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Arctic Riverine CDOM and its effects on the Polar Marine Light Field

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Abstract

It is well-known that CDOM (Chromophoric Dissolved Organic Matter) can have a significant effect on biological activity in the photic zones of aquatic ecosystems. However, the *extent* of CDOM's interference with biological activity is not well-known. We examined this issue in great detail in the mixed surface layer of the Arctic Ocean. We studied the impacts of CDOM's light attenuation on Arctic phytoplankton populations to discover if riverine CDOM's presence in the Arctic ocean could inhibit and possibly prevent local phytoplankton populations from performing photosynthesis. We incorporated biogeochemistry concepts and data with oceanographic models and calculations to approach the problem. The results showed that riverine CDOM can indeed significantly impact the productivity of phytoplankton populations during the spring and summer months near the major Arctic river mouths we chose to examine. Although our study was detailed and inclusive of many variables, the issue of CDOM's light attenuation and its effects on phytoplankton populations must be explored on a global scale to help understand if riverine CDOM could prove disastrous for phytoplankton populations.

Introduction

Phytoplankton are the basis of the oceanic food chain and they play an important role in both regulating and magnifying climate change's effects in the Arctic. Phytoplankton and other autotrophic populations alter the ocean's absorption of solar radiation through photosynthesis. This process can greatly influence high latitude seawater temperatures and may contribute to the loss of sea ice. CDOM (Chromophoric Dissolved Organic Matter) also absorbs and reflects solar radiation, and it does so best in the blue-violet and UV spectrums (Blough and Vecchio, 2002). The blue-violet wavelengths of light are also peak absorption wavelengths for the chlorophyll-a pigment present in phytoplankton. (Lalli and Parsons, 1993). Riverine inputs of CDOM thus compete with phytoplankton for the already scarce amount of radiation that is available to the ecosystems of the Arctic Ocean.

Methods

The distribution of riverine CDOM in the Arctic Ocean is modeled here using the Parallel Ocean Program, version 2 (POP2). We use a unique configuration of POP, coupled to the sea ice simulator CICE, with a nominal resolution of 0.3°. The model is forced with the CORE normal-year data set, which is an annually repeating cycle of the climatological atmospheric state, superimposed with typical synoptic atmospheric variability. The model simulates tracers emanating from riverine sources, distributed either in a 'curtain' across a river estuary, or adjacent to the delta, depending on the geometry of these river mouths. The rivers considered are Kolyma, Khatanga, Ob, Yenisey, Lena, Mackenzie, and Yukon Rivers. We consider a wide range of tracer species, namely a neutral tracer, an age tracer, a set of decaying tracers (decay time scales of 10, 31.6, 100, 316 and 1000 days), and a set of settling tracers (settling velocities of 0.1, 0.316, 1.0, 3.16, 10 m/day). The tracers are reset to 1 (0 for the age tracer) in the source region at each time step. The model was spun-up from a climatological ocean state. After 30 years, we introduced our tracers and ran for another 5 years. Two of those tracer experiments were performed, both starting at year 31, and experiencing the same ocean circulation. Our first experiment (SedDec3) simulated a total of 12 tracers, namely the full suite of tracer species described above, but at all river mouths at the same time. Our second experiment (SedDec5) simulated a total of 10 tracers, namely one tracer species (with a 316-day decay time scale) but in 10 different source regions (the rivers above, but splitting up the Lena in 3 sectors, and the Mackenzie in 2). In addition to tracer distributions, other variables were saved as monthly averages, in particular the velocity fields, temperature and salinity, mixed layer depth, and incoming solar shortwave radiation.

After the model and initial Matlab script were complete, we performed an extensive literature study to learn all the necessary variables to use along with their quantities for each month. First we used the Beer-Lambert Law to help mold the formula for the average intensity (W/m^2) over the mixed layer in the Arctic Ocean. We integrated the Beer-Lambert Law with respect to the depth of the mixed layer (0 to 30 meters on average) to arrive at our desired formula. The following formula represents the average solar radiation penetrating the well-mixed surface layer of the Arctic Ocean and was used for matlab computations.

$$I(\text{average}) = \frac{-\frac{I(\text{initial})}{A}\,[e^{-(A*z)} - 1]}{z}$$

Z represents the depth of the mixed layer, $I_{(\text{initial})}$ represents the amount of PAR present in the mixed layer, and A represents the attenuation factor. This attenuation factor includes many variables such as the concentrations (DOM, Dye tracer), attenuation factors (CDOM, seawater, and large sediments), and dilution factors (chemical and physical). Since both CDOM and the chlorophyll-a pigment found in all phytoplankton have peak absorption rates in the blue-violet spectrum (Blough and Vecchio, Lalli and Parsons) a wavelength of 443nm was chosen to represent the wavelength where most interference between the two would occur. Much of the literature used for this project supported a wavelength similar to 443nm. CDOM absorption is strongest in blue then decreases exponentially with increasing wavelength (Kim *et al.*, 2015). Also, the relationship between the attenuation coefficient and chlorophyll concentrations in the Arctic Ocean has the form of a power function and the best fit is at 443nm (Wang *et al.*, 2014). This is the wavelength chosen for all the attenuating agents.

The attenuation data for CDOM at 375nm for the Mackenzie, Yukon, Kolyma, Lena, Yenisey, and Ob rivers in varying months are found in Table 1 of Stedmon's paper along with the DOC concentrations for the same months and rivers. (Stedmon, 2011). We averaged and converted these attenuation values to 443 nm using the equation below from Chapter 10 of the book <u>Biogeochemistry of Marine Dissolved Organic Matter</u> edited by Dennis A. Hansell and Craig A. Carlson.

$$a(\lambda) = a(\lambda i) * e^{-S(\lambda - \lambda i)}$$

The values a(λ) and a(λi) represent the absorption coefficients at any wavelength a(λ) and a reference wavelength a(λi). S represents how quickly the absorption decreases with increasing wavelength. The S values were also taken from Stedmon's Table 1. The chlorophyll-a attenuation values taken from Wang et al. and Longhurst. provided both the chlorophyll concentration and attenuation data for the 443 nm wavelength. Chapter two of Lalli and Parsons provided the information necessary to create our PAR estimate. We implemented PAR dynamically over the mixed layer by halving the total shortwave radiation values across the entire model. Other important variables considered were the decay timescale of 316 days for CDOM (Stedmon, 2011) and a dilution factor to account for physical, chemical, and biological removal in estuarine regions. Some researchers suggest there is little to no chemical/biological removal of dissolved organics in estuaries (Dittmar, 2003) while others advocate for anywhere from four to 60 percent is removed (Hedges, 1997). We estimated a physical dilution factor γ according to the formula:

$$\gamma = \frac{C_{Out}}{C_R} = \frac{U_R}{U_R + U_{In}}$$

Here, C_R and U_R and the CDOM concentration and volume flux at the estuary head, and U_{In} is the ambient oceanic flow, and C_{Out} the CDOM concentration of the diluted river water. In our model, as in most global ocean climate models, riverine freshwater fluxes are not actually represented by actual volume sources; instead their impact on the freshwater budget is modeled by a virtual salt flux that freshens the surface layer in a region around the river mouth. Hence, U_R is zero in our model, and taken from river flow observations. To estimate U_{In}, we calculated the total volume flux that entered the tracer source region of each river. With monthly values of these input variables available, we can calculate monthly values of γ. However, for our baseline model we use a value of 0.3. The monthly U_R values are courtesy of an ArcticRIMS database of discharge stations (http://rims.unh.edu/data/station/list.cgi?col=1) and the Woods Hole Oceanographic Institute's discharge data from their "Arctic Ocean Model Intercomparison Project" (http://www.whoi.edu/page.do?pid=30587). ArcticRIMS is a regional, integrated hydrological monitoring system for the Pan-Arctic land mass and WHOI is a reputable nonprofit oceanographic research organization.

Matlab coding and graphics were used to implement our data and display our results. Multiple sources of literature were referenced to find the variables and parameters necessary to plot the average intensity over the mixed layer of the Arctic Ocean. One such variable was the concentration distributions of riverine CDOM for six Arctic rivers (the Mackenzie, Yukon, Kolyma, Lena, Yenisey, and Ob) which was simulated in detail. We have accounted for many other marine attenuation factors, such as clear seawater which has an attenuation coefficient of 0.017 (m^{-1}) at a wavelength of 440nm (Smith and Baker, 1981). The remaining attenuating factors were accounted for during sensitivity testing. Other types of sensitivity tests include decay timescales of CDOM, varying dilution factors, and optical properties of suspended solids and sediments. We also took the amount of PAR (Photosynthetically Available Radiation) absorbed over the well-mixed upper layer of the Arctic Ocean into account (Lalli and Parsons, 1993). At the end of the project, we were able to discern the total area affected near each river mouth (km^2) by the amount of PAR that CDOM absorbs from the system. We found that CDOM's attenuation of PAR affects a large portion of the Arctic coastal regions during the summer months near the six river mouths we chose to study.

Results and Discussion

The figure below is our baseline model output for the month of June. It shows a comparison plot of CDOM attenuation both included and not included in the system. All other values for each variable in the model are calibrated for June as well.

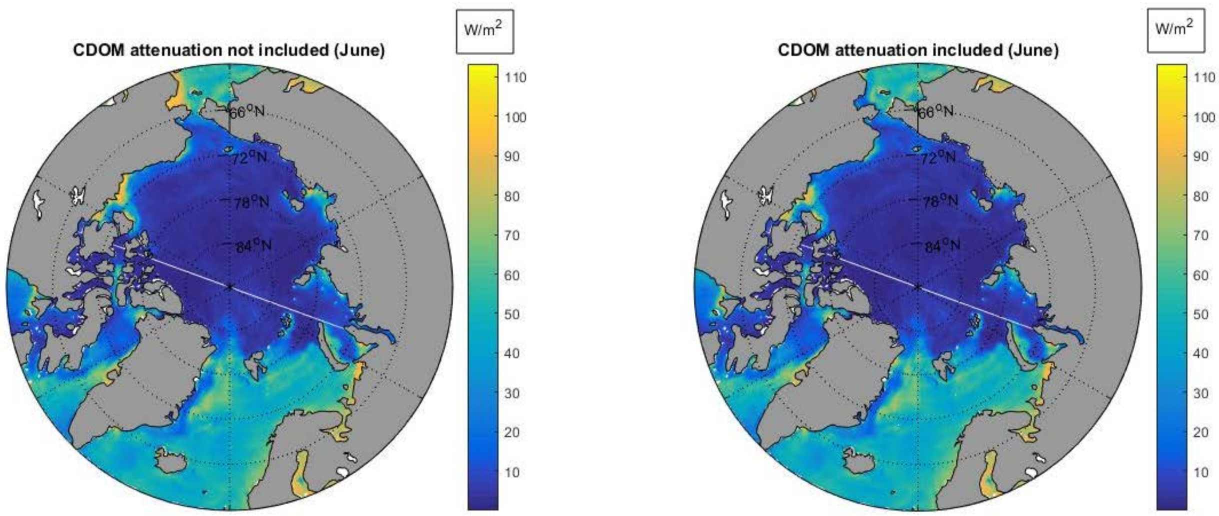

Figure 1: Comparison plot of CDOM attenuation included and not included for the month of June. More details about the plot can be found in the following paragraph.

The color bar on the right is in units of Watts per meter squared and it represents the average intensity over the well-mixed surface layer of the Arctic Ocean. Notice the dark blue area in the center of the plot. This represents the extent of sea ice and explains the lack of solar radiation entering the open ocean. Also, the bright yellow areas seen near the coasts of the model can be explained by the depth of the ocean at these points. In these shallow coastal areas, the mixed layer depth is often limited by the water depth, so the average light intensity is higher than in the deep ocean where the mixed layer can permeate much deeper. When CDOM attenuation is not included, as much as 110 W/m^2 enters the surface layer of the ocean in many places near the coast. The Mackenzie, Yukon, and Lena river mouths seem to allow the most light-penetration in June out of the six rivers of interest. On the right plot, when CDOM attenuation is included in the system, these same areas allow much less light penetration. Although this seems promising, we wanted to make our conclusions more concrete and quantitative, so we expanded on the baseline model. To find out exactly how much area is affected by CDOM attenuation (and how much CDOM is disrupting phytoplankton's photosynthetic capabilities) we created a difference plot which is seen below.

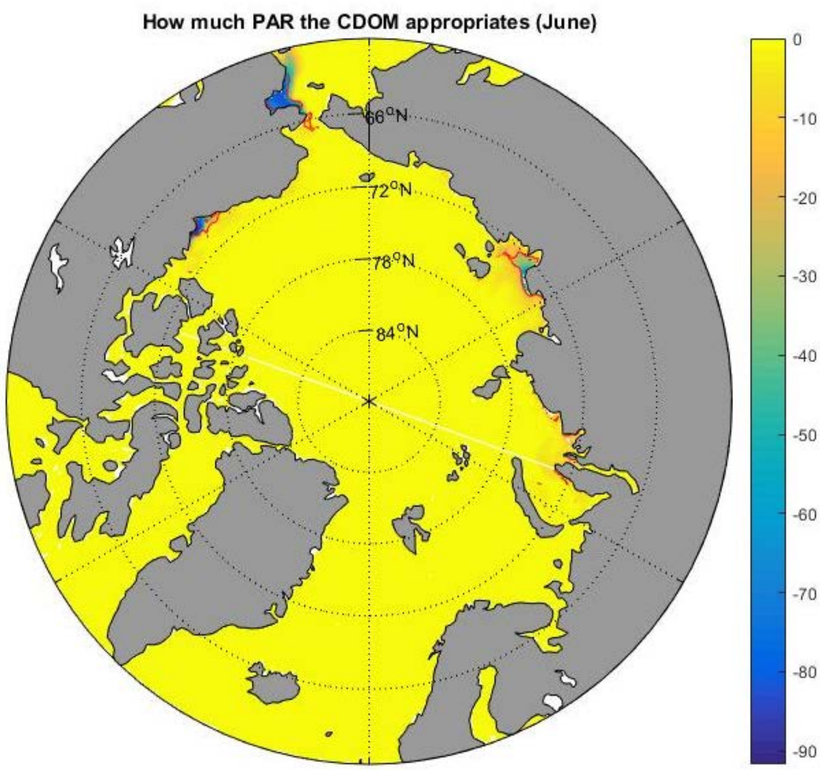

Figure 2: Difference plot of CDOM attenuation included and not included for the month of June with a 30 W/m^2 contour line. More details about the plot and the contour line can be found in the following paragraph.

The average (optimal) saturation light intensity for growth for the major classes of Arctic phytoplankton is between 25 and 45 W/m^2 (Walsh *et al.*, 2004). We chose 30 as the threshold above which plankton will be able to flourish. The red contour indicates where the inclusion of CDOM's optical properties will decrease the available PAR from above to below 30. This means that the areas inside this contour are the areas where phytoplankton theoretically will not be able to grow. To make our results more quantitative, we found out exactly how much area near each river mouth was affected from CDOM attenuation. This graph can be seen below.

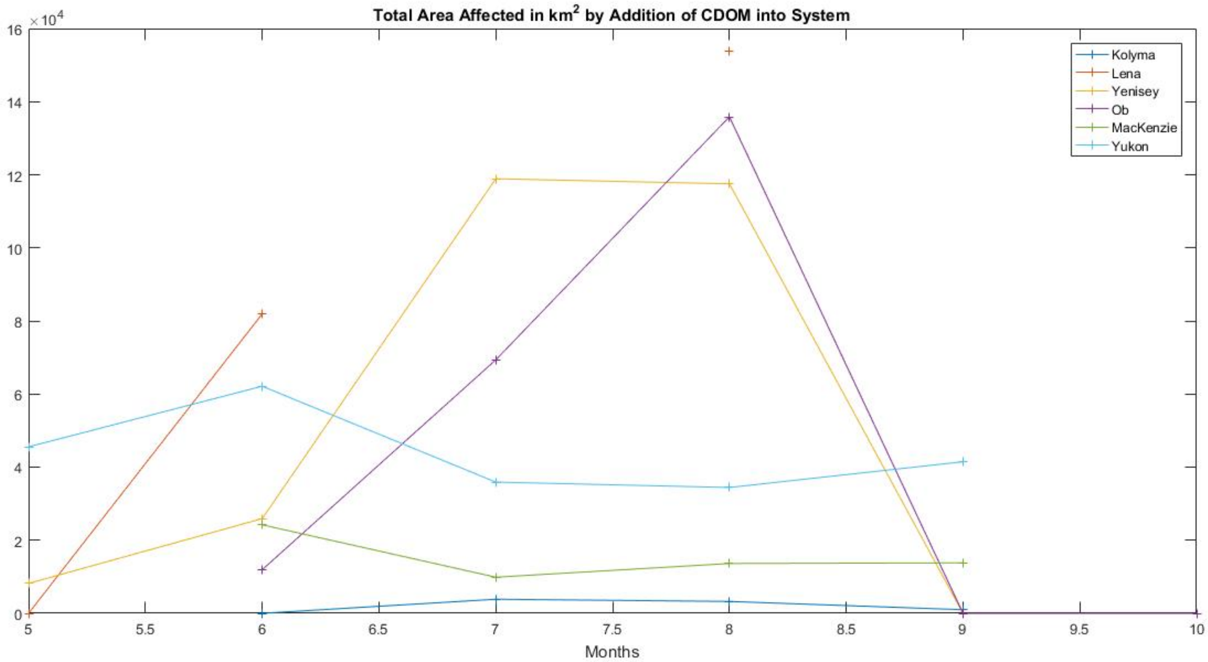

Figure 3: Graph of the total area affected by CDOM attenuation for each river during the months of May to October. More details about the graph and its features can be found in the following paragraph.

Here is the graph of all the rivers for the months of May through October that shows exactly how much area is being affected by CDOM attenuation. This analysis uses the second (SedDec5) data set, where every river is represented by its own tracer. Notice, there are incomplete lines for each river in certain months. This represents a lack of CDOM attenuation data at our preferred wavelength of 443 nm. Also, specifically for the time between September and October, there is not a complete line for any river except the Ob river and this is most likely due to the fact that there was not a decrease from above to below 30 W/m^2 in the model. The large differences observed for all six rivers can be attributed to their different discharge rates and DOC inputs along with the local ocean circulation, sea ice concentration, and mixed layer depth. Despite their stark differences, all the rivers (aside from the much smaller Kolyma river) exhibit large areas affected from CDOM attenuation. Based on our data, CDOM appropriates a significant amount of PAR from the mixed layer of the Arctic Ocean during the summer months. This means that it could easily have a large effect on Arctic phytoplankton populations which could have negative consequences. Now what needs to be added to the model is the phytoplankton concentrations for these same months of May through October. Since we know the extent of the areas affected near each river mouth, we must compare this to the areas inhabited by phytoplankton and see if these results are still significant. We plan to use SeaWiFs chlorophyll-a data to represent Arctic phytoplankton populations.

Future Research

In the model, we only considered the quickly settling sediments due to the complexity of the smaller and more slowly settling sediments. We assumed the principle of geometric scattering for the sediments included in the baseline model and in the future we will look further into applying the Mie scattering theory for suspended sediments and other solids. However, some researchers suggest that even the smaller suspended sediments that we were so concerned with settle out of suspension close to the river mouths so this will need to be further studied (Markussen, 2016). We must also delve deeper into the literature to account for the gaps in the CDOM attenuation data.

Our research can be further extended in relation to the dilution factor. We will organize more sensitivity tests on chemical and biological dilution factors in the estuarine regions. The dilution factor is critical because it could severely alter the extent of the river plumes and therefore the extent which CDOM affects phytoplankton in the Arctic. This analysis will be supplied by COSIM physical oceanographers after a more extensive literature study about the subject.

In the future, we hope to branch out from looking at just CDOM attenuation; we plan to integrate more limiting factors such as nutrients to the model to make more accurate assumptions about the capabilities of phytoplankton populations to survive in the Arctic. Ultimately, we would like to explore the effects of CDOM in other parts of the world and make predictions as to how much of a threat CDOM attenuation can truly be in a global perspective.

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