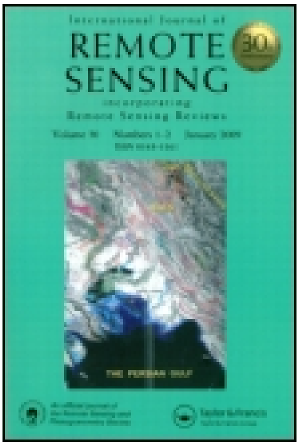

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Cover

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1. Introduction

The Kara Sea (for geographic location and names see figure 1(*a*)) has a unique hydrological feature: it annually receives a record amount of river run-off ($\sim$1350 km^3), which is equivalent to a 1.52 m deep freshwater layer if spread throughout the entire area of the Kara Sea (Ivanov 1997, Volkov *et al*. 2002). This accounts for about 56% of the total river run-off into the coastal seas of the Arctic Ocean. Such an extraordinary rate of freshwater supply into the Kara Sea is due to two inflowing great Siberian rivers, Ob and Yenisey: together with two other, much smaller rivers (Pyasina and Nizhnyaya Taymyra) they constitute 94.2% of the entire amount of fresh water entering into the Kara Sea (Volkov *et al*. 2002). The seasonal variations are significant, with a typical freeze-up period from October to May.

Along with the river run-off impact, inflow of warmer and nutrient-enriched waters from the Barents Sea also affect the hydrological regime in the Kara Sea. However, the presence of the Novaya Zemlya and Vaygach Islands in the west, the Franz Josef Land in the north and Severnaya Zemlya Islands accentuate the impact of river run-off on the hydrological regime as well as the trophic status of the sea (Matishov and Pavlova 1990).

River waters in the Kara Sea expand over significant distances from the respective river mouths. Although there is a general transport of waters from the west towards the east, the pattern of spread of freshened waters in the Kara Sea depends predominantly upon the prevailing winds, and thus can vary from year to year. Either fan-like (figure 1(*a*)), or northern (figure 1(*b*)) or else eastern (figure 1(*c*)) options of distribution of desalinated waters in the Kara Sea can establish in summer. At depth, under the freshened waters, there is a layer of salinity jump that restrains wind mixing. In summer, the surface waters contain between 50 and 70% of river water at the northern and north-western boundaries of the Kara Sea, whereas in the south this share can be in excess of 90%. A persistent cyclonic circulation in the south-western part of the Kara Sea (between the Novaya Zemlya Island and the Yamal Peninsula) can draw the freshened waters off the northern part of the

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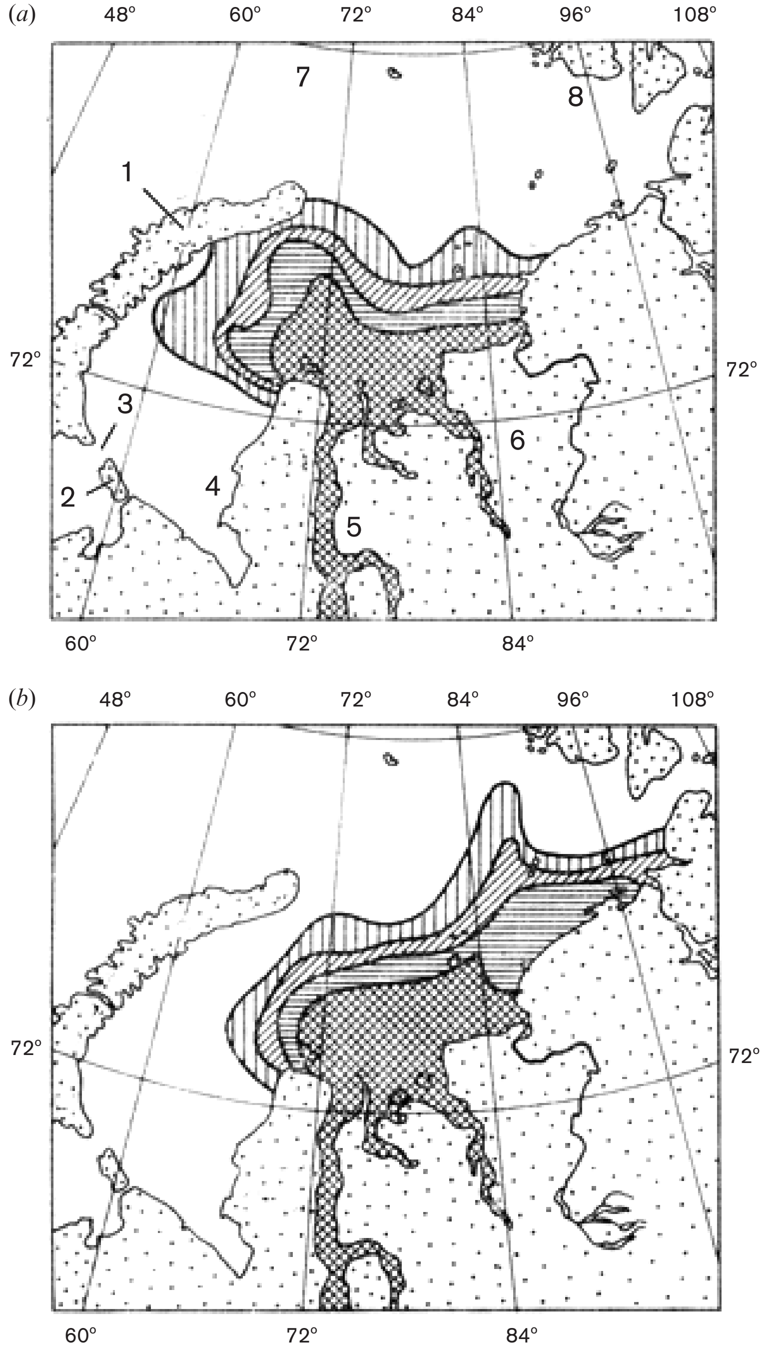

Figure 1. Characteristic distribution patterns for spread of river run-off waters throughout the Kara Sea during summer: (*a*) fan-like, (*b*) northern, and (*c*) eastern. The numbers in the legend stand for: I, 50–70%; II, 70–80%; III, 80–90%; IV, >90% of desalination of marine waters (after Volkov *et al.* 2002). Names of locations mentioned in the paper are given with Arabic figures (1–8): 1, Novaya Zemlya Island; 2, Vaigatch Island; 3, Karskie Vorota Strait; 4, Yamal Peninsula; 5, Ob River; 6, Yenisey River; 7, vicinity of the Franz Josef Land; 8, Severnaya Zemlya Islands.

(*c*)

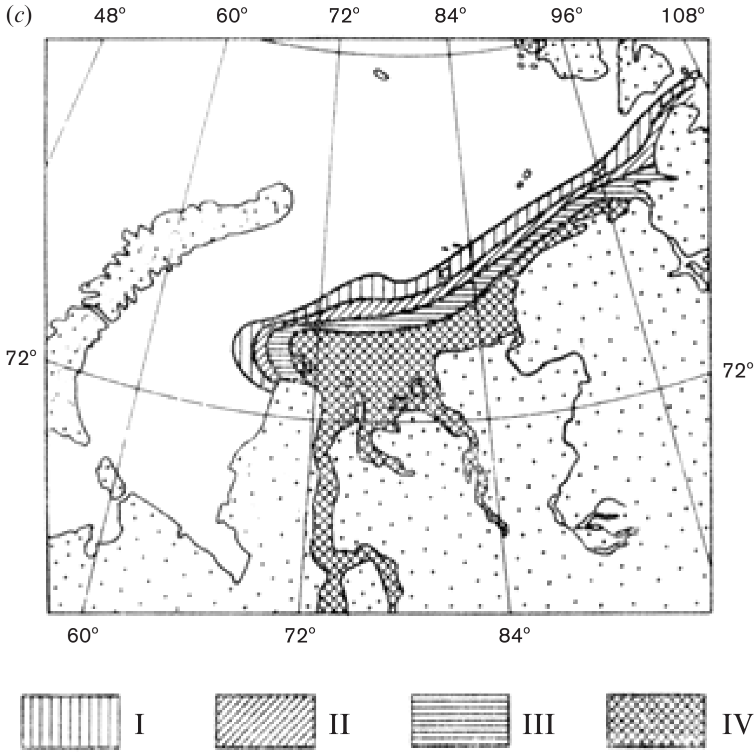

Figure 1. (*Continued.*)

Novaya Zemlya down to the Karskie Vorota Strait and there also entraining the Barents Sea waters bring them further up to the Yamal Peninsula.

The swampy soils abundant within the watershed of the main rivers flowing into the Kara Sea result in bringing significant amounts of dissolved fractions of soil humus along with the river run-off. In addition, owing to land run-off and erosion of river banks and river beds, enhanced amounts of suspended matter and nutrients reach the Kara Sea and eventually become spread over its vast areas. Man-made pollutants stocked, such as radionuclides (Volkov *et al.* 2002), in these areas potentially may also be washed out into the Kara Sea.

The above processes all strongly influence the hydrochemical and hydrobiological conditions in the Kara Sea. However, their investigation is seriously hampered by severe weather conditions and can only be performed during two to three months when in the Kara Sea there are sufficiently vast ice-free areas suitable for research vessel investigations.

Invariably suffering from undersampling, shipborne studies fail to produce the desired data at the spatial and temporal resolution required for attaining an adequate insight into the highly dynamic in-water processes in the sea.

Therefore optical remote sensing from satellites, under favourable weather and light conditions, can efficiently contribute to studies for exploring the spatial and temporal variations of the water quality and trophic status of the Kara Sea, which is the topic for this note.

2. Remote sensing methodology

Utilization of satellite optical Earth observation sensors for studying the Kara Sea is challenged by at least two major impediments, namely, the model for characterizing the major optically-active aquatic constituents and the model for proper atmospheric correction over such optically complex waters.

The first one arises from the fact discussed above that the Kara Sea waters are spatially highly heterogeneous, being significantly influenced by massive inputs of terrigenous suspended and dissolved matters. Therefore, the coastal waters are definitely non-case I waters, according to the Morel classification (Morel and Prieur 1977). It implies that the standard in-water chlorophyll pigment retrieval algorithm used for NASA Moderate Resolution Imaging Spectroradiometer (MODIS) data over open oceanic waters (case I water) is not suitable for the Kara Sea hydro-optical conditions. Besides, not only phytoplankton chlorophyll but also dissolved organic and water turbidity are important parameters for a better understanding of the trophic status in the sea. Therefore, some more sophisticated water quality retrieval techniques are required for the retrieval of optically active components in the Kara Sea.

For processing the MODIS images we applied our advanced operational algorithm based upon combining the neural network (NN) and the Levenberg–Marquardt (LM) multivariate procedures (Pozdnyakov *et al*. 2005). Having been subjected to a preliminary processing, also incorporating the atmospheric correction, the satellite image is further treated by calculating for each pixel the corresponding subsurface remote sensing reflectance spectrum $R_{rsw}(\lambda)$ (Pozdnyakov *et al*. 2003). First, the normalized upwelling radiance ($L_w(\lambda)$) is achieved on the basis of ancillary data, namely instantaneous extraterrestrial solar flux ($F_0(\lambda)$) and Sun zenith angle θ_0, and is available from the MODIS level-2 data.

For each pixel, $R_{rsw}(\lambda)$ serves as input for a broad-band (B-B) NN procedure (NN-1): the concentrations of phytoplankton chlorophyll-*a* (*chl-a*), suspended minerals (*sm*) and dissolved organic matter (*doc*), assumed as the major colour-producing agents (CPAs) in natural water, were retrieved within the ranges (0–70 $\mu g\,l^{-1}$; 0–30 $mg\,l^{-1}$ and 0–30 $mgC\,l^{-1}$, respectively). If one of the CPA concentrations as determined by the B-B NN emulator falls in the concentration range 0–5 (in respective units), a corresponding narrow-band NN (NN-2, NN-3 or NN-4) is applied.

In the next step, the CPA concentration vector $\boldsymbol{C_0}$ thus determined is used to obtain an array of initial concentrations $\boldsymbol{C}_0$. We have used the range running from 0.7 to 1.3 C with the assumption that the maximal measurement error is 15% (Pozdnyakov *et al.* 2005). From the created pool of initial concentrations $\boldsymbol{C}_0$, starting concentrations for each CPA are randomly taken as input for the LM procedure crowning the retrieval process. If available for the waterbody under investigation, minimum and maximum concentrations of *chl*, *sm* and *doc* are imposed on the pursued multivariate search of the optimal CPA concentration vector.

The output from the coupled NN→LM sequence are estimates of concentrations of *chl*, *sm* and *doc*. The retrieval algorithm is pending both on a hydro-optical model appropriate for the waterbody studied and a parametric relationship (e.g. Jerome *et al*. 1996) relating $R_{rsw}(\lambda)$ and the water bulk absorption and backscattering coefficients a and b_b. We have used the hydro-optical model suggested by Pozdnyakov and Grassl (2003) for mesotrophic waters.

The other challenge for attaining accurate retrieval of CPAs is the atmospheric correction. The aerosol composition in the atmosphere over the Kara Sea (especially in summertime) can differ from the aerosol types encompassed by the lookup tables used by the standard MODIS atmospheric correction code (Gordon and Voss 1999). Besides, in summer, fogs not infrequently occur over the open water areas in the Kara Sea, and can, therefore, contaminate the atmospheric path radiance, and eventually the legitimate signal captured by the satellite sensor.

Our multistage algorithm is outfitted with two quality assessment units. The first eliminates the pixels suffering from imprecise atmospheric correction. It manifests itself in (a) negative values of R_{rsw} at short wavelengths (400–450 nm) due to an overestimation of the path radiance, and (b) enhanced values of R_{rsw} in the blue part of the spectrum followed by a dip in either the second or third channel(s) due to an underestimation of the path radiance.

The second quality assurance is intended to dismiss/mask pixels corresponding to such areas of the waterbody under surveillance whose hydro-optical properties significantly differ from those covered by the applied hydro-optical model. It might be due to either the area-specific composition of *doc*, and/or *sm* or the presence of some particular phytoplankton species or their residuals which go beyond the scope of the employed hydro-optical model.

Due to the interference of cloudiness over the Kara Sea in August 2003, only 14 MODIS images (taken between 5 and 12 August) proved to be useful, but none of them was completely free of cloud-screened areas. To obtain spatial distributions of the CPAs (i.e. *chl*, *sm* and *doc*) throughout the entire sea, the results of CPA retrievals were merged and respective image mosaics were generated. For all cloud-free pixels the mean value of the CPAs were generated as the arithmetic mean of the values obtained in each MODIS scene.

3. Results and discussion

The results of retrieval of chlorophyll (*chl*), sediments (*sm*) and dissolved organic compounds (*doc*) as obtained through the application of our methodology to the MODIS data are shown in figures 2 to 4 respectively. The highest *sm* concentrations (figure 3) are mainly confined to the Ob and Yenisey estuaries, in particular to the nearshore areas within the estuaries. The content of *sm* proves to be far less abundant in the central and offshore parts of the Kara Sea. Somewhat enhanced

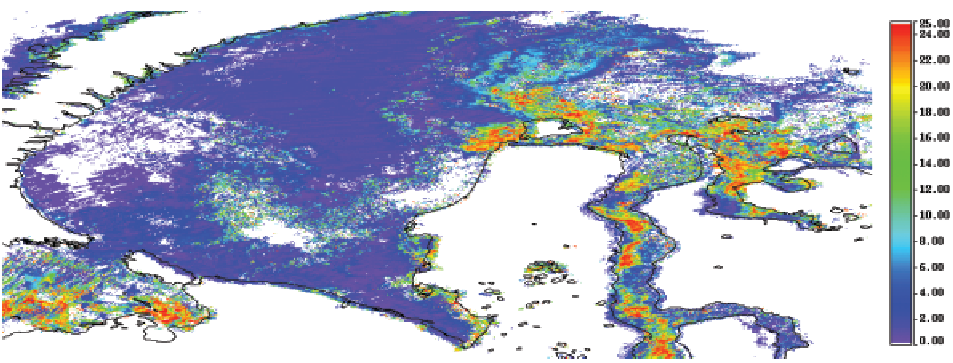

Figure 2. The spatial averaged distribution of *chl* as retrieved from the MODIS images over the Kara Sea, during the period 5–12 August 2003.

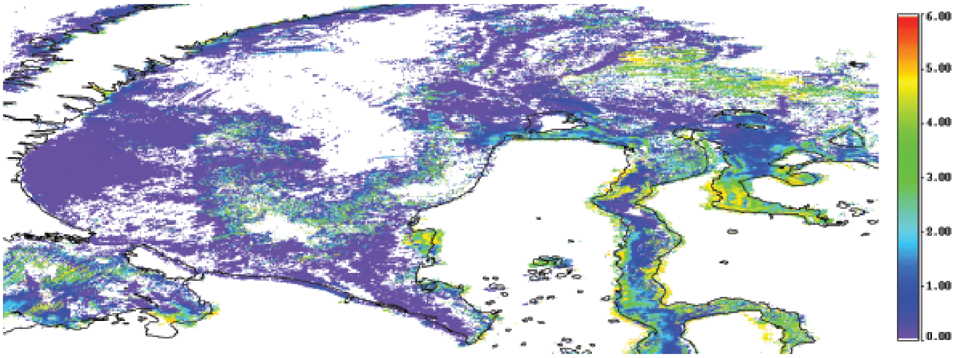

Figure 3. The spatial averaged distribution of *sm* as retrieved from the MODIS images over the Kara Sea, during the period 5–12 August 2003.

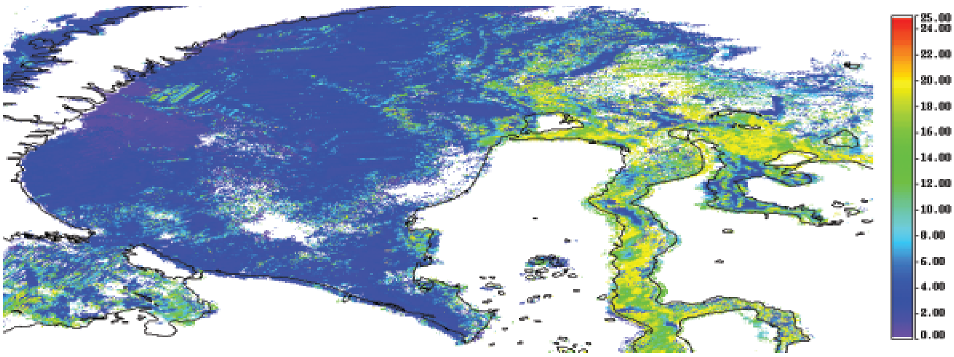

Figure 4. The spatial averaged distribution of *doc* as retrieved from the MODIS images over the Kara Sea, during the period 5–12 August 2003.

concentrations of *sm* in the north-western region of the Kara Sea are probably due to the transport of sediments from the coastline of Novaya Zemlia. The distributions of *chl* (figure 2, see also cover) and *doc* (figure 4) both exhibit a more patchy structure within the estuaries and a more significant offshore extension into the Kara Sea. Our overall assessment based upon these data, indicates that the impact of the sediment transport in the surface layer is rather locally confined to the estuaries and their mouth regions. Nevertheless, the plankton blooms, as expressed through high *chl* concentrations, occur both locally in the estuaries and further offshore in the Kara Sea.

The *chl* concentration distribution in the Kara Sea as resolved in our processed MODIS data, indicates that in the summer of 2003 the predominant winds determined a distinctively eastern surface layer spread of the river run-off waters from the Ob and Yenisey rivers. The concurrent spatial distributions of *sm* and *doc* in particular comply very well with this corollary: both constituents are most abundant to the east from the Ob River estuary and adhere to the coastal zone between the Yamal Peninsula and the Severnaya Zemlya Islands (compare with figure 1(*c*)).

Accordingly, the northern area of the south-western region of the Kara Sea (west of Yamal Peninsula (4 in figure 1(*a*)) is fairly devoid of any impact of riverine waters, poorly productive, and the *doc* and *sm* concentrations are very low.

At the same time, as seen in the low left-hand part of figures 2 and 4, the nutrient-rich and warmer Barents Sea waters appear as rich in *chl* and contain appreciable amounts of *doc*, thus confirming a rather high trophic level of this aquatic area.

The satellite data (figures 2–4) indicate the presence of large areas with enhanced concentrations of *chl* in the south-western region of the Kara Sea extending from the Karskie Vorota Strait to the northern coast of the Yamal Peninsula. As has been pointed out above, there is a persistent cyclonic circulation in the south-western part of the Kara Sea entraining the productive Barents Sea waters off the northern part of the Novaya Zemlya down to the Karskie Vorota Strait and then further up to the Yamal Peninsula.

The adequacy of the CPA concentrations retrieved by our algorithm can be qualitatively compared with field observations of chlorophyll, dissolved organic matter and sediment distributions in the Kara Sea (Gaye-Haake *et al.* 2003, Köhler *et al.* 2003, Nöthing *et al.* 2003). The *chl* concentrations as retrieved from the MODIS data (figure 2) vary in rather wide ranges, reaching in some locations values as high as $23\,\mu g\,l^{-1}$. According to Nöthing *et al.* (2003) in some years (e.g. 1999) *in situ* measurements gave *chl* maximum concentrations up to $13–15\,\mu g\,l^{-1}$.

The retrieved *doc* concentrations also are very variable with the maximum values up to $20\,mgC\,l^{-1}$. The available *in situ* data (Köhler *et al.* 2003) indicate that the maximum *doc* levels were registered at $\sim$13–15 $mgC\,l^{-1}$. This points to the tendency of the ocean colour data to overestimate the desired water quality parameters. However, satellite data resolve better the relative spatial distributions in the CPAs.

According to our retrievals, in some areas of the Kara Sea the maximum *sm* concentrations are $3–4\,mg\,l^{-1}$. Gaye-Haake *et al.* (2003) report that the total suspended matter in the waters of the region under discussion can be up to *ca* $4.7\,mg\,l^{-1}$, with the inorganic component accounting for up to *ca* 72%.

Thus, the above comparisons of *in situ* and retrieved data indicate that the spatial patterns in *chl*, *sm* and *doc* distributions comply closely with the known oceanographic data. Discrepancies in the absolute values of *in situ* measured and retrieved concentrations of CPAs are believed to be due to the fact that the hydro-optical model used in our algorithm has not been developed specifically for the Kara Sea. This inevitably is bound to introduce some systematic retrieval errors, leaving, however, the general features of the CPA spatial distribution patterns quite adequate.

Consequently, the simultaneously recovered spatial distributions of *chl*, *sm* and *doc* (figures 2–4) are believed to be the first simultaneous mapping of these three water quality parameter fields in the Kara Sea obtained from optical satellite Earth observation data reflecting the impact of river discharge impact on the trophy of the sea. The methodology described and the availability of satellite Earth observation ocean colour data (SeaWiFS, MODIS and MERIS) from the region during the last six years will allow for both seasonal and inter-annual mapping of the influence of the Ob and Yenisey rivers on the Kara Sea ecosystem.

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References

Gaye-Haake, B., Unger, D., Nöthing, E.-M., Okolodkov, Yu., Hahl, K. and Ittekkt, V., 2003, Particle fluxes from short-term sediment trap deployments in late summer in the southern Kara Sea. In *Siberian River Run-off in the Kara Sea. Characterisation, Quantification, Variability and Environmental Significance*, R. Stein, K. Fahl, D.K. Futterer, E. Galimov and O. Stepanets (Eds), pp. 309–328 (Amsterdam: Elsevier).

Gordon, H.R. and Voss, K.J., 1999, MODIS normalized waterleaving radiance algorithm theoretical basis document (MOD 18) version 4. Department of Physics, University of Miami, Coral Gables, FL 33124, USA, under Contract Number NAS531363, 30 April 1999.

Ivanov, V.V., 1997, Inflow and spread of river water throughout the Kara Sea. In *Natural Conditions in the Kara and Barents Seas*, V. Volkov, G. Kosheleva, V. Smolyanitski and T. Vinje (Eds), pp. 214–220 (Oslo: Norsk Polarinstitute Publ.).

Jerome, J.H., Bukata, R.P. and Miller, J.R., 1996, Remote sensing reflectance and its relationship to optical properties of natural water. *International Journal of Remote Sensing*, **17**, 43–52.

Köhler, H., Meon, B., Gordeev, V., Spitzy, A. and Amon, R., 2003, Dissolved organic matter (DOM) in the estuaries of Ob and Yenisei and the adjacent Kara Sea, Russia. In *Siberian River Run-off in the Kara Sea. Characterisation, Quantification, Variability and Environmental Significance*, R. Stein, K. Fahl, D.K. Futterer, E. Galimov and O. Stepanets (Eds), pp. 28–38 (Amsterdam: Elsevier).

Matishov, G.G. and Pavlova, L.G., 1990, *General Ecology of Polar Oceans* (Leningrad: Nauka Publ.) (in Russian).

Morel, A. and Prieur, L., 1977, Analysis of variations in ocean colour. *Limnology and Oceanography*, **22**, 709–722.

Nöthing, E.-M., Okolodkov, Yu., Larionov, V. and Makarevich, P., 2003, Phytoplankton distribution in the inner Kara Sea: a comparison of three summer investigations. In *Siberian River Run-off in the Kara Sea. Characterisation, Quantification, Variability and Environmental Significance*, R. Stein, K. Fahl, D.K. Futterer, E. Galimov and O. Stepanets (Eds), pp. 163–183 (Amsterdam: Elsevier).

Pozdnyakov, D. and Grassl, H., 2003, *Colour of Inland and Coastal Waters: a Methodology of its Interpretation* (Chichester: Springer Praxis).

Pozdnyakov, D., Bakan, S. and Grassl, H., 2000, Atmospheric correction of color images of case II waters—a review. Report No. 308. Max-Planck Institute for Meteorology Publ., 35–53.

Pozdnyakov, D., Pettersson, L., Johannessen, O.M., Liaskovski, A., Filatov, N. and Bobylev, L., 2003, SeaWiFS maps water quality parameters of the White Sea. *International Journal of Remote Sensing*, **24**, 4055–4071.

Pozdnyakov, D., Korosov, A., Grassl, H. and Pettersson, L., 2005, An advanced algorithm for operational retrieval of water quality from satellite data in the visible. *International Journal of Remote Sensing* (this issue).

Volkov, V.A., Johannessen, O.M., Borodachev, V.E., Voinov, G.N., Pettersson, L.H., Bobylev, L.P. and Kouraev, A.V., 2002, *Polar Seas Oceanography. An Integrated Case Study of the Kara Sea* (Chichester: Springer/Praxis).