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Geoscientific
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Discussions

Interactive comment on "ORCHIDEE MICT-LEAK (r5459), a global model for the production, transport and transformation of dissolved organic carbon from Arctic permafrost regions, Part 2: Model evaluation over the Lena River basin" *by* Simon P. K. Bowring et al.

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Dear Anonymous Reviewer #1,

Thank you for your concise, informative and constructive assessment of this paper. In what follows, we will respond first to your general comments, followed by specific comments.

Response to General Comments:

General Comment 1

This portion of the study present the results of the model evaluation in the Lena River Delta. The first result that one notices is that there are some fairly significant problems with the simulated discharge, both in the timing and the magnitude. As the authors note, there is too much spring flow and the timing is a bit off, not enough growing season/fall baseflow. Plus it seems as though the model underestimates discharge by 50-100%. This is addressed in the manuscript directly, but little analysis is given about it. The failure of the model to accurately model the annual discharge results in really substantial uncertainties in the budget for DOC exports. However, this is not at all quantified in the current analysis, which undermines any substantial conclusions on DOC export from the study. Until the issues with discharged are corrected, these numbers on DOC export and processing are most likely inaccurate. As an absolute minimum, the uncertainties resulting from the discrepancies with discharge need to be quantified.

Thank you for pointing out what is clearly an issue with interpreting model results at face value. In the first part of this two-part paper, we showed that this model development version of ORCHIDEE, ORCHIDEE MICT-LEAK, was devoted to the development and inclusion of a permafrost-specific DOC and dissolved CO2 generation, transport and evasion module to the high-latitude version (ORCHIDEE-MICT) of the land surface model ORCHIDEE. The hydrology scheme in this model version is almost entirely unchanged from that latter version (ORCHIDEE-MICT), which is itself one of two parent model versions leading to this particular model instantiation. ORCHIDEE-MICT has itself already been subjected to a lengthy evaluation paper at the Pan-Arctic scale in Geoscientific Model Development (Guimberteau et al., 2018). Indeed, the sole substantial addition to the hydrology module in this model version (ORCHIDEE MICT-LEAK) is that floodplain inundation is now represented, with some significant but not cumulatively substantial impacts on water discharge. Otherwise, this work is focused only on the production, metabolisation and transport of DOC from plant and soil matter in the Arctic. In this particular sense, our improvement of the model does not directly involve the representation of the hydrological cycle, which is itself dependent on how the surface energy balance, vegetative uptake and soil flow dynamics and, perhaps most importantly, the specific set of climatological data used as model input, are represented and read by the model, respectively. However, model output is clearly strongly impacted by these factors, both individually and in sum, and we agree that stronger quantification and explanation of the inadequacy of the hydrological module, and its effects on the DOC-generating module's results, is necessary. We also feel that a more hydrology-independent metric for model evaluation should have been used. These we address in what follows by providing further identificaiton for the factors causing low hydrological discharge, quantification of the dependency of DOC discharge error on water discharge error (DOC error (%) dependent on hydrological error), followed by summary of the remaining possible causes of error, including substantial error introduced by choice of climatological forcing dataset and, finally, introduce a new evaluation metric to evaluate DOC representation in the model that is quasi- but not fully-independent, from modelled hydrological discharge.

First, we more concretely address the causes of the model-observation mismatch in hydrological discharge, by adding the following new text to the manuscript:

"Deficiencies in modelled hydrology correspond to those found in Fig. 12 of Guimberteau et al. (2018), indicating that the modifications made in this model version, which focus on the DOC cycle, have not further degraded the hydrological performance of the model, the causes of which are described below. Low simulated discharge for the Lena basin, particularly during the late summer and autumn, is consistent with prior, Pan-Arctic simulations conducted by Guimberteau et al. (2018), who ran ORCHIDEE-MICT using both the GSWP3 and CRU-NCEP v7 datasets and evaluated them over 1981-2007. Despite the substantially better hydrological performance of ORCHIDEE under GSWP3 climate, they described a near-systematic underestima-

tion of summer/autumn discharge rates for both datasets over the Yukon, Mackenzie, Lena and Kolyma basins. Furthermore, the discrepancy of model output between climatological datasets was almost as large as the discrepancy between model output and observational data in that study, which analysed this in great depth, suggesting that the source of error is both a covariate of model process representation and parameterisation, as well as the climatological datasets themselves. Model hydrological representation and empirically derived climate input data are then subject to interaction with modelled soils (e.g. infiltration), vegetation (e.g. canopy interception) and thermodynamics (e.g. freezing and consequent partitioning of surface vs subsurface water transport) from which river discharge is computed, confounding full interpretation of sources of bias, briefly described below.

Model process deficiency in this regard was identified by Guimberteau et al. (2018) as residing in an overly restrictive representation of water impermeability through frozen topsoil, which decreases the residence time of running water by directing it to runoff rather than subsurface flow, and in the process increases the susceptibility of the total water volume to evapotranspiration from incoming shortwave radiation. This would bias both the timing (over-partitioning of water to high runoff periods) and volume of water (low bias) reaching the river stem and its eventual discharge into the ocean, respectively, as demonstrated by model output. Guimberteau et al. (2018) suggest that representation of sub-grid-scale infiltration mechanisms under frozen conditions, such as soil freezing-drying that would enhance infiltration, be included in future, yet-to-be implemented iterations of ORCHIDEE. Furthermore, we suggest that the lack of representation of lakes in ORCHIDEE, which serve to increase the time lag between precipitation/melt and oceanic discharge, may likewise be a powerful source of bias in the timing of discharge fluxes represented by the model.

Unsurprisingly, simulated surface runoff has been shown to be strongly affected by differences in precipitation between datasets (Biancamaria et al., 2009; Fekete et al., 2004), while biases in these and evapotranspiration datasets that are used to both drive and evaluate the hydrological models, are a powerful source of water balance biases in high-latitude basins (Wang et al., 2015). Indeed, climatological dataset estimates for the spatial distribution of high latitude winter snowfall are generally problematic, owing to the low density of meteorological stations (Burke et al., 2013), wind-related issues with in-field collection and measurement that lead to systematic underestimates of snowfall rates (Yang et al., 2005), creating biases in the climatological datasets that only show up when the integrator of their model input -in this case river discharge - is modelled. In addition, the wintertime partitioning of precipitation between rain and snow, a function of 2m air temperatures in the forcing datasets, strongly affects the volume and timing of runoff (Guimberteau et al., 2018; Haddeland et al., 2011). Indeed, 69% of the spatial variance of the spring freshet has been attributed to snow water-equivalent bias during the pre-melt season (Rawlins et al., 2007). In addition, errors in forcing of soil evaporation due to inaccuracies in incoming shortwave radiation, as well as biases in the parameterisation of canopy interception -a function of simulated LAI -can lead to upward biases in evapotranspiration rates (Guimberteau et al., 2018)."

The subsequent evaluation subsection then begins as follows:

"4.2.2 Model Evaluation: DOC Annual Discharge

Modelled aggregate DOC discharge is strongly affected by the underestimation of river water discharge."

This is done to clarify that DOC discharge is indeed strongly contingent on water discharge.

Next, we compare how (obs. vs. model) DOC discharge differential (%) compares to the (obs. vs. model) river discharge differential. Then by applying the regression slope of the relationship between DOC and river discharge to the mean river discharge discrepancy of 36%, we find that 84% of the differential between observed and simulated DOC discharge can be explained by the underperformance of the hydrology module. We then go through the various other modelled modules (NPP, radiative balance, etc.)

that can affect how end-result hydrological outflows, with this largely new text:

"The observed vs. simulated mean annual water discharge differential hovers at 36% (Figs. 3d, 4c), close to the 43% differential between observed and simulated DOC discharge, giving some indication that, given the linear relationship between water and DOC discharge, most of the DOC discrepancy can be explained by the performance of the hydrology and not the DOC module, the latter of which was the subject of developments added in ORCHIDEE M-L. Applying the regression slope of the relationship in Fig. 3d (9E-06 mgC per m3s-1) to the mean river discharge discrepancy of 36%, we find that 84% of the differential between observed and simulated discharge can be explained by the underperformance of the hydrology module.

Further sources of error are process exclusion and representation/forcing limitations. Indeed, separate test runs carried out using a different set of climatological input forcing show that changing from the GSWP3 input dataset to bias-corrected projected output from the IPSL Earth System Model under the second Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b (Frieler et al., 2017; Lange, 2016, 2018)) increases DOC discharge to the ocean to 4.14 TgC yr-1 (+37%), largely due to somewhat higher precipitation rates in that forcing dataset (see Table S3). Thus, the choice of input dataset itself introduces a significant degree of uncertainty to model output.

In addition, this model does not include explicit peatland formation and related dynamics, which is the subject of further model developments (Qiu et al., 2018) yet to be included in this iteration. With peatlands thought to cover ∼17% of the Arctic land surface (Tarnocai et al., 2009), and with substantially higher leaching concentrations, this may be a significant omission from our model. The remaining biases likely arise from errors in the interaction of simulated NPP, respiration and DOC production and decomposition, which will impact on the net in and out -flow of dissolved carbon to the fluvial system. However, the DOC relationship with these variables is less clear-cut than with river discharge. Indeed, regressions (Fig. 3e) of annual DOC versus NPP (TgC yr-1) show that DOC is highly sensitive to increases in NPP, but is less coupled to it (more scattered, R2=0.42) than other simulated fluvial carbon variables shown, CO2 evasion and soil CO2 export. Thus low biases in simulated NPP can potentially strongly or weakly influence DOC export production. The differences in correlation and slope of the variables in Fig. 3e are expected: CO2 evasion is least sensitive yet most tightly coupled to NPP (R2=0.52), while CO2 export is intermediate between the two for both (R2=0.43) –CO2 export is the intermediate state between DOC export and CO2 evasion. The greater correlation (R2) with NPP of DOC compared to evasion is understandable, given that DOC leaching is a covariate of both GPP and runoff, whereas evasion flux is largely dependent on organic inputs (production) and temperature (see Part 1). "

Finally, we evaluate the seasonal DOC discharge in terms of DOC concentration, which was not done in the first draft of this manuscript. The reasoning for this is that DOC concentrations are less dependent on hydrological discharge than bulk DOC fluxes, and thus offer a clearer means by which to evaluate the DOC module as a standalone product. This evaluation shows that indeed, DOC concentrations are reasonably well represented compared to observations for the majority of the year's bulk DOC discharge, but underestimates concentrations during wintertime. The latter deficiency is consistent with the observation from Guimberteau et al. (2018) that the model poorly simulates wintertime subsurface water flow in the soil, which, by exaggerating the soil vertical impermeability of permafrost, greatly reduces the amount of DOC leachate that can be transferred to the (warmer) subsoil and laterally transferred into the river. Thus we add the following subsection to the manuscript:

"While total DOC discharge captures the integral of processes leading to fluvial biogeochemical outflow, simulations of this are highly sensitive to the performance of modelled hydrology and climatological input data. A more precise measure for the performance of the newly-introduced DOC production and transport module, that is less sensitive to reproduction of river water discharge, is DOC concentration. This is because while the total amount of DOC entering river water depends on the amount of water available

as a vehicle for this flux (hydrology), the concentration of DOC depends on the rate of soil carbon leaching, itself depending largely on the interaction of soil biogeochemistry with primary production and climatic factors. This we evaluate in Figure 5a, This shows that for the majority of the thaw period or growing season (April-September), which corresponds to the period during which over 90% of DOC production and transport occurs, the model largely tracks the observed seasonality of DOC concentrations in Arctic-GRO data averaged over 1999-2007. There is a large overestimate of the DOC concentration in May owing to inaccuracies in simulating the onset of the thaw period, while the months June-September underestimate concentrations by an average of 18%. On the other hand, frozen period (November-April) DOC concentrations are underestimated by between ∼30-500%. This is due to deficiencies in representing wintertime soil hydrological water flow in the model, which impedes water flow when the soil is frozen, as discussed in Section 4.2.1. Because of this deficiency, slow-moving groundwater flows that contain large amounts of DOC leachate are under-represented. This interpretation is supported by the fact that in both observations and simulations, at low discharge rates (corresponding to wintertime), DOC concentrations exhibit a strong positive correlation with river discharge, while this relationship becomes insignificant at higher levels of river discharge (Fig. 5b). Thus wintertime DOC concentrations suffer from the same deficiencies in model representation as those for water discharge. In other words, the standalone representation of DOC leaching is satisfactory, while when it is sensitive to river discharge, it suffers from the same shortfalls identified in Section 4.2.1 and 4.2.2."

The accompanying figures to this text are shown below:

General Comment 2:

The manuscript text in this model evaluation section is quite long and a bit disorganized. It could really use a major re-working to streamline and refine the points.

We agree that the manuscript lacked some concision and could have been shortened.

On the other hand, both reviewers asked for some additional material to be added into the introduction, evaluation and interpretation segments of the manuscript. As such, the manuscript has been entirely edited to account for these shortcomings. In doing so, we have focussed on text readability, reducing repetition and simplifying the nature of the text itself, substantially reducing the length of the original text body. The number of textual changes are too numerous and in some cases too lengthy to enumerate piecemeal here, so we ask that you refer to the 'track-changes' version of the new manuscript draft to evaluate these changes directly. In addition, we have moved one entire subsection (Evaluation of NPP and Soil Respiration) from the main body to the Supplement (Text S2), given that this has already been evaluated, albeit at a larger scale, in Guimberteau et al. (2018) and given that its evaluation here detracts somewhat from the central foci of our manuscript.

General Comment 3:

Throughout the main text & supplement: Maps all require lat/long labels (grid labels). lat/long grids necessary. Really hard to read with blue background; can't tell the watershed outline, can't differentiate terrestrial vs. Arctic Ocean.

Thank you for spotting this issue of legibility in the manuscript. All maps have been revised as follows: (i) lon/lat labels have been introduced and increased in their font size. (ii) The terrestrial continental boundary has been included in all maps in red, with inland water body boundaries given in grey. (iii) A spatial mask has been applied to in shaded blue or grey, as shown in the following figure examples.

Response to Specific Comments:

33: continuing the numbered list doesn't seem to make sense Thank you for noticing this unnecessary notation. This has been corrected.

91: check figure order The figure order has now been totally revised.

125: does is make sense to call the transient model the control? We feel it makes sense

to call the transient the control with respect to what are factorial model 'experiments' (CO2/CLIM) that hold one or another controlling climatological factor constant. We feel that for more general readership, this makes reading and understanding the results less burdensome and linguistically technocratic.

813: I don't think Svalbard has forests Thank you for spotting this. Indeed, the relevant study refers only shrubs and other small primary producers on Svalbard, and is therefore not representative of much of the vegetation overlying the Lena river basin. Reflecting this, we have removed this reference in its entirety from the text.

834-843: doesn't fit in this section Thank you for spotting this inconsistency. This has been moved to section 4.2.2 (lines 539-550) as part of the interpretation of DOC discharge dependence on NPP.

Figure 2: what do the CO2 numbers at the top mean? These refer to the fact that the carbon release from these sources or processes in model output is in gaseous form, in this case CO2. On the other hand, as noted in the figure caption, all values for carbon flux are carbon-equivalent (C) in units of Tg yr-1.

Fig. 3: too much snowmelt, too little baseflow. We assume you refer to Figure 3c, and indeed this observation is correct. We have identified, and tried to describe and explain in greater depth this part of the model output in this second draft of the manuscript (please see response to General Comment 1).

Fig 4a: legend order confusing, figure isn't super useful. Thank you for taking the time to note this. We have removed the 'total organic carbon' range from the original figure to streamline the number of sources used in this diagram. On the other hand, the general relevance of this diagram is, we feel justified, for a number of reasons. First, it lays out the modelled discharge of DOC over the 20th Century, both annually and for an annualised 30 year running mean, to show that the model outputs a long-term and unequivocal increase in DOC discharge from the Lena river over the 20th Century. This is of interest since there are no DOC discharge observations spanning this length of time, or, indeed the length of time necessary to construct a long-term observational trendline. Secondly, on the same diagram we include the average of the last ten years of simulated DOC discharge (horizontal lines) and also mark empirical estimates of the same quantity from various empirical studies within that approximate timeframe. The reasons for this are that (i) We can benchmark the trendline mentioned against any potential systematic 'gap' in observed versus simulated DOC discharge, which we show in the manuscript is indeed a systematic one derived from errors in the hydrological module. This would imply that even if modelled absolute values are inaccurate relative to observations, the trendline might still reflect a real tendency over the 20th Century. (ii) We discuss the difference in observational estimates and, despite coming to the conclusion that the latest estimates are likely the most accurate, include them all in the diagram to illustrate that the empirical numbers are at the end of the day also estimates.

Fig 4d: extra dotted lines are confusing Thank you for this observation. We agree that the diagram is not necessarily the easiest to follow, as is often the case for dual-axis figures, but it is our opinion that directly comparing the modelled and observed DOC and CO2 seasonality is useful for interpreting how and whether these two variables evolve and/or co-evolve over the course of the year. For this reason we don't feel that separating these two variables is in the interest of the manuscript.

Fig 5. Doesn't contain much new info, what does p-1 mean? We agree that this is perhaps not the most interesting facet of the model output, and have moved the figure to the Supplement (Fig. S2). The (p-1) is carried over from the 'p'eriod used as a temporal unit in Kutscher et al. (2017) from whom this figure is directly derived. The unit explained in the accompanying figure caption, by the sentence: "Map adapted from Fig. 2 in Kutscher et al. (2017) showing proportional sub-basin contributions of TOC outflow to total TOC discharge in June and July (designated as their sampling period 'p-1') of 2012-2013, as observed in Kutscher et al., 2017 (black arrows)".

Fig 8: units of per pixel make not much sense. This has been changed to units of

mgC m-2d-1, and to increase readability, we have removed one of the sub-figures (floodplains) from the diagram.

Table S1: is it Tootchi et al., 2018 or Tootchi et al., 2019? Text says one, Table says another.

Thank you for your diligence, this error has been corrected.

Please also note the supplement to this comment:
https://www.geosci-model-dev-discuss.net/gmd-2018-322/gmd-2018-322-AC2-supplement.pdf

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Interactive comment on Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-322, 2019.

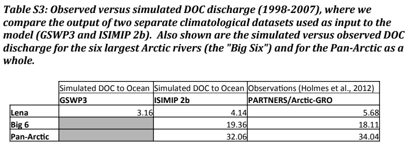

Table S3: Observed versus simulated DOC discharge (1998-2007), where we compare the output of two separate climatological datasets used as input to the model (GSWP3 and ISIMIP 2b). Also shown are the simulated versus observed DOC discharge for the six largest Arctic rivers (the "Big Six") and for the Pan-Arctic as a whole.

	Simulated DOC to Ocean	Simulated DOC to Ocean	Observations (Holmes et al., 2012)
	GSWP3	**ISIMIP 2b**	**PARTNERS/Arctic-GRO**
Lena	3.16	4.14	5.68
Big 6	▨	19.36	18.11
Pan-Arctic	▨	32.06	34.04

Fig. 1.

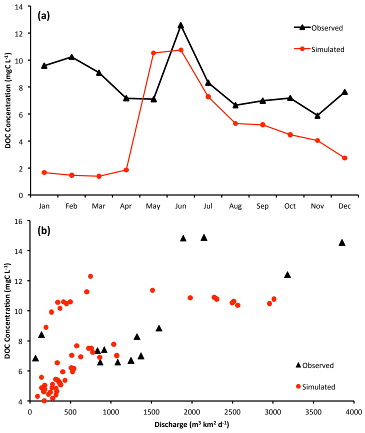

Figure 5: (a) Simulated and observed (Arctic-GRO/Holmes et al., 2012) DOC concentration seasonality for the Lena basin over the period 1999-2007. (b) Plots of DOC concentration versus river discharge as in observations (Raymond et al., 2007) and simulations, where simulations data points are monthly averages taken over the period 1999-2007

Fig. 2.

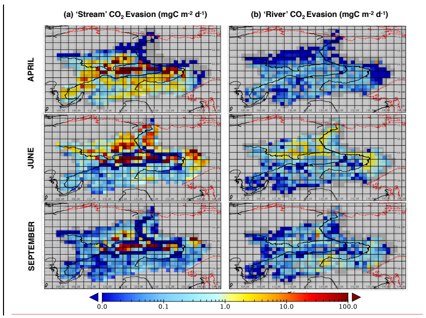

Figure 8: Maps of CO$_2$ evasion from the surface of the two fluvial hydrological pools in the model, (a) streams and (b) rivers in April, June and September. All maps use the same (log) scale in units of (mgC m^{-2} d^{-1}).

Fig. 3.

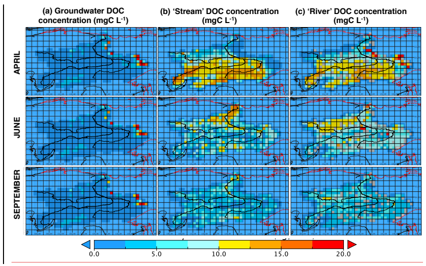

Figure 6: Maps of **(a)** DOC concentrations (mgC L^{-1}) in groundwater ('slow' water pool), **(b)** stream water pool, **(c)** river water pool in April, June and September (first to third rows, respectively), averaged over the period 1998-2007. The coastal boundary and a water body overlay have been applied to the graphic in red and black, respectively, and the same scale applies to all diagrams. All maps have the Lena basin area shaded in the background.

Fig. 4.

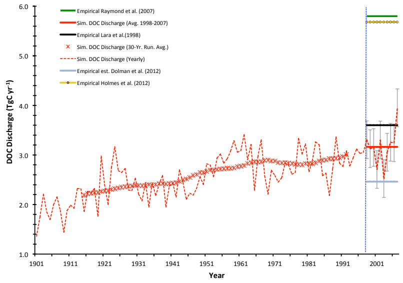
Empirical Raymond et al. (2007)
Sim. DOC Discharge (Avg. 1998-2007)
Empirical Lara et al.(1998)
Sim. DOC Discharge (30-Yr. Run. Avg.)
Sim. DOC Discharge (Yearly)
Empirical est. Dolman et al. (2012)
Empirical Holmes et al. (2012)
DOC Discharge (TgC yr-1)
6.0
5.0
4.0
3.0
2.0
1.0
1901
1911
1921
1931
1941
1951
1961
1971
1981
1991
2001
Year

Fig. 5.