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Geoscientific
Model Development
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 #2,

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

In this manuscript, using the ORCHIDEE MICT-LEAK described by the first part in accompanying paper, the authors assessed production, concentration, CO2 evasion, and riverine transport of dissolved organic carbon (DOC) over the Lena River Basin. They conducted long-term simulations and made attempts to factor out driving factors in DOC change in the study area. The research topic is potentially interesting in terms of large-scale carbon budget, land-ocean linkage, and carbon-climate interactions. For example, the long-term increase of DOC discharge (e.g., Fig. 4a) looks intriguing, because this can affect biogeochemistry in the Arctic Ocean. On the other hand, I have two major concerns on this manuscript. First, the simulated results were compared only with several literature data: e.g., Raymond et al. (2007), Kutscher et al. (2017), and Denfeld et al. (2013). The comparisons were not adequately quantitative, and so I could not figure out whether the model well captured observations. The low performance in simulating river discharge may indicate that the model hydrology should be improved before conducting DOC-related analyses.

Thank you for your kind words. Here, we respond to your points sequentially.

We understand your concern regarding the relatively small number of studies referred to for quantitative evaluation of model output. However, the fact remains that there are very few observational studies specific to the Lena River basin whose sampling scale at both spatial and temporal level are adequate for diagnosing output from a global-scale land surface model. Indeed, this can be indirectly inferred from the fact that even observed annual DOC discharge, which might in other world regions be considered a relatively straightforward, first order diagnostic, carries estimates whose values differ by a factor of over two. It is for this reason that we have, for this metric for example, chosen to include empirical estimates from six different studies, if only to illustrate that only one or two of these are likely to most closely approximate real-world DOC discharge (e.g. Raymond et al. 2007, Holmes et al. 2012). Likewise, as we point out in the manuscript, for some variables there simply do not exist observational estimates at any scale. This is true for example for river surface CO2 evasion from the Lena river, for which we had to resort to measurements from the Kolyma river for evaluation, or groundwater-sourced hydrological discharge. We reiterate that many studies that have been carried out over the Lena basin have an inadequate spatial or temporal sampling resolution for our scale of evaluation, which is that of the basin. In this sense, we are of the opinion that we have largely covered the spectrum of the relevant and appropriate observational literature, summarised in the new Supplementary table below, in evaluating ORCHIDEE M-L. In addition, we have added one more evaluation source for CO2 evasion from the Ob river in Western Siberia, for comparison, as is now included in the following text:

"Likewise, mean annual evasion rates of <0.8 up to around 7 gC m-2 d-1 have been found for the Ob and Pur rivers in Western Siberia (Serikova et al., 2018)."

Thank you for pointing out what is clearly an issue with interpreting model results at face value. Note to the Editor: The remainder of this response to General Comment 1 can be found in the Response to Reviewer #1, and is repeated verbatim in the following paragraphs. 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 underestimation 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 input from bias-corrected projections from the IPSL Earth System Model under the second Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b (Frieler et al., 2017; Lange, 2016, 2018)) protocol 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 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

Second, the model simulations were conducted at a spatial resolution of 1 degree (about 100 km), but it looks too coarse to capture the spatial heterogeneity in this region. As the authors stated (Line 535), the model could not include small streams

because of the coarse-scale river-routing scheme.

Thank you for noting this poorly explained portion of the original text, which has also been rewritten for Part 1 of this study. The smaller order streams of Strahler orders 1-3 are actually implicitly represented, although their surface area is not calculated by the model. To be clear, this is the overland flow of water calculated at the sub-grid scale, such that the movement from one quadrant of a grid cell to another quadrant of that same cell is represented by the 'fast' (or 'stream' as referred to in the manuscript) hydrological pool, which is then aggregated to the whole grid cell. We explain this in the following additional text:

"As noted in Part 1 of this study, although the model as a whole conducts simulations at the 1 degree scale, the routing of water and carbon, as well as the evasion of the latter, occurs at the sub-grid scale, such that we are able to simulate spatially explicit rivers whose size approximates Strahler order 4, and through the 'fast' water pool in the model are able to simulate streams of Strahler order 1-3. "

General Comment 3

The manuscript provides numerous figures and text is a bit lengthy. In contrast, Simulation Rationale and Setup sections are brief and I felt inadequate. Data for comparison were described in Results and Discussion sections (e.g., Line 365–368, Line 615–621). I recommend moving these data descriptions to a section in Methods and Data. Therefore, the manuscript can be largely truncated and should be thoroughly reorganized.

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. Figure 5 has now been moved to the Supplement (now Fig. S2), while Fig. 8 has been truncated by removing one of the evasion map suites (floodplains) to increase the size and readability of the overall image.

The observational data compared, as addressed already in our Response to General Comment 1, is now summarised in Table S2 of the Supplement. In addition, we have substantially expanded segments of the Introduction/Methods/Data sections, to provide greater description and context to model functioning and the input data used. We have also included a Figure directly drawn from Part 1 of this study (the model's carbon module schematic), to provide greater understanding to the reader for how the model functions (See Fig. S1) Descriptive changes in this vein are summarised in the following additional texts:

"In essence, photosynthetically fixed plant carbon is transformed by microbial degradation to DOC and CO2; the DOC is itself either respired to CO2 or adsorbed, or exchanged with particulate soil carbon. DOC can then be transferred by precipitation-dependent water flow laterally across the terrestrial landmass, in surface or subsurface flows to streams and rivers, whereupon it may either be respired within the water column or exported to the marine realm. A flow diagram depicting these flows and the residence times of the respective carbon pools, reproduced from Part 1 of this study, is given in Figure S1a,b."

"Climatological forcing is input from the Global Soil Wetness Project Phase 3 (GSWP3) v.0 data, based on 20th Century reanalysis using the NCEP land-atmosphere model

and downscaled to a 0.5°, 3-hourly resolution covering the period 1901 to 2007 (Supplement, Table S1). This is then upscaled to 1° resolution and interpolated to a 30 minute timestep to comply with the timestep of ORCHIDEE's surface water and energy balance calculation period. Precipitation was partitioned into rainfall and snowfall, and a correction for wind-induced undercatch was applied separately. These are described in greater detail in Guimberteau et al. (2018) Over the simulation period under this climatological forcing dataset, the Lena basin experiences a mean thaw period warming of 1.8°C, while atmospheric CO2 concentrations increase by 85.6ppm. The GSWP3 dataset was chosen for its prior suitability as input its relative performance in simulating the interannual variability and seasonality of Pan-Arctic riverine discharge in ORCHIDEE-MICT (Guimberteau et al., 2018), as compared to another data-driven climate forcing product, CRUNCEP v7 (Kalnay et al., 1996; New et al., 1999).. Indeed, under CRUNCEP v7, ORCHIDEE-MICT was shown to underestimate river discharge by as much as 83% over the Yukon basin. An improved floodplains area input file for the Lena basin (Tootchi et al., 2019) was used to drive the simulation of floodplain dynamics (Supplement, Table S1). The model structure is described in Part 1 of this study, however we describe how the fluxes are generated with respect to the results obtained by this study in some detail in the initial description of the results, below (Section 4.1). "

"Simulations were run over the Lena river basin (Fig. 3a) for the climate, CO2 and vegetation input forcing data (Supplement, Table S1) over 1901-2007 at a 1 degree resolution (Fig. 1), to evaluate the simulated output of relevant carbon fluxes and hydrologic variables against their observed values, as well as those of emergent phenomena arising from their interplay (Fig. 1). We evaluate at the basin scale because the isolation of a single geographic unit allows for a more refined analysis of simulated variables than doing the same over the global Pan-Arctic, much of which remains poorly accounted for in empirical databases and literature. The literature studies used in this evaluation are summarised in Table S2. "

Response to Specific Comments:

Specific Comments:

Specific Comment 1:

Line 45–46: In main text, no part discussed about ‘1.8_C warming’ and ‘+85.6 ppm CO2 rise’. Why did you mention these values in Abstract?

Indeed, thank you for spotting this omission. These have now been included in the main text body (’Simulation Rationale’) with the following text:

"Over the simulation period under this climatological forcing dataset, the Lena basin experiences a mean thaw period warming of 1.8°C, while atmospheric CO2 concentrations increase by 85.6ppm."

Specific Comment 2:

Line 81: Did you examine the accuracy of GSWP3 in the study region? Especially for precipitation, some climate datasets may have serious biases.

When using historical data -generated climatological datasets (as opposed to those generated by climate models), it has been shown by Guimberteau et al. (2018) that for the Pan-Arctic in general and for the Lena in particular, GSWP-3 already performs substantially better than the CRU-NCEP dataset (a widely used climatological data suite) with respect to timing and magnitude of simulated hydrological discharge. Our own decadal-scale preliminary test runs using the ’Princeton’ (PGMF) dataset comes to the same conclusion, that GSWP3 results in comparatively better simulated river discharge. Thus there may indeed be some precipitation bias in the input datasets. As noted in the response to General Comment 2, we have also compared the modelled hydrographs when using GSWP3 and ISIMIP2b (see Table S2), which gives a substantial rise in both river and DOC discharge in the latter compared to GSWP3. We did not choose to run with the ISIMIP dataset because it is itself model-generated, while for the land surface model as a whole, we feel it is preferable to make use of the existing

historically-generated data.

Specific Comment 3:

Linen 580: Remove (g C m–2 d–1).

This has now been removed.

Specific Comment 4:

Line 787: Why did you discuss about NPP and soil respiration of Siberian forests in this position of the manuscript? I lost context here.

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.

Specific Comment 5:

Line 869: As long as I know, a version of ORCHIDEE (e.g., Naipal et al., 2018, Biogeosciences, 15, 4459–4480) includes POC erosion module.

It is correct that Naipal et al. (2018) introduced an erosion emulator to the default version of ORCHIDEE. However, as is the case with many such model developments that are made roughly simultaneously, the erosion module is not yet compatible with the high latitude version of ORCHIDEE, and thus the DOC module here is neither compatible with the erosion module. Of course in principle this should be addressed immediately for a more ’complete’ model, however in practice such code merges are extremely time-consuming and thus beyond the temporal scope of this evaluation paper.

Specific Comment 6:

Line 924: The ratio of DOC export relative to NPP, _1.5%, would be an important result but does not appears in Abstract

These have now been included in the Abstract with the following text:

"Riverine DOC exports total ∼1.5% of NPP, and of the ∼34TgC yr-1 left over as input to terrestrial and aquatic systems after NPP is diminished by heterotrophic respiration....."

Please also note the supplement to this comment:
https://www.geosci-model-dev-discuss.net/gmd-2018-322/gmd-2018-322-AC1-supplement.pdf

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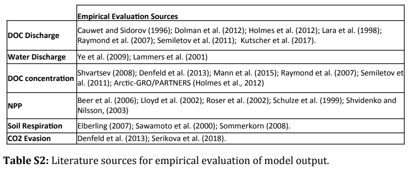
Interactive comment on Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-322, 2019.

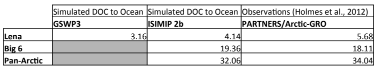


	Empirical Evaluation Sources
DOC Discharge	Cauwet and Sidorov (1996); Dolman et al. (2012); Holmes et al. (2012); Lara et al. (1998); Raymond et al. (2007); Semiletov et al. (2011); Kutscher et al. (2017).
Water Discharge	Ye et al. (2009); Lammers et al. (2001)
DOC concentration	Shvartsev (2008); Denfeld et al. (2013); Mann et al. (2015); Raymond et al. (2007); Semiletov et al. (2011); Arctic-GRO/PARTNERS (Holmes et al., 2012)
NPP	Beer et al. (2006); Lloyd et al. (2002); Roser et al. (2002); Schulze et al. (1999); Shvidenko and Nilsson, (2003)
Soil Respiration	Elberling (2007); Sawamoto et al. (2000); Sommerkorn (2008).
CO2 Evasion	Denfeld et al. (2013); Serikova et al. (2018).

Table S2: Literature sources for empirical evaluation of model output.

Fig. 1.

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. 2.

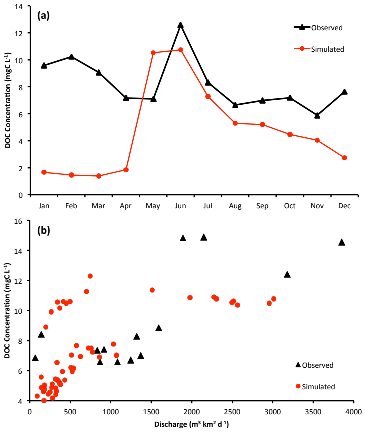


Figure 5: (a) Simulated and observed (Arctic-GRO/Holmes et al., 2012) DOC concentration seasonality for the Lena basin over the period 1999-2007. (b) Plots of DOC concentration versus river discharge as in observations (Raymond et al., 2007) and simulations, where simulations data points are monthly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

Fig. 3.