Global Change and Remote Sensing of CDOM in Arctic Coastal Waters

T. Kutser
Estonian Marine Institute
University of Tartu, Estonia
Mäealuse 14, Tallinn, 12618, Estonia

***Abstract*-The amount of CDOM in arctic waters plays an important role both from global carbon cycle point of view and from radiative heating point of view of surface waters. The first part of this paper summarizes the current situation in remote sensing mapping of CDOM concentration in Arctic Ocean. Radiative heating calculations were carried out with Hydrolight 5.0 model in order to estimate the impact of variable amount of CDOM on heating of Arctic surface waters. Also the total area where the Arctic Ocean waters differ from the clear oceanic waters was estimated using MODIS K_d(490) product.**

I. INTRODUCTION

The necessity to understand and predict ever changing climate on Earth increased dramatically the need to understand global carbon cycle. The largely unaccounted form of carbon is DOC – dissolved organic carbon. It was suggested that the DOC pool in oceans is largely old and refractory and thus unavailable for biological consumption. It was viewed as unimportant to carbon fluxes. Therefore, the DOC is largely ignored in the global carbon studies. However, resent studies show that lakes and estuaries play very important role in the global carbon cycle [1-4].

Determining the true role of the aquatic DOC pool in the global carbon cycle is practically impossible without using remote sensing methods. The only part of electromagnetic radiation that can penetrate water surface and thus give us any information about the water properties is visible light. Consequently, we can try to study the DOC pool only if its quantity has an impact on water color. Optically active component of DOC is called colored (chromophoric) dissolved organic matter – CDOM that consist of large organic molecules absorbing strongly light at shorter wavelengths. Remote sensing of CDOM has been more of a byproduct as absorption of light by CDOM at shorter wavelengths is the main reason why chlorophyll retrieval algorithms, that are often based on blue-to-green ratios, fail in coastal waters. The need in quantitative detection of CDOM has been mainly related to improving the accuracy of chlorophyll-a retrieval. For example in such CDOM-dominated systems like the Baltic Sea chlorophyll retrieval error is usually a few hundred percent and most of it can be attributed to absorption of light by CDOM [5-7].

The importance of remote sensing estimates of marine CDOM content has increased during recent years. This can be attributed to the studies on global carbon cycle, air-sea exchange of gases, using of CDOM as a tracer of riverine input in coastal waters, and the impact of CDOM on underwater light climate. The terrestrial dissolved organic carbon entering waters is a food source for bacteria. CDOM is also photo-oxidized in surface water due to sunlight. CO_2 is released in both of the processes. Thus the role of Nordic and Arctic coastal waters in global carbon cycle will increase as predicted warmer and wetter climate in higher latitudes will increase the amount of CDOM entering coastal waters. Especial attention will be on Arctic waters as thawing permafrost should increase the amount of CDOM entering into the Arctic Ocean. More CDOM in water should increase radiative heating (and faster loss in sea ice) due to stronger absorption of light.

The aim of this paper is to review the current situation in quantitative mapping of CDOM from space and to estimate the extent of the extra warming of Arctic Ocean surface waters due to the potential increase in CDOM from thawing permafrost.

II. METHODS

A. Radiative transfer modelling

Hydrolight 5.0 radiative transfer model [8] was used. A Case II water type model was defined with chlorophyll-a concentration of 0.5 mg/m^3, and suspended minerals concentration of 2 mg/m^3. CDOM absorption at 375 nm was varied between 0.1 m^{-1} and 40 m^{-1}. The modeling was performed for latitude 70N and for a middle of summer cloud free day.

Radiative heating rate [9] – the average rate the solar radiation heats a layer of water, was calculated for the waters with variable CDOM concentration.

$$RHR(z)=(E_{z1}-E_{z2})/(\rho c_p \Delta z), \quad (1)$$

where RHR(z) is radiative heating rate for certain water layer, E_{z1} and E_{z2} are irradiances (here 400-700 nm) at the top and bottom of the water layer, ρ is the density of seawater, c_p is the specific heat of seawater and Δz is the thickness of the water layer (here 0.5 m).

Also the normalized radiative heating rate differences were calculated for different waters compared to the clearest water type used in the model simulations

$$(RHR_x-RHR_{clear})/RHR_{clear,} \quad (2)$$

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where RHR_x is a radiative heating rate of water mass with different CDOM concentrations and the RHR_{clear} is the clearest water ($a_{CDOM}(375)=0.1\ m^{-1}$) used in our study.

B. Remote sensing data

MODIS diffuse attenuation coefficient $K_d(490)$ product was used to estimate the extent of water area influenced by terrestrial input. MODIS Terra August 2008 monthly product image with 4x4 km spatial resolution was used. The baseline between open ocean and river influenced waters was selected visually after examining the image. The approximate cut-off value was $0.1\ m^{-1}$.

III. Results and Discussion

A. Quantitative mapping of coastal CDOM

Several authors [10-15] have demonstrated that the Arctic Ocean differs from other oceanic waters and cannot be considered as clear oceanic water from optical point of view. The main difference is relatively high amount of CDOM in the Arctic waters. For example Matsuoka et al. [10] have shown that 76% of non-water light absorption at 443 nm (where is the maximum of chlorophyll-a absorption dominating the absorption in clear oceanic waters) is by CDOM. Concentration of CDOM does not co-vary with chlorophyll-a in Arctic waters. It means that the majority of CDOM is not a phytoplankton degradation product but is imported from land. This is not surprising as the Arctic Ocean receives about 10% of global freshwater input [16] while its volume is only 1% of all oceans [17]. It has also been shown [18] that the discharge of six largest Eurasian rivers has increased by 7% between 1936 and 1999. The higher than "normal" for oceanic waters concentration of CDOM suggests that standard ocean color algorithms cannot be used in retrieval of concentrations of optically active substances in Arctic waters.

The methods used for CDOM retrieval in marine (and inland) waters can be divided into two groups: band-ratio type empirical algorithms and analytical methods. In case of the first group statistical relationships are sought between the CDOM concentration and band ratios, combinations of band ratios or more sophisticated algorithms. Usually these algorithms include a band in blue part of spectrum, where the absorption of light by CDOM is strong, and a green to red band where the absorption of light by CDOM should be negligible. Such algorithms have been proposed by several authors [19-22]. Band ratios utilizing blue wavelengths are more successful in clear oceanic waters where even a small amount of CDOM has significant impact on water leaving signal in blue part of spectrum. The situation is more sophisticated in case of CDOM-rich waters. Practically all light entering waterbody may be absorbed by CDOM at blue wavelengths and there may be no radiation to be measured by remote sensing sensors. Sensitivity and calibration of blue bands of different sensors is problematic and atmospheric correction of satellite data collected above coastal and inland waters is still an unsolved problem. Thus, the variation in ocean color at blue wavelengths is often out of detection limits of many satellite sensors. Therefore, the shorter wavelength used in the band ratio algorithms has to be from green rather than blue part of spectrum. Such algorithms have been developed by several authors [20, 23-25] for relatively CDOM-rich coastal waters or estuaries.

Another approach in ocean color remote sensing is using physics based methods. These methods are based on bio-optical or radiative transfer models. Typically the models use three optically active substances: phytoplankton (chlorophyll-a), CDOM, and suspended matter and consequently all the three parameters are retrieved in the process of interpretation of remote sensing data. The retrieval methods vary. For example some authors [26-28] have used similarity method where each remote sensing spectrum is compared with multitude of reflectance spectra modeled in the process of interpretation of remote sensing data. This method is rather time consuming in case of large imagery. An alternative approach is creating spectral library using modeling (or large amount of *in situ* data) and then comparing the modeled/measured reflectance spectra with know water properties with the image spectra to retrieve chlorophyll-a, CDOM and suspended matter concentrations. Different methods can be used in the process. For example Kutser [29] used Spectral Angle Mapper to compare measured and modeled reflectance spectra but Brando and Dekker [30] used a matrix inversion technique.

Lee et al. [31] proposed a combined method to retrieve ocean absorption coefficient from remote sensing reflectance. Their aim was deriving chlorophyll-a from remote sensing data but the same approach could be used for CDOM provided there will be a reliable method to separate absorption caused by phytoplankton from the absorption caused by CDOM. Maritorena et al. [32] have proposed an empirical relationship to remove phytoplankton absorption from the total absorption at 443 nm. However, there are also colored detrital particles in the water column which optical properties are fairly similar (exponential decrease in absorption coefficient with increasing wavelength) to the CDOM. Separating these two components may be problematic.

The literature cited above allows to draw two conclusions. First of all most of the ice-free Arctic Ocean is a CDOM-dominated area. Consequently, remote sensing algorithms developed for retrieval of different water quality parameters in the open ocean cannot be used in Arctic. Although some authors claim that they have developed the first validated CDOM retrieval algorithms for coastal waters [22] it is highly unlikely that these algorithms can be used in Arctic. The $a_{CDOM}(355)$ range where the algorithm [22] was validated is between $0.12\ m^{-1}$ and $1.3\ m^{-1}$ [22]. The $a_{CDOM}(355)$ measurements carried out in Arctic coastal waters show values up to $44.4\ m^{-1}$ [12]. It is highly unlikely that the same algorithm will perform well in such range. It is more likely that the CDOM retrieval methods and algorithms developed and validated by other authors for CDOM-dominated environments

like the Baltic Sea [20, 23, 26] or even for lakes [28, 33-35] have to be used. Thus, there is strong need in developing and validating CDOM retrieval algorithm(s) for Arctic waters to be able to study the true role of Arctic Ocean in the global carbon cycle.

B. Radiative heating of surface waters due to change in CDOM

Accurate estimate of the amount of CDOM in the Arctic Ocean is also needed to be able to study the role of CDOM in melting of Arctic sea-ice sheet and trends in this role over last decades. As this information is currently not available with sufficient accuracy the radiave heating rate values were compared to the clearest water type used in our model simulations in order to get estimate of the increase in RHR due to potentially increasing CDOM values. Also the MODIS $K_d(490)$ monthly product was used as a proxy to estimate the total ice-free area of Arctic Ocean where the impact of CDOM may be measurable.

The $K_d(490)$ value in offshore waters may vary not only due to changing CDOM concentration. For example phytoplankton blooms also increase the $K_d(490)$ value. However, the phytoplankton biomass has to be very high for Arctic waters (chlorophyll-a around 6 mg/m^3) before it's contribution into absorption coefficient at 490 nm is in the same order of magnitude than the absorption by CDOM which amount ($a_{CDOM}(355)$) is equal to 1 m^{-1}. Such blooms occur in Arctic waters but are relatively rare. Thus, we may assume that elevated $K_d(490)$ values in Arctic waters are primarily due to increased amount of CDOM.

Ice-free areas north of 65N were selected in a MODIS Terra $K_d(490)$ product image to estimate the area impacted by coastal input and differing optically from open ocean waters. The areas with the highest $K_d(490)$ values were the Kara Sea and the White Sea. The total area with elevated $K_d(490)$ values was about 17 million km^2. Thus, the area where optical water properties differ from clear ocean waters is relatively large.

Infrared and near-infrared radiation is absorbed in the upper few meters of the water column and the differences in RHR occur due to differences in deep-penetrating visible wavelengths [9]. Visible wavelengths usually penetrate to tens of meters and contain more energy than infrared wavelengths. Therefore, they play more important role in radiative heating of water below top few meters.

Chang and Dickey [36] have shown that cloud cover, concentration of chlorophyll and CDOM have the greatest impact on radiative heating of surface water in weekly timescale. Our aim is to figure out how much the variation in optical water properties changes the radiative heating of surface water if the illumination conditions are the same. Therefore, the cloud effect is not considered in this study. Chang and Dickey [36] carried out their study in Atlantic coastal waters where the concentration of chlorophyll was below 5,89 mg/m^3 and $a_{CDOM}(355)$ was below 3 m^{-1}. Even in such conditions one of their findings was that CDOM has significant impact on radiative heating of the surface water. The literature cited above showed that order of magnitude higher $a_{CDOM}(355)$ values exist in Arctic coastal waters. Thus the radiative heating in such waters is predominantely caused by CDOM.

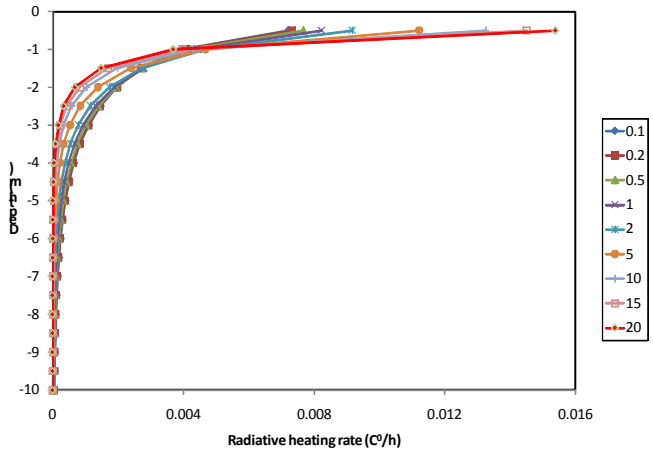

Figure 1. Radiative heating rate of 0.5 m thick layers of water with variable amount of CDOM and fixed amount of chlorophyll-a and suspended matter. The numbers in the legend indicate $a_{CDOM}(355)$ values (in m^{-1}) used in Hydrolight modelling

The modeling results shown in Figure 1 indicate that most of the visible light is absorbed in top 2 meters in case of CDOM rich water.

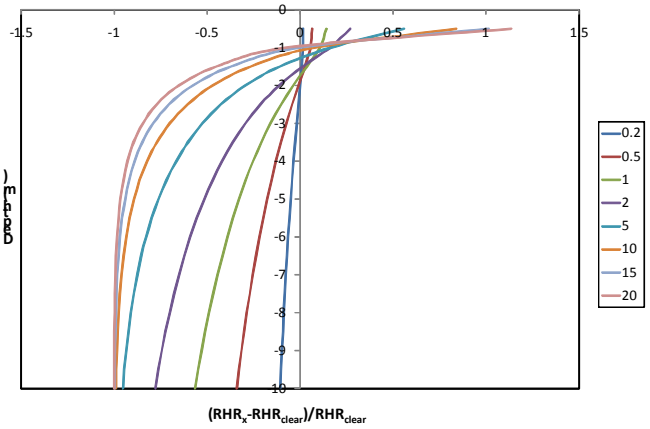

Figure 2. Normalized radiative heating rate difference between waters with different amount of CDOM and the clearest water type ($a_{CDOM}(355)$ = 1m^{-1}) used in the modelling. The numbers in the legent indicate $a_{CDOM}(355)$ values (in m^{-1}).

Figure 2 illustrates the changes in radiative heating rate with increasing amount of CDOM. It is seen that the RHR increases by two percent in top 0.5 m if the $a_{CDOM}(355)$ increases by 0.1 m^{-1}. (from 0.1 to 0.2). In such case the increase in RHR can be observed in top two meters (positive values in Figure 2) and decrease in deeper waters (negative values in Figure 2). If $a_{CDOM}(355)$ values reach 15 m^{-1} then the RHR of top half meter is practically doubled compared to clear

oceanic water and nearly all radiative heating occurs in top meter of the water column.

The modeling results illustrate clearly the Arctic surface waters trap visible light much more effectively than ocean waters due to elevated amount of CDOM. Consequently, potential warming of Arctic and thawing of permafrost will increase the amount of CDOM discharged into Arctic Ocean and this will cause further melting of sea ice as the radiative heating of top 1-2 meters of water column increases significantly with increasing CDOM.

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