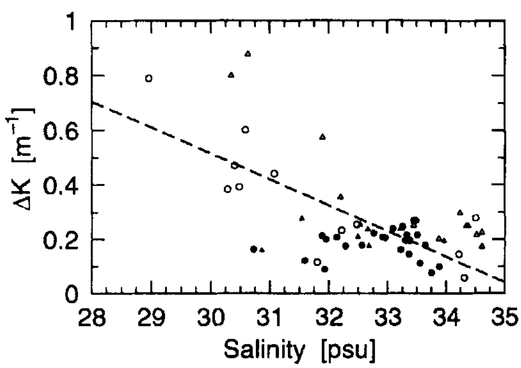

Fig. 9. Calculated values of ΔK as a function of salinity S for the 38 optical stations where S was available. Explanation: ○ = Greenland Sea, 1991; ● = northern Barents Sea, 1991; △ = Greenland Sea, 1993; ▲ = northern Barents Sea, 1993. The dashed line is the best fit to the observations from the Greenland Sea in 1991.

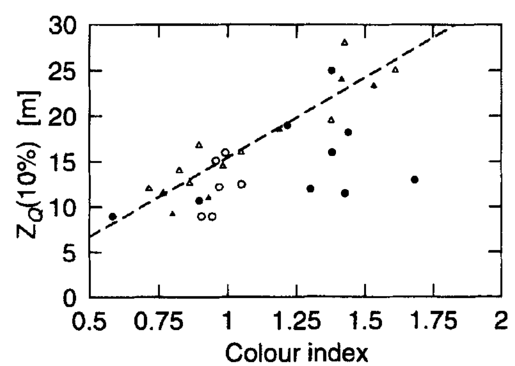

Fig. 10. The 10% depth of integrated quanta irradiance, $Z_q(10\%)$, as a function of the colour index at 0 m (symbols as in Fig. 9). The dashed line gives the best fit to the observations from 1993.

which produce significantly larger vertical attenuation coefficients at 306 nm than at 465 nm. The most likely component in the ocean with such a property is yellow substance (Aas & Høkedal 1996). Probably eq. (1) applies to conditions where the content of yellow substance is low, and where the variation in K is due mainly to a varying amount of phytoplankton particles and associated debris.

The yellow substance content can be determined by spectrophotometric analysis of filtered water samples. Because the necessary equipment was not available during our cruises, samples were taken and stored for later analysis, but unfortunately they had by then become contaminated and had to be rejected. This restricts our discussion of the yellow substance to a comparison with the observed salinity. Linear relations between yellow substance and salinity, where the content of yellow substance decreases with increasing salinity, have been observed in the Baltic Sea by Kalle (1949) and Jerlov (1955), in the Kattegat and Skagerrak by Højerslev (1971), and in a section between Iceland and Nova Scotia by Walsh et al. (1992). More complex patterns will occur when more than two water types are mixed, as demonstrated by Højerslev (1980, 1994) and Højerslev et al. (1996).

The difference between the observed value of $K(306)$ and the value estimated from the observed value of $K(465)$ by eq. (1) will be termed ΔK:

$$\Delta K = K(306)_{obs} - K(306)_{est}$$
$$\approx K(306)_{obs} - [0.078\ m^{-1}] - 1.04\ K(465)_{obs}. \qquad (6)$$

If the difference ΔK is caused by yellow substance, it can then be expected to decrease with increasing salinity.

The quantity ΔK was calculated for the 38 optical stations where data for the salinity S were available. Linear correlation restricted to the observations from the Greenland Sea in 1991 produces the line

$$\Delta K = [3.37\ m^{-1}]\left(1 - \frac{S}{35.43}\right) \qquad (7)$$

with the correlation coefficient $r = -0.81$ (Fig. 9). Since yellow substance in Svalbard waters may originate from local river sources as well as from different run-offs into the Arctic Ocean and other areas, it is not surprising that observations from other years and other regions deviate from the relation given by eq. (7) in Fig. 9.

If ΔK is assumed to be entirely due to yellow substance, it may be approximated by the expression

$$\Delta K \approx a_y(306)/\mu(306) \qquad (8)$$

where $a_y(306)$ is the absorption coefficient of yellow substance, and $\mu(306)$ is the mean cosine of the zenith angle for the downwelling UV-B radiance. A crude estimate of the last quantity can be obtained by assuming that the downward UV-B radiance is constant within the Snell circle, that is for zenith angles θ in the range $0-48°$, and zero outside this range:

$$\mu(306) \approx \frac{\int_0^{48°} \sin\theta \cos\theta \, d\theta}{\int_0^{48°} \sin\theta \, d\theta} = 0.83. \qquad (9)$$

Consequently the mean value $0.27\,m^{-1}$ of ΔK in Fig. 9 may correspond to a mean absorption coefficient $a_y(306) \approx 0.22\,m^{-1}$ for yellow substance.

Relations between $Z_Q(10\%)$ and other optical quantities

The euphotic zone may be defined as "that region in which light is sufficient to support the growth and reproduction of plants" (Lalli & Parsons 1993). From this definition it follows that the lower boundary will vary geographically and for different species. However, as a rule of thumb $Z_Q(1\%)$ is often taken as a measure of the lower boundary for phytoplankton (Kirk 1983), and in certain regions and for certain species this may be permitted. The euphotic zone for benthic algae seems to extend to deeper layers than for phytoplankton, and in extremely clear tropical water it even reaches below the 0.001% level (Littler et al. 1985). The quantities $Z_Q(10\%)$, $Z_Q(1\%)$ and $Z_Q(0.1\%)$ discussed in this paper are then primarely optical (and not biological) properties of the vertical water column.

If the quanta irradiance has not been observed, it will be useful to have relations between $Z_Q(1\%)$ and the other optical quantities. In our case the length of the underwater cable did not allow $Z_Q(1\%)$ to be observed directly at all stations, so instead relations based on $Z_Q(10\%)$ have been studied. When $Z_Q(10\%)$ is determined, $Z_Q(1\%)$ can be estimated from eq. (4).

Jerlov (1974b) was the first to point out that a strong correlation usually exists between the transmittances of blue and integrated quanta irradiance in ocean waters with a low content of yellow substance. The present observations from the Svalbard waters result in

$$Z_Q(10\%) \approx [6\ m] + 0.44 Z_{465}(10\%). \qquad (10)$$

with $r = 0.81$.

Our observations of the ratio between the 10% depths of quanta irradiance and the Secchi disc depth D result in the mean value and the standard deviation

$$Z_Q(10\%)/D \approx 1.2 \pm 0.3. \qquad (11)$$

The colour index F is defined as the ratio $L_u(446)/L_u(514)$, where L_u is the radiance from nadir on the wavelengths 446 and 514 nm. It is usually measured at 1 m depth or just beneath the surface. If the correlation analysis between the colour index F, extrapolated to the surface, and $Z_Q(10\%)$ is restricted to the observations from 1993, the result becomes

$$Z_Q(10\%) \approx [-2.0\ m] + [17.4\ m]\ F(0\ m) \qquad (12)$$

with $r = 0.92$. The observations from 1991 are not evenly distributed around the line given by eq. (12), as illustrated by Fig. 10, and they seem to have a smaller slope.

By applying the colour index at 1 m depth the 1993 observations produce

$$Z_Q(10\%) \approx [-0.4\ m] + [16.4\ m]\ F(1\ m) \qquad (13)$$

with $r = 0.93$.

Discussion

Comparison with earlier investigations

During late May to early June in 1973 blue irradiance was recorded at six stations in the Svalbard area by Aas & Berge (1976). On this occasion Atlantic surface water (salinity above 35.0 psu) was observed as far north as 76.5°N. The observations gave $Z_{465}(10\%) = 7.5 \pm 3$ m in waters with salinities below 35.0 psu, and $Z_{465}(10\%) = 16.5 \pm 7$ m in the Atlantic water. Similarly $Z_{465}(1\%)$ became 16 ± 7 m for the non-Atlantic and 40 ± 17 m for the Atlantic water. The non-Atlantic mean values in 1973 were then less than half of the present observations (21 and 41 m, respectively), while the Atlantic values were of the same magnitude. The mean values of $Z_Q(10\%)$ and $Z_Q(1\%)$ could be estimated to be about 8 and 19 m, respectively, for the non-Atlantic waters, which again are only about half the present results (16 and 35 m).

In September 1979 Højerslev (1980, 1982a) obtained the value 0.20–$0.25\,m^{-1}$ for $K(310)$ in the Svalbard area, and this corresponds to a $Z_{310}(10\%)$ of 9–12 m and a $Z_{310}(1\%)$ of 18–23 m. The observed value of $Z_Q(1\%)$ was in the range 50–56 m. These results are all greater than any of our observations, and about twice our mean values. The values of the absorption coefficient of yellow substance 375 nm, $a_y(375)$, were in the range $0.01–0.02\ m^{-1}$. The variation of this coefficient with wavelength λ may be approximated by an exponential function (Jerlov 1968; Lundgren 1976):

$$a_y(\lambda) = a_y(\lambda_o)e^{-\gamma(\lambda-\lambda_o)}. \quad (14)$$

The quantity γ varies only slightly with wavelength but has a more significant variation in space. In the Baltic Sea and in the Gulf of Mexico γ has been observed to vary in the range $0.011–0.017\ nm^{-1}$ (Lundgren 1976; Carder et al. 1989) and elsewhere in the range $0.010–0.020\ nm^{-1}$ (Bricaud et al. 1981; Højerslev 1988). If we apply the value $0.014\ nm^{-1}$ for γ, the ratio $a_y(306)/a_y(375)$ becomes 2.6. The 1979 observations will then correspond to $a_y(306) \approx 0.03–0.05\ m^{-1}$, which is an order of magnitude less than our estimated mean value of $0.22\ m^{-1}$.

Nyquist (1979) found for Baltic waters that a yellow substance concentration of 1 mg/l corresponded to $a_y(450) = 0.212\ m^{-1}$, while the observations of Carder et al. (1989) in the Gulf of Mexico indicated that $a_y(450) = 0.007–0.13\ m^{-1}$ with the mean value $0.022\ m^{-1}$ for the same concentration. The last value is a factor 10 less than the result of Nyquist, and due to this uncertainty we have abstained from estimates of the yellow substance concentration.

No significant differences in our observations of Z_{306}, Z_{465}, and Z_Q were found between the years 1991 and 1993. This might lead to the premature conclusion that the results in Figs. 5–8 represent the average conditions for the area, but the observations in 1973 (Aas & Berge 1976) and in 1979 (Højerslev 1980) demonstrate that large changes in the optical conditions may occur. The 1973 observations were made from late May to early June, and some of the stations were visibly influenced by plankton blooms. The 1979 observations were made in late September, one month later than our observations, and represented a situation with a significantly lower content of yellow substance than in our case, probably due to a stronger influence from Atlantic waters. The freshwater run-off from Svalbard will normally start in June, obtain its maximum in July–August, and fade away in September (Repp 1988); this cycle is likely to influence the biological and optical conditions in the surrounding surface waters. Seasonal changes in available daylight may also induce changes in phytoplankton production and thus in the optical conditions.

In general the vertical attenuation coefficients may be influenced by the solar altitude. However, because this altitude usually is less than 35° in the Svalbard area, the diffuse sky irradiance will always be much larger than the direct solar irradiance in the UV-B and blue parts of the spectrum (Baker & Smith 1990). As a consequence the solar influence on the vertical attenuation coefficient in these waters will also be small, and the observed large differences between the three investigations can then hardly be attributed to seasonal changes in the mean solar altitude, but must mainly be due to differences in the absorption coefficient.

Comparison with adjacent oceanic regions

In the Atlantic waters of the Norwegian Sea, Højerslev & Aas (1991) found the average value of $Z_{310}(1\%)$ to be at a depth of 23 m or more, and the maximum depth of 33 m was found north of the Faroe Islands. This is more than twice the values in the present results from Svalbard waters. Calkins & Thordardottir (1982) have presented values of $K_{UV\text{-}B}$ measured in the areas west of Iceland. Their observations lead to values of $Z_{UV\text{-}B}(10\%)$ in the range 13 ± 6 m, which also are greater than our result.

It may be added the UV radiation seems to penetrate to greater depths in the Antarctic than in the Arctic. Gieskes & Kraay (1990) reported values of $Z_{340}(1\%)$ up to 60 m in the Weddel Sea, and Smith et al. (1992) have presented an irradiance observation from the Bellinghausen Sea where $Z_{340}(1\%)$ and $Z_{310}(1\%)$ were about 35 and 30 m, respectively. By applying eq. (14) the result of Gieskes & Kraay may be converted to $Z_{310}(1\%) \approx 39$ m, which is 17% less than the corresponding depth of 47 m observed in the Gulf of Mexico by Højerslev (1985). The last value corresponds to clearer water at 310 nm than the clearest natural waters estimated by Smith & Baker (1981). The smallest observed values of $Z_{310}(1\%)$ in natural waters seem to range from 35 cm in a Baltic coastal lagoon (Piazena & Häder 1994) to 17 cm in Lake Cromwell, Québec (Scully & Lean 1994).

Observations from the Norwegian Sea and the southern part of the Barents Sea, including coastal waters (Aas 1980), gave the mean value and the standard deviation of $Z_{465}(10\%)$ as 17 ± 9 m, and the corresponding values for $Z_{465}(1\%)$ as 40 ± 20 m. Similarly the results for $Z_Q(10\%)$ and $Z_Q(1\%)$ became 14 ± 6 m and 36 ± 14 m, respectively. These values are rather close to the present observations. The relation between the 10% depths of quanta and blue irradiance for the same area was obtained as

$$Z_Q(10\%) \approx [3\ m] + 0.63 Z_{465}(10\%) \qquad (15)$$

with the correlation coefficient $r = 0.98$ (Aas (1980). The values of $Z_Q(10\%)$ estimated by eq. (10) and (15), respectively, will only differ by 1–2 m for Svalbard waters.

Dalløkken et al. (1994, 1995) found for their stations, mainly between 15°W–25°E and 70°–75°N in the southern Greenland Sea, that pre-bloom, bloom and post-bloom conditions were quite different. $Z_{441}(1\%)$ had the pre-bloom mean value 72 m and the post-bloom value 35 m, and the corresponding values for $Z_Q(1\%)$ were 53 and 38 m, respectively. The total range of $Z_Q(1\%)$ extended from 16 m (bloom) to 66 m (pre-bloom), and the similar range of $Z_{465}(1\%)$ seems to have been 17–116 m. The post-bloom values resemble the present observations which are classified as Jerlov's Ocean Water Type *III*, but the pre-bloom penetration depths are 50–75% greater than our mean values and belong to Ocean Water Type *II*.

In May 1972 under the ice in the Arctic Ocean north of Ellesmere Island, Smith (1973) measured the vertical irradiance coefficient at 490 nm to be 0.0444 m^{-1}. The value of $Z_{490}(1\%)$ would then be about 100 m, which corresponds to the very clear Ocean Water Type *IB* in Jerlov's classification, in contrast to the present mean Type *III*. It should be noted that also the observations $Z_Q(1\%) = 66$ m and $Z_{465}(1\%) = 116$ m by Dalløkken et al. (1995) classify as Type *IB*.

From observations at the Fladen Ground in the northern part of the North Sea, Højerslev (1982b) obtained a relation between the colour index at the surface, $F(0\ m)$, and the 10% depth of quanta irradiance, $Z_Q(10\%)$, which for our purposes may be more conveniently rewritten as

$$Z_Q(10\%) = [-22.0\ m] + [38.9\ m]\ [F(0\ m) + 0.07]^{0.5} \qquad (16)$$

When $F(0\ m)$ fluctuates in the range from 0.7 to 1.6, the difference between the estimates of $Z_Q(10\%)$ from eqs. (12) and (16) will lie in the range 2–3 m.

An equation between $F(1\ m)$ and $Z_Q(10\%)$, based on data which also includes observations from the North Sea, the Baltic Sea and the Belts (Højerslev & Jerlov 1977), coincides better with the present observations:

$$Z_Q(10\%) = [4\ m] + [12.2\ m] F(1\ m). \qquad (17)$$

For a variation of $F(1\ m)$ in the range from 0.6 to 1.6, the difference between eqs. (13) and (17) becomes 0–2 m.

The colour index is closely related to the methods employed in remote sensing. The differences which result from the expressions (12)–(16) and (13)–(17) demonstrate that an algorithm obtained for one area in the Norwegian Sea cannot always be transferred to another without problems. Fig. 10 also indicates that the algorithms may vary from one year to another. It may then become far more complicated to estimate the depth of the euphotic zone in these waters by remote sensing than in ocean areas with a low yellow substance content.

In the Norwegian Sea and the southern part of the Barents Sea the mean value and the standard deviation of the ratio between the 10% depth of quanta irradiance and the Secchi disc depth D has been found to be (Aas 1980)

$$Z_Q(10\%)/D \approx 1.5 \pm 0.3 \qquad (18)$$

The mean value of D around Svalbard in the present investigation is 12.5 m, which means that eq. (18) on average will estimate $Z_Q(10\%)$ about 4 m too deep, as compared with eq. (11). Here it should be pointed out that although the Secchi disc depth is mainly a function of the inherent optical properties, it is also influenced by the conditions at the surface and by the daylight level. The wave height reduces the observed depth (Højerslev 1986), and the reflection of atmospheric light at the air–water interface has a similar effect. The daylight level decreases with increasing latitude, and this will increase the liminal contrast threshold of the human eye (Blackwell 1946), which again leads to a reduced Secchi disc depth. All these effects may have contributed to the difference between eqs. (11) and (18).

Conclusions

The present investigation, together with the earlier works by Aas & Berge (1976) and Højerslev (1980), demonstrate clearly the complexity of the optical conditions in Svalbard waters. The mean

1% depths of the UV-B, blue and quanta irradiances have been observed to vary in the ranges 10–21 m, 16–41 m, and 19–53 m, respectively. Observations by Dalløkken et al. (1994, 1995) south of 75°N suggest that these ranges may be extended. It is possible that the observed variability is partly or entirely caused by seasonal changes in river run-off and available daylight. For the moment we must conclude that, although we know something of the variability, we do not have sufficient information to estimate the average conditions and the seasonal variations with satisfactory accuracy.

Studies of the relations between the vertical attenuation coefficients and the surface salinity indicate that yellow substance in the Svalbard area originates from different freshwater run-offs.

Similarities as well as differences in the optical properties between Svalbard waters and the adjacent regions have been observed. Comparisons of statistical relations between the quanta irradiance and the colour index, the Secchi disc depth, and the blue irradiance demonstrate that algorithms obtained for one area in the Norwegian Sea may result in significant errors in other areas. Our results also indicate that such algorithms may vary from one year to another.

Acknowledgements. – The field work and the laboratory analysis were supported by the Norwegian Polar Institute and the Norwegian Institute for Water Research (NIVA), and in particular we recognise T. Løyning and K. Sørensen for their significant parts of the optical measurements. We also wish to thank the crew of the R/V LANCE for their assistance during the field work, and two anonymous referees who contributed valuable comments to the paper.

References

Aas, E. 1969: On submarine irradiance measurements. Rep. Dept. Phys. Oceanogr. No. 6. Univ. Copenhagen. 47 pp.

Aas, E. 1980: Relations between total quanta, blue irradiance and Secchi disc observations in the Norwegian and Barents seas. Pp. 11–27 in Kullenberg, G. (ed.): Studies in physical oceanography. Papers dedicated to professor Nils G. Jerlov in commemoration of his seventieth birthday. Rep. Dept. Phys. Oceanogr. No. 42. Univ. Copenhagen.

Aas, E. 1993: Calibration of a marine radiance and colour index meter. Rep. Dept. Geophys. No. 87. Univ. Oslo. 24 pp.

Aas, E. 1994: A simple method for radiance calibration. Pp. 39–44 in Wernand, M. (ed.): *European workshop on optical ground truth instrumentation for the validation of space-borne optical remote sensing data of the marine environment 23–25 Nov. 1993.* Netherlands Institute for Sea Research, Rep. No. 1994–3.

Aas, E. & Berge, G. 1976: Irradiance observations in the Norwegian and Barents Seas. Rep. Dept. Geophys. No. 23. Univ. Oslo. 42 pp.

Aas, E. & Høkedal, J. 1996: Properties of marine optical components in the ultraviolet part of the spectrum. Rep. Dept. Geophys. No. 99. Univ. Oslo. 15 pp.

Baker, K. S. & Smith, R. C. 1990: Irradiance transmittance through the air-water interface. Pp. 556–565 in Spinrad, R. W. (ed.): *Ocean Optics X, 16–18 April 1990, Orlando, Florida.* SPIE Proc. 1302.

Blackwell, H. R. 1946: Contrast thresholds of the human eye. *J. Opt. Soc. Am. 36,* 624–643.

Bricaud, A., Morel, A. & Prieur, L. 1981: Absorption by dissolved organic matter of the sea (yellow substance) in the UV and visible domains. *Limnol. Oceanogr. 26,* 43–53.

Calkins, J. & Thordardottir, T. 1982: Penetration of solar UV-B into waters off Iceland. Pp. 309–319 in Calkins, J. (ed.): *The role of solar ultraviolet radiation in marine ecosystems.* Plenum Press, New York.

Carder, K. L., Steward, R. G., Harvey, G. R. & Ortner, P. B. 1989: Marine humic and fulvic acids: Their effects on remote sensing of ocean chlorophyll. *Limnol. Oceanogr. 34,* 68–81.

Dalløkken, R., Sandvik, R. & Sakshaug, E. 1994: Variations in bio-optical properties in the Greenland/Iceland/Norwegian seas. Pp. 266–276 in Jaffe, J. S. (ed.): *Ocean Optics XII, 13–15 June 1994, Bergen, Norway.* SPIE Proc. 2258.

Dalløkken, R., Sandvik, R. & Sakshaug, E. 1995: Seasonal variations in the Greenland Sea: effect of phytoplankton light absorptions. Pp. 33–43 in Skjoldal, H. R., Hopkins, C., Erikstad, K. E. & Leinaas, H. P. (eds.): *Ecology of fjords and coastal waters.* Elsevier, Amsterdam.

Fahey, D. W. 1995: Polar ozone. Pp. 3.1–3.52 in Ennis, C. A. (ed.): *Scientific Assesment of ozone depletion: 1994.* WMO, Global Ozone Res. Monitor. Proj., Rep. No. 37.

Forsberg, C. F. 1983: Sedimentological and early diagenetic studies in the Barents Sea. Thesis, Dept. Geol. Univ. Oslo. 75 pp. + appendix, 135 pp.

Gieskes, W. W. C. & Kraay, G. W. 1990: Transmission of ultraviolet light in the Weddel Sea: Report of the first measurements made in the Antarctic. *Biomass Newsletter 12,* 12–14.

Halldal, P. & Halldal, K. 1973: Phytoplankton, chlorophyll, and submarine light conditions in Kings Bay, Spitsbergen in July 1971. *Norw. J. Bot. 20,* 99–108.

Højerslev, N. K. 1971: Tyndall and fluorescence measurements in Danish and Norwegian waters related to dynamical features. Rep. Dept. Phys. Oceanogr. No. 16. Univ. Copenhagen. 46 pp.

Højerslev, N. K. 1974a: Daylight measurements for photosynthetic studies in the Western Mediterranean. Rep. Dept. Phys. Oceanogr. No. 26. Univ. Copenhagen. 38 pp.

Højerslev, N. K. 1974b: Inherent and apparent optical properties of the Baltic. Rep. Dept. Phys. Oceanogr. No. 23. Univ. Copenhagen. 89 pp.

Højerslev, N. K. 1978: Solar middle ultraviolet (UV-B) measurement in coastal waters rich in yellow substance. *Limnol. Oceanogr. 23,* 1076–1079.

Højerslev, N. K. 1980: On the origin of yellow substance in the marine environment. Pp. 39–56 in Kullenberg, G. (ed.): Studies in physical oceanography. Papers dedicated to professor Nils G. Jerlov in commemoration of his seventieth birthday. Rep. Dept. Phys. Oceangr. No. 42. Univ. Copenhagen.

Højerslev, N. K. 1982a: Yellow substance in the sea. Pp. 263–281 in Calkins, J. (ed.): *The role of solar ultraviolet radiation in marine ecosystems*. Plenum Press, New York.

Højerslev, N. K. 1982b: Bio-optical properties of the Fladen-Ground: "Meteor" – FLEX-75 and FLEX-76. *J. Cons. int. Explor. Mer, 40*, 272–290.

Højerslev, N. K. 1985: Bio-optical measurements in the Southwest Florida Shelf ecosystem. *J. Cons. int. Explor. Mer, 42*, 65–82.

Højerslev, N. K. 1986. Visibility of the sea with special reference to the Secchi disc. Pp. 294–305 in Blizard, M. A. (ed.): *Ocean Optics VIII, 31 March–2 April 1986, Orlando, Florida*. SPIE Proc. 637.

Højerslev, N. K. 1988: Natural occurrences and optical effects of gelbstoff. Rep. Dept. Phys. Oceanogr. No. 50. Univ. Copenhagen. 30 pp.

Højerslev, N. K. 1994: Origin of the Kattegat water. Pp. 357–365 in Jaffe, J. S. (ed.): *Ocean Optics XII, 13–15 June 1994, Bergen, Norway*. SPIE Proc. 2258.

Højerslev, N. K. & Aas, E. 1991: A relationship for the penetration of ultraviolet B radiation into the Norwegian Sea. *J. Geophys. Res. 96*, 17003–05.

Højerslev, N. K., Holt, N. & Aarup, T. 1996: Optical measurements in the North Sea–Baltic Sea transition zone. I. On the origin of the deep water in the Kattegat. *Cont. Shelf Res. 16*, 1329–1342.

Højerslev, N. & Jerlov, N. 1977: The use of the colour index for determining quanta irradiance in the sea. Rep. Dept. Phys. Oceanogr. No. 35. Univ. Copenhagen. 12 pp.

Høkedal, J. 1993: Svekninga av nedoverretta UVB-irradians i farvanna rundt Kong Karls Land og i Grønlandshavet. Kalibreringa av et UVB-irradiansmeter. Thesis, Dept. Geophys. Univ. Oslo. 75 pp.

Høkedal, J. & Aas, E. 1994: Calibration of two single-channel instruments for UV-B and blue irradiance. Rep. Dept. Geophys. No. 88. Univ. Oslo. 17 pp.

Jerlov, N. G. 1955: Factors influencing the transparency of the Baltic waters. Rep. Oceanogr. Inst. Gothenburg, No. 25. 19 pp.

Jerlov, N. G. 1968: *Optical oceanography*. Elsevier, Amsterdam. 194 pp.

Jerlov, N. G. 1974a: Significant relationships between optical properties of the sea. Pp. 77–94 in Jerlov, N. G. & Steemann Nielsen, E. (eds.): *Optical aspects of oceanography*. Academic Press, London.

Jerlov, N. G. 1974b: A simple method for measuring quanta irradiance in the ocean. Rep. Dept. Phys. Oceanogr. No. 24. Univ. Copenhagen. 10 pp.

Jerlov, N. G. 1976: *Marine optics*. Elsevier, Amsterdam. 231 pp.

Joseph, J. 1949: Über die Messung des "Vertikalen Extinktionz-koeffizienten". *Dtsch. Hydrogr. Z. 2*, 255–267.

Kalle, K. 1949: Fluoreszenz und Gelbstoff im Bottnischen und Finnischen Meerbusen. *Dtsch. Hydrogr. Z. 2*, 117–124.

Kirk, J. T. O. 1983: *Light and photosynthesis in aquatic ecosystems*. University Press, Cambridge. 401 pp.

Kullenberg, G. 1984: Observations of light-scattering distributions in the transition zone to the Arctic Ocean. *Rapp. P.-v. Réun. Cons. int. Explor. Mer, 185*, 102–110.

Kullenberg, G. & Xu, Z. 1986: On suspended matter, as observed by light scattering in the Fram Strait–Svalbard area. *Neth. J. Sea Res. 20*, 155–161.

Lalli, C. M. & Parsons, T. R. 1993: *Biological oceanography, an introduction*. Pergamon Press, Oxford. 301 pp.

Littler, M. M., Littler, D. S., Blair, S. M. & Norris, J. N. 1985: Deepest known plant life discovered on an uncharted seamount. *Science, 227*, 57–59.

Lundgren, B. 1976: Spectral transmittance measurements in the Baltic. Rep. Dept. Phys. Oceanogr. No. 30. Univ. Copenhagen. 38 pp.

McKenzie, R. L. 1995: Surface ultraviolet radiation. Pp. 9.1–9.22 in Ennis, C. A. (ed.): *Scientific assessment of ozone depletion: 1994*. WMO, Global Ozone Res. Monitor. Proj., Rep. No. 37.

Nyquist, G. 1979: Investigation of some optical properties of seawater with special reference to lignin sulfonates and humic substances. Dr. thesis, Dept. Anal. Mar. Chem. Univ. Gothenburg, 223 pp.

Piazena, H. & Häder, D.-P. 1994: Penetration of solar UV irradiation in coastal lagoons of the southern Baltic Sea and its effect on phytoplankton communities. *Photochem. Photobiol. 60*, 463–469.

Repp, K. 1988: The hydrology of Bayelva, Spitsbergen. *Nordic Hydrol. 19*, 259–268.

Roemer, S. C. & Hoagland, K. D. 1981: Immersion effect and cosine collecting properties of LI-COR underwater sensors. 11 pp. in: Instruction manual. LI-185B Quantum Radiometer, PUB 8004–03.

Scully, N. M. & Lean, D. R. S. 1994: The attenuation of ultraviolet radiation in temperate lakes. *Arch. Hydrobiol. Beih. 43*, 135–144.

Shifrin, K. S. 1988: *Physical optics of ocean water*. Am. Inst. Phys., New York. 285 pp.

Simonot, J.-Y. & Le Treut, H. 1986: A climatological field of mean optical properties of the world ocean. J. Geophys. Res. 91, 6642–46.

Smith, R. C. 1973: Optical properties of the Arctic upper water. *Arctic, 26*, 303–313.

Smith, R. C. & Baker, K. S. 1981: Optical properties of the clearest natural waters (200–800 nm). *Appl. Opt. 20*, 177–184.

Smith, R. C., Prézelin, B. B., Baker, K. S., Bidigare, R. R., Boucher, N. P., Coley, T., Karentz, D., MacIntyre, S., Matlick, H. A., Menzies, D., Ondrusek, M., Wan, Z. & Waters, K. J. 1992: Ozone depletion: Ultraviolet radiation and phytoplankton biology in Antarctic waters. *Science, 255*, 952–959.

Taalas, P., Damski, J., Korpela, A., Koskela, T., Kyrö, E. & Braathen, G. 1995: Connections between atmospheric ozone, the climate system and UV-B radiation in the Arctic. Pp. 411–426 in Wang, W.-C. & Isaksen, I. S. A. (eds.): *Atmospheric ozone as a climate gas. NATO ASI Series, 32*. Springer-Verlag, Berlin.

Walsh, J. J., Carder, K. L. & Müller-Karger, F. E. 1992: Meridional fluxes of dissolved organic matter in the North Atlantic Ocean. *J. Geophys. Res. 97*, 15625–15637.

Zeng, J., Jin, Z. & Stamnes K. 1993: Impact of stratospheric ozone depletion on UV penetration into the ocean at high latitudes. Pp. 56–63 in Eilertsen, H. C. (ed.): *Underwater light measurements, 29 June 1993, Tromsø, Norway*. SPIE Proc. 2048.

Zerefos, C. S. 1995: The recent variability of atmospheric ozone in the middle latitudes of the Northern Hemisphere and solar ultraviolet radiation. Pp. 447–452 in Wang, W.-C. & Isaksen, I. S. A. (eds.): *Atmospheric ozone as a climate gas. NATO ASI Series, 32*. Springer-Verlag, Berlin.