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La Rochelle, November 8, 2017

Object: Revision of the manuscript bg-2017-286

Dear Editor,

Please find attached a revised version of the manuscript entitled “Towards an assessment of riverine dissolved organic carbon in surface waters of the Western Arctic Ocean based on remote sensing and biogeochemical modeling” by V. Le Fouest, A. Matsuoka, M. Manizza, M. Shernetsky, B. Tremblay, and M. Babin. Based on your recommendations about the manuscript # bg-2017-286, we thank you to allow us providing a revised version of the manuscript which takes into account all the reviewers’ comments. Following your request, we provide below a point-by-point response to the reviewers and a list of all relevant changes made in the manuscript. The changes corresponding to the major comments of both reviewers are coloured in red in the revised version.

Yours sincerely,



Dr. Vincent Le Fouest

Referee #1

We gratefully thank **referee #1** 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. “Satellite remote sensing obviously can convey information on the directional flow of river plumes carrying DOC, but depth penetration from satellite platforms is modest, so without field sampling, comparison of one set of estimates with another produced by biogeochemical modeling seems like a limited and incomplete outcome.”

We agree with that comment in the sense that numerical modeling and remote sensing are not exhaustive approaches. Both are fully dependent from field measurements as their setup (e.g. forcings and differential equations for the model, algorithms for remote sensing) necessarily requires large in-situ databases. In our study, the model was constrained by riverine DOC observations at the boundaries of its numerical domain (see Manizza et al., 2009) while the semi-empirical remote sensing algorithm we used was developed based on field measurements (see Matsuoka et al., 2017). As explicitly mentioned in the manuscript, the modeling and remote sensing approaches combined together provide a relevant insight on the terrigenous DOC (tDOC) dynamics over a wide spatial and temporal scale, but limited to the surface coastal waters where tDOC concentrations are the highest.

In order to account for the referee’s comment, we modified the end of the abstract (lines 33-36) as follows: “The combination of model and satellite data provide promising results to extend this work to the entire AO so as to quantify, in conjunction with in-situ data, the expected changes in tDOC fluxes and their potential impact on the AO biogeochemistry at basin scale.”

2. “Moreover, many of the important areas of concern in the context of climate change revolve around the dynamics of DOC degradation. This process has higher rates in the spring freshet that later in the summer, and the different pools of marine and riverine DOC have different degrees of bioavailability. I didn’t see this addressed significantly”

According to this comment, we improved the first paragraph of the Perspective section. The text was modified as follows (lines 298-316): “In addition, the model involves some limitations mostly due to the biogeochemical processing of tDOC, which is complex to translate into robust mechanistic equations as highly dependent on the availability of in-situ data in Arctic waters. For instance, the riverine tDOC compartment is split in the model into a labile and a non-labile fraction (see Le Fouest et al., 2015). This parameterization strongly constrains the removal of tDOC by bacterioplankton and therefore the tDOC concentrations simulated within surface waters. In natural waters, however, tDOC is made of a complex mixture of compounds that differ by their chemical composition and age (Mann et al., 2016) and so along the seasons (Wickland et al., 2012, Mann et al., 2012). The chemical nature of tDOC impacts its bioavailability estimated to average 6 % to 46 % of the total tDOC pool with marked disparities amongst the seasons and the rivers (Mann et al., 2012). Nevertheless, the general trend for the six major Arctic rivers (Kolyma, Yukon, Mackenzie, Ob, Yenisey and Lena) is a more labile tDOC pool in winter than in spring and summer (Wickland et al., 2012). In the Kolyma River, Mann et al. (2012) report a higher labile fraction in spring (~20 %) than in summer (<10 %) as the exported tDOC is younger during the freshet. Such a pattern is, however, not clearly evidenced in the Mackenzie River (e.g. Wickland et al., 2012). We suggest that a more realistic representation in the model of the nature of the organic matter entering the coastal waters including the riverine flux of both dissolved organic carbon and nitrogen along with an improved C:N stoichiometry for bacterioplankton uptake (see Le Fouest et al., 2015) might improve the tDOC concentrations simulated in surface AO waters.”

3. “I didn’t see this addressed significantly, including including the extent to which DOC is removed in the river delta or near-shore zone, and after it is accounted for in flux estimates, but before it reaches the open ocean where estimates can be made from satellite platforms.”

The text was also modified as follows (lines 317-322): “In the model, the seasonal forcing of tDOC was based on DOC measurements gathered hundreds kilometers upstream the rivers’ mouths. This prevented any DOC enrichment of the Mackenzie River water as it flows through the delta (see Emmerton et al., 2008) with, as a consequence, a likely underestimation of tDOC concentrations simulated in nearshore waters. Therefore, the quantification of the tDOC flux from the watersheds to the coastal AO poses as another key issue to addressing the role of tDOC in the biogeochemistry of shelf waters.”

4. “It is also significant that much of the spring freshet flows over and under coastal sea ice from the Mackenzie River, but there is little inference about how that is accounted for.”

In the model, the river flow and tDOC concentrations spread under coastal sea ice. By contrast, there were no tDOC data where sea ice above the sea surface was present in the remote sensing dataset. Therefore, only the grid points where both simulated and remotely sensed tDOC coincided were analyzed.

5. “Comparisons are made to primary production, and it is stated that DOC from rivers represents 10-19% of the carbon fixed by primary production in the Arctic Ocean as a whole and up to 34% of primary production in the coastal Beaufort Sea, but the labile nature of organic carbon that is formed by marine production is quite different from most of the organic carbon in RDOC.”

The reviewer’s comment is relevant in the sense that most of tDOC is refractory to biological use while biogenic carbon formed by primary producers can flow more easily within the food webs when it does not sink out of the euphotic zone (~10%; Buesseler, 1998). However, the purpose of our sentence was primarily to scale a bulk comparison between these two main sources of organic carbon that fuel the upper water column, irrespective to their nature and fate. We hence modified the sentence as follows (lines 59-64): “As the organic carbon formed by phytoplankton, terrigenous DOC (tDOC) can be considered as new carbon fueling annually the upper AO. To that respect, and regardless of its distinct nature and fate, the flux of riverine DOC would be equivalent to 10-19 % of the AO primary production (Stein and Macdonald, 2004; Bélanger et al., 2013). In the oligotrophic Beaufort Sea, this proportion would reach ~34 % (S. Bélanger, pers. comm.).”

6. “It should be mentioned that the authors acknowledge some of these limitations in a general sense, including seasonal challenges to gathering satellite data, and the complex nature of RDOC in the Perspectives section, although those limitations are not reflected in the abstract of the study, which reads more optimistically.”

The limitations pointed out by the reviewer were developed in our detailed answers to comments 2 and 3. We also modified the beginning of the third paragraph of the Perspective section (lines 331-340) to develop on some aspects of the remote sensing: “In our study, the remotely sensed tDOC concentrations retrieved in shelf waters provide the advantage of already integrating the effect of the watersheds processes such as mobilization, transformation and transport at the seasonal and synoptic time scales. However, we acknowledge that the temporal coverage of the remote sensing data is restricted to spring and summer. Because of clouds and sea ice, we miss the winter season when tDOC is the most labile (e.g. Wickland et al., 2012) and likely subject to remineralization. In the Mackenzie River, about 25 % of the annual load of labile tDOC occurs during winter (Wickland et al., 2012). Despite this limitation, and in regard to the model-satellite data comparison, the assimilation of remotely sensed tDOC data into Arctic models could still offer an interesting

perspective as it might result in more realistic simulated fields of tDOC in spring and summer when the river discharge and tDOC export is the highest.”

7. “The manuscript could be improved by light editing by a Native English language writer.”

The English has been improved.

8. “Data supporting the study are available on-line, but no metadata or “read-me file” explaining use of the on-line files is provided.”

A read-me file is now provided with the data in the archive.

9. “I see no reason the manuscript couldn’t be improved and accepted for publication, but I am skeptical of its potential for providing a more transformative understanding of dissolved organic carbon cycling in the Arctic.”

To our knowledge, this study is the first to compare cutting-edge tDOC data derived from remote sensing datasets and outputs from a predictive Arctic model. We show that the two approaches compare favorably in terms of tDOC concentrations and lateral fluxes and that they could be associated to overcome, at least partially, their own limitations. The study also attempts to shed light on the potential to further develop the two approaches to contribute for a better understanding of the tDOC dynamics and fate within AO waters in past and future decades, and so along with the increasing sampling effort done in the Arctic. To that respect, we think this study could be relevant for publication.

New cited references

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Emmerton, C. A., Lesack, L. F. W., and Vincent, W. F.: Nutrient and organic matter patterns across the Mackenzie River, estuary and shelf during the seasonal recession of sea-ice, *J. Marine Syst.*, 74, 741–755, doi:10.1016/j.jmarsys.2007.10.001, 2008.

Referee #2

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:

“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.”

We added this text to introduce the last paragraph of the Perspectives section (lines 349-359): “Improving the capability of Arctic models to resolve the fate and pathways of tDOC 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 exported to the coastal AO, 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 as dissolved organic carbon and nitrogen of both allochthonous and autochthonous origin are likely to play an important role in mediating bacterioplankton growth and tDOC remineralization in Arctic coastal waters impacted by river plumes.”

“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 terrigenous DOC (tDOC) concentrations 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 (lines 79-81): “To this end, riverine DOC concentrations at the sea surface obtained from a previous model run described in Le Fouest et al. (2015) and tDOC concentrations 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 (lines 33-36): “The combination of model and satellite data provide promising results to extend this work to the entire AO so as to quantify, in conjunction with in-situ data, the expected changes in tDOC fluxes and their potential impact on the AO biogeochemistry at basin scale.”. 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 (lines 39-41): “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 (lines 41-45): “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 (lines 47-52): “With the warming of the lower atmosphere, the permafrost undergoes a substantial thawing (Romanovsky et al., 2010) likely to alter the organic carbon content and quality of inland waters. In the past decades, the flux of dissolved organic carbon (DOC) 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 responses to climate change suggest that the direction of future trends of DOC concentrations and fluxes to the AO are 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 (lines 53-55): “Coastal waters are supplied in riverine organic carbon all year round with a maximal flux in spring-early summer when the freshwater 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 latter part is developed from line 188 to line 192 in section 3.1.

“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 (lines 58-64): “The pan-Arctic flux of riverine DOC to the AO is estimated to 33-37.7 TgC yr⁻¹ (Holmes et al., 2012; Manizza et al., 2009; McGuire et al., 2009; Raymond et al., 2007). As the organic carbon formed by phytoplankton, terrigenous DOC (tDOC) can be considered as new carbon fueling annually the upper AO. To that respect, and regardless of its distinct nature and fate, the flux of riverine DOC would be equivalent to 10-19 % of the AO primary production (Stein and Macdonald, 2004; Bélanger et al., 2013). In the oligotrophic Beaufort Sea, this proportion would reach ~34 % (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 text was modified as follows (lines 67-70): “Riverine DOC can also modulate the air-sea fluxes of CO₂. In present climatic conditions, Manizza et al. (2011) suggest that the mineralization of riverine DOC into dissolved inorganic carbon would induce a 10 % decrease of the net oceanic CO₂ uptake at the pan-Arctic scale.”

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 section 2.1 was modified as follows (lines 98-115): “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/>). After geometric correction, remote sensing reflectance, R_{rs}(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 (a_{CDOM}(443)) were derived from the R_{rs}(λ) data using the gsmA algorithm (Matsuoka et al., 2017) that optimizes the difference between satellite R_{rs}(λ) and R_{rs}(λ) calculated using parameterization of absorption and backscattering coefficients for Arctic waters (Matsuoka et al., 2011, 2013). tDOC concentrations were estimated from the a_{CDOM}(443) data using an empirical relationship between DOC and a_{CDOM}(443) established in the Southern Beaufort Sea (Matsuoka et al., 2013). Since DOC concentrations estimated using ocean color data are based on a highly significant DOC versus a_{CDOM}(443) relationship (R² = 0.97; Matsuoka et al., 2012), the DOC is considered to be of terrestrial origin. Errors of intercept, slope, and a_{CDOM}(443) were propagated into the in-situ (empirical) DOC versus a_{CDOM}(443) relationship. It resulted into a mean uncertainty of the tDOC concentration estimates of 28 % (see Appendix A2 of Matsuoka et al., 2017). Scene images of tDOC concentrations were used to make monthly composite images at 1 km horizontal resolution.”

“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 (lines 118-122): “We used sea surface tDOC concentrations and ocean currents simulated over 2003-2011 by a previous pan-Arctic model run (“RIV run”) whose setup is fully detailed in Le Fouest et al. (2015). The pan-Arctic 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 used to generate the “RIV run”.”

“112 - please state how Raymond calculated this estimate.”

The sentence was modified as follows (lines 134-137): “The total annual load of tDOC in the model is 37.7 TgC yr⁻¹. It is consistent with previous values reported in Raymond et al. (36 TgC yr⁻¹; 2007) and Holmes et al. (34 TgC yr⁻¹; 2012) and obtained by using load estimation models linking riverine DOC 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 (lines 143-146): “We set to 15 % the percentage of tDOC entering the model as usable by the bacterioplankton compartment. This value was estimated based on the mean yearly percentages of the total load of riverine DOC 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 (lines 160-164): “Monthly fluxes of tDOC were calculated and summed along two cross-shelf transects (see upper-middle panel in Fig. 1). At each grid cell, the model flux estimate was computed as the product of the simulated sea surface current velocity with the simulated tDOC concentration. The remote sensing flux estimate was computed as the product of the simulated sea surface current velocity with the remotely sensed tDOC concentration.”

Results & Discussion

“146 - you define an acronym for simulated RDOC (RDOCsim) in the methods but then don’t use it in this section.”

RDOC was substituted by tDOC and, as such, RDOCsim has been 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 (lines 175-183): “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 tDOC supply from the Mackenzie River specified as boundary conditions in the model (2.54 TgC yr⁻¹). Similarly, tDOC eroded from permafrost stored in the North American shores would account for only $\sim 0.5-1.6 \times 10^{-4}$ TgC yr⁻¹ (Tanski et al., 2016; Ping et al., 2011, using a DOC:POC ratio of 1:900 as in Tanski et al., 2016) to $\sim 2 \times 10^{-3}$ TgC yr⁻¹ (McGuire et al., 2009). With regard to these flux values, tDOC originating from both melted sea ice and eroded permafrost, 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.”

Line 176, “ 2×10^{-4} TgC yr⁻¹” was replaced by “ 2×10^{-4} TgC yr⁻¹” and so on when necessary.

“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 (line 188-190): “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 (lines 195-198): “Further offshore on the Mackenzie shelf, as delimited by the 300 m isobaths both remotely sensed and simulated concentrations of tDOC were within the range of values measured in spring (~110-230 mmolC m⁻³; Osburn et al., 2009) and summer (~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 a 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 tDOC.

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 (lines 205-227): “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 to summer. The model capability for predicting tDOC relative to the average of the remote sensing counterparts was estimated by the model efficiency index ($-\infty < \text{MEF} \leq 1$) (Nash and Sutcliffe, 1970). The MEF is a normalized statistic that relates the residual variance between the simulated and remotely sensed tDOC concentrations to the variance within the remotely sensed tDOC data (see Eq. 3). A MEF value near zero means that the residual variance compares to the remotely sensed variance, i.e. 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. For all months, the MEF was positive (0.26-0.60) suggesting that tDOC concentrations simulated by the model were an acceptable predictor relative to tDOC concentrations derived from remote sensing, especially in June-July. In order to give a more even weight to all of the data and to limit the skewness towards the higher tDOC concentrations, metrics based on log-transformed tDOC data were also computed. 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 RMSE could be partly due to high tDOC concentrations as suggested by the relatively low geometric RMSE (1.07). Finally, the computed 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 tDOC removal was likely underestimated in the model in late summer."

"General Text could benefit from editing for English grammar."

The English has been improved.

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

References have been 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 $a_{CDOM}(443)$ ($R^2 = 0.97, p < 0.0001$; 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 $a_{CDOM}(443)$ ($a_{CDOM}(443)$ versus salinity relationship: $R^2 = 0.95, p < 0.0001$, Fig. 5a of Matsuoka et al., 2012), the estimated relative fraction of terrestrial DOC retrieved would be ~ 0.92 , i.e. the product of $R^2 = 0.95$ (from the $a_{CDOM}(443)$ versus salinity relationship) with $R^2 = 0.97$ (from the DOC versus $a_{CDOM}(443)$ relationship). Note that a direct relationship between DOC and salinity ($R^2 = 0.89, p < 0.0001$; 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 has been added in the text in section 2.1.

We have replaced the term RDOC by tDOC (for terrigenous DOC) for more accuracy.

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1 **Towards an assessment of riverine dissolved organic carbon in surface waters of the Western**
2 **Arctic Ocean based on remote sensing and biogeochemical modeling**

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24 **Abstract**

25 Future climate warming of the Arctic could potentially enhance the load of terrigenous dissolved
26 organic carbon (tDOC) of Arctic rivers due to increased carbon mobilization within watersheds. A
27 greater flux of tDOC might impact the biogeochemical processes of the coastal Arctic Ocean (AO)
28 **and ultimately its capacity of absorbing atmospheric CO₂**. In this study, we show that sea surface
29 tDOC concentrations simulated by a physical-biogeochemical coupled model in the Canadian
30 Beaufort Sea for 2003-2011 compare favorably with estimates retrieved by satellite imagery. Our
31 results suggest that, over spring-summer, tDOC of riverine origin contributes to 35 % of primary
32 production and that an equivalent of ~10 % of tDOC is exported westwards with **the** potential for
33 fueling the biological production of the eastern Alaskan nearshore waters. **The combination of**
34 **model and satellite data provide promising results to extend this work to the entire AO so as to**
35 **quantify, in conjunction with in-situ data, the expected changes in tDOC fluxes and their potential**
36 **impact on the AO biogeochemistry at basin scale.**

37

38 **1. Introduction**

39 The Arctic Ocean (AO) receives ~10% of the global freshwater discharge (Opsahl et al., 1999 and
40 references therein) of which the larger part (~54-64 %) originates from six main pan-Arctic rivers
41 (Haine et al., 2015; Holmes et al., 2012; Aagaard and Carmack, 1989). Over the past 30 years, the
42 Arctic freshwater cycle intensified as reflected by changes in snow cover (Bring et al., 2016),
43 evapotranspiration from terrestrial vegetation (Bring et al., 2016), and precipitation (Vihma et al.,
44 2016). It resulted into an increase of the freshwater discharge from North American and Eurasian
45 rivers by ~2.6 % and ~3.1 % per decade, respectively (Holmes et al., 2015). More than half the soil
46 organic carbon stock on Earth is contained in the permafrost of the Arctic watersheds (Tarnocai et
47 al., 2009). With the warming of the lower atmosphere, the permafrost undergoes a substantial
48 thawing (Romanovsky et al., 2010) likely to alter the organic carbon content and quality of inland
49 waters. In the past decades, the flux of dissolved organic carbon (DOC) decreased in the Yukon
50 River (40 %; Striegl et al., 2005) while it increased at the Mackenzie River mouth (~39 %; Tank et
51 al., 2016). These contrasting responses to climate change suggest that the direction of future trends
52 of DOC concentrations and fluxes to the AO are very uncertain (Abbott et al., 2016).

53 The coastal AO influenced by large river plumes is hence exposed to changing conditions. Coastal
54 waters are supplied in riverine organic carbon all year round with a maximal flux in spring-early
55 summer when the freshwater discharge reaches a seasonal maximum. In river waters, DOC is
56 present in higher concentration than the particulate form (Le Fouest et al., 2013; Dittmar et al.,
57 2003). It accounts for more ~82 % of the flux of total riverine organic carbon (McGuire et al., 2009).
58 The pan-Arctic flux of riverine DOC to the AO is estimated to 33-37.7 TgC yr⁻¹ (Holmes et al.,
59 2012; Manizza et al., 2009; McGuire et al., 2009; Raymond et al., 2007). As the organic carbon
60 formed by phytoplankton, terrigenous DOC (tDOC) can be considered as new carbon fueling
61 annually the upper AO. To that respect, and regardless of its distinct nature and fate, the flux of
62 riverine DOC would be equivalent to 10-19 % of the AO primary production (Stein and Macdonald,
63 2004; Bélanger et al., 2013). In the oligotrophic Beaufort Sea, this proportion would reach ~34 % (S.

64 Bélanger, pers. comm.). Riverine DOC is hence a significant pool in the Arctic carbon cycle that
65 can markedly modify the biological production and biogeochemistry of the AO waters. Within the
66 pelagic food web, riverine DOC can be assimilated and transformed, promoting both phytoplankton
67 and bacterioplankton production (Le Fouest et al., 2015; Tank et al., 2012). Riverine DOC can also
68 modulate the air-sea fluxes of CO₂. In present climatic conditions, Manizza et al. (2011) suggest
69 that the mineralization of riverine DOC into dissolved inorganic carbon would induce a 10 %
70 decrease of the net oceanic CO₂ uptake at the pan-Arctic scale. In East Siberian shelves, the
71 degradation of terrestrial organic carbon would be partly responsible for the sea surface
72 acidification (Semiletov et al., 2016).

73 In recent studies, riverine DOC flux data were used in a 3D ocean-biogeochemical coupled model
74 to investigate the fate of riverine DOC within surface Arctic waters (Le Fouest et al., 2015; Manizza
75 et al., 2013, 2011, 2009). However, simulated spatial and temporal changes in riverine DOC
76 concentrations have not yet been compared with remote sensing data to assess the model predictive
77 ability. Such a model-satellite comparison allows validating the model and then using it with
78 confidence to resolve the annual cycle of riverine DOC, a prerequisite for a robust assessment of the
79 riverine DOC contribution to the Arctic carbon cycle. To this end, riverine DOC concentrations at
80 the sea surface obtained from a previous model run described in Le Fouest et al. (2015) and tDOC
81 concentrations derived from remote sensing data were analyzed for the Canadian Beaufort Sea. As
82 riverine DOC accounts for more than 99 % of the total tDOC exported to the AO (McGuire et al.,
83 2009), we will use the term tDOC for both the model and remotely sensed data. Our goals are to
84 compare tDOC data derived from the model and from remote sensing using skill metrics, to assess
85 the model capacity to reproduce the observed seasonal and spatial variability in tDOC, and to
86 provide bulk estimates of the seasonal tDOC stock and lateral fluxes within the surface coastal
87 waters using a combination of these two approaches.

88 The paper is organized as follows. First, we describe the two different approaches used to quantify
89 tDOC within the AO, i.e. a semi-analytical method based on remote sensing and a regional ocean-

90 biogeochemical coupled model that includes explicit fluxes of riverine DOC to the AO. Second, we
91 compare the distribution and export flux of tDOC within surface waters of the Beaufort Sea
92 estimated by the model and remote sensing. Finally, we discuss future developments of
93 biogeochemical models necessary to simulate successfully the carbon budget of Arctic coastal
94 waters in a warming world.

95

96 **2. Material and methods**

97 **2.1 Remote sensing data**

98 Level 1A scene images acquired from the MODerate-resolution Imaging Spectroradiometer
99 (MODIS) aboard Aqua satellite were downloaded from the NASA ocean color website
100 (<https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/L1/>). After geometric correction, remote sensing
101 reflectance, $R_{rs}(\lambda)$ data at 412, 443, 488, 531, 555, and 667 nm were obtained by applying
102 atmospheric correction proposed by Wang and Shi (2009) with modifications adapted to Arctic
103 environments (Doxaran et al., 2015; Matsuoka et al., 2016). The light absorption coefficients of
104 colored dissolved organic matter at 443 nm ($a_{CDOM}(443)$) were derived from the $R_{rs}(\lambda)$ data using
105 the *gsmA* algorithm (Matsuoka et al., 2017) that optimizes the difference between satellite $R_{rs}(\lambda)$
106 and $R_{rs}(\lambda)$ calculated using parameterization of absorption and backscattering coefficients for
107 Arctic waters (Matsuoka et al., 2011, 2013). tDOC concentrations were estimated from the
108 $a_{CDOM}(443)$ data using an empirical relationship between DOC and $a_{CDOM}(443)$ established in the
109 Southern Beaufort Sea (Matsuoka et al., 2013). Since DOC concentrations estimated using ocean
110 color data are based on a highly significant DOC versus $a_{CDOM}(443)$ relationship ($R^2 = 0.97$;
111 Matsuoka et al., 2012), the DOC is considered to be of terrestrial origin. Errors of intercept, slope,
112 and $a_{CDOM}(443)$ were propagated into the in-situ (empirical) DOC versus $a_{CDOM}(443)$ relationship. It
113 resulted into a mean uncertainty of the tDOC concentration estimates of 28 % (see Appendix A2 of
114 Matsuoka et al., 2017). Scene images of tDOC concentrations were used to make monthly
115 composite images at 1 km horizontal resolution.

116

117 **2.2 3D physical-biogeochemical model data**

118 We used sea surface tDOC concentrations and ocean currents simulated over 2003-2011 by a
119 previous pan-Arctic model run (“RIV run”) whose setup is fully detailed in Le Fouest et al. (2015).
120 The pan-Arctic model data were extracted on the remote sensing geographical domain focused on
121 the southern Beaufort Sea. We provide here a brief description of the physical-biogeochemical
122 coupled model used to generate the “RIV run”. The MITgcm (MIT general circulation model)
123 ocean-sea ice model (Nguyen et al., 2011, 2009; Losch et al., 2010; Condrón et al., 2009) has a
124 variable horizontal resolution of ~18 km and covers the Arctic domain with open boundaries at
125 55°N on the Atlantic Ocean and Pacific Ocean sides. The open ocean boundaries are constrained by
126 potential temperature, salinity, flow, and sea-surface elevation derived from integrations of a global
127 configuration of the MITgcm model (Menemenlis et al., 2005). Atmospheric forcings (10 m winds,
128 2 m air temperature and humidity, and downward long and short-wave radiation) are taken from the
129 six-hourly data sets of the Japanese 25 year ReAnalysis (JRA-25) (Onogi et al., 2007). In addition
130 to precipitations, the hydrologic forcing includes a monthly climatology of freshwater discharge
131 from 10 pan-arctic watersheds (Manizza et al., 2009). Monthly mean estuarine fluxes of freshwater
132 are based on an Arctic Runoff database (Lammers et al., 2001; Shiklomanov et al., 2000). For each
133 watershed, the river discharge forcing is associated with a monthly climatology of riverine DOC
134 concentration (Manizza et al., 2009). **The total annual load of tDOC in the model is 37.7 TgC yr⁻¹. It**
135 **is consistent with previous values reported in Raymond et al. (36 TgC yr⁻¹; 2007) and Holmes et al.**
136 **(34 TgC yr⁻¹; 2012) and obtained by using load estimation models linking riverine DOC**
137 **concentrations to river discharge data.** The physical model is coupled with a 10-compartment
138 biogeochemical model (Lee et al., 2016; Le Fouest et al., 2015). The biogeochemical model
139 explicitly accounts for dissolved inorganic nutrients (nitrate and ammonium), small and large
140 phytoplankton, protozooplankton, mesozooplankton, bacterioplankton, detrital particulate and
141 dissolved organic nitrogen, and tDOC (Lee et al., 2016; Le Fouest et al., 2015). The tDOC

142 compartment couples the marine and terrestrial cycling of organic matter though tDOC recycling
 143 into inorganic nutrients by bacterioplankton. We set to 15 % the percentage of tDOC entering the
 144 model as usable by the bacterioplankton compartment. This value was estimated based on the mean
 145 yearly percentages of the total load of riverine DOC considered as biodegradable DOC for six
 146 major Arctic rivers given in Wickland et al. (2012).

147

148 **2.3 Analysis**

149 Remotely sensed and simulated tDOC data were binned for the months of June, July, August and
 150 September over the 9-year period (2003-2011) to get the best areal coverage in the satellite
 151 composites. The remotely sensed tDOC concentrations were regridded on the model horizontal grid.
 152 Skill metrics were used to compare the remotely sensed estimates of tDOC with their simulated
 153 counterparts. The metrics included the correlation coefficient (r), the unbiased root mean square
 154 error (RMSE), the Nash-Sutcliffe model efficiency index (MEF), the geometric bias, and the
 155 geometric RMSE (see Stow et al., 2009; Doney et al., 2009; Nash and Sutcliffe, 1970). The metrics
 156 are computed as follows:

157

$$r = \frac{\sum_{n=1}^N (sat_n - \overline{sat})(mod_n - \overline{mod})}{\sqrt{\sum_{n=1}^N (sat_n - \overline{sat})^2 \sum_{n=1}^N (mod_n - \overline{mod})^2}} \quad (Eq. 1)$$

$$unbiased\ RMSE = \sqrt{\frac{1}{N} \sum_{n=1}^N (mod_n - sat_n - (\overline{mod} - \overline{sat}))^2} \quad (Eq. 2)$$

$$MEF = \frac{\sum_{n=1}^N (sat_n - \overline{sat})^2 - \sum_{n=1}^N (sat_n - mod_n)^2}{\sum_{n=1}^N (sat_n - \overline{sat})^2} \quad (Eq. 3)$$

$$geometric\ bias = e^{(\overline{mod} - \overline{sat})} \quad (Eq. 4)$$

$$geometric\ RMSE = \sqrt{e^{\left(\frac{1}{N} \sum_{n=1}^N (mod_n - sat_n)^2\right)}} \quad (Eq. 5)$$

158

159 where N is the number of tDOC data, and \overline{sat} and \overline{mod} are the remotely sensed and the simulated
160 tDOC averages, respectively. Monthly fluxes of tDOC were calculated and summed along two
161 cross-shelf transects (see upper-middle panel in Fig. 1). At each grid cell, the model flux estimate
162 was computed as the product of the simulated sea surface current velocity with the simulated tDOC
163 concentration. The remote sensing flux estimate was computed as the product of the simulated sea
164 surface current velocity with the remotely sensed tDOC concentration.

165

166 3. Results and discussion

167 3.1 tDOC concentrations and distribution

168 Over the Mackenzie shelf, the plume of high-tDOC ($> 120 \text{ mmolC m}^{-3}$) had a maximal areal extent
169 in June for both the model and the satellite data (Fig. 1). This coincided with the seasonal peak of
170 river discharge in June as parameterized in the model and generally depicted by in-situ time series
171 (Yang et al., 2015). From July to September, the high-tDOC areal extent progressively decreased
172 following the seasonal pattern of riverine freshwater discharge (see Yang et al., 2015; Manizza et al.,
173 2009). This seasonal pattern was observed both in the model and satellite data. The simulated tDOC
174 concentrations were lower than in the satellite record in Mackenzie Bay and east of the Mackenzie
175 Bay, especially in June (by 44 % in average) and July (by 27 % in average). In the Beaufort and
176 Chukchi seas, first year sea ice represents a carbon flux to the ocean of $2 \times 10^{-4} \text{ TgC yr}^{-1}$ (Rachold
177 et al., 2004). This flux is 4 orders of magnitude lower than the tDOC supply from the Mackenzie
178 River specified as boundary conditions in the model (2.54 TgC yr^{-1}). Similarly, tDOC eroded from
179 permafrost stored in the North American shores would account for only $\sim 0.5\text{-}1.6 \times 10^{-4} \text{ TgC yr}^{-1}$
180 (Tanski et al., 2016; Ping et al., 2011, using a DOC:POC ratio of 1:900 as in Tanski et al., 2016) to
181 $\sim 2 \times 10^{-3} \text{ TgC yr}^{-1}$ (McGuire et al., 2009). With regard to these flux values, tDOC originating from
182 both melted sea ice and eroded permafrost, not taken into account in the model, are hence not
183 believed to explain the model-satellite discrepancies (Fig. 1). Other factors might contribute to these
184 model-satellite differences observed nearshore. First, the model does not distinguish between the

185 two main pathways of the Mackenzie River discharge entering the shallow delta zone. In June, the
186 Mackenzie Bay receives most of the fresh and turbid river water (~66 %) while the remaining ~33 %
187 spreads east of the delta in Kugmallit Bay (Davies, 1975). This pattern was particularly well
188 captured by the remotely sensed data in June-July (Fig. 1). **Second, the inner Mackenzie shelf (< 20**
189 **m depth) is bounded during winter by a thick ridged ice barrier grounded on the sea floor called**
190 **stamukhi (Macdonald et al., 1995).** The stamukhi retains the turbid river water within the inner shelf
191 in winter. When sea ice breaks up and the freshet reaches its seasonal maximum in spring, the
192 retained turbid waters spread farther within the coastal zone. Contrary to the model, the remote
193 sensing data could resolve this particular feature explaining the higher tDOC concentrations
194 observed nearshore in June (see Fig. 1). Such a pattern observed for tDOC is also reported for
195 terrigenous particulate organic matter (Doxaran et al., 2015). **Further offshore on the Mackenzie**
196 **shelf, as delimited by the 300 m isobaths both remotely sensed and simulated concentrations of**
197 **tDOC were within the range of values measured in spring (~110-230 mmolC m⁻³; Osburn et al.,**
198 **2009) and summer (~60-100 mmolC m⁻³; Para et al., 2014).** Overall, the model and the satellite data
199 captured the seasonal cycle and spatial distribution of tDOC concentrations in the study area.

200 Skill metrics were computed over the whole study area (see Fig. 1) to provide a quantitative
201 comparison of tDOC simulated with the model and satellite data (Table 1). For all months, the
202 correlation coefficient was relatively high ($0.78 < r < 0.82$) within the range of values obtained for sea
203 surface dissolved inorganic nutrients simulated by global models ($r > 0.75$; Doney et al., 2009).
204 Regardless of amplitude, the r values showed that the simulated and remotely sensed tDOC
205 concentrations presented similar patterns of variation. **The size of the model-satellite discrepancies**
206 **was given by the unbiased RMSE. Overall, the unbiased RMSE decreased from June (41.4 mmolC**
207 **m⁻³) to September (29.3 mmolC m⁻³).** This result suggested that the model accuracy increased from
208 **spring to summer. The model capability for predicting tDOC relative to the average of the remote**
209 **sensing counterparts was estimated by the model efficiency index ($-\infty < \text{MEF} \leq 1$) (Nash and**

210 Sutcliffe, 1970). The MEF is a normalized statistic that relates the residual variance between the
211 simulated and remotely sensed tDOC concentrations to the variance within the remotely sensed
212 tDOC data (see Eq. 3). A MEF value near zero means that the residual variance compares to the
213 remotely sensed variance, i.e. that the model predictions are as accurate as the mean of the satellite
214 data. As the MEF increases towards a value of one, the residual variance becomes increasingly
215 lower than the observed variance. For all months, the MEF was positive (0.26-0.60) suggesting that
216 tDOC concentrations simulated by the model were an acceptable predictor relative to tDOC
217 concentrations derived from remote sensing, especially in June-July. In order to give a more even
218 weight to all of the data and to limit the skewness towards the higher tDOC concentrations, metrics
219 based on log-transformed tDOC data were also computed. For all months, the geometric RMSE was
220 close to one and span between 1.02 and 1.12. It suggested that the model-satellite data dispersion
221 was relatively small when the positive skewness was reduced. In June, the relatively high unbiased
222 RMSE could be partly due to high tDOC concentrations as suggested by the relatively low
223 geometric RMSE (1.07). Finally, the computed geometric bias informs on the direction of the
224 model-satellite discrepancies. For all months, the geometric bias (1.07-1.32) was higher than one
225 meaning that the model tended, on average, to overestimate the observations over the whole domain.
226 The highest geometric bias was reported in August (1.32), when the river discharge was low,
227 suggesting that tDOC removal was likely underestimated in the model in late summer. A Taylor
228 diagram (Taylor, 2001) was produced to provide a synthetic and complementary overview of how
229 the simulated and remotely sensed tDOC concentrations compared seasonally in terms of
230 correlation, amplitude of variations (given by the standard deviations), and normalized model-
231 satellite discrepancies (Fig. 2). All months differed by their normalized RMSE and amplitude of
232 variations while the correlation coefficient was close to ~ 0.8 (see Table 1). The model best
233 performed in simulating tDOC in July, just after the seasonal peak of river discharge, followed by
234 the months of June and August. June and August were very close months despite distinct seasonal
235 patterns of river discharge (high and low, respectively), whereas September showed the highest

236 model-satellite data dispersion. With respect to satellite estimates, the skill metrics overall
237 suggested that the model could reliably simulate tDOC concentrations in surface waters over a wide
238 range of river discharge and tDOC load.

239

240 **3.2 tDOC stock and lateral export fluxes**

241 The overall agreement between the model and the satellite tDOC concentrations allowed the
242 assessment of the mean areal stock and lateral fluxes of tDOC using the mean surface ocean
243 circulation simulated by the MITgcm (Table 2). The monthly-averaged (June to September) areal
244 stock of tDOC over the Mackenzie shelf as delimited by the 300 m isobaths was estimated to 1.37
245 TgC (Table 2). The bias between the model and the satellite data was the highest in August but did
246 not exceed +8.2 % (0.1 Tg C). This result is consistent with the highest geometric bias reported in
247 August (Table 1). In the model, the removal of tDOC through photo-oxidation (Bélanger et al.,
248 2006) was not taken into account. Assuming an annual mean mineralization rate of tDOC of ~0.02
249 TgC (Bélanger et al., 2006), this process would explain <2 % of the reported tDOC difference. In
250 the model, bacterioplankton consumed tDOC to produce ammonium usable in turn by
251 phytoplankton. In the Beaufort Sea, this pathway contributed to primary production by 35 % on
252 average over 2003-2011. However, the simulated rates of bacterioplankton production (< 30 mgC
253 m⁻² d⁻¹) still remained in the lower range of those measured in the Beaufort Sea (25-68 mgC m⁻² d⁻¹;
254 Ortega-Retertua et al., 2012; Vallières et al., 2008). The likely underestimation of the tDOC
255 removal by bacterioplankton in the model during summer months might also contribute to the
256 reported bias between the model and the satellite data. Nevertheless, the bias remained moderate
257 with respect to values reported for June, July and September (-1.5 % to -2.8 %) (Table 2).

258 Combining the modeling and remote sensing approaches allowed for the reconstruction of the
259 dominant surface pattern in lateral tDOC fluxes in the Canadian Beaufort Sea from June to
260 September (Fig. 3). Two north-south transects were defined east (Cape Bathurst) and west

261 (Mackenzie Trough) of the Mackenzie shelf (see upper-middle panel in Fig. 1). The net seasonal
262 flux was westward along the two transects following the anticyclonic circulation pattern of the
263 Beaufort gyre (Mulligan et al., 2010) and was maximum in June and September. The flux was at
264 least three times higher along the western transect near the Mackenzie Trough than east at Cape
265 Bathurst. This suggests a net export of tDOC towards the Alaskan part of the Beaufort Sea. In
266 contrast, whilst the flux in July and August remained oriented westward near the Mackenzie Trough,
267 it was reversed at Cape Bathurst. In July, the tDOC flux was still 1.3 to 1.7 times higher along the
268 western transect. In August, however, there was more tDOC (~1.4-fold) exported eastward at Cape
269 Bathurst than exported westward near the Mackenzie Trough.

270 Along the two transects, the simulated fluxes were higher than those derived from remotely sensed
271 tDOC concentrations (Fig. 3). The monthly bias between the model and the satellite flux estimates
272 varied between 0 % and +18.2 %. The bias on the seasonal net flux was moderate (+8.3 %) near the
273 Mackenzie Trough but reached +25 % at Cape Bathurst. The seasonal mean flux however was one
274 order of magnitude lower than near the Mackenzie Trough. The flux estimates suggested that,
275 despite discrepancies in tDOC concentrations, the modeling and remote sensing approaches
276 provided robust estimates of the lateral transport of tDOC in surface waters in late spring-summer.
277 Because of sea ice and cloud cover, the satellite retrieval was limited to a temporal window
278 covering a third of a year only, i.e. from June to September. The yearly mean lateral flux of tDOC
279 was computed from the simulated data along the Mackenzie Trough transect and it reached 0.31
280 TgC. The flux of tDOC cumulated over June to September along this transect (0.12-0.13 TgC)
281 represented ~42 % of this annual flux (0.31 TgC), which is consistent with the fraction of the
282 annual discharge of freshwater by the Mackenzie that occurs during spring-summer (~50 %;
283 McClelland et al., 2012). Using stable isotope techniques on pelagic particulate organic matter, Bell
284 et al. (2016) showed that OC originating from the Mackenzie outflow in summer was incorporated
285 within benthic-pelagic food webs as far as the eastern Alaskan shelf. In nearshore waters of this part
286 of the Beaufort Sea, the study of Dunton et al. (2006) using stable isotopes also suggested that

287 tDOC from the Mackenzie River could add to the local terrigenous carbon inputs mediated by
288 coastal erosion and smaller rivers to fuel the biological production in summer. Using the model and
289 satellite data, we report that an equivalent of ~10 % (0.12-0.13 TgC) of the cumulated flux of tDOC
290 delivered by the Mackenzie River over spring-summer (1.32 TgC) was exported westward in the
291 Alaskan Beaufort Sea along the Mackenzie Trough transect.

292

293 **4. Perspectives**

294 The results of our study suggest that the model is in fair agreement with the surface tDOC fields
295 remotely sensed in spring-summer when most of the riverine flux occurs. The comparison allows an
296 evaluation of the model and justifies its use to resolve the annual cycle of tDOC. Because satellite
297 imagery provides data only during spring-summer, further uncertainties still remain in the model in
298 fall-winter in terms of tDOC concentrations and spatial distribution. **In addition, the model involves**
299 **some limitations mostly due to the biogeochemical processing of tDOC, which is complex to**
300 **translate into robust mechanistic equations as highly dependent on the availability of in-situ data in**
301 **Arctic waters. For instance, the riverine tDOC compartment is split in the model into a labile and a**
302 **non-labile fraction (see Le Fouest et al., 2015). This parameterization strongly constrains the**
303 **removal of tDOC by bacterioplankton and therefore the tDOC concentrations simulated within**
304 **surface waters. In natural waters, however, tDOC is made of a complex mixture of compounds that**
305 **differ by their chemical composition and age (Mann et al., 2016) and so along the seasons**
306 **(Wickland et al., 2012, Mann et al., 2012). The chemical nature of tDOC impacts its bioavailability**
307 **estimated to average 6 % to 46 % of the total tDOC pool with marked disparities amongst the**
308 **seasons and the rivers (Mann et al., 2012). Nevertheless, the general trend for the six major Arctic**
309 **rivers (Kolyma, Yukon, Mackenzie, Ob, Yenisey and Lena) is a more labile tDOC pool in winter**
310 **than in spring and summer (Wickland et al., 2012). In the Kolyma River, Mann et al. (2012) report**
311 **a higher labile fraction in spring (~20 %) than in summer (<10 %) as the exported tDOC is younger**
312 **during the freshet. Such a pattern is, however, not clearly evidenced in the Mackenzie River (e.g.**

313 Wickland et al., 2012). We suggest that a more realistic representation in the model of the nature of
314 the organic matter entering the coastal waters including the riverine flux of both dissolved organic
315 carbon and nitrogen along with an improved C:N stoichiometry for bacterioplankton uptake (see Le
316 Fouest et al., 2015) might improve the tDOC concentrations simulated in surface AO waters.
317 In the model, the seasonal forcing of tDOC was based on DOC measurements gathered hundreds
318 kilometers upstream the rivers' mouths. This prevented any DOC enrichment of the Mackenzie
319 River water as it flows through the delta (see Emmerton et al., 2008) with, as a consequence, a
320 likely underestimation of tDOC concentrations simulated in nearshore waters. Therefore, the
321 quantification of the tDOC flux from the watersheds to the coastal AO poses as another key issue to
322 addressing the role of tDOC in the biogeochemistry of shelf waters. Recently, watersheds models
323 were developed to assess this tDOC flux (Tank et al., 2016; Kicklighter et al., 2013; Holmes et al.,
324 2012). Such models provide realistic estimates but still require improvements as watersheds
325 properties and mechanistic processes underlying the tDOC mobilization and riverine transport are
326 complex to set up (see Kicklighter et al., 2013). The remote sensing of high resolution ocean color
327 data is increasingly used to assess tDOC concentrations in large pan-Arctic rivers during the open
328 water season (Herrault et al., 2016; Griffin et al., 2011). Ocean color techniques could then prove
329 useful in the future to improve the tDOC time series set at models boundaries by accounting for
330 instance for year-to-year variations of tDOC concentrations during the freshet period.
331 In our study, the remotely sensed tDOC concentrations retrieved in shelf waters provide the
332 advantage of already integrating the effect of the watersheds processes such as mobilization,
333 transformation and transport at the seasonal and synoptic time scales. However, we acknowledge
334 that the temporal coverage of the remote sensing data is restricted to spring and summer. Because of
335 clouds and sea ice, we miss the winter season when tDOC is the most labile (e.g. Wickland et al.,
336 2012) and likely subject to remineralization. In the Mackenzie River, about 25 % of the annual load
337 of labile tDOC occurs during winter (Wickland et al., 2012). Despite this limitation, and in regard to
338 the model-satellite data comparison, the assimilation of remotely sensed tDOC data into Arctic

339 models could still offer an interesting perspective as it might result in more realistic simulated fields
340 of tDOC in spring and summer when the river discharge and tDOC export is the highest. Physical
341 and biological data have already been assimilated into Arctic predictive models to make the
342 simulated sea surface temperature, salinity, sea ice extent and thickness, and chlorophyll more
343 reliable (Simon et al., 2015; Massonnet et al., 2015). We may hence expect the assimilation of
344 remotely sensed tDOC concentrations to mitigate, at least partly, the issues linked to setting up
345 realistic tDOC forcings within predictive models. For instance, the assimilation of remotely sensed
346 tDOC data in open waters might help accounting for the interannual variations of tDOC delivered
347 by rivers, which are not resolved by the coupled model that is constrained by a monthly climatology
348 of tDOC load (see Manizza et al., 2009).

349 Improving the capability of Arctic models to resolve the fate and pathways of tDOC in the AO will
350 require certain limitations to be unlocked. To this purpose, future model developments should lie on
351 the always increasing observational effort realized by mean of field campaigns and new remote
352 sensing techniques. As a prerequisite, we can reasonably encourage improvements of the riverine
353 forcings to better encompass the seasonal to interannual variability of the terrigenous dissolved
354 organic matter exported to the coastal AO, both in qualitative and quantitative terms. We also
355 suggest bacterioplankton dynamics to be better represented in biogeochemical models. In particular,
356 the processes related to the competition for resources as dissolved organic carbon and nitrogen of
357 both allochthonous and autochthonous origin are likely to play an important role in mediating
358 bacterioplankton growth and tDOC remineralization in Arctic coastal waters impacted by river
359 plumes. Realistic fields of tDOC simulated by Arctic ocean-biogeochemical coupled models would
360 help for a more accurate assessment of CO₂ fluxes at the ocean-atmosphere interface. Arctic models
361 that would combine realistic terrestrial fluxes of organic matter along with a robust representation
362 of the pathways and processes responsible for its transformation in the AO would open an
363 interesting perspective to address the effect on the Arctic carbon cycle of ongoing and future
364 changes in the land-ocean continuum. The increase in seawater temperature of the AO due to global

365 warming (Timmermans, 2016) might promote in the future the metabolism and respiration rates of
366 marine bacterioplankton (Vaquer-Sunyer et al., 2010; Kritzberg et al., 2010). This enhanced
367 microbial activity could then liberate extra nutrients provided by the remineralization of terrigenous
368 organic matter that will then be available for primary production. This process might have an
369 impact not only on the seasonal cycle of PP in the AO but also implications for the higher levels of
370 the marine food webs of the AO, both benthic and pelagic.

371

372 **Data availability**

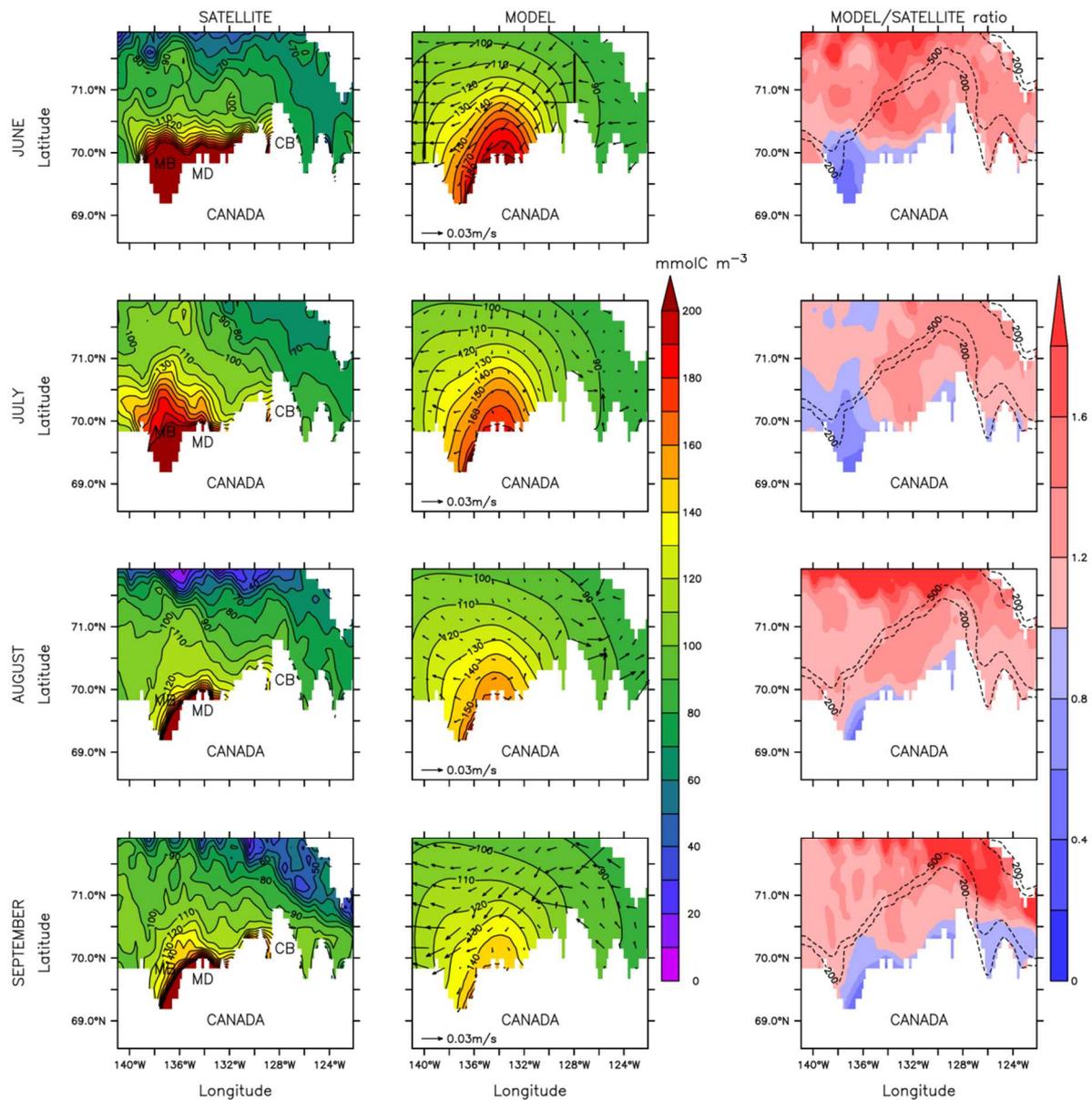
373 Data used in this study are available at [http://www.obs-lienss.cnrs.fr/Publications/BGD](http://www.obs-lienss.cnrs.fr/Publications/BGD_data_nc.tar)
374 [_data_nc.tar](#).

375

376 **Acknowledgments**

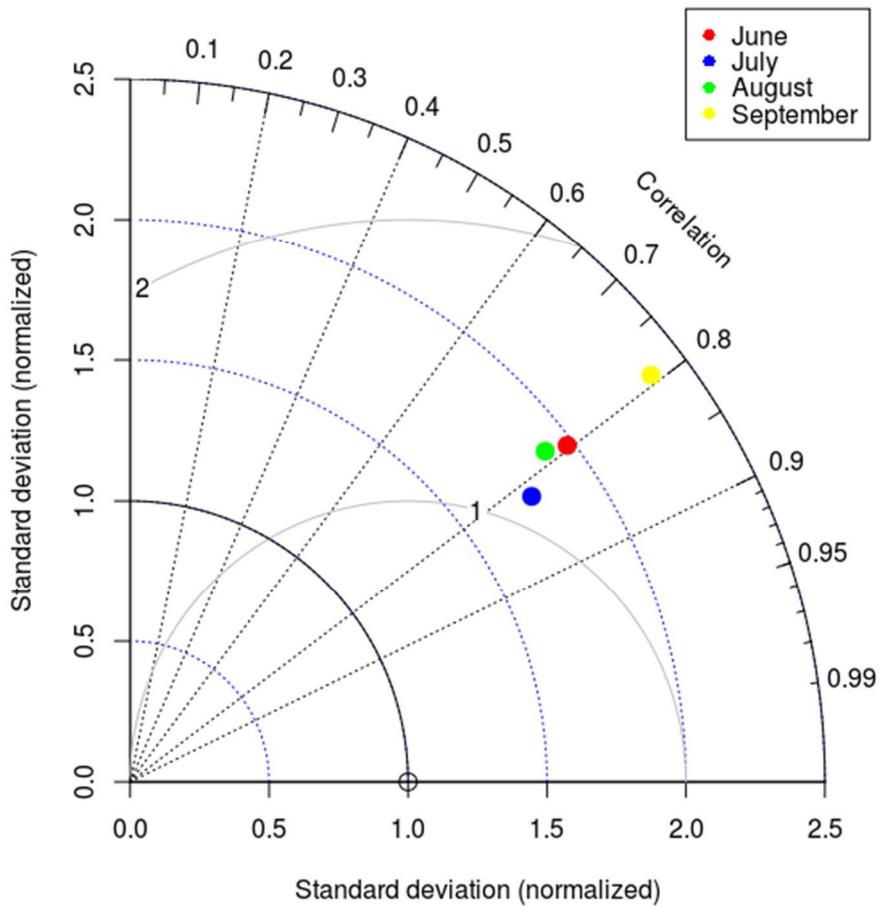
377 This research was funded by the Centre national d'études spatiales (CNES) grant #131425-BC T23
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382 thank Dimitris Menemenlis and the Estimation of Circulation and Climate of the Ocean (ECCO)
383 group from MIT for providing the physical model we used in this study

384



385

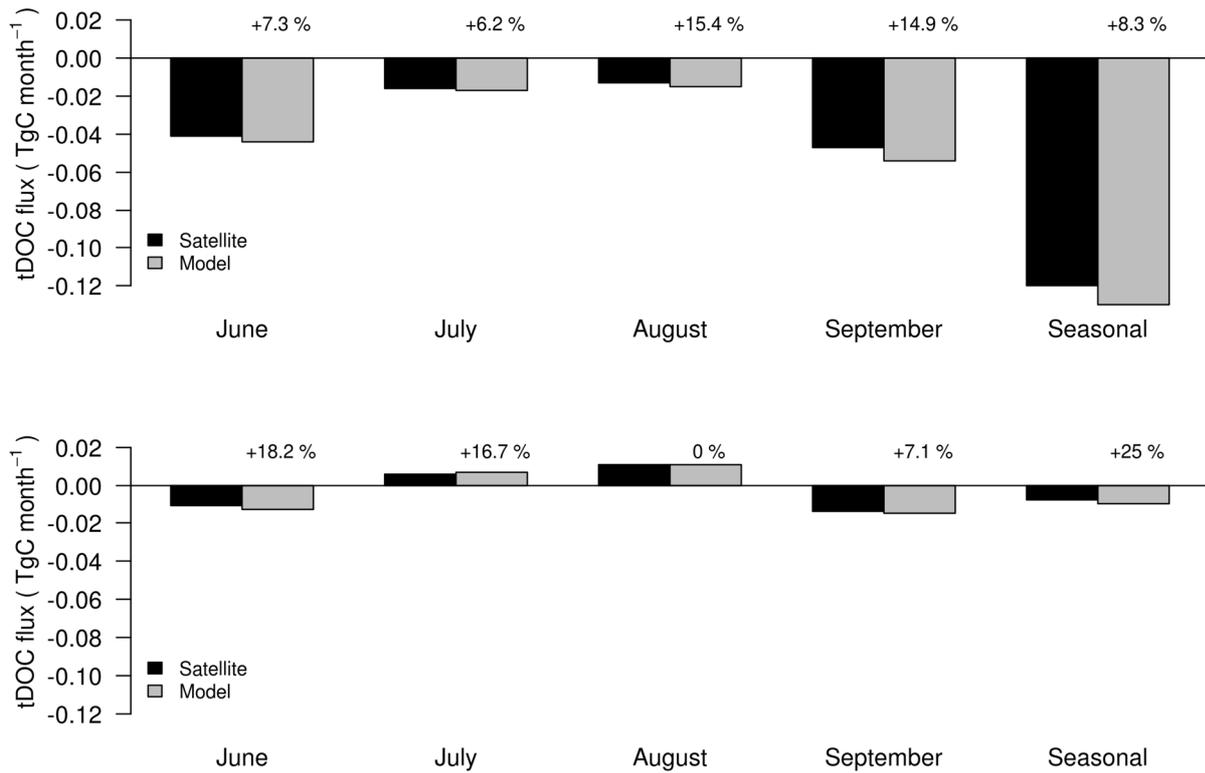
386 **Figure 1.** Monthly climatology (2003-2011) of surface tDOC concentration (mmolC m^{-3}) in the
 387 Beaufort Sea estimated from remotely sensed ocean color data (left panels) and by the
 388 biogeochemical model (middle panels) for June, July, August and September. The Mackenzie Bay
 389 (MB), Mackenzie delta (MD) and Cape Bathurst (CB) cited in the text are shown on the left panels.
 390 The isolines of tDOC concentration are overlaid (black full lines). In the middle panels, simulated
 391 surface currents (m s^{-1}) are overlaid. The two straight lines in the upper-middle panel refer to
 392 transects along which surface tDOC fluxes were computed. The right panels show the model over
 393 satellite tDOC data ratio with the 200 m and 500 m isobaths overlaid.



394

395 **Figure 2.** Taylor diagram displaying a statistical comparison between the simulated and remotely
 396 sensed tDOC concentrations. The x-axis and y-axis show the model standard deviation relative to
 397 the satellite standard deviation. The open circle on the x-axis represents the reference point. The
 398 model-satellite correlation is represented in polar coordinates (angle from the x-axis). The light grey
 399 full lines indicate the RMSE relative to the satellite standard deviation.

400



401

402 **Figure 3.** Monthly flux of surface tDOC (TgC month⁻¹) computed along transects located west of
 403 the Mackenzie Trough (139°W ; 69.5°N-71°N) (upper panel) and at Cape Bathurst (128°W ;
 404 69.5°N-71°N) (lower panel). Transects are shown in figure 1 in the upper-middle panel. Negative
 405 values indicate a westward flux. Percentages refer to the model data relative to the satellite data.

406 The seasonal flux refers to the 4-month net flux.

407

408 **Table 1.** Skill metrics of comparison computed based on the 2003-2011 monthly climatologies of
409 tDOC.

410

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

411

412

413 **Table 2.** Areal stock (TgC) of sea surface tDOC computed over the Mackenzie shelf (delimited by
414 the 300 m isobaths) from the model and satellite data. The bias (%) refers to the model data relative
415 to the satellite data. The seasonal areal stock refers to the 4-month average \pm standard deviation.

	June	July	August	September	Seasonal
Model	1.48	1.40	1.32	1.28	1.37 \pm 0.07
Satellite	1.51	1.44	1.22	1.30	1.37 \pm 0.11
Bias	-2	-2.8	+8.2	-1.5	0

416

417

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