Biogeosciences Discuss., 10, C8917–C8931, 2014
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Biogeosciences Discussions

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Interactive Comment

Interactive comment on "A synthesis of light absorption properties of the Pan-Arctic Ocean: application to semi-analytical estimates of dissolved organic carbon concentrations from space" *by* A. Matsuoka et al.

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Reviewer #1: Antonio Mannino

General comments: Matsuoka et al. present constituent absorption data for several Arctic regions and apply these data and a previously published semi-analytical (SA) CDOM algorithm to develop and present pan-Arctic satellite distributions of aCDOM443 using MODIS monthly climatology. One of the major findings is that CDOM contributes

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the greatest proportion of absorption to the Arctic Ocean compared to particle absorption. Existing DOC relationships with aCDOM for two Arctic regions (Kara and Laptev seas and Beaufort Sea) and SA CDOM algorithm were applied to generate a MODIS climatology of DOC for those regions. The applicability of the aCDOM443 and DOC algorithms for areas beyond the regions sampled is not addressed. The evaluation of the satellite-derived DOC based on general comparisons to measured values rather than more rigorous validation approaches (e.g., Bailey and Werdell, 2006 RSE). The satellite DOC retrievals should be removed from the manuscript unless an analysis can be conducted to demonstrate the capability of the algorithm to retrieve DOC, even a comparison of matchups of in situ DOC and satellite DOC for in situ DOC used in the satellite algorithm development would be useful. The work presented does improve our understanding of the optical properties of the Arctic and their spatial distributions. The application of satellite absorption products from the SA will permit further analysis of the optical properties of the Arctic in both space and time. Unfortunately, the authors do not interpret the distributions of the the satellite data presented in much detail, other than differences between the WAO and EAO.

Answer: Thank you for your comments. Estimating DOC concentrations geographically and temporally is crucial to better understand recent modifications in DOC budget of the Arctic Ocean. This estimation is possible and reliable 1) when CDOM absorption is derived using a semi-analytical algorithm, that less depends on its spatial and temporal variability compared to an empirical algorithm, based on optical properties [Morel and Maritorena, 2001; references are shown at the end], and 2) when a tight DOC versus CDOM absorption relationship for river-influenced coastal waters is established using field measurements. Thus, this paper firstly focuses on examining optical properties using the quality-checked and the largest datasets of the Arctic Ocean. CDOM algorithm was then logically developed and the application for estimating DOC concentrations in Arctic river-influenced coastal waters is further proposed. The reliability of the CDOM and DOC algorithms were also examined based on statistics. Our CDOM algorithm was directly evaluated using datasets for the Western Arctic Ocean (WAO)

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(Figure 7). This evaluation was not possible for the Eastern Arctic Ocean (EAO) due to unavailability of data in that area. However, because the CDOM algorithm is based on optical properties, especially chlorophyll a (chl a) specific phytoplankton absorption (a*$\varphi(\lambda)$), indirect evaluation was possible by examining the difference in the phytoplankton absorption ((a$\varphi(\lambda)$) versus chl a concentrations relationships between WAO and EAO. As a result, no significant difference between the two areas was found (Figure 5b). This result indirectly suggests that our CDOM algorithm performs reasonably well for EAO as well as for WAO. This is presently one of the best and logical approaches to evaluate the algorithm for EAO. In this study, DOC concentrations were estimated only within ranges where tight relationships between DOC and CDOM are observed; 0.018 < aCDOM(443) < 1.08 m-1; 55 μM < DOC < 500 μM for WAO [Matsuoka et al., 2012], and 0.39 < aCDOM(443) < 8.4 m-1; 166 μM < DOC < 1660 μM for EAO [now Walker et al., 2013]. We did not estimate DOC concentrations beyond the area sampled. Statistics showed that our DOC estimates using ocean color data were reasonable compared to in situ measurements (please see section 3.4; Figure 12). A matchup analysis for southern Beaufort Sea further demonstrated that the DOC algorithm performs reasonably well for river-influenced coastal waters, confirming the reliability (see attached Figure X). Unfortunately, because we didn't get an agreement from a colleague to use in situ DOC data (unpublished data) used for this matchup result, this result was not presented in the text. Detailed examination of temporal and spatial variability in DOC estimates was also added as appendix A4 of the text (see attached Figure A4).

Specific comments: See additional comments on the manuscript. 1. The title of the article is not consistent with the data presented. The field data synthesized come from a modest portion of the Arctic – northeastern Alaska/Chuckchi, Beaufort Sea and Laptev Sea with a few data points from the Kara Sea. The satellite distributions of aCDOM443 in Fig. 8 are truly pan-Arctic, but the validity of the SA algorithm is not evaluated beyond the regions sampled on the MALINA and ICESCAPE1 and 2 cruises. Also, the satellite DOC distributions are not evaluated using a rigorous approach.

Answer: In the title, “Pan-Arctic” was corrected as “Arctic”. For the rest, please see our detailed answers to your general comments.

2. Page 6, lines 128-139 and Fig. 1: There is inconsistency in the attribution of season to the cruise data presented. For example, NABOS data collected from 14-30 September are classified as Summer, but the MR cruise from 1 September to 13 October is classified as Autumn. Cruise dates could be listed in Figure 1 rather than season or the MR cruise could be classified as Summer/Autumn. Regardless, if season is used, then it would be best to define the period for each season. Especially, since prior work in other regions have shown differences in aCDOM to DOC relationships (intercept primarily) with season. This could impact the application of the DOC algorithms/relationships as indicated by the authors in the conclusion section.

Answer: To avoid misleading, seasons were replaced by cruise dates in Figure 1. This modification does not influence our results.

3. Section 2.5 (lines 264-268) describes some limited statistical analyses, yet there are many other statistical computations presented in the Results and Discussion. It is not clear how the r2 and p-values were calculated. Were these Pearson productmoment correlations, Spearman rank correlation or linear regression analyses? How is normalized mean bias computed?

Answer: Explanation for other statistics was added in section 2.5 of the text as follows: Geometric mean and geometric SD were thus obtained for these variables in this study. Otherwise, arithmetic mean and SD were used. r2 and p-value were calculated using linear regression analysis. To evaluate the performance of our CDOM algorithm, root mean square error (RMSE), mean normalized bias (MNB), and absolute percent difference (APD) were used (please see section 2.5)

4. Page 15 – line 352: The 9% uncertainty value listed for aCDOM443 is not consistent with the data shown on Fig. 7. There are many data points close to +/-35% error compared to points that fall on the 1:1 line. How was the 9% value computed? What is

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the mean absolute percent difference of the error values plotted on Fig. 7?

Answer: "9%" was calculated using mean normalized bias (MNB). To avoid misleading, the sentence was corrected as follows: "aCDOM(443) can be derived using our CDOM algorithm with mean normalized bias (MNB) of 8.58 % and absolute percent difference (APD) of 11.72 %".

5. Page 10-11 – lines 269-27; Fig. 10; lines 410-417: The authors indicate that the Walker et al. DOC to aCDOM relationship is based on data from the mouths of 5 rivers, 4 of which are from the Russian portion of the Arctic and the 5th being the Mackenzie [this cannot be verified as Walker et al. is in press and the journal was not listed]. Because the Walker et al. relationship yielded erroneous satellite DOC values for the Beaufort Sea, based on comparison with field data from the literature, the M12 relationship derived for the Beaufort Sea was applied. So, the DOC satellite retrievals for the two Arctic regions are based on the 2 lines shown on Fig. 10. The data and statistics associated with these regression lines are not shown. Since no data are shown for these regression lines, why not simply list the equations and references. There is no need for figure 10. The corroboration of the satellite DOC is limited to a qualitative comparison of the range of DOC observed from the literature (lines 410-417). The Walker et al. DOC relationship was applied to obtain satellite DOC distributions well beyond the coastal region of the Kara Sea and Laptev Sea. There are no corroborating results to demonstrate how well the approach retrieves satellite DOC. This is particularly important when applying a relationship such as from Walker et al. to a region well beyond where the data were collected (mouth of the rivers). If one of the objectives of the article is to present "Pan-Arctic scale" satellite DOC distributions, then there must be a rigorous evaluation as to how well the algorithms perform as was accomplished for aCDOM443. Also, DOC retrievals are limited to a much smaller region of the Arctic (Fig. 11) than aCDOM443 (Fig. 8). There is limited explanation in the manuscript for this. The non-remote sensing community has not fully accepted satellite data as a source of high-quality data products. Thus, scientists applying remote sensing data

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must be cautious in presenting new satellite products that are not rigorously evaluated as we may further alienate the larger scientific community. The burden is upon the remote sensing experts to demonstrate the quality of the satellite data products that are developed. The authors should provide a more robust evaluation of the DOC satellite product or remove it entirely from the manuscript.

Answer: The reason why we applied the regressions for WAO and EAO separately is as follows: In the relationship now published by Walker et al.[2013] (DOC = 245 + 171 * aCDOM(443)), the intercept is too high for the mouth of the Mackenzie river (245 μM) in the WAO, when compared to published values (55-97 μM: Osburn et al., 2009; Matsuoka et al., 2012). The high intercept is likely influenced by a lower DOC to aCDOM(443) ratio at high aCDOM(443) values (> 1.1 m-1) in the EAO. Thus, for the WAO, we used the relationship recently obtained by Matsuoka et al. [2012] (i.e., DOC (μM) = 55 + 357 * aCDOM(443)), not because that Walker's relationship yields erroneous satellite DOC values for the Beaufort Sea. The Walker's DOC versus aCDOM(443) relationship was established mostly using a large dataset from Kara and Laptev seas. Thus, we estimated DOC concentrations in these areas using this relationship (again, we did not estimate DOC concentrations beyond the area sampled). DOC concentrations were estimated for river-influenced coastal waters where tight relationship between DOC and CDOM are observed. This is the reason why Figure 11 shows DOC estimates in smaller region compared to that for CDOM absorption. This explanation was added in the section 2.4. For the rest, please see our detailed response to your general comments.

There are publically available datasets of DOC from SBI and likely other cruises that could help address the evaluation of the DOC algorithm presented here.

Answer: We applied our DOC algorithm where tight relationships between DOC and CDOM are observed using field measurements. For SBI study area (i.e., Chukchi and western part of the Southern Beaufort Sea), no such relationship was observed. Thus, the evaluation was not made using this mentioned dataset.

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6. Page 16 – lines 382-383: A linear regression analysis was conducted on the DOC vs aCDOM data to derive the intercepts and slope values. Was a type II or type I regression applied? Did the DOC values meet normality assumptions for the regression analysis?

Answer: Model I regression was applied. The DOC values didn't meet normality assumption using a Komolgorov-Smirnov test.

7. Page 16, lines 385-392: Fig. 11 does not show much seasonal variability in DOC within the Beaufort Sea region. One would expect seasonal differences due to in situ DOC production by phytoplankton as well as from terrestrial contributions from variability in river runoff.

Answer: To address spatial and temporal variability in DOC estimates, appendix A4 was added in the text. Because DOC concentrations in river-influenced coastal waters were estimated using a DOC versus CDOM relationship, identifying DOC originating from phytoplankton would be difficult using our method. We acknowledge that this important issue should be examined in further study.

8. Page 17, lines 414-417: This sentence is a bit confusing and not completely correct. Semi-analytical (SA) algorithms such as this one and GSM are fundamentally empirical, just more sophisticated than band ratio or other empirical algorithms. The true value of "semi-analytical" algorithms is the inversion of radiometric data for obtaining the various optical parameters. Also, within this semi-analytical algorithm, there are empirical relationships such as deriving aNAP from bbp. The SA algorithm is regionally tuned, so I don't understand the distinction between this SA and the other algorithms cited – "this algorithm depends less on empirical relationships established for particular time periods and areas."

Answer: Semi-analytical algorithm is partly but not fundamentally empirical [Morel and Maritorena, 2001]. For our algorithm, as for GSM, solutions are found by mathematically optimizing the difference between remote sensing reflectance (Rrs(λ)) measured and Rrs(λ) calculated based on absorption and backscattering coefficients [Garver and Siegel, 1997; Maritorena et al., 2002]. "semi-analytical algorithm" that you mean is rather "analytical inversion algorithm". Note that a purely analytical algorithm is not suitable for deriving biogeochemical variables [Morel and Maritorena, 2001].

9. Pages 16-17: In its current form, there is not much value in the discussion pertaining to DOC. The issue that DOC is higher in the Siberian seas than the Beaufort Sea is already known based on field data presented in the literature. If the DOC algorithm could be validated or confirmed, then a more detailed discussion of the satellite DOC observations in warranted. Figure 11 appears to show higher DOC later in summer for the Laptev Sea. Can this be attributed to river runoff, in situ primary production or melting sea ice? The increase in DOC seems to correspond with increases in aCDOM443.

Answer: Please see our answer to your specific comment #7.

10. The seasonal and spatial variability of aCDOM could be further exploited in the manuscript to further demonstrate the utility of satellite data to improve our understanding of Arctic biogeochemistry and oceanography.

Answer: Spatial and temporal variability in DOC estimates were added in appendix A4.

11. Table 1 – the column headers show % for the absorption constituents, yet the values in the table are proportions rather than percentages. These should be consistent.

Answer: Corrected.

12. Table 3 can be deleted altogether by including the regression values within Fig. 6 caption or on the plot. Were Pearson correlation analyses conducted or regressions? The caption states correlation, but Table 3 reports r2 values.

Answer: The table 3 and Figure 6 are important results to estimate phytoplankton absorption at other wavelength ($a_\varphi(\lambda)$) using $a_\varphi(443)$ based on the statistics. We thus kept these as it is. Regression analysis was performed for $a_\varphi(\lambda)$ versus $a_\varphi(443)$ relationships.

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13. Fig. 8 and 11 – individual figures too small to see the aCDOM443 and DOC distributions within the coastal waters of the Arctic. Fig. 11 could be modified to show the Siberian and Beaufort regions in separate plots to enlarge these regions. Don't see much of a DOC gradient in the Beaufort Sea due to the color scale in Fig. 11.

Answer: Figures 8 and 11 are valuable to show how different in CDOM and DOC between WAO and EAO. To better show spatial and temporal variability in these variables, local images of DOC estimates for the southern Beaufort Sea were added in Figure A4 (see text of the appendix A4).

14. Authors should consider including a reference on MERIS retrievals of DOC within the Kara Sea by Korosov et al. 2012 - Advances in Space Research, 50, 1173–1188.

Answer: This paper was cited as a reference.

Our answers to your comments in the supplement file are as follows:

Page 6, lines 138-139: Need to mention what was being evaluated here – ap

Answer: This sentence was corrected as " these independent datasets were used for evaluating the Bricaud and Stramski [1990] method to derive phytoplankton absorption" (Now lines Page 7, line 144).

Page 8, lines 179-180: Why not simply use the sums of ap and acdom? This would avoid any uncertainties rom the de-pigmentation and the spectral decomposition for the NABOS cruise.

Answer: Proportions of each absorption component to the total non-water absorption were calculated as follows:

$ai(\lambda)/(ap(\lambda) + aCDOM(\lambda)) = ai(\lambda)/((ap(\lambda) - aNAP(\lambda)) + aNAP(\lambda) + aCDOM(\lambda)) = ai(\lambda)/(a\varphi(\lambda) + aNAP(\lambda) + aCDOM(\lambda))$

, where i represents either φ, NAP, or CDOM. Thus, our result doesn't change.

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Page 11, Line 246: Don't understand why this equation is included in this sentence. The topic is DOC to aCDOM350 not aCDOM443. Is this equation from Walker et al.? If the article is in press, then the citation in the reference list should include the journal name.

Answer: This sentence was corrected as "Walker et al. [2013] recently showed a consistent relationship between DOC and CDOM absorption coefficient at 350 nm [aCDOM(350), m-1] for waters at the mouth of the five major Arctic rivers (i.e., Lena, Yenisei, Ob, Mackenzie and Kolyma rivers; DOC (mg L-1) = 2.907 + 0.4059 * aCDOM(350)). The DOC vs. aCDOM(350) relationship was converted into DOC vs. aCDOM(443) relationship by assuming a SCDOM of 0.0175 nm-1 calculated using data from 350 to 600 nm in the EAO, as reported by Aas et al. [2002] [i.e., DOC (μM) = 245 + 171 * aCDOM(443)]." (Now page 11, lines 252-257) Walker et al.[2013] is now listed in the reference.

Page 11, lines 247-249: This sentence does not make sense as written. How does one apply S to obtain DOC vs. aCDOM443 relationship. Was S used to compute aCDOM443 from aCDOM350? What was the reference wavelength used if the widely used spectral slope equation was applied?

Answer: By converting aCDOM(350) into aCDOM(443) using a SCDOM of 0.0175 nm-1, DOC versus aCDOM(443) relationship was obtained. Ranges of wavelength used for calculating a spectral slope vary among the literature [Twardowski et al., 2004]. For EAO, two spectral slopes were reported [Aas et al., 2002; Stedmon et al., 2011]. While we used the one by Aas et al.[2002] (i.e., 0.0175), the choice of a spectral slope resulted in a change of only 7 % of the slope of the DOC versus aCDOM(443) relationship. This did not influence our results.

Page 11, lines 249-254: One point that should be made is whether aCDOM443 is retrieved equally well from the S300 and S350 slopes. A more significant point is how variable S for the various systems? One of the problems here is that two different pa-

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rameters being compared S350 and S300. How do the different S parameters impact aCDOM443? Comparing the difference in slope of DOC vs aCDOM443 seems less of an issue. Fundamentally, it's the differences in aCDOM443 between the 2S parameters that matter.

Answer: Please see my detailed answers to your comments on Page 11, lines 247-249.

Page 11, lines 255-258: Clearly, the DOM composition differs between the EAO and Mackenzie River resulting in the different DOC to CDOM ratios. This is not unusual. There are likely differences in vegetation between watersheds that influence the relative amounts of chromophoric and non-chromophoric DOM.

Answer: We agree. The following sentence was added: "Different DOC versus salinity relationships between WAO and EAO were also reported [Hansell et al., 2004]. There are likely differences in vegetation between watersheds that influence the relative amounts of colored and non-colored DOM" (Now page 17, lines 408-411).

Page 11, lines 265-266: Did you test the normality of the log values for these variables or then non-transformed values?

Answer: Yes. However, because this sentence was not completely appropriate, we modified it as "The normality of distribution for log-transformed aCDOM(443) and atw(443) values was examined for Arctic waters using a Kolmogorov-Smirnov test. If the normality of distribution was verified for a variable, we conducted either T-test (two variables) or ANOVA to examine a difference in mean values for each pair of data. If a variable was not normally distributed, we conducted a nonparametric Wilcoxon rank sum test." (Now page 12, lines 276-280).

Page 14, lines 328-330: The log-log plot in Fig. 5b shows quite a bit of scatter around the regression line that would likely yield quite high uncertainty in satellite retrievals.

Answer: A similar relationship is taken into account in our CDOM algorithm. Evaluation showed that this algorithm performs well (Figure 7 and Table 5). This result indirectly

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suggests that $a_\varphi(443)$ versus chl a relationship is reasonable.

Page 15, Line 352: This 9% values is not consistent with the data shown on Fig. 7. There are many data points that fall on the 1:1 line. What is the mean absolute percent difference of the error values plotted on Fig. 7?

Answer: Please see our response to your specific comment #4.

Page 16, Lines 385-392: What about a statistical evaluation of satellite-derived DOC and in situ DOC?

Answer: Please see our response to your general comments.

References: -Hansell, D. A., Kadko, D., and Bates, N. R.: Degradation of terrigenous dissolved organic carbon in the western Arctic Ocean, Science, 304, 858-861, 2004. -Garver, S. A., and Siegel, D. A.: Inherent optical property inversion of ocean color spectra and its biogeochemical interpretation 1. Time series from the Sargasso Sea, J. Geophys. Res., 102(C8), 18607-18625, 1997, -Matsuoka, A., Bricaud, A., Benner, R., Para, J. Sempére, R., Prieur, L., Bélanger, S., and Babin, M.: Tracing the transport of colored dissolved organic matter in water masses of the Southern Beaufort Sea: relationship with hydrographic characteristics, Biogeosci., 9, doi:10.5194/bg-9-925-2012, 2012. -Maritorena, S., Siegel, D. A., and Peterson, R. A.: Optimization of a semi-analytical ocean color model for global-scale applications et al., Applied Optics, 41(15), 2705-2714, 2002. -Morel, A. and Maritorena, S.: Bio-optical properties of oceanic waters: A reappraisal, J. Geophys. Res., 106(C4), 7163-7180, 2001. -Osburn, C., Retamal, L., and Vincent, W. F.: Photoreactivity of chromophoric dissolved organic matter transported by the Mackenzie River to the Beaufort Sea, Mar. Chem., 115. 10-20, 2009. -Twardowski, M., S., Boss, E., Sullivan, J. M., and Donaghay, P. L.: Modeling the spectral shape of absorption by chromophoric dissolved organic matter, Mar. Chem., 89, 69-88, 2004. -Walker, S., A., Amon, R. M. W., and Stedmon, C. A.: Variations in high-latitude riverine fluorescent dissolved organic matter: A comparison of large Arctic rivers, J. Geophys. Res., 118, 1-14, doi:10.1002/2013/JG002320, 2013.

Figure captions Figure X. (a) Monthly composite image of aCDOM(443) (m-1) during CFL Arctic cruise from 23 June to 28 July 2008. Estimates of DOC concentrations in red circles (stations 1-4) are corresponding to those in (b). (b) Matchup of satellite-derived DOC estimates with in situ measurements. Red circles represent samples obtained in river-influenced waters. For this matchup, satellite data with $\pm$ 1 day of in situ observations were accepted. Result showed that our DOC estimates using ocean color data were reasonable compared to in situ measurements for river-influenced waters.

Figure A4. Satellite-derived DOC concentrations in the surface layer for selected MODIS-Aqua satellite data recorded in 2009 (top), 2010 (middle), and 2011 (bottom).

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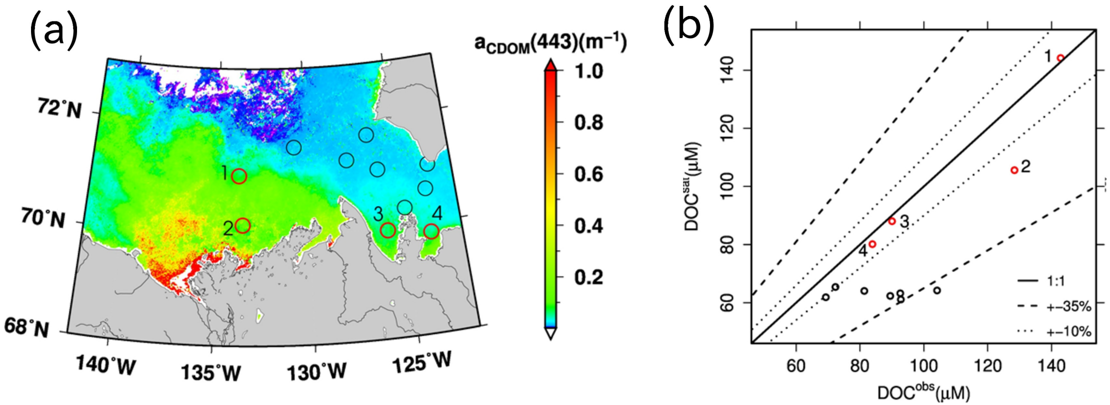

Fig. 1.

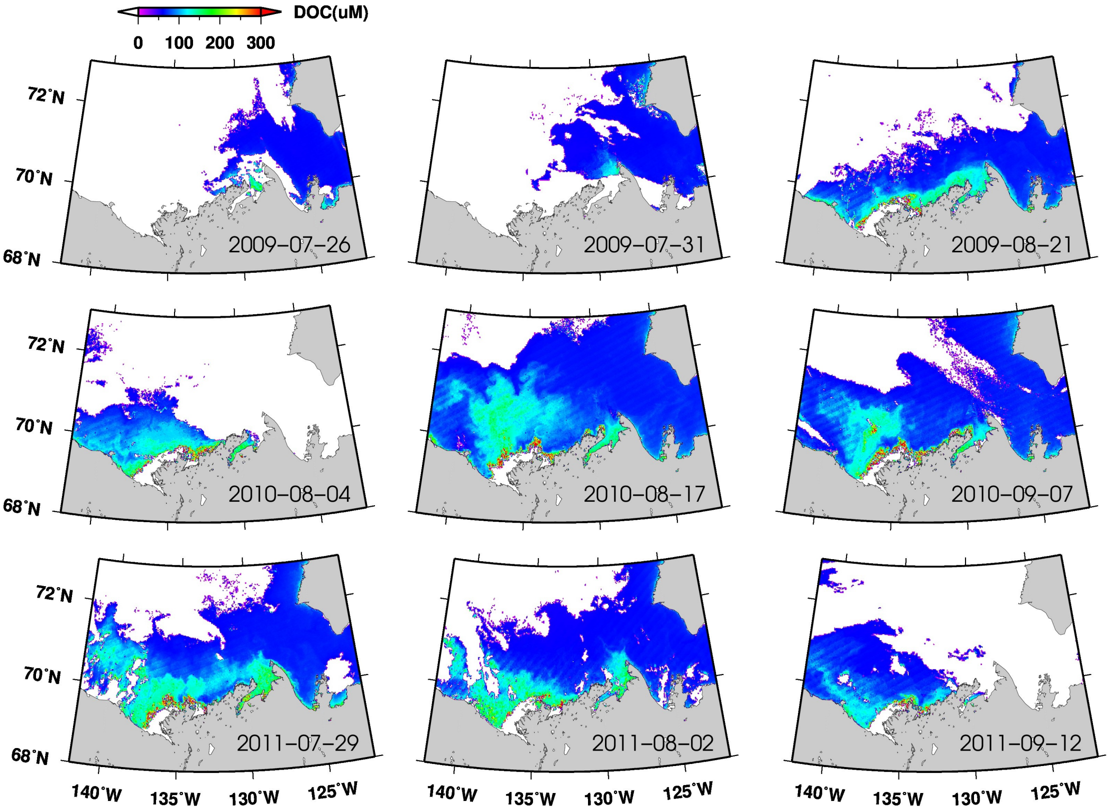

Fig. 2.

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