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Interactive comment on "Towards an assessment of riverine dissolved organic carbon in surface waters of the Western Arctic Ocean based on remote sensing and biogeochemical modeling" *by* Vincent Le Fouest et al.

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We gratefully thank referee #2 for her/his constructive comments with respect to our manuscript. In order to improve the manuscript with respect to these comments, we amended the manuscript as suggested by the referee wherever it was possible. Note that, when needed, comments were merged together to bring more clarity in the answer:

1. "I see the manuscript strengths as showing the direction of travel for this type of

research, so as such I would like to see the later section about future directions to be strengthened, and more definitive suggestions provided."

Line 302, we added this text to introduce the last paragraph of the section Perspectives: "Improving the capability of Arctic models to resolve the fate and pathways of RDOC in the AO will require certain limitations to be unlocked. To this purpose, future model developments should lie on the always increasing observational effort realized by mean of field campaigns and new remote sensing techniques. As a prerequisite, we can reasonably encourage improvements of the riverine forcings to better encompass the seasonal to interannual variability of the terrigenous dissolved organic matter, both in qualitative and quantitative terms. We also suggest bacterioplankton dynamics to be better represented in biogeochemical models. In particular, the processes related to the competition for resources, because dissolved organic carbon and nitrogen of both allochtonous and autochtonous origin are likely to play an important role in bacterioplankton growth in coastal waters impacted by river plumes."

2. "Further, it was not always clear to me what was new, or re-analysis of previously published research." "Line 70 - so this is the same biogeochemical model results from Le Fouest 2015? Please make this explicit here. What about the remote sensing component, is that new or also from previous work?"

The study of Le Fouest et al. (2015) analyzed model outputs (primary and bacterioplankton production) obtained from a model run described as the "RIV run" in Le Fouest et al. (2015). The current study used other output data from the same model run "RIV run" but that were not analyzed yet. Those include RDOC concentration and ocean currents. The remote sensing data are very new and based on the new methods recently published in Matsuoka et al. (2017).

For more clarity, the sentence was reworded as follows: "To this end, sea surface RDOC concentrations obtained from a previous model run described in Le Fouest et al. (2015) and derived from remote sensing data were analyzed for the Canadian

Beaufort Sea.”

Introduction “Line 27 - no need for thus.”

“thus” was removed.

“Line 31 - no need for riverine as implicit in RDOC.”

“riverine” was removed.

“Line 32 - with *the* potential for fueling”

“a potential” was replaced by “the potential”.

“Line 35 - Awkward ending. Maybe consider something like: “Future studies could apply...the entire AO to quantify..”

The sentence was modified as follows: “Future studies could apply the combination of model and satellite data extended to the entire AO to quantify the expected changes in RDOC fluxes and their potential impact on AO biogeochemistry.”. The sentence “This is left for future work” was removed.

“Line 39 - did you mean from the *six* great Arctic rivers in this paper?”

The sentence has been modified as follows: “The Arctic Ocean (AO) receives ∼10% of the global freshwater discharge (Opsahl et al., 1999 and references therein) of which the larger part (∼54-64%) originates from six main pan-Arctic rivers (Haine et al., 2015; Holmes et al., 2012; Aagaard and Carmack, 1989).”

“Line 40-41 - other factors contribute to the this intensification e.g. snow cover reduction, terrestrial productivity changes. Needs more detail here or suggest that increasing precipitation is one example.” “Line 41 - grammar needs correcting”

The sentence was modified as follows: “Over the past 30 years, the Arctic freshwater cycle intensified as reflected by changes in snow cover (Bring et al., 2016), evapotranspiration from terrestrial vegetation (Bring et al., 2016), and precipitation (Vihma et al.,

2016). It resulted into an increase of the freshwater discharge from North American and Eurasian rivers by ∼2.6% and ∼3.1% per decade, respectively (Holmes et al., 2015).”

“Line 43 – contains half the soil *organic C stock”

“soil carbon stock” was replaced by “soil organic carbon stock”.

“Line 45 - maybe worth mentioning that it is currently unclear though if aquatic OC concentrations will increase, and that some studies suggest that OC concentrations may reduce (see Abbott et al 2016 and Striegl et al. 2005 for example).” “Line 46 - not particularly suitable reference for the later part of the sentence re. changing OC concentration and composition. Suggest you use another and move the excellent Romanovsky one earlier in sentence.”

The last two sentences were modified as follows: “With the warming of the lower atmosphere, the permafrost undergoes a substantial thawing (Romanovsky et al., 2010) likely to alter the organic carbon (OC) content and quality of inland waters. In the past decades, the flux of riverine dissolved organic carbon (RDOC) decreased in the Yukon River (40%; Striegl et al., 2005) while it increased at the Mackenzie River mouth (∼39%; Tank et al., 2016). These contrasting trends reinforce the idea that the direction of future trends of RDOC concentrations and fluxes from land to ocean remains very uncertain (Abbott et al., 2016).”

“Line 49 - these rivers flow all year round, so OM supply does not only occur after the ice breakup period.”

The text was modified as follows to give a general sense to the sentence: “Coastal waters influenced by river plumes are hence exposed to changing conditions in terms of OC flux from land. They are generally supplied in riverine OC all year round with a maximal flux in spring-early summer when the river discharge reaches a seasonal maximum. ”. With respect to other coastal areas, the Beaufort Sea system is quite particular as the inner Mackenzie shelf (< 20 m depth) is bounded during winter by a thick ridged ice barrier grounded on the sea floor called stamukhi (Macdonald et al., 1995). The stamukhi retains the turbid river water within the inner shelf in winter. When sea ice breaks up and the freshet reaches its seasonal maximum in June, the turbid waters retained inshore spread farther within the coastal zone. This part is developed in lines 161 to 165.

"Line 50 - seasonal in twice."

"seasonal river flow" was replaced by "river flow".

"Line 57 - unusual to have a pers comm here as well as the Manizza paper. Recommend removing as adds little evidence."

The sentences were modified as follows: "The pan-Arctic flux of RDOC ($\sim$35-37.7 TgC yr-1; Holmes et al., 2012; Manizza et al., 2009; Raymond et al., 2007; Opsahl et al., 1999) is hence a significant pool of the carbon cycle. For comparison, it represents $\sim$10% to $\sim$19% of the carbon fixed by phytoplankton in the whole AO (Stein and Macdonald, 2004; Bélanger et al., 2013) and reaches up $\sim$34% of primary production in the oligotrophic Beaufort Sea (S. Bélanger, pers. comm.)."

"Line 61 - can this be written more clearly. Its an important point, so how is RDOC reducing C uptake by 10%? Or is it offsetting this?"

The sentence was modified as follows: "Furthermore, RDOC can modulate the air-sea fluxes of CO2 at the pan-Arctic scale. The mineralization of RDOC produces dissolved inorganic carbon with, as a result, a decrease by 10% of the net oceanic CO2 uptake in present climatic conditions (Manizza et al., 2011)."

Materials and methods "90 - more details on the satellite products used and their source would be useful here." "93 - unclear grammar here so not sure how you are coming up with this uncertainty value."

The paragraph was modified as follows: "Monthly composites of remotely

sensed RDOC concentrations are calculated as follows: Level 1A scene images acquired from the MODerate-resolution Imaging Spectroradiometer (MODIS) aboard Aqua satellite were downloaded from the NASA ocean color website (https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/L1/). Temporal data covered from June to September for the 2003-2013 period. After geometric correction, remote sensing reflectance, Rrs(λ) data at 412, 443, 488, 531, 555, and 667 nm were obtained by applying atmospheric correction proposed by Wang and Shi (2009) with modifications adapted to Arctic environments (Doxaran et al., 2015; Matsuoka et al., 2016). The light absorption coefficients of colored dissolved organic matter at 443 nm (aCDOM(443)) were derived from the Rrs(λ) data using the gsmA algorithm (Matsuoka et al., 2017) that optimizes the difference between satellite Rrs(λ) and Rrs(λ) calculated using parameterization of absorption and backscattering coefficients for Arctic waters (Matsuoka et al., 2011, 2013). RDOC concentrations were estimated from the aCDOM(443) data using an empirical relationship between RDOC and aCDOM(443) established in the Southern Beaufort Sea (Matsuoka et al., 2013). Scene images of DOC concentrations were used to make monthly composite images at 1 km horizontal resolution. Errors of intercept, slope, and aCDOM(443) were propagated into the in-situ (empirical) DOC versus aCDOM(443) relationship. Mean uncertainty of DOC concentration estimates was hence determined to be 28% according to statistical analysis(see Appendix A2 of Matsuoka et al., 2017)."

"97 - so are you including new model runs here or are they the same as subsequently published?"

The first two sentences were modified as follows: "We used sea surface RDOC concentrations and ocean currents simulated by a pan-Arctic model run described in Le Fouest et al. (RIV run; 2015). The model data were extracted on the remote sensing geographical domain focused on the southern Beaufort Sea. We provide here a brief description of the physical-biogeochemical coupled model. The MITgcm (MIT general circulation model) ocean-sea ice model (Nguyen et al., 2011, 2009; Losch et al., 2010;

Condron et al., 2009) has a variable horizontal resolution of ∼18 km and covers the Arctic domain with open boundaries at 55°N on the Atlantic Ocean and Pacific Ocean sides."

"112 - please state how Raymond calculated this estimate."

The sentence was modified as follows: "The total annual load of RDOC in the model is 37.7 TgC yr-1. It is consistent with the values reported by Raymond et al. (36 TgC yr-1; 2007) and Holmes et al. (34 TgC yr-1; 2012) and obtained by load estimation models linking the RDOC concentrations to river discharge data. "

"119 - does Wickland really show this? I think she shows that between 12-18% of RDOC is available but that the average % is 15% in the Yukon river only. Please provide detail on assumptions."

The 15% value given in the manuscript was estimated using the yearly mean percentages of the total RDOC load considered as biodegradable DOC for six major Arctic rivers (Kolyma, Yukon, Mackenzie, Ob, Yenisey and Lena) given in Table 5 in Wickland et al. (2012).

The sentence was modified as follows: "We set to 15% the percentage of RDOC entering the model as usable by the bacterioplankton compartment. This value was estimated using the yearly mean percentages of the total RDOC load considered as biodegradable DOC for six major Arctic rivers given in Wickland et al. (2012)."

"136 - please reword this sentence for clarity."

The sentence was modified as follows: "Monthly fluxes of RDOC were calculated along two cross-shelf transects (see upper-middle panel in Fig. 1). The model estimates were computed as the product of the simulated sea surface current velocity with the simulated RDOC concentration. The remote sensing estimates were computed as the product of the simulated sea surface current velocity with the remotely sensed RDOC concentrations."

Results & Discussion "146 - you define an acronym for simulated RDOC (RDOCsim) in the methods but then don't use it in this section."

RDOC will be substituted by DOCt and, as such, RDOCsim will be removed.

"148 - quite speculative this. Are you suggesting that this may account for the differences and can you justify this with any estimates? Most would not consider ice-derived plankton terrestrially derived also, so please re-phrase." "156 – ok so here you say this is not likely to be the cause."

The sentence "Terrigenous DOC originating from both melted sea ice and permafrost erosion along the coastline were not taken into account in the model." was removed. The text was modified as follows to bring more clarity: "In the Beaufort and Chukchi seas, first year sea ice represents a carbon flux to the ocean of 2 × 10-4 TgC yr-1 (Rachold et al., 2004). This flux is 4 orders of magnitude lower than the RDOC supply from the Mackenzie River specified as boundary conditions in the model (2.54 TgC yr-1). Similarly, DOC eroded from permafrost stored in the Canadian Arctic shores would account for only ∼ 0.5 × 10-4 (Tanski et al., 2016) to ∼ 1.6 × 10-4 TgC yr-1 (Ping et al., 2011, using a DOC:POC ratio of 1:900 as in Tanski et al., 2016). With regard to these flux values, terrigenous DOC originating from both melted sea ice and permafrost erosion along the coastline, not taken into account in the model, are hence not believed to explain the model-satellite discrepancies (Fig. 1). "

"150 & 154 - should this read 2 x 10? Please update."

"2 10-4 TgC yr-1" was replaced by "2 × 10-4 TgC yr-1". "0.5 10-4" and "1.6 10-4 TgC yr-1" were replaced by "0.5 × 10-4" and "1.6 × 10-4 TgC yr-1", respectively.

"157 (e.g. ??)"

The factors potentially involved to explain the model-satellite discrepancies are developed within the paragraph just after this sentence.

"162 - less than 20 m of depth/ distance?"

The sentence was modified as follows: “Second, the inner Mackenzie shelf (< 20 m depth) is bounded during winter by a thick ridged ice barrier grounded on the sea floor called stamukhi (Macdonald et al., 1995).”

“168 - Further offshore?”

The sentence was modified as follows: “Further offshore on the Mackenzie shelf, as delimited by the 300 m isobaths remotely sensed and simulated concentrations of RDOC were both within the range of values measured in spring ($\sim$110-230 mmolC m-3; Osburn et al., 2009) and summer ($\sim$60-100 mmolC m-3; Para et al., 2014).”

“183 - I’m not clear on how this works? RMSE shows that the model was more ‘accurate’ after the spring flush. Yet, the MEF index shows that model and observations were closest during and just after the flush? Can you explain the discrepancy here, or am I misunderstanding?” “184 - why does a positive MEF indicate this?” “195 - please re-word to make this sentence clearer.”

A cross-verification of the metrics revealed an small error in the calculation of the geometric bias and RMSE shown in Table 1. It resulted into only a slight departure from the original values. We provide the corrected values in the new Table 1 below:

Table 1. Skill metrics of comparison computed based on the 2003-2011 monthly climatologies of RDOC. Metric June July August September Correlation coefficient 0.79 0.82 0.78 0.79 Unbiased RMSE (mmolC m-3) 41.4 29.4 26.0 29.3 Model efficiency 0.49 0.60 0.26 0.38

Geometric statistics using log-transformed data Model bias 1.24 1.07 1.32 1.21 RMSE 1.07 1.02 1.12 1.06

The text was modified as follows: “The size of the model-satellite discrepancies was given by the unbiased RMSE. Overall, the unbiased RMSE decreased from June (41.4 mmolC m-3) to September (29.3 mmolC m-3). This result suggested that the model accuracy increased from spring, i.e. during seasonal peak of river discharge in agreement

with Manizza et al. (2009) and Yang et al. (2015), to summer. The model capability for predicting RDOC relative to the average of the remote sensing counterparts was estimated by the model efficiency index ($-\infty<$MEF≤ 1) (Nash and Sutcliffe, 1970).The MEF is a normalized statistic that relates the residual variance between the simulated and remotely sensed RDOC concentrations to the variance within the remotely sensed RDOC data. A MEF near zero means that the residual variance compares to the remotely sensed variance, i.e. and that the model predictions are as accurate as the mean of the satellite data. As the MEF increases towards a value of one, the residual variance becomes increasingly lower than the observed variance. The MEF was positive (0.26-0.60) for all months suggesting that RDOC concentrations simulated by the model were an acceptable predictor relative to RDOC concentrations derived from remote sensing, especially in June-July. Metrics based on log-transformed RDOC data were also computed to give a more even weight to all of the data and to limit the skewness towards the higher RDOC concentrations. For all months, the geometric RMSE was close to one and span between 1.02 and 1.12. It suggested that the model-satellite data dispersion was relatively small when the positive skewness was reduced. In June, the relatively high unbiased RMS could be partly due to high RDOC concentrations as suggested by relatively low geometric RMSE (1.07). Finally, the geometric bias informs on the direction of the model-satellite discrepancies. For all months, the geometric bias (1.07-1.32) was higher than one meaning that the model tended, on average, to overestimate the observations over the whole domain. The highest geometric bias was reported in August (1.32), when the river discharge was low, suggesting that RDOC removal was likely underestimated in the model in late summer. “

“General Text could benefit from editing for English grammar.”

The English will be improved.

“References are not in alphabetical order in places e.g. Raymond ref higher up etc.”

References will be sorted in alphabetical order.

“Is it appropriate to use RDOC as a term for the flux of C in the shelf region when it may be derived of a significant proportion of non riverine-derived OC?”

In the model, the RDOC compartment refers to DOC of riverine origin only.

With respect to remote sensing, the algorithm used in Matsuoka et al. (2017) was based on a valid and highly significant relationship between DOC and aCDOM(443) ($r2=0.97, p<0.0001$; Fig. 9a of Matsuoka et al., 2012). This type of relationship can only be observed in a river mouth. Because the algorithm was dependent on aCDOM(443) (aCDOM(443) versus salinity relationship: $r2=0.95$, $p<0.0001$, Fig. 5a of Matsuoka et al., 2012), the estimated relative fraction of terrestrial DOC retrieved would be $\sim$0.92, i.e. the product of $r2=0.95$ (from the aCDOM(443) versus salinity relationship) with $r2=0.97$ (from the DOC versus aCDOM(443) relationship). Note that a direct relationship between DOC and salinity ($r2=0.89$, $p<0.0001$; Fig. 8a of Matsuoka et al., 2012) confirmed that $\sim$90% of DOC observed in the river mouth was of terrestrial origin. So it can safely be argued that most ($\sim$90%) of the DOC that was estimated by remote sensing was of terrestrial origin. This new section will be added in the text in section 2.1.

Nevertheless, we will replace the term RDOC by DOCt (for terrigenous DOC) for more accuracy.

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