Biogeosciences, 15, 6867–6884, 2018
https://doi.org/10.5194/bg-15-6867-2018

Biogeosciences Open Access EGU

Riverine particulate C and N generated at the permafrost thaw front: case study of western Siberian rivers across a 1700 km latitudinal transect

Ivan V. Krickov[1], **Artem G. Lim**[1], **Rinat M. Manasypov**[1,2], **Sergey V. Loiko**[1], **Liudmila S. Shirokova**[2,3], **Sergey N. Kirpotin**[1], **Jan Karlsson**[4], **and Oleg S. Pokrovsky**[3]

[1]BIO-GEO-CLIM Laboratory, Tomsk State University, Lenina av., 36, Tomsk, Russia
[2]N. Laverov Federal Center for Integrated Arctic Research, Russian Academy of Sciences, 23 Naberezhnaya Severnoi Dviny, 163000, Arkhangelsk, Russia
[3]GET UMR 5563 CNRS, University of Toulouse, 14 Avenue Edouard Belin, 31400 Toulouse, France
[4]Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå University, 901 87 Umeå, Sweden

Correspondence: Oleg S. Pokrovsky (oleg.pokrovsky@get.omp.eu)

Received: 24 May 2018 – Discussion started: 25 June 2018
Revised: 12 October 2018 – Accepted: 29 October 2018 – Published: 19 November 2018

Abstract. In contrast to numerous studies on the dynamics of dissolved (< 0.45 µm) elements in permafrost-affected high-latitude rivers, very little is known of the behavior of river suspended (> 0.45 µm) matter (RSM) in these regions. In order to test the effect of climate, permafrost and physio-geographical landscape parameters (bogs, forest and lake coverage of the watershed) on RSM and particulate C, N and P concentrations in river water, we sampled 33 small and medium-sized rivers (10–100 000 km^2 watershed) along a 1700 km N–S transect including both permafrost-affected and permafrost-free zones of the Western Siberian Lowland (WSL). The concentrations of C and N in RSM decreased with the increase in river watershed size, illustrating (i) the importance of organic debris in small rivers which drain peatlands and (ii) the role of mineral matter from bank abrasion in larger rivers. The presence of lakes in the watershed increased C and N but decreased P concentrations in the RSM. The C : N ratio in the RSM reflected the source from the deep soil horizon rather than surface soil horizon, similar to that of other Arctic rivers. This suggests the export of peat and mineral particles through suprapermafrost flow occurring at the base of the active layer. There was a maximum of both particulate C and N concentrations and export fluxes at the beginning of permafrost appearance, in the sporadic and discontinuous zone (62–64° N). This presumably reflected the organic matter mobilization from newly thawed organic horizons in soils at the active latitudinal thawing front. The results suggest that a northward shift of permafrost boundaries and an increase in active layer thickness may increase particulate C and N export by WSL rivers to the Arctic Ocean by a factor of 2, while P export may remain unchanged. In contrast, within a long-term climate warming scenario, the disappearance of permafrost in the north, the drainage of lakes and transformation of bogs to forest may decrease C and N concentrations in RSM by 2 to 3 times.

1 Introduction

High-latitude rivers are most vulnerable to ongoing climate change via altering their hydrological regime (Bring et al., 2016) and widespread permafrost thaw that stimulates nutrient release (Vonk et al., 2015). For carbon (C), the particulate fraction (POC) contributes substantially to the total organic C export from the continent to the ocean (Schlesinger and Melack, 1981; Lal, 2003; Ludwig and Probst, 1996; Galy et al., 2015; Li et al., 2017; Coppola et al., 2018); a 2-fold increase of Arctic rivers POC fluxes by 2100 is predicted (Gordeev and Kravchishina, 2009). Although the reasons for strong variations of POC in freshwater are not yet fully understood (Tian et al., 2015; Lee et al., 2016; Yang et al., 2016), the temperature (Hilton, 2017) and runoff (Goñi et al., 2013) combined with local storm events (Jeong et al., 2012; Wiegner et al., 2009) are widely recognized as the most important driving factors. This may be especially true for northern aquatic systems, being highly sensitive to flood events, due to shallow water paths and a short transit time in watersheds.

Of special interest to POC of the Arctic rivers is that, if soil organic C escapes degradation during river transport and is thus buried in marine sediments, it can contribute to a geological carbon dioxide sink (e.g., Hilton et al., 2015). Further, the potentially increased transport of P and N may significantly change primary productivity in riverine ecosystems (Wrona et al., 2016; McClelland et al., 2007), thereby impeding the rigorous predictions of climate change's impact on Arctic terrestrial–aquatic ecosystems. Despite significant efforts in characterizing the fluxes, chemistry and origin of particulate organic matter (POM) in large Arctic rivers (Lobbes et al., 2000; Dittmar and Kattner, 2003; Unger et al., 2005; Guo et al., 2004; Guo and Macdonald, 2006; Gladyshev et al., 2015; Emmerton et al., 2008; McClelland et al., 2016; Gareis and Lesack, 2017), these studies do not allow for the assessment of mechanisms of POM generation in the watershed. In particular, the role of the size of the river watershed and its landscape (physio-geographical) parameters are still poorly known. Thus, although detailed studies of particulate nutrients in small Arctic rivers helped to constrain seasonal features of export fluxes (Cai et al., 2008; Dornblaser and Striegl, 2007; Lamoureux and Lafreniére, 2014; McClelland et al., 2014), the key driving environmental factors of particulate nutrient concentration and stoichiometry in Arctic rivers – permafrost coverage and lakes and forest proportion in the watershed – remain poorly resolved.

In this regard, large continental plains such as the Western Siberian Lowland (WSL), which contains sizeable reservoirs of frozen and thawed organic carbon, N, P and inorganic nutrients (Sheng et al., 2004; Stepanova et al., 2015; Raudina et al., 2017), may be especially useful in assessing environmental control on particulate nutrient transport to the Arctic Ocean. A vast amount of frozen peat in this region can strongly affect the coastal Arctic system in the event of permafrost thaw and enhanced export of river suspended matter (RSM) from the watersheds. Due to the high homogeneity of the WSL landscape, lithology and topography, one can use the natural north–south gradient of the permafrost zone distribution to assess the direct impact of permafrost conditions on river water chemistry.

Detailed studies of the dissolved fraction of WSL river waters demonstrated several typical features occurring over a sizeable gradient of climate and permafrost. In pioneering works of Frey and co-authors it was shown that southern permafrost-free regions export 3 to 4 times greater amounts of dissolved C, N and P (Frey and Smith, 2005; Frey et al., 2007a, b; Frey and McClelland, 2009), and that wetlands exert a significant positive effect on carbon and nutrient concentrations in small rivers (Frey et al., 2007a; Frey and McClelland, 2009). Although the majority of these features were confirmed by a more recent study of dissolved carbon and nutrients in WSL rivers over main hydrological seasons (Pokrovsky et al., 2015 and Vorobyev et al., 2017, respectively), an assessment of particulate load transport in WSL rivers has not yet been performed, and the mechanisms controlling particulate C, N and P mobilization from WSL soils to the Arctic Ocean remain unknown.

To improve the current understanding of the magnitude and seasonality of riverine particulate nutrient exports, we quantified concentrations of C and macronutrients (N, P) across a vast latitudinal gradient (1700 km), with a special emphasis on the permafrost-bearing zone during three main hydrological regimes: (1) the peak of spring flood (early June 2016), (2) the summer base flow (August 2016) and (3) the autumn high flow before the ice (October 2016). We aimed to characterize the effect of latitude, permafrost coverage and fundamental landscape features (proportion of bogs, lakes and forest in the watershed) as well as the size of the river itself on particulate C, N and P concentrations and the relative fraction of particulate nutrient transport versus total (particulate + dissolved) nutrient transport. We further used acquired knowledge to infer the mechanisms of particulate nutrient mobilization from soils to rivers and applied these mechanisms to predict change in particulate nutrient concentrations under climate warming, landscape evolution and progressive permafrost thaw in the largest frozen peatland province in the world.

2 Study site and methods

The rivers were sampled in the WSL, a huge (> 2 million km^2) peatland and forest zone situated in the taiga forest, forest-tundra and tundra zone. The position of biomes follows the decrease of mean annual air temperature (MAAT) from −0.5 °C in the south to −9.5 °C in the north (Trofimova and Balybina, 2014). The annual precipitation increases from 550 mm at the latitude of Tomsk to 650–700 mm at Noyabrsk and further decreases to 600 mm at the lower reaches of the Taz River. The annual river runoff gradually increases northward, from 160–220 mm yr^{-1} in the permafrost-free region to 280–320 mm yr^{-1} in the Pur and Taz river basins located in the discontinuous-to-continuous permafrost zone (Nikitin and Zemtsov, 1986). The permafrost distribution also follows the latitudinal gradient of MAAT and changes from absent, isolated and sporadic in the south to discontinuous and continuous in the north (Baulin et al., 1967). The peat has actively formed since the beginning of the Holocene until the freezing of bogs in the Sub-Boreal period (4500–9000 BP). After that, the rate of peat formation in bog areas decreased (Peregon et al., 2007; Batuev, 2012). The main mineral substrates underlying the frozen peat layers of the WSL are quaternary clays, sands and siltstone (Klinova et al., 2012;

Nazarov, 2007). The mineral substrates are quite similar across the WSL and were subjected to the strong influence of aeolian processes in the beginning of the Holocene (Velichko et al., 2011). The vegetation of polygonal, mound and ridge-hollow bogs is essentially oligotrophic and dominated by dwarf shrubs, lichens and mosses. The forest of southern part of the WSL is dominated by Siberian fir, Siberian spruce, Siberian pine, Scots pine, birch and small-leafed linden. Further details of WSL physio-geographical settings, peat and a lithological description of the territory are provided elsewhere (Kremenetski et al., 2003; Stepanova et al., 2015; Pokrovsky et al., 2015; Raudina et al., 2017). For each biome (taiga, forest tundra and tundra) several rivers with different watershed sizes were chosen, and the sampling campaign was performed along a latitudinal transect following previous strategies for the WSL river-dissolved load (Pokrovsky et al., 2015, 2016; Vorobyev et al., 2017).

Altogether, we sampled 33 rivers that belong to the watersheds of Ob, Pur and Taz, including these large rivers as well (Fig. 1). The landscape parameters of sampled catchment were determined by digitizing available soil, vegetation, lithological and geocryological maps (Table S1 in the Supplement and Vorobyev et al., 2017). There was no covariation between river size and other landscape parameters including permafrost coverage. Sampling was performed during three main hydrological seasons: (1) spring flood (17 May–15 June 2016), (2) summer baseflow (1–29 August 2016) and (3) autumn baseflow before ice (24 September–13 October 2016). Note that the most interesting period – in terms of soil connection to the rivers – occurred in late autumn, when the active layer depth was at its maximum. This period has not been covered in previous studies of dissolved WSL river load. The reason for sampling in both the summer and autumn period is to test the role of connectivity between soil fluids and the rivers. In fact, the main factor controlling elemental behavior during accelerating permafrost thaw and release of dissolved and particulate C and nutrients to surrounding aquatic landscapes is the connectivity between soils and rivers or lakes, which occurs via water and solute transport along the permafrost table ("suprapermafrost flow"). The suprapermafrost (shallow subsurface) water occurs in the active layer, typically at the border between the thawed and frozen part of the soil profile (Woo, 2012). In the frozen peat bogs of WSL, the active (unfrozen) layer thickness (ALT) is maximal at the end of unfrozen season, which is typically from the end of September to the beginning of October (Raudina et al., 2018).

The sampling strategy consisted of moving from south to north in spring and autumn over a period of 2–3 weeks, following the natural change of seasons. This allowed us to sample all rivers of the transect at approximately the same time after the ice melted and before they froze. The year 2016 was normal for western Siberia in terms of spring, summer and autumn precipitation, but the temperature was 4 and 2.7 °C higher than normal spring and summer, respectively, and was not different from the average T in autumn (Rosgidromet, 2017). For assessing inter-annual variations in RSM concentrations, we analyzed the RSM samples collected in WSL rivers across the same transect during a previous campaign in the spring of 2014 and 2015 and the summer and autumn of 2014 and 2015.

Large water samples were collected from the middle of the river at 0.5 m depth in pre-cleaned polypropylene jars (30 to 50 L) and were allowed to decant over 2–3 days. The water of the bottom layer of the barrels (approx. 30 % of the initial volume) was centrifuged on-site for 20 min at 3500 rpm using 50 mL Nalgene tubes; sediment was frozen at −18 °C and freeze-dried later in the laboratory. In addition to decantation and centrifugation, RSM was collected via direct filtration of large volumes (20 to 30 L) of river water with an Inox (AISI 304) Teflon® PTFE-coated filtration unit (Fisher Bioblock) equipped with 142 mm acetate cellulose Sartorius membranes (0.45 µm) and operated at 5–7 bar. An average flow rate of 1–2 $L\,h^{-1}$ was created by a peristaltic pump (MasterFlex B/T) with Teflon tubing. For determination of total concentration of suspended material, smaller volumes of freshly collected river water (1–2 L) were filtered on-site (at the river bank or in the boat) with pre-weighted acetate cellulose filters (47 mm, 0.45 µm) and Nalgene 250 mL polystyrene filtration units using a Mityvac® manual vacuum pump.

There was reasonably good agreement, typically within 10 %, between the concentration of RSM collected in large barrels via decantation followed by centrifugation, a direct high-pressure filtration using 142 mm membranes and vacuum filtration using Nalgene 250 mL unit. The agreement was better than ±10 % for large rivers in summer and autumn, when the mineral component dominated the RSM. The difference between two methods was between 10 % and 20 % for small organic-rich rivers containing peat and plant debris, especially in spring.

The C and N concentrations in RSM collected from a large-volume separation procedure was measured using catalytic combustion with CuO at 900 °C, with an uncertainty of ≤ 0.5 % using Thermo Flash 2000 CN Analyzer at Tomsk University. The samples were analyzed before and after 1 : 1 HCl treatment to distinguish between total and inorganic C; however the ratio of $C_{\mathrm{organic}} : C_{\mathrm{carbonate}}$ in RSM was always above 20, and the contribution of carbonate C to total C in the RSM was equal on average 0.3 ± 0.3 % (2 SD, $n = 30$). In addition to RSM, we compared total and HCl-treated C analysis in the peat soil column (organic part and 3 separate mineral horizons) sampled from the middle part of river transect. The $C_{\mathrm{carbonate}}$ share was below 2 % of total C content for both the mineral and organic part of soil columns. The analyses we performed could not distinguish mineral N linked to clays (NH_4^+ cation) and organic N in the RSM. For P, the RSM samples were subjected to full acid leaching in a clean room following ICP-MS (Agilent 7500 ce) analyses using methods for C_{org}-rich natural samples described by

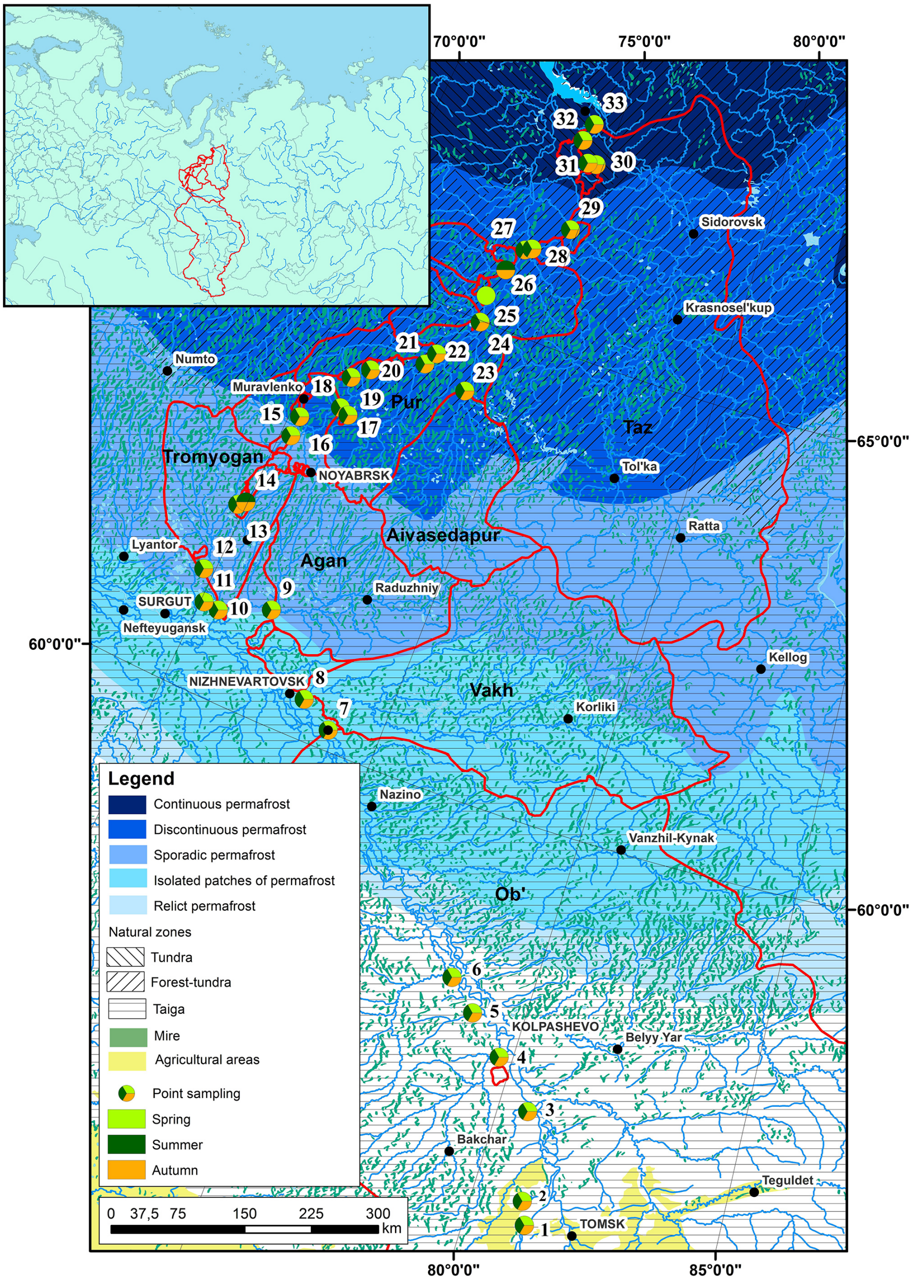

Figure 1. Sampling sites and physio-geographical context of WSL territory investigated in this work. The sampling numbers are explained in Table S1.

Stepanova et al. (2015). Water samples for dissolved organic carbon (DOC) and total dissolved phosphorus (P_{tot}) were filtered on-site through 0.45 µm acetate cellulose filters (Millipore, Sartorius) and analyzed following methods previously described by Pokrovsky et al. (2015, 2016).

A regression analysis was used to quantify the relationship between C, N and P concentrations in RSM and the % of permafrost, wetlands, lake and forest coverage of the watershed as well as the surface area of the watershed ($S_{watershed}$). In order to assess a general impact of the permafrost on RSM nutrient concentrations, we separated all sampled rivers into five categories according to the permafrost distribution on their watersheds: (1) permafrost-free (south of 61° N), (2) isolated (61 to 63.5° N), (3) sporadic (63.5 to 65° N), (4) discontinuous (65 to 66° N) and (5) continuous permafrost zones (north of 66° N). The non-parametric statistics were used, because, based on Shapiro–Wilk test of the normality of variables, the data on C, N and P concentrations in RSM and the % of element in suspended form were not normally distributed. For these reasons, we used the median,

Table 1. Mean (±SD) values of RSM, C, N and P concentrations (mass %) and relative proportion of suspended over total (suspended + dissolved) C and P for five permafrost zones and three seasons across the WSL transect.

Season	Variable	Permafrost				
		Absent	Isolated	Sporadic	Discontinuous	Continuous
Spring	RSM, $mg\,L^{-1}$	6.2 ± 4.9	4.9 ± 1.5	7.2 ± 3.0	7.7 ± 2.5	10.2 ± 4.9
	C, %	12.7 ± 13.0	17.5 ± 6.5	21 ± 14	7.4 ± 8.5	3.6 ± 3.2
	N, %	1.4 ± 1.5	1.3 ± 0.8	1.8 ± 1.8	0.6 ± 0.7	0.3 ± 0.3
	P, %	0.32 ± 0.28	0.33 ± 0.26	0.30 ± 0.25	0.11 ± 0.004	0.21 ± 0.18
	% C_{RSM} of total C	3.5 ± 2.4	8.4 ± 6.7	13.2 ± 7.9	4.9 ± 5.0	3.1 ± 2.2
	% P_{RSM} of total P	30.0 ± 21.5	59.2 ± 18.7	55.6 ± 21.9	40.2 ± 36.2	44.5 ± 30.4
Summer	RSM, $mg\,L^{-1}$	10.0 ± 4.6	7.5 ± 2.9	10.2 ± 3.7	5.8 ± 1.5	3.6 ± 2.5
	C, %	10.7 ± 4.6	24.7 ± 8.9	20.0 ± 6.0	12.6 ± 5.9	13.5 ± 2.1
	N, %	0.9 ± 0.3	1.9 ± 0.6	1.6 ± 0.7	1.2 ± 0.6	1.2 ± 0.2
	P, %	0.86 ± 0.68	0.39 ± 0.34	0.45 ± 0.27	0.48 ± 0.46	0.72 ± 0.34
	% C_{RSM} of total C	10.7 ± 10.1	15.6 ± 4.4	21.0 ± 4.2	12.2 ± 5.3	5.6 ± 3.0
	% P_{RSM} of total P	57.0 ± 25.2	53.5 ± 21.8	67.9 ± 17.8	55.1 ± 28.7	32.6 ± 18.7
Autumn	RSM, $mg\,L^{-1}$	3.4 ± 2.4	5.1 ± 1.4	8.7 ± 3.3	10.7 ± 2.6	8.9 ± 3.4
	C, %	11.0 ± 6.0	25.7 ± 8.0	17.4 ± 6.5	13.6 ± 6.9	7.3 ± 3.5
	N, %	0.9 ± 0.5	1.7 ± 0.4	1.2 ± 0.5	1.1 ± 0.5	0.7 ± 0.4
	P, %	0.93 ± 0.64	0.33 ± 0.15	0.57 ± 0.21	0.70 ± 0.45	0.30 ± 0.21
	% C_{RSM} of total C	4.35 ± 3.9	12.4 ± 4.8	17.2 ± 7.5	18.9 ± 11.4	4.8 ± 2.8
	% P_{RSM} of total P	42.8 ± 32.7	71.9 ± 9.9	82.8 ± 11.4	76.9 ± 14.0	40.8 ± 8.6

first and third quartiles to trace the dependence of nutrient concentration on the type of permafrost distribution. The differences in suspended C, N and P concentrations between different seasons and between each two adjacent permafrost zones were tested using a Mann–Whitney U test for a paired data set with a significance level of 0.05. For unpaired data, a non-parametric H criterion Kruskal–Wallis test was performed for all watershed sizes and all permafrost zones.

3 Results

3.1 C, N and P concentrations in RSM and their link to seasons and watershed size

Mean bulk RSM concentration in the WSL river waters did not depend on the season of open-water period of the year and was equal to 7.1 ± 3.9, 8.1 ± 4.1 and $7.0 \pm 3.7\,mg\,L^{-1}$ in spring, summer and autumn, respectively (Table 1). The RSM concentrations weakly depended on the size of the watersheds ($S_{watershed}$) with a negative relationship in autumn ($R^2 = 0.33$, $p < 0.05$; Fig. S1a in the Supplement). Further, the RSM concentrations increased with permafrost coverage and latitude ($R^2 = 0.56$ and 0.41), although this was visible only in autumn (Fig. S1b, c; Table S2). The sporadic permafrost zone exhibited the highest RSM concentration in summer (Fig. S1d). Finally, there was no correlation ($p > 0.05$) between lake, bog or forest coverage and the RSM concentrations ($R^2 < 0.2$; see also Table S2). For RSM concentrations, statistically significant differences between different permafrost zones, notably between permafrost-free and permafrost-bearing regions, were evidenced in summer and autumn using the Kruskal–Wallis and Mann–Whitney tests (Table S3).

The concentrations of C, N and P in WSL rivers averaged over three seasons were equal to 15.3±9.7 %, 1.2±0.9 % and 0.49 ± 0.42 % in mass of RSM (1.05 ± 0.805, 0.083 ± 0.066 and $0.035 \pm 0.036\,mg\,L^{-1}$ in the river water). The watershed size sizably affected the C concentration; there was a power-law decrease of C with the size of watershed ($R^2 = 0.28$, 0.47 and 0.25 in spring, summer and autumn, respectively Fig. 2a), but there was no relationship with the N and P concentrations in RSM ($R^2 < 0.2$, Fig. 2b, c). Generally, a 2- to 3-fold decrease in C_{org}, from ca. 20 %–30 % in rivers with $S_{watershed} < 100\,km^2$ to $C_{org} = 5$ %–10 % in rivers with $S_{watershed} > 10\,000\,km^2$ was observed. The C : N ratio of RSM was independent of the watershed size in spring but decreased 2–3 times with an increase in $S_{watershed}$ ($R^2 = 0.4$) in summer and autumn (Fig. 2d).

The inter-annual variations of suspended nutrient concentration in WSL rivers were of secondary order importance when compared to season and watershed size control. We did not find any inter-annual differences (at $p < 0.05$) in RSM concentrations and P concentrations in RSM collected in June and August in 2014, 2015, and 2016 for the same eight rivers (Agan, Tromyogan, Pyakupur, Ayvasedapur, Purpe, Yamsovey, Pur and Taz; Table S1).

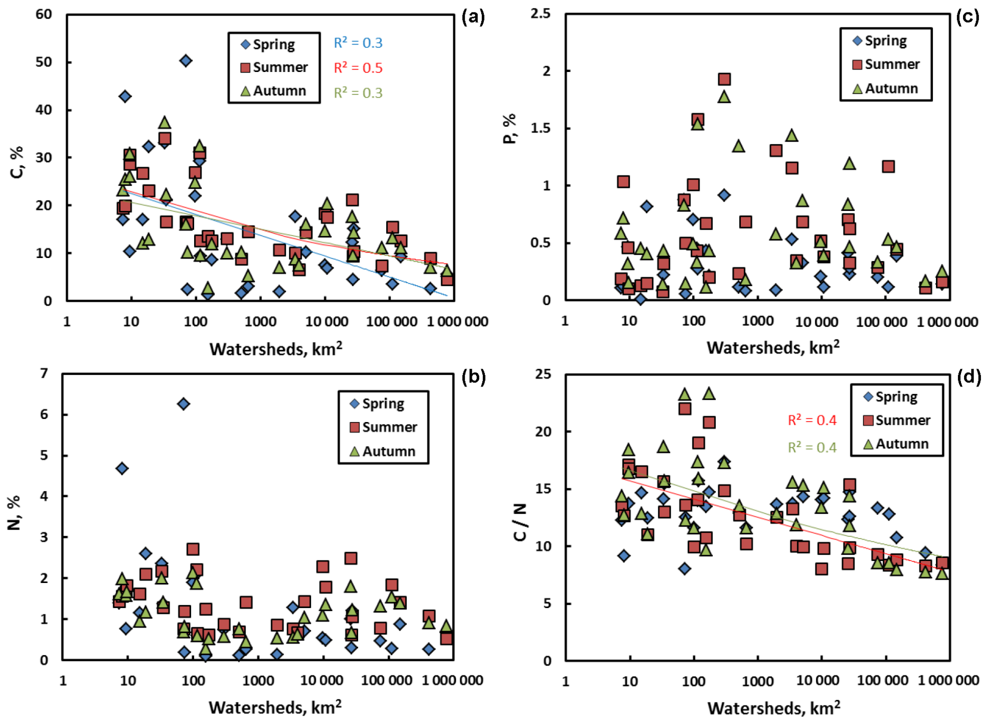

Figure 2. Particulate (> 0.45 µm) C **(a)**, N **(b)** and P **(c)** concentrations in the RSM (%), and C : N ratio **(d)** in RSM as a function of river watershed size. The solid lines represent a power-law fitting of the data with regression coefficients shown for each season in corresponding panels. Only the curves with $R^2 > 0.3$ are depicted.

3.2 Role of permafrost distribution and landscape parameters for C, N and P concentrations and fraction of particulate nutrients

There was a local maximum of C and N concentrations in isolated and sporadic permafrost zone (Fig. 3a, b, d, e), which was not seen for P (Fig. 4c, f). Overall, the differences in C and N concentrations in RSM among different permafrost zones were significant, as verified by the non-parametric Kruskal–Wallis H test ($0.005 < p < 0.05$), while the difference in P concentrations between permafrost zones was not significant ($p > 0.05$, see Table S3c, d). Specifically, the C demonstrated a maximum concentration (significant at $p < 0.02$ during all three seasons) at 62–64° N (Fig. S2a). The latitude did not impact N and P concentrations in RSM per se (Fig. S2b, c). However, significant differences between adjacent permafrost zones were evidenced by C and N in summer and autumn (Table S3d).

The landscape parameters of the watershed (bogs, lakes and forest coverage) sizably affected ($p < 0.05$) suspended C and N. Bogs and lakes in the watershed increased the concentrations of C and N in RSM, whereas forest generally decreased C in RSM (Fig. 4a–c for C, and Fig. S3a–c for N). This increase in C and N (%) with bog and lake coverage and a decrease in forest presence was mostly visible in summer and autumn. The increase in lake coverage of the watershed led to a decrease in P concentrations in RSM in summer and autumn ($R^2 = 0.31$ and 0.22, respectively; Fig. S3d-e-f) that was especially visible in autumn in the permafrost-free zone ($R = -0.88$; Table S2). During this period, the P concentrations in RSM positively correlated with the presence of forest in the permafrost zone ($R = 0.60$; Table S2).

The Mann–Whitney U test for the impact of watershed parameters demonstrated significant differences in C and N concentrations (all seasons) and P concentrations (summer baseflow) between watersheds having < 10 % and > 10 % lake coverage (see Table S3e). The differences were also observed among watersheds with < 50 % and > 50 % of bogs for C (all seasons) and N (summer and autumn; Table S3f). Finally, the forest coverage (< 30 % and > 30 %) exhibited a significant effect on C and N (all seasons) and P (autumn baseflow; see Table S3g).

The share of particulate carbon versus total carbon (dissolved + particulate C) did not demonstrate any significant dependence on $S_{\text{watershed}}$, bogs, forest and permafrost proportions on the watershed ($R^2 < 0.3$, not shown). However, there was a localized maximum of the particulate carbon fraction around 64° N within the isolated-to-sporadic permafrost zone (Fig. 5a and c). The presence of lakes sizably increased the particulate over total transport of C in rivers ($R^2 = 0.52$ and 0.32 in spring and summer, respectively, Fig. 5b). The share of particulate phosphorus versus total

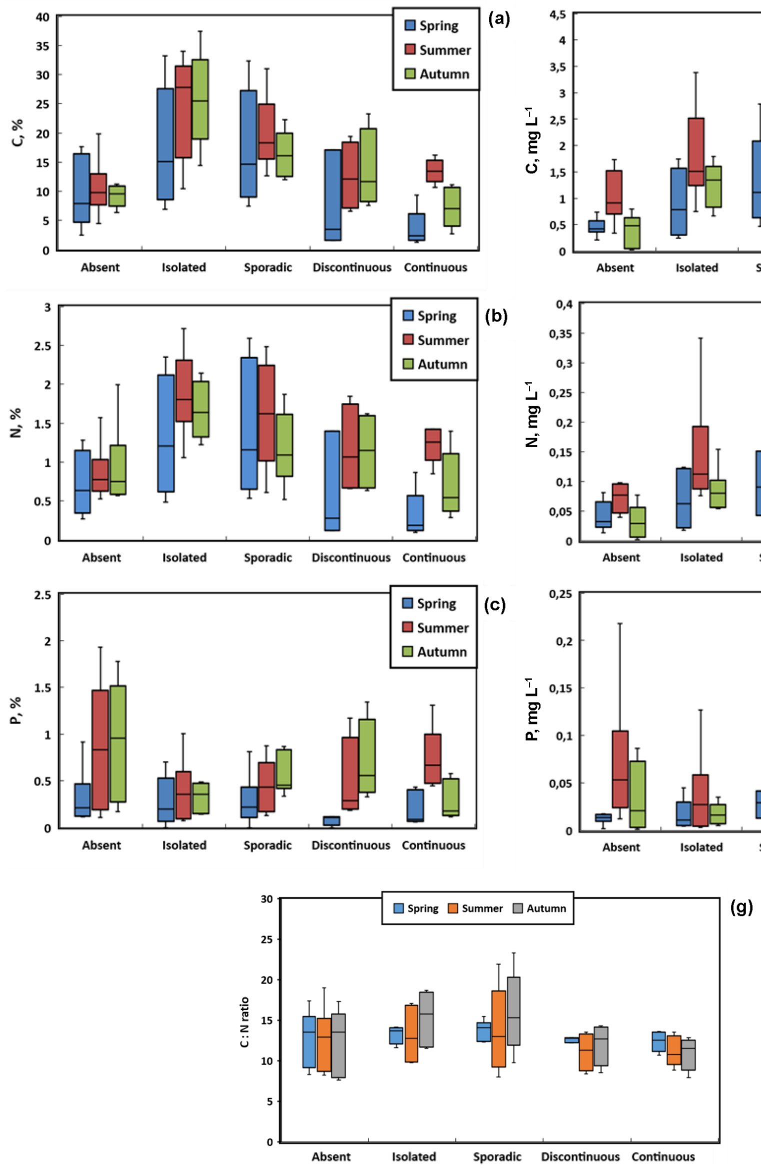

Figure 3. Box plot of first and third quartiles (25 % and 75 %) of C **(a)**, N **(b)** and P **(c)** concentrations in RSM (%) in five permafrost zones over three seasons. The C, N and P concentrations in the river water are shown in panels **(d)**, **(e)** and **(f)**, respectively, and a C : N ratio is shown in **(g)**.

phosphorus ranged from 10 % to 90 %. It did not demonstrate any link to the size of river watershed, percentage of forest and bogs, and type of permafrost distribution (not shown).

3.3 C, N, P and RSM export fluxes by WSL rivers

Based on available hydrological data, we calculated open-water-period fluxes of C, N and P in WSL rivers. This analysis takes into account the spatial and temporal variability of river discharge, performed using hydrological approaches elaborated for the dissolved (< 0.45 µm) fraction of the river water (Pokrovsky et al., 2015, 2016). The seasonal fluxes of C, N, P and RSM export by WSL rivers were calculated separately for the spring (May and June), summer (July, August and September) and autumn periods (September–October) for each 2°-wide latitudinal belt of the full WSL territory, following the approach developed for dissolved C and major and trace elements in the river water (Fig. S4). These three seasons of the open-water period represent by far the largest contribution to overall annual element and RSM yield, following the results for other Arctic rivers (McClelland et al., 2016). Thus, six ice-covered months (November to April) represent only 12 % of annual POC export flux by the Ob River. Based on the results of three main seasons, open-

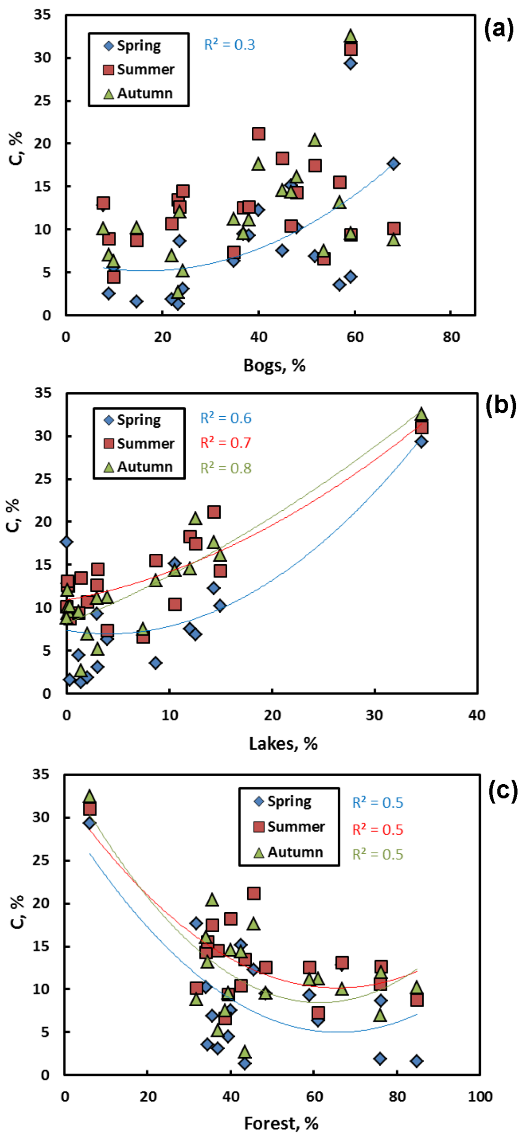

Figure 4. The dependence of C concentrations in RSM (%) on the coverage of watershed by bogs **(a)**, lakes **(b)** and forest **(c)**. The solid lines represent second-degree polynomial fitting of the data with regression coefficients shown for each season in corresponding panels.

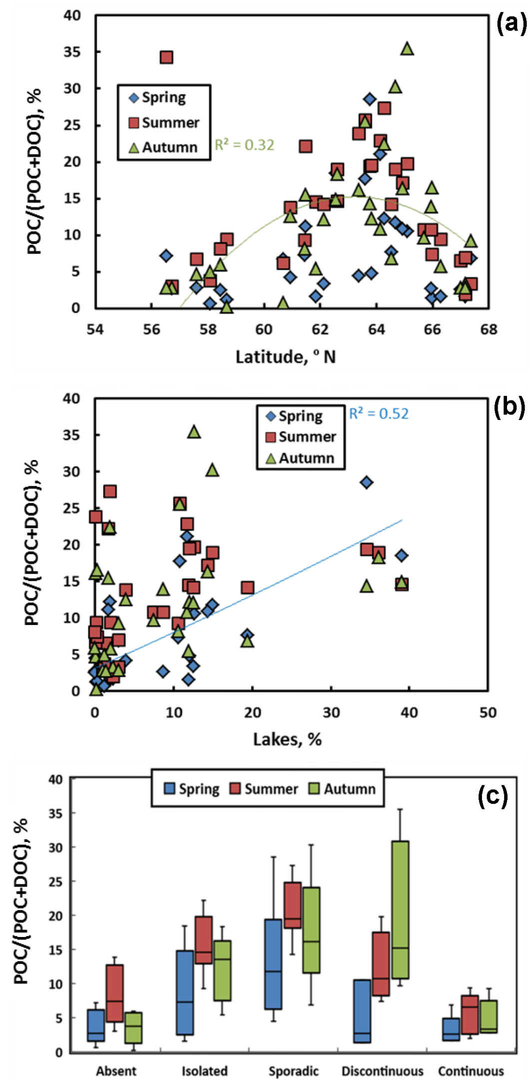

Figure 5. Fraction of particulate OC of total (dissolved + particulate) form plotted as a function of latitude **(a)**, lake fraction on the watershed **(b)** and a box plot of fractions for five permafrost zones **(c)**. The solid lines in **(a)** and **(b)** represent a second-degree polynomial (**a**: autumn) and linear (**b**: spring) fitting of the data, with regression coefficients equal to 0.32 and 0.52, respectively.

water-period export fluxes of C, N, P and RSM were calculated (Fig. 6). There is a clear maximum of C and N export fluxes at the beginning of permafrost appearance, in the isolated-to-sporadic permafrost zone. The obtained particulate C and N yields are comparable with other Siberian rivers. For the two largest WSL rivers, Pur and Taz, we found May-to-October export fluxes of 69 and 80 kg C km^2 yr^{-1}, which are lower than the annual POC yield of the Ob River (191 kg C km^{-2} yr^{-1}) but similar to that of the Yenisey River (103 kg C km^{-2} yr^{-1}; McClelland et al., 2016).

4 Discussion

4.1 Concentrations of C, N and P in the RSM and impact of the watershed size

The RSM values in WSL rivers (2 to 18 mg L^{-1}) are similar to other boreal rivers of low runoff, which drain peatlands such as Severnaya Dvina (2.3 to 16 mg L^{-1}; Pokrovsky et al., 2010), but are lower than the Ob River itself (around 30 mg L^{-1}; Gebhardt et al., 2004) and other big rivers of the Kara Sea basin (average 22 mg L^{-1}; Gordeev et al., 1996). The POC values of the WSL rivers (0.5 to 3.0 mg L^{-1} POC)

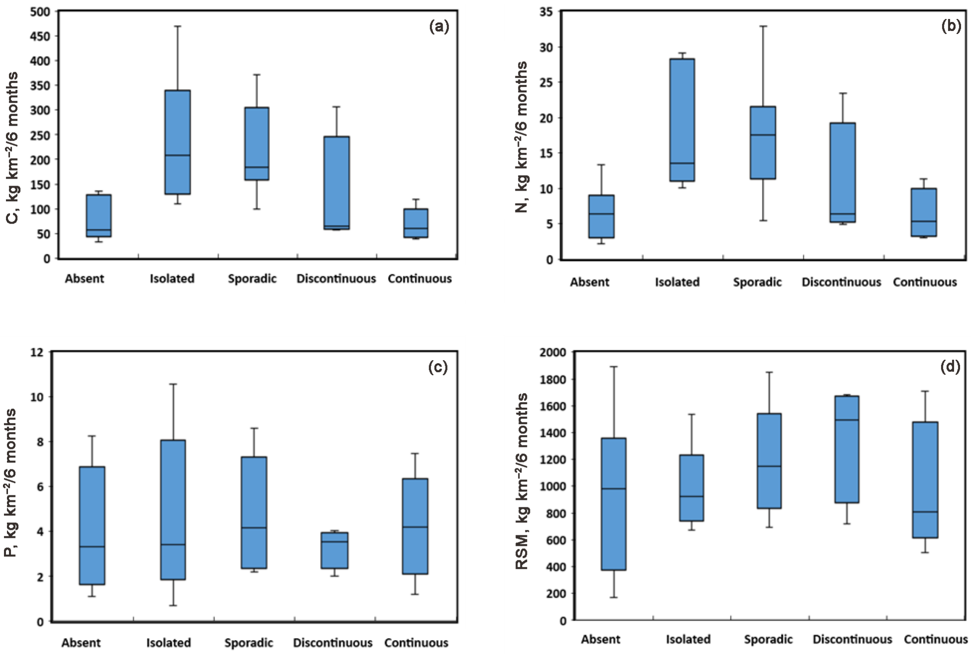

Figure 6. Total open-water-season (May to October) fluxes of particulate C **(a)**, N **(b)** and P **(c)**, and suspended matter **(d)** in five permafrost-free and four distinct permafrost zones of WSL (box plots of first and third quartiles). There is a clear maximum of C and N export at the beginning of permafrost appearance, in the isolated-to-sporadic permafrost zone.

are consistent with recent data on WSL river transects sampled in 2015 (Vorobyev et al., 2017) and are in agreement with those of the Ob–Taz River confluence measured in June (1.3 mg L^{-1}; Gebhardt et al., 2004), the Ob River at Salekhard in May through October (0.8 to 2.4 mg POC L^{-1}; Le Fouest et al., 2013), the low reaches of the Ob River (1.2 to 2.4 mg POC L^{-1}; McClelland et al., 2016), the mean multi-annual values of POC in subarctic rivers of northern Eurasia draining peatlands (3.2, 0.3, 0.9 mg POC L^{-1} for Severnaya Dvina, Pechora and Ob; as compiled in Gordeev et al., 1996) and the Lena River basin (0.5 mg L^{-1}; Kutscher et al., 2017).

However, the C_{org} concentrations in RSM of WSL rivers (5 % to 40 %), notably in small- and medium-sized (< 10 000–100 000 km^2) ones, are an order of magnitude higher than those in other world rivers, which drain mineral substrates (typically 1 % C_{org} in RSM; Meybeck, 1993) and are significantly higher than the values of the Siberian rivers (2.3 %, 3.6 %, 5.8 % and 3.0 % for Ob, Yenisey, Lena and Kolyma, respectively; Gordeev and Kravchishina, 2009). For example, the typical concentrations of C_{org} in RSM of large ($S_{watershed} > 100\,000$ km^2) central Siberian rivers that drain larch forest are only 0.4 % to 0.5 % (Pokrovsky et al., 2005). The C_{org} concentrations in the RSM of Severnaya Dvina River (which has a sizeable proportion of bogs and lakes within its watershed compared to WSL rivers) are 2.7 ± 0.7 % in May and 4.8 ± 1.1 % in August (Savenko et al., 2004). The N_{org} content in RSM ranges from 0.3 % to 1.8 % (0.05 to 0.2 mg particulate N_{tot} L^{-1}), which is much higher than that in sedimentary rocks (0.05 % to 0.06 %; Houlton et al., 2018) but is comparable with the value reported for the freshwater part of Ob River estuary (0.16 mg N L^{-1}; Gebhardt et al., 2004), the Ob River at Salekhard in May to October (0.1 to 0.3 mg PON L^{-1}; PON – particulate organic nitrogen; Le Fouest et al., 2013), the Yukon River (0.14 ± 0.09 mg particulate N L^{-1}; Guo and MacDonald, 2006) and small rivers in the North Slope, Alaska (0.05 to 0.6 mg PON L^{-1}; McClelland et al., 2014).

High concentrations of C (and N) in the RSM of WSL rivers may stem from the organic nature of soils that prevail on river watersheds. The Histosols, one of the dominant soil groups of WSL, are capable of providing a sizeable amount of organic particles given the higher susceptibility of peat to physical disintegration compared to mineral soils. The enrichment of the river water in C-rich particles may occur at both the river bank (especially in small rivers flowing through the wetlands) and within the extensive floodplains via the remobilization of organic-rich sediments during high flow periods.

The concentrations of C and N in RSM decreased with increase in $S_{watershed}$, thereby illustrating the importance of organic particles in small rivers draining the peatlands and the role of mineral matter from bank abrasion in larger rivers. The impact of watershed size is more significant for C than for N. Presumably this is because N is more affected by autochthonous processes, and because particulate

N may partly be generated from phytoplankton and macrophytes in the river. Small rivers ($S_{\mathrm{watershed}} < 100$–$1000\,\mathrm{km}^2$) exhibited the largest scatter in particulate C, N and P concentrations. This is probably due to multiple sources of POM and the very short transit time in the watershed that results in fast responses of river particulate load to minor variations in surface hydrology, including high sensitivity to local storm events.

The decrease of C : N in the RSM from small to large rivers likely reflected a shift in the main origin of suspended matter, from peat in small rivers to more lithogenic (deep soil) in large rivers. This was mostly visible in summer and autumn; in spring the rivers exhibited a very homogeneous C : N signature that may be linked to a dominant source of RSM from bank abrasion and sediment transport as well as deposition within the riparian zone. In fact, the flood plain of the Ob River and other rivers of the WSL extend to more than 10 times the width of the main channel (Vorobyev et al., 2015). Note that the C : N ratio in large rivers ($> 100\,000\,\mathrm{km}^2$) approaches that of average sedimentary rocks (8.1; Houlton et al., 2018). In this regard, highly homogeneous C : N ratios in the particulate load of Arctic rivers (7 to 18 for Mackenzie, Yukon, Kolyma, Lena, Yenisey and Ob regardless of season; McClelland et al., 2016) are interpreted as the mixture of deep soil sources where C : N < 10 (Schädel et al., 2014) and upper organic-rich horizons of soils have elevated C : N (Gentsch et al., 2015). The Ob River demonstrates the youngest POC of all Arctic rivers (-203 ‰ to -220 ‰ Δ^{14}C; McClelland et al., 2016), which certainly indicates a relatively fresh (ca. 1000–2000 years old) origin of particulate carbon that is presumably from intermediate peat horizons.

We believe that variations in C : N in RSM reflect different sources of organic material feeding the river depending on seasons and latitudes. A compilation of C : N ratios in peat and mineral horizons as well as in thermokarst lake sediments for four main sites of latitudinal transect considered in this study is given in Fig. S5 of Supplement. The range of C : N values in RSM rivers (10 to 20) is closer to that in sediments of thermokarst lakes (20 to 30). Note that the resuspension of sediments may be an important source of water column POC (Yang et al., 2016).

The minerotrophic bogs, which are mostly linked to rivers via hydrological networks, have a C : N ratio in upper peat horizons ranging from 24 to 28. In mineral soils of the region, the C : N range is between 10 and 15, regardless of latitude, from the tundra-situated Taz River riparian zone to the taiga-situated middle channel of the Ob River. For upper organic horizons the C : N is always higher than the bottom mineral horizons. The old alluvial deposits of the Pyakupur River (discontinuous permafrost zone) had only 0.2 % of POC, with C : N equal to 6. Overall, there is an enrichment in N relative to C in the course of water transport of organic and organic-mineral solid particles from soils and riparian deposits to the river water.

Another important observation following from the consistently low C : N ratios of RSM across rivers of various size and climatic zones is that the flocculation and aggregation of riverine dissolved organic matter (DOM) in lotic waters of Siberian lowlands may be quite low. Further, the absence of a significant relationship between the lake proportion at the watershed and the C : N ratio implies the negligible impact of DOM coagulation due to photolysis (von Wachenfeldt et al., 2008; von Wachenfeldt and Tranvik, 2008) or bacterial activity (von Wachenfeldt et al., 2009), with the subsequent transformation of coagulation products (Kortelainen et al., 2006b, 2013) as it is known in European humic lakes. Note that, because the range of C : N in RSM of WSL is far from that reported for DOM in soil solutions of boreal taiga (ca. 100, Ilina et al., 2014; 40 to 80, Dymov et al., 2013) and humic (peatland) lakes (> 50, Chupakov et al., 2017), the coagulation of DOM from soil waters producing particles in the rivers is also unlikely.

4.2 A maximum of C and N in the isolated and sporadic permafrost zone and the impact of river watershed characteristics

Complementary to previous results on dissolved ($< 0.45\,\mu$m) C and N concentrations in WSL rivers acquired by Frey et al. (2007a) and Vorobyev et al. (2017) that demonstrated the weak or nonexistent impact of permafrost on DOC and dissolved organic nitrogen (DON), the particulate C and N were affected by the presence of permafrost in summer and autumn but were not affected by its presence in spring. Moreover, during freshet the permafrost distribution did not influence the bulk RSM concentration in WSL rivers. This strongly implies that the delivery of RSM in rivers, and its chemical composition, is tightly linked to the thickness of the active layer and are limited by the transport of soil particles over the suprapermafrost flow to the river channel. This thickness is highest in September at the end of the active season. In agreement with this, the C and N demonstrated a maximum concentration and export fluxes at 62–64° N, in the isolated-to-sporadic permafrost zone, that were most visible during summer and autumn (Figs. 3a–b and 6a–b). This latitudinal belt can be considered as a large-scale thawing front for the frozen peat that corresponds to the southern boundary of permafrost persistence. It is important to note that WSL rivers exhibit maximum CO_2 emission fluxes at the isolated-to-sporadic permafrost belt (Serikova et al., 2018), which could be linked to the strong processing of POC and PON in the water column of WSL rivers. Interestingly, that rate of POC biodegradation, leading to potential CO_2 emissions, sizably exceeds that of DOC in boreal humic waters (Attermeyer et al., 2018). Furthermore, a maximum percentage of particulate C over total C (suspended + dissolved) was also in the isolated and sporadic permafrost zones in spring; this maximum shifted to the sporadic permafrost zone in summer and moved northward to the discontinuous permafrost zone in autumn (Fig. 5c). We believe that this corresponds to a progressive increase in the thickness of the active layer that controls the degree of peat and mineral particles leaching from the soil profile to the river. The thickness of this layer increases from spring to autumn, and more importantly, it moves northward during this period (Trofimova and Balybina, 2014). The enhanced mobilization of nutrients at the "hot spot" of permafrost thaw in frozen peat landscapes was recently demonstrated on a local scale in western Siberia (Loiko et al., 2017).

The impact of watershed characteristics on particulate C and N was clearly pronounced, with increased C and N concentrations in RSM where there were increased bog and lake proportions and decreased C and N concentrations where there was increasing forest coverage. The stronger impact of lakes compared to bogs on C concentration in RSM suggests that the generation of C-rich particles occurs more efficiently in large water bodies than in stagnant shallow water bodies. Given the very short transit time of water from the surrounding peat to the lakes via suprapermafrost flow (Ala-aho et al., 2018a, b; Raudina et al., 2018), the allochthonous chromophoric DOM-rich material from peat soil water that arrives to the lakes may be subjected to fast degradation and coagulation, as shown in Scandinavian lakes (Kortelainen et al., 2006b; von Wachenfeldt and Tranvik, 2008). Second, the peat abrasion at the border of the thermokarst lakes and thaw ponds, which are highly abundant in the territory (Polishchuk et al., 2017, 2018), occurs due to wave erosion and thermoabrasion (Shirokova et al., 2013; Manasypov et al., 2015). The physical disintegration of peat at the lake coast likely generates a large amount of suspended organic-rich material that can be exported to hydrological networks during, for example, lake drainage or already existing connecting channels (Kirpotin et al., 2008, 2011). Note that the maximal lake coverage of the WSL territory is in the 63 to 64° N latitudinal belt (Polishchuk et al., 2017), where maximum C and N concentrations and RSM export fluxes also occur. Because the majority of thermokarst lakes are isolated water bodies without inlets and outlets, this connectivity is achieved via water movement along the permafrost table in the thawed active layer (Raudina et al., 2018), in the form of the so-called suprapermafrost flow between peat bogs, lakes and rivers.

Finally, for particulate P, neither its concentration nor the particulate fraction were affected by permafrost distribution, probably due to the various processes of biological uptake and the mineral precipitation controlling the removal of P, both in the soil profile and in the river water. For example, lakes and bogs retained particulate P, similar to that of dissolved P, which is in agreement with global assessments (Bouwman et al., 2013), P behavior in European northern wetlands and lakes (Lidman et al., 2014), and recent results on dissolved P in the WSL rivers (Vorobyev et al., 2017).

4.3 Mechanisms of RSM generation and prospectives for climate warming in western Siberia

A framework of particulate C, N and P generation in WSL rivers across the permafrost gradient is shown in Fig. 7. We suggest that the concentration and export fluxes of suspended particles depend on both the supply and losses in the catchments. The sources of suspended particles in WSL rivers include the following: (i) vegetation litter, which is washed by surficial flow to the river, especially in spring; (ii) surface (peat) soil horizons, which are also most active in spring, especially in the north; (iii) deep peat and mineral horizons, which provide the particles via bank abrasion in spring and via suprapermafrost flow in summer and autumn; (iv) lake coastal abrasion due to wave erosion; and finally, (v) the autochthonous organic debris of macrophytes, periphyton and phytoplankton, whose contribution is maximal in summer and autumn. A non-steady-state physical erosion of peat soils in WSL provides maximum particulate nutrients within the most fragile zone of actively thawing permafrost between 62 and 64° N of the isolated-to-sporadic permafrost zone. The maximal thickness of the active layer progressively moves north during the active season, thereby leading to maximal export of particulate C, N and P at the thawing front. However, we also suggest that part of the difference in mobilized particulates is masked by retention in recipient waters. The transit time of water and particles in the southern WSL rivers is much longer than that in northern rivers (Ala-aho et al., 2018a, b); hence the biological uptake mechanisms (Richardson et al., 2013; Attermeyer et al., 2018), together with physiochemical processes such as the photodegradation of POC (Mayer et al., 2006; Riggsbee et al., 2008) or cryocoagulation (Pokrovsky et al., 2018), have sufficient time to act on suspended matter of soil and shallow subsurface waters and to remove the nutrients from the river water as well. In rivers of the continuous permafrost zone, a relatively small stock of nutrient-rich particles within the soil profile and on soil surface (as plant litter) is largely compensated for by a more rapid flushing and shorter travel time through soils and rivers as well as lower microbial and phytoplankton activity. As a result, the zone of isolated-to-sporadic permafrost exhibits both the maximal release of soil particles and minimal uptake by in-stream processes. Further to the north, shallow unfrozen peat depth and low biomass cannot supply sufficiently high suspended nutrients, and the particulate transport of C and N decreases. In contrast, for P, opposite gradients in supply and in-stream removal may cancel out the net effect of temperature and permafrost on suspended P in the river water.

Based on these results we can speculate on the conditions following warming and permafrost thaw. The drainage of the lakes and the colonization of the bogs by forest is a very common scenario of landscape evolution in western Siberia under ongoing climate warming (Kirpotin et al., 2009, 2011). Scenarios of thermokarst lake evolution under

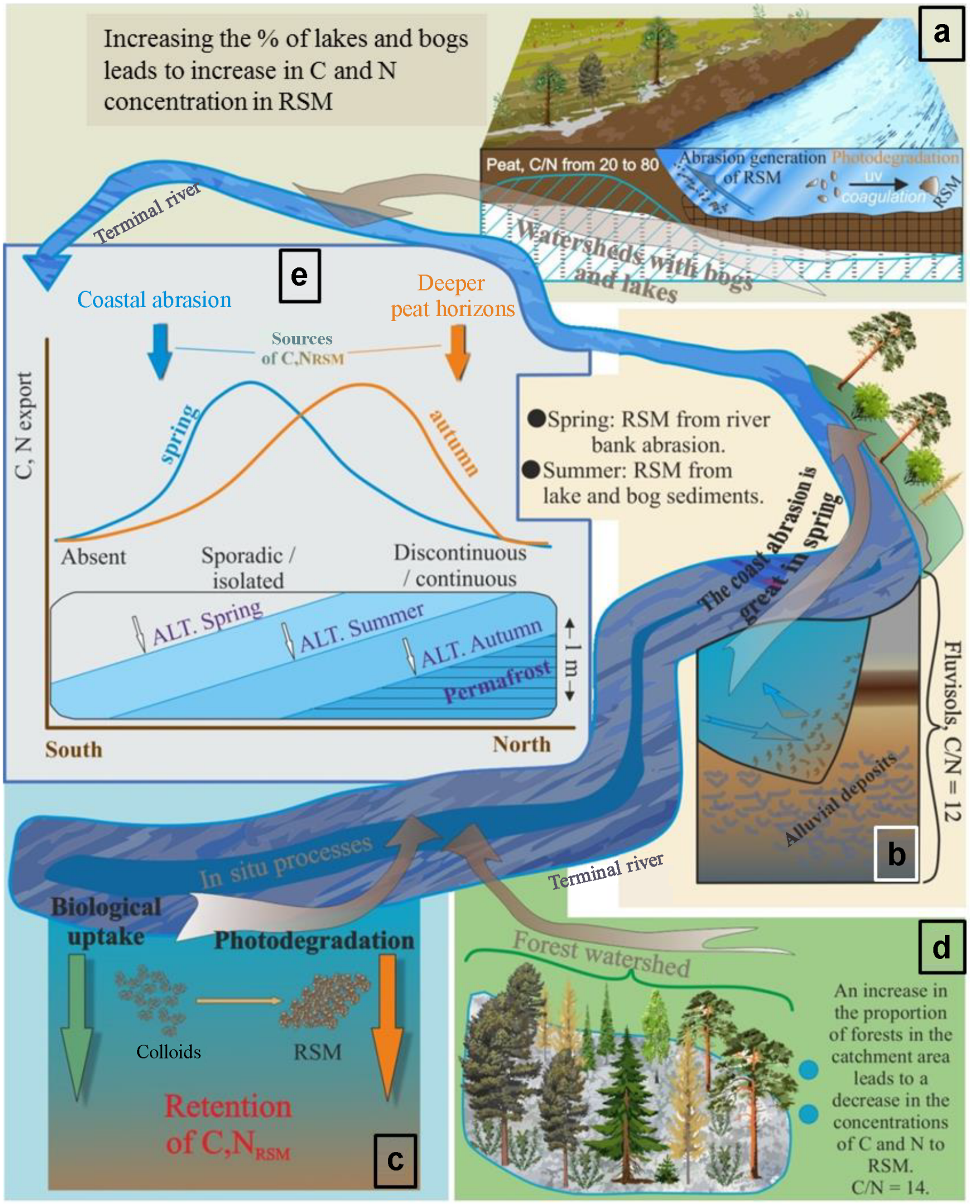

Figure 7. A cartoon of spatial and temporal partitioning of particulate nutrients in WSL rivers across the permafrost gradient. The panels **(a)**, **(b)**, **(c)** and **(d)** represent the main sources (**a**: lakes and bogs in summer, and **b**: alluvial deposits in spring) and sinks (**c**: photodegradation and bio-degradation, and **d**: uptake by taiga forest) of particulate nutrients in WSL rivers. The panel **(e)** depicts the spatial gradient of C and N in RSM occurring in spring (blue line) and autumn (red line). A non-steady-state physical erosion of peat soils in WSL provides the maximum of particulate nutrients within the zone of most "fragile" actively thawing permafrost. The maximal thickness of the active layer progressively moves to the north during the active season, thus leading to the maximal removal of particulate C, N and P at the thawing front.

climate warming and permafrost thaw in western Siberia include (1) the draining of large thermokarst lakes into hydrological network, which is especially pronounced in discontinuous permafrost zone (Smith et al., 2005; Polishchuk et al., 2014) and (2) the appearance of new depressions, subsidence and small thaw ponds (< 100–$1000\,m^2$), which is evidenced across all permafrost zones in this region (Shirokova et al., 2013; Bryksina and Polishchuk, 2015). In terms of landscape change, the area of hollows and subsidence will increase, and the coverage of palsa by mounds and polygons will decrease (Moskalenko, 2012; Pastukhov and Kaverin, 2016; Pastukhov et al., 2016). From a short-term prospective (10–50 years), assuming a soil temperature rise of 0.15° to 0.3°C per 10 years in WSL (Pavlov and Malkova, 2009; Anisimov et al., 2012), the northern part of the WSL (discontinuous and continuous permafrost zones) will transform into sporadic and isolated permafrost zones (Anisimov and Reneva, 2006). This will lead to an increase in C and N concentrations in the RSM, C and N particulate export yield of the watershed and an overall increase in the particulate transport versus dissolved transport of C and P. Given the contemporary maximum of C and N at the permafrost thawing front, this increase may be 2 fold. However, from a longer-term prospective (50–100 years), even the continuous permafrost zone may disappear (Romanovsky et al., 2008; Nadyozhina et al., 2008); this will decrease the particulate C and N concentrations in the northern rivers and, consequently, their export to the coastal zone of the Kara Sea. Judging from the actual difference in nutrient concentrations and fluxes among adjusting permafrost zones, this decrease may be of around a factor of 2 to 3. Furthermore, from the same long-term prospective, the drainage of lakes and disappearance of bogs due to the colonization of northern palsa by forests (Anisimov et al., 2011; Anisimov and Sherstiukov, 2016; Kirpotin et al., 2008, 2009, 2011) should lead to a further decrease in the particulate nutrient load of WSL rivers.

5 Conclusions

Relatively low-bulk RSM concentrations in WSL rivers stem from low runoff in this flat peatland province of boreal and subarctic zones. High concentrations of C and N in the RSM of WSL rivers reflect the essentially organic nature of soils across the WSL. At the isolated-to-sporadic permafrost zone, we observed maximum concentrations of C and N in the RSM, a maximal fraction of particulate OC relative to the total (dissolved + particulate), and maximal export fluxes. This suggests the enhanced generation of RSM rich in C and N at the thawing front of permafrost, where the thickness of the active layer is maximal. The C and N concentrations in the particulate load of WSL rivers decrease with the forest coverage of the watershed and increase with the proportion of lakes and bogs; however, the bulk concentration of RSM did not depend on landscape parameters of the watersheds. This implies the generation of particles rich in C and N via coastal peat abrasion and sediment resuspension, rather than the photo- and bio-coagulation of DOM in lentic surface waters that are hydrologically connected to rivers. Indeed, the consistently low C : N ratios of RSM suggest the low importance of the flocculation and aggregation of DOM in WSL inland waters. To model a northward permafrost boundary and forest line shifting with an increase in air and soil temperature we used a scenario substituting space for time for climate warming in the WSL that was well developed for the dissolved fraction of C and nutrients. From a short-term climate warming prospective, the effect of a northward shift of permafrost boundary may produce about a 2-fold increase in particulate C and N concentrations and export fluxes in rivers of the discontinuous and continuous permafrost zones, and thus may enhance the delivery of these nutrients by the northernmost WSL rivers to the Arctic Ocean. From a long-term prospective, the disappearance of permafrost in the northern part of WSL will decrease the concentrations and the export of these nutrients to their current level. The P is unlikely to be significantly affected by permafrost change. Moreover, within a long-term climate warming scenario, the drainage of lakes and transformation of bogs to forest may decrease nutrient concentration in RSM and corresponding export flux to the Arctic Ocean.

Data availability. River suspended matter (RSM) and particulate nutrient concentration in RSM of western Siberian rivers sampled in 2016 is available at Research Gate, https://doi.org/10.13140/rg.2.2.36650.93121 (Pokrovsky, 2018).

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/bg-15-6867-2018-supplement.

Author contributions. OSP, SNK and JK contributed to study design. IVK, AGL, RMM and SVL organized sampling campaigns and logistics. AGL and IVK performed the analyses. IVK analyzed data and prepared figures and tables. IVK and OSP wrote the paper. SVL, LSS and JK helped with the interpretation of the results.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work was mainly supported by the Russian Scientific Fund no. 18-17-00237 “Mechanisms of hydrochemical runoff of the Ob River flood zone” (analyses, modeling). Partial support from the Russian Fund for Basic Research project no. 18-35-00563\18, the Ministry of Education and Science of the Russian Federation no. 6.7515.2017/9.1, and VR (the Swedish Research Council) grant no. 325-2014-6898 is also acknowledged.

Edited by: Nobuhito Ohte
Reviewed by: two anonymous referees

References

Ala-aho, P., Soulsby, C., Pokrovsky, O. S., Kirpotin, S. N., Karlsson, J., Serikova, S., Manasypov, R. M., Krickov, I., Lim, A., and Tetzlaff, D.: Permafrost and lakes control river isotope composition across a boreal-arctic transect in the western Siberia lowland, Environ. Res. Lett., 13, 034028, https://doi.org/10.1088/1748-9326/aaa4fe, 2018a.

Ala-Aho, P., Soulsby, C., Pokrovsky, O. S., Kirpotin, S. N., Karlsson, J., Serikova, S., Vorobyev, S. N., Manasypov, R. M., Loiko, S., and Tetzlaff, D.: Using stable isotopes to assess surface water source dynamics and hydrological connectivity in a high-latitude wetland and permafrost influenced landscape, J. Hydrol., 556, 279–293, https://doi.org/10.1016/j.jhydrol.2017.11.024, 2018b.

Anisimov, O. and Reneva, S.: Permafrost and Changing Climate: The Russian Perspective, AMBIO, 35, 169–175, 2006.

Anisimov, O. A. and Sherstiukov, A. B.: Evaluating the effect of climatic and environmental factors on permafrost in Russia, Earth's Cryosphere, XX, 78–86, 2016.

Anisimov, O. A., Zhiltsova, E. L., and Reneva, S. A.: Estimation of critical levels of climate change impact on natural land ecosystems of Russian territory, Meteorology and Hydrology, 11, 723–730, https://doi.org/10.3103/S1068373911110033, 2011.

Anisimov, O. A., Anokhin, A., Lavrov, S. A., Malkova, G. V., Pavlov, A. V., Romanovskiy, V. E., Streletskiy, D. A., Kholodov, A. L., and Shiklomanov, N. I.: Continental multiyear permafrost, Methods of study the sequences of climate changes for nature system, edited by: Semenov, S. M., Moscow, VNIIGMI, 268–328, 2012 (in Russian).

Attermeyer, K., Catalán, N., Einarsdottir, K., Freixa, A., Groeneveld, M., Hawkes, J. A., Hawkes, J. A.; Bergquist, J., and Tranvik, L. J.: Organic carbon processing during transport through boreal inland waters: Particles as important sites, J. Geophys. Res.-Biogeo., 123, 2412–2428, https://doi.org/10.1029/2018JG004500, 2018.

Batuev, V. I.: Formation of water runoff from mound bogs (case study of Western Siberia), TSPU Bulletin, 122, 146–152, 2012.

Baulin, V. V., Belopukhova, E. B., Dubikov, G. I., and Shmelev, L. M.: Geocryological conditions of western Siberia Lowland, Nauka Publishing House, Moscow, 1967 (in Russian).

Bouwman, A. F., Bierkens, M. F. P., Griffioen, J., Hefting, M. M., Middelburg, J. J., Middelkoop, H., and Slomp, C. P.: Nutrient dynamics, transfer and retention along the aquatic continuum from land to ocean: towards integration of ecological and biogeochemical models, Biogeosciences, 10, 1–22, https://doi.org/10.5194/bg-10-1-2013, 2013.

Bring, A., Fedorova, I., Dibike, Y., Hinzman, L., Mård, J., Mernild, S. H., Prowse, T., Semenova, O., Stuefer, S. L., and Woo, M.-K.: Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges, J. Geophys. Res.-Biogeo., 121, 621–649, https://doi.org/10.1002/2015JG003131, 2016.

Bryksina, N. A. and Polishchuk, Y. M.: Analysis of changes in the number of thermokarst lakes in permafrost of Western Siberia on the basis of satellite images, Kriosfera Zemli (Earth's Cryosphere), 19, 100–105, 2015 (in Russian).

Cai, Y., Guo, L., Douglas, T. A., and Whitledge, T. E.: Seasonal variations in nutrient concentrations and speciation in the Chena River, Alaska, J. Geophys. Res.-Biogeo., 113, G03035, https://doi.org/10.1029/2008JG000733, 2008.

Chupakov, A., Ershova, A., Moreva, O. Yu, Shirokova, L. S., Zabelina, S. A., Vorobieva, T. Y., Klimov, S. I., Brovko, O. S., and Pokrovsky O. S.: Seasonal dynamics of dissolved carbon in contrasting stratified lakes of the subarctic, Boreal Environ. Res., 22, 213–230, 2017.

Coppola, A. I., Wiedemeier, D. B., Galy, V., Haghipour, N., Hanke, U. M., Nascimento, G. S., Usman, M., Blattmann, T. M., Reisser, M., Freymond, C. V., Zhao, M., Voss, B., Wacker, L., Schefuß, E., Peucker-Ehrenbrink, B., Abiven, S., Schmidt, M. W. I., and Eglinton, T. I.: Global-scale evidence for the refractory nature of riverine black carbon, Nat. Geosci., 11, 584–588, 2018.

Dittmar, Th. and Kattner, G.: The biogeochemistry of the river and shelf ecosystem of the Arctic Ocean: a review, Mar. Chem., 83, 103–120, https://doi.org/10.1016/S0304-4203(03)00105-1, 2003.

Dornblaser, M. M. and Striegl, R. G.: Nutrient (N, P) loads and yields at multiple scales and subbasin types in the Yukon River basin, Alaska, J. Geophys. Res.-Biogeo., 112, G04S57, https://doi.org/10.1029/2006JG000366, 2007.

Dymov, A. A., Dzhangurov, E. V., and Startsev, V. V.: Soils of the northern part of subpolar Urals: morphology, physicochemical properties, and carbon and nitrogen pools, Eurasian Soil Sci., 5, 507–516, 2013.

Emmerton, C. A., Lesack, L. F. W., and Vincent, W. F.: Mackenzie River nutrient delivery to the Arctic Ocean and effects of the Mackenzie Delta during open water conditions, Global Biogeochem. Cy., 22, GB1024, https://doi.org/10.1029/2006GB002856, 2008.

Frey, K. E. and McClelland, J. W.: Impacts of permafrost degradation on arctic river biogeochemistry, Hydrol. Process., 23, 169–182, https://doi.org/10.1002/hyp.7196, 2009.

Frey, K. E. and Smith, L. C.: Amplified carbon release from vast West Siberian peatlands by 2100, Geophys. Res. Lett., 32, L09401, https://doi.org/10.1029/2004GL022025, 2005.

Frey, K. E., McClelland, J. W., Holmes, R. M., and Smith, L. C.: Impacts of climate warming and permafrost thaw on the riverine transport of nitrogen and phosphorus to the Kara Sea, J. Geophys. Res.-Biogeo., 112, G04S58, https://doi.org/10.1029/2006JG000369, 2007a.

Frey, K. E., Siegel, D. I., and Smith, L.C.: Geochemistry of west Siberian streams and their potential response to permafrost degradation, Water Resour. Res., 43, W03406, https://doi.org/10.1029/2006WR004902, 2007b.

Galy, V., Peucker-Ehrenbrink, B., and Eglinton, T.: Global carbon export from the terrestrial biosphere controlled by erosion, Nature, 521, 204–207, https://doi.org/10.1038/nature14400, 2015.

Gareis, J. A. L. and Lesack, L. F. W.: Fluxes of particulates and nutrients during hydrologically defined seasonal periods in an ice-affected great Arctic river, the Mackenzie, Water Resour. Res., 53, 6109–6132, https://doi.org/10.1002/2017WR020623, 2017.

Gebhardt, A. C., Gaye-Haake, C., Unger, D., Lahajnar, N., and Ittekkot, V.: Recent particulate organic carbon and total suspended matter fluxes from the Ob and Yenisei Rivers into the Kara Sea (Siberia), Mar. Geol., 207, 225–245, https://doi.org/10.1016/j.margeo.2004.03.010, 2004.

Gentsch, N., Mikutta, R., Alves, R. J. E., Barta, J., Capek, P., Gittel, A., Hugelius, G., Kuhry, P., Lashchinskiy, N., Palmtag, J., Richter, A., Šantrčucková, H., Schnecker, J., Shibistova, O., Urich, T., Wild, B., and Guggenberger, G.: Storage and transformation of organic matter fractions in cryoturbated permafrost soils across the Siberian Arctic, Biogeosciences, 12, 4525–4542, https://doi.org/10.5194/bg-12-4525-2015, 2015.

Gladyshev, M. I., Kolmakova, O. V., Tolomeev, A. P., Anishchenko, O. V., Makhutova, O. N., Kolmakova, A. A., Kravchuk, E. S., Glushchenko, L. A., Kolmakov, V. I., and Sushchik, N. N.: Differences in organic matter and bacterioplankton between sections of the largest Arctic river: Mosaic or continuum?, Limnol. Oceanogr., 60, 1314–1331, https://doi.org/10.1002/lno.10097, 2015.

Goñi, M. A., Hatten, J. A., Wheatcroft, R. A., and Borgeld, J. C.: Particulate organicmatter export by two contrasting small mountainous rivers from the Pacific Northwest, U.S.A., J. Geophys.

Res.-Biogeo., 118, 1–23, https://doi.org/10.1002/jgrg.20024, 2013.

Gordeev, V. V. and Kravchishina, M. D.: River flux of dissolved organic carbon (DOC) and particulate organic carbon (POC) to the Arctic Ocean: what are the consequences of the global changes?, in: Influence of Climate Change on Changing Arctic and Sub-Arctic Conditions, Springer, 145–160, 2009.

Gordeev, V. V., Martin, J. M., Sidorov, I. S., and Sidorova, M. V.: A reassessment of the Eurasian river input of water, sediment, major elements, and nutrients to the Arctic Ocean, Am. J. Sci., 296, 664–691, 1996.

Guo, L. and Macdonald, R. W.: Source and transport of terrigenous organic matter in the upper Yukon River: Evidence from isotope ($d^{13}C$, $D^{14}C$, and $d^{15}N$) composition of dissolved, colloidal, and particulate phases, Global Biogeochem. Cy., 20, GB2011, https://doi.org/10.1029/2005GB002593, 2006.

Guo, L., Zhang, J.-Z., and Guéguen, C.: Speciation and fluxes of nutrients (N, P, Si) from the upper Yukon River, Global Biogeochem. Cy., 18, GB1038, https://doi.org/10.1029/2003GB002152, 2004.

Hilton, R. G.: Climate regulates the erosional carbon export from the terrestrial biosphere, Geomorphology, 277, 118–132, https://doi.org/10.1016/j.geomorph.2016.03.028, 2017.

Hilton, R. G., Galy, V., Gaillardet, J., Dellinger, M., Bryant, C., O'Regan, M., Gröcke, D. R., Coxall, H., Bouchez, J., and Calmels, D.: Erosion of organic carbon in the Arctic as a geological carbon dioxide sink, Nature, 524, 84–87, https://doi.org/10.1038/nature14653, 2015.

Ilina, S. M., Drozdova, O. Y., Lapitskiy, S. A., Alekhin, Y. V., Demin, V. V., Zavgorodnyaya, Y. A., Shirokova, L. S., Viers, J., and Pokrovsky, O. S.: Size fractionation and optical properties of dissolved organic matter in the continuum soil solution-bog-river and terminal lake of a boreal watershed, Org. Geochem., 66, 14–24, 2014.

Jeong, J. J., Bartsch, S., Fleckenstein, J. H., Matzner, E., Tenhunen, J. D., Lee, S. D., Park, S. K., and Park, J.-H.: Differential storm responses of dissolved and particulate organic carbon in a mountainous headwater stream, investigated by high-frequency, in situ optical measurements, J. Geophys. Res.-Biogeo., 117, 1–13, https://doi.org/10.1029/2012JG001999, 2012.

Kirpotin, S., Polishchuk, Y., Zakharova, E., Shirokova, L., Pokrovsky, O., Kolmakova, M., and Dupre, B.: One of possible mechanisms of thermokarst lakes drainage in West-Siberian North, Int. J. Environ. Stud., 65, 631–635, https://doi.org/10.1080/00207230802525208, 2008.

Kirpotin, S., Polishchuk, Y., Bryksina, N., Sugaipova, A., Kouraev, A., Zakharova, E., Pokrovsky, O. S., Shirokova, L., Kolmakova, M., Manassypov, R., and Dupre B.: West Siberian palsa peatlands: distribution, typology, hydrology, cyclic development, present-day climate-driven changes and impact on CO_2 cycle, Int. J. Environ. Stud., 68, 603–623, https://doi.org/10.1080/00207233.2011.593901, 2011.

Kirpotin, S. N., Berezin, A., Bazanov, V., Polishchuk, Y., Vorobiev, S., Mozgolin, B., Akerman, E., Mironucheva-Tokareva, N., Volkova, I., Dupré, B., Pokrovsky, O., Kouraev, A., Zakharova, E., Shirokova, L., Viers, J., and Kolmakova, M.: Western Siberia wetlands as indicator and regulator of climate change on the global scale, Int. J. Environ. Stud., 66, 409–421, https://doi.org/10.1080/00207230902753056, 2009.

Klinova, E. A., Faibusovich, Ya. E., and Abakumova, L. A.: State Geological Map of the Russian Federation at a scale of 1 : 1 000 000, West Siberian Series, Map of the Pliocene-Quaternary formations, R-43 (Surgut), Cartographic factory VSEGEI, St. Petersburg, 2012 (in Russian).

Kortelainen, P., Rantakari, M., Huttunen, J. T., Mattsson, T., Alm, J., Juutinen, S., Larmola, T., Silvola, J., and Martikainen, P. J.: Sediment respiration and lake trophic state are important predictors of large CO_2 evasion from small boreal lakes, Glob. Change Biol., 12, 1554–1567, https://doi.org/10.1111/j.1365-2486.2006.01167.x, 2006.

Kortelainen, P., Rantakari, M., Pajunen, H., Huttunen, J. T., Mattsson, H., Juutinen, S., Larmola, T., Alm, J., Silvola, J., and Martikainen, P. J.: Carbon evasion/accumulation ratio in boreal lakes is linked to nitrogen, Glob. Biogeochem. Cy., 27, 363–374, 2013.

Kremenetski, K. V., Velichko, A. A., Borisova, O. K., MacDonald, G. M., Smith, L. C., Frey, K. E., and Orlova, L. A.: Peatlands of the West Siberian Lowlands: Current knowledge on zonation, carbon content, and Late Quaternary history, Quaternary Sci. Rev., 22, 703–723, https://doi.org/10.1016/S0277-3791(02)00196-8, 2003.

Kutscher, L., Mörth, C.-M., Porcelli, D., Hirst, C., Maximov, T. C., Petrov, R. E., and Andersson, P. S.: Spatial variation in concentration and sources of organic carbon in the Lena River, Siberia, J. Geophys. Res.-Biogeo., 122, 1999–2016, https://doi.org/10.1002/2017JG003858, 2015.

Lal, R.: Soil erosion and the global carbon budget, Environ. Int., 29, 437–450, https://doi.org/10.1016/S0160-4120(02)00192-7, 2003.

Lamoureux, S. F. and Lafrenière, M. J.: Seasonal fluxes and age of particulate organic carbon exported from Arctic catchments impacted by localized permafrost slope disturbances, Environ. Res. Lett., 9, 045002, https://doi.org/10.1088/1748-9326/9/4/045002, 2014.

Lee, M.-H., Payeur-Poirier, J.-L., Park, J.-H., and Matzner, E.: Variability in runoff fluxes of dissolved and particulate carbon and nitrogen from two watersheds of different tree species during intense storm events, Biogeosciences, 13, 5421–5432, https://doi.org/10.5194/bg-13-5421-2016, 2016.

Le Fouest, V., Babin, M., and Tremblay, J.-É.: The fate of riverine nutrients on Arctic shelves, Biogeosciences, 10, 3661–3677, https://doi.org/10.5194/bg-10-3661-2013, 2013.

Li, M., Peng, C., Wang, M., Xue, W., Zhang, K., Wang, K., Shi, G., and Zhu, Q.: The carbon flux of global rivers: A re-evaluation of amount and spatial patterns, Ecol. Indic., 80, 40–51, https://doi.org/10.1016/j.ecolind.2017.04.049, 2017.

Lidman, F., Kohler, S. J., Morth, C.-M., and Laudon, H.: Metal transport in the boreal landscape – the role of wetlands and the affinity for organic matter, Environ. Sci. Technol., 48, 3783–3790, https://doi.org/10.1021/es4045506, 2014.

Lobbes, J. M., Fitznar, H. P., and Kattner, G.: Biogeochemical characteristics of dissolved and particulate organic matter in Russian rivers entering the Arctic Ocean, Geochim. Cosmochim. Ac., 64, 2973–2983, https://doi.org/10.1016/S0016-7037(00)00409-9, 2000.

Loiko, S. V., Pokrovsky, O. S., Raudina, T., Lim, A., Kolesnichenko, L. G., Shirokova, L. S., Vorobyev, S. N., and Kirpotin, S. N.: Abrupt permafrost collapse enhances organic carbon, CO_2, nutrient, and metal release into surface waters, Chem. Geol., 471, 153–165, https://doi.org/10.1016/j.chemgeo.2017.10.002, 2017.

Ludwig, W. and Probst, J. L.: Predicting the oceanic input of organic carbon by continental erosion, Global Biogeochem. Cy., 10, 23–41, https://doi.org/10.1029/95GB02925, 1996.

Manasypov, R. M., Vorobyev, S. N., Loiko, S. V., Kritzkov, I. V., Shirokova, L. S., Shevchenko, V. P., Kirpotin, S. N., Kulizhsky, S. P., Kolesnichenko, L. G., Zemtzov, V. A., Sinkinov, V. V., and Pokrovsky, O. S.: Seasonal dynamics of organic carbon and metals in thermokarst lakes from the discontinuous permafrost zone of western Siberia, Biogeosciences, 12, 3009–3028, https://doi.org/10.5194/bg-12-3009-2015, 2015.

Mayer, L. M., Schick, L. L., Skorko, K., and Boss, E.: Photodissolution of particulate organic matter from sediments, Limnol. Oceanogr., 51, 1064–1071, https://doi.org/10.4319/lo.2006.51.2.1064, 2006.

McClelland, J. W., Stieglitz, M., Pan, F., Holmes, R. M., and Peterson, B. J.: Recent changes in nitrate and dissolved organic carbon export from the upper Kuparuk River, North Slope, Alaska, J. Geophys. Res.-Biogeo., 112, G04S60, https://doi.org/10.1029/2006JG000371, 2007.

McClelland, J. W., Townsend-Small, A., Holmes, R. M., Pan, F., Stieglitz, M., Khosh, M., and Peterson, B. J.: River export of nutrients and organic matter from the North Slope of Alaska to the Beaufort Sea, Water Resour. Res., 50, 1823–1839, https://doi.org/10.1002/2013WR014722, 2014.

McClelland, J. W., Holmes, R. M., Raymond, P. A., Striegl, R. G., Zhulidov, A. V., Zimov, S. A., Zimov, N., Tank, S. E., Spencer, R. G. M., Staples, R., Gurtovaya, T. Y., and Griffin, C. G.: Particulate organic carbon and nitrogen export from major Arctic rivers, Global Biogeochem. Cy., 30, 629–643, https://doi.org/10.1002/2015GB005351, 2016.

Meybeck, M.: C, N, P and S in rivers: from sources to global inputs, in: Interaction of C, N, P, and S biogeochemical cycles and global change, edited by: Wollast, R., Mackenzie, F., and Chou, L., NATO ASI Series, Berlin, Heidelberg, Springer-Verlag, 163–193, 1993.

Moskalenko, N. G.: Cryogenic landscape changes in the West Siberian northern taiga in the conditions of climate change and human-induced disturbances, Earth's Cryosphere, 16, 38–42, 2012.

Nadyozhina, E. D., Shkolnik, I. M., Pavlova, T. V., Molkentin, E. K., and Semioshina, A. A.: Permafrost response to the climate warming as simulated by the regional climate model of the main geophysical observatory, Kriosfera Zemli, XII, 3–11, 2008 (in Russian).

Nazarov, D. V.: New data on Quaternary deposits of central part of the western Siberian Arctic, Regional Geology and Metallogeny, 30–31, 213–221, 2007 (in Russian).

Nikitin, S. P. and Zemtsov, V. A.: The variability of hydrological parameters of western Siberia, Nauka, Novosibirsk, 204 pp., 1986 (in Russian).

Pastukhov, A. V. and Kaverin, D. A.: Ecological state of peat plateaus in northeastern European Russia, Russian J. Ecology, 47, 125–132, https://doi.org/10.1134/S1067413616010100, 2016.

Pastukhov, A. V., Marchenko-Vagapova, T. I., Kaverin, D. A., and Goncharova, N. N.: Genesis and evolution of peat plateuas in the sporadic permafrost area in the European North-East (middle basin of the Kosyu river), Earth's Cryosphere, XX, 3–13, 2016.

Pavlov, A. V. and Malkova, G. V.: Mapping of trends of the contemporary ground temperature changes in the Russian north, Kriosfera Zemli, XIII, 32–39, 2009 (in Russian).

Peregon, A., Uchida, M., and Shibata, Y.: Sphagnum peatland development at their southern climatic range in West Siberia: trends and peat accumulation patterns, Environ. Res. Lett., 4, 045014, https://doi.org/10.1088/1748-9326/2/4/045014, 2007.

Pokrovsky, O. S., Schott, J., Kudryavtzev, D. I., and Dupre, B.: Basalts weathering in Central Siberia under permafrost conditions, Geochim. Cosmochim. Ac., 69, 5659–5680, https://doi.org/10.1016/j.gca.2005.07.018, 2005.

Pokrovsky, O. S., Viers, J., Shirokova, L. S., Shevchenko, V. P., Filipov, A. S., and Dupré, B.: Dissolved, suspended, and colloidal fluxes of organic carbon, major and trace elements in Severnaya Dvina River and its tributary, Chem. Geol., 273, 136–149, https://doi.org/10.1016/j.chemgeo.2010.02.018, 2010.

Pokrovsky, O. S., Manasypov, R. M., Loiko, S., Shirokova, L. S., Krickov, I. A., Pokrovsky, B. G., Kolesnichenko, L. G., Kopysov, S. G., Zemtzov, V. A., Kulizhsky, S. P., Vorobyev, S. N., and Kirpotin, S. N.: Permafrost coverage, watershed area and season control of dissolved carbon and major elements in western Siberian rivers, Biogeosciences, 12, 6301–6320, https://doi.org/10.5194/bg-12-6301-2015, 2015.

Pokrovsky, O. S., Manasypov, R. M., Loiko, S. V., Krickov, I. A., Kopysov, S. G., Kolesnichenko, L. G., Vorobyev, S. N., and Kirpotin, S. N.: Trace element transport in western Siberian rivers across a permafrost gradient, Biogeosciences, 13, 1877–1900, https://doi.org/10.5194/bg-13-1877-2016, 2016.

Pokrovsky, O. S., Karlsson, J., and Giesler, R.: Freeze-thaw cycles of Arctic thaw ponds remove colloidal metals and generate low-molecular weight organic matter, Biogeochemistry, 137, 321–336, 2018.

Polishchuk, Y., Kirpotin, S. N., and Bryksina, N.: Remote study of thermokarst lakes dynamics in West-Siberian permafrost, in Permafrost: Distribution, Composition and Impacts on Infrastructure and Ecosystems, edited by: Pokrovsky, O. S., Nova Science Publishers, New York 2014, 173–204, 2014.

Polishchuk, Y. M., Bogdanov, A. N., Polischuk, V. Y., Manasypov, R. M., Shiorkova, L. S., Kirpotin, S. N., and Pokrovsky, O. S.: Size-distribution, surface coverage, water, carbon and metal storage of thermokarst lakes (> 0.5 ha) in permafrost zone of the Western Siberia Lowland, Water, 9, 228, https://doi.org/10.3390/w9030228, 2017.

Polishchuk, Y. M., Bogdanov, A. N., Muratov, I. N., Polishchuk, V. Y., Lim, A., Manasypov, R. M., Shirokova, L. S., and Pokrovsky, O. S.: Minor contribution of small thaw ponds to the pools of carbon and methane in the inland waters of the permafrost-affected part of western Siberian Lowland, Environ. Res. Lett., 13, 045002, https://doi.org/10.1088/1748-9326/aab046, 2018.

Raudina, T. V., Loiko, S. V., Lim, A. G., Krickov, I. V., Shirokova, L. S., Istigechev, G. I., Kuzmina, D. M., Kulizhsky, S. P., Vorobyev, S. N., and Pokrovsky, O. S.: Dissolved organic carbon and major and trace elements in peat porewater of sporadic, discontinuous, and continuous permafrost zones of western Siberia, Biogeosciences, 14, 3561–3584, https://doi.org/10.5194/bg-14-3561-2017, 2017.

Raudina, T. V., Loiko, S. V., Lim, A., Manasypov, R. M., Shirokova, L .S., Istigechev, G. I., Kuzmina, D. M., Kulizhsky, S. P., Vorobyev, S. N., and Pokrovsky, O. S.: Permafrost thaw and climate warming may decrease the CO_2, carbon, and metal concentration in peat soil waters of the Western Siberia Lowland, Sci. Total. Environ., 634, 1004–1023, https://doi.org/10.1016/j.scitotenv.2018.04.059, 2018.

Richardson, D. C., Newbold, J. D., Aufdenkampe, A. K., Taylor, P. G., and Kaplan, L. A.: Measuring heterotrophic respiration rates of suspended particulate organic carbon from stream ecosystems, Limnol. Oceanogr.-Meth., 11, 247–261, https://doi.org/10.4319/lom.2013.11.247, 2013.

Riggsbee, J., Orr, C., Leech, D., Doyle, M., and Wetzel, R.: Suspended sediments in river ecosystems: photochemical sources of dissolved organic carbon, dissolved organic nitrogen, and adsorptive removal of dissolved iron, J. Geophys. Res.-Biogeo., 113, G03019, https://doi.org/10.1029/2007JG000654, 2008.

Romanovsky, V. E., Kholodov, A. L., Marchenko, S. S., Oberman, N. G., Drozdov, D. S., Malkova, G. V., Moskalenko, N. G., Vasiliev, A. A., Sergeev, D. O., and Zheleznyak, M. N.: Thermal State and Fate of Permafrost in Russia: First Results of IPY, in: Proceedings of the 9th International Conference on Permafrost, edited by: Kane, D. L. and Hinkel, K. M., University of Alaska, Fairbanks, vol. 2, 1511–1518, 29 June–3 July 2008.

Rosgidromet, R. F.: Doklad ob osobennostyakh klimata na territorii Rossiyskoy Federatsii za 2016 god, M.: Federal'naya sluzhba po gidrometeorologii i monitoringu okruzhayushchey sredy, Rosgidromet, Moscow, 2017 (in Russian).

Savenko, V. S., Pokrovskii, O. S., Dupre, B., and Baturin, G. N.: The chemical composition of suspended matter of major rivers of Russia and adjacent countries, Dokl. Akad. Nauk, 398, 97–101, 2004 [Dokl. Earth Sci. 398, 938, 2004].

Schädel, C., Schuur, E. A. G., Bracho, R., Elberling, B., Knoblauch, C., Lee, H., Luo, Y., Shaver, G. R., and Turetsky, M. R.: Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data, Glob. Change Biol., 20, 641–652, https://doi.org/10.1111/gcb.12417, 2014.

Schlesinger, W. H. and Melack, J. M.: Transport of organic carbon in the world's rivers, Tellus, 33, 172–187, https://doi.org/10.3402/tellusa.v33i2.10706, 1981.

Serikova, S., Pokrovsky, O. S., Ala-Aho, P., Kazantsev, V., Kirpotin, S., Kopysov, S., Krickov, I., Laudon, H., Manasypov, R., Shirokova, L. S., Soulsby, C., Tetzlaff, D., and Karlsson, J.: High riverine CO_2 emissions at the permafrost boundary of Western Siberia, Nat. Geosci., 11, 825–829, https://doi.org/10.1038/s41561-018-0218-1, 2018.

Sheng, Y., Smith, L. C., MacDonald, G. M., Kremenetski, K. V., Frey, K. E., Velichko, A. A., Lee, M., Beilman, D. W., and Dubinin, P.: A high-resolution GIS-based inventory of the west Siberian peat carbon pool, Global Biogeochem. Cy., 18, GB3004, https://doi.org/10.1029/2003GB002190, 2004.

Shirokova, L. S., Pokrovsky, O. S., Kirpotin, S. N., Desmukh, C., Pokrovsky, B. G., Audry, S., and Viers, J.: Biogeochemistry of organic carbon, CO_2, CH_4, and trace elements in thermokarst water bodies in discontinuous permafrost zones of Western Siberia, Biogeochemistry, 113, 573–593, https://doi.org/10.1007/s10533-012-9790-4, 2013.

Smith, L., Sheng, Y., Macdonald, G., and Hinzman, L.: Disappearing Arctic lakes, Science, 308, p. 1429, https://doi.org/10.1126/science.1108142, 2005.

Stepanova, V. M., Pokrovsky, O. S., Viers, J., Mironycheva-Tokareva, N. P., Kosykh, N. P., and Vishnyakova, E. K.: Elemental composition of peat profiles in western Siberia: Effect of the micro-landscape, latitude position and permafrost coverage, Appl. Geochem., 53, 53–70, https://doi.org/10.1016/j.apgeochem.2014.12.004, 2015.

Tian, H., Yang, Q., Najjar, R., Ren, W., Friedrichs, M. A. M., Hopkinson, C. S., and Pan, S.: Anthropogenic and climatic influences on carbon fluxes from Eastern North America to the Atlantic ocean: a process-based modeling study, J. Geophys. Res.-Biogeo., 120, 752–772, https://doi.org/10.1002/2014JG002760, 2015.

Trofimova, I. E. and Balybina, A. S.: Classification of climates and climatic regionalization of the West-Siberian plain, Geography and Natural Resources, 35, 114–122, https://doi.org/10.1134/S1875372814020024, 2014.

Unger, D., Gaye-Haake, B., Neumann, K., Gebhardt, A. C., and Ittekkot, V.: Biogeochemistry of suspended and sedimentary material in the Ob and Yenisei rivers and Kara Sea: amino acids and amino sugars, Cont. Shelf. Res., 25, 437–460, https://doi.org/10.1016/j.csr.2004.09.014, 2005.

Vonk, J. E., Tank, S. E., Bowden, W. B., Laurion, I., Vincent, W. F., Alekseychik, P., Amyot, M., Billet, M. F., Canário, J., Cory, R. M., Deshpande, B. N., Helbig, M., Jammet, M., Karlsson, J., Larouche, J., MacMillan, G., Rautio, M., Walter Anthony, K. M., and Wickland, K. P.: Reviews and syntheses: Effects of permafrost thaw on Arctic aquatic ecosystems, Biogeosciences, 12, 7129–7167, https://doi.org/10.5194/bg-12-7129-2015, 2015.

von Wachenfeldt, E. and Tranvik, L. J.: Sedimentation in boreal lakes – The role of flocculation of allochthonous dissolved organic matter in the water column, Ecosystems, 11, 803–814, https://doi.org/10.1007/s10021-008-9162-z, 2008.

Von Wachenfeldt, E., Sobek, D., Bastviken, D., and Tranvik, L. J.: Linking allochthonous dissolved organic matter and boreal lake sediment carbon sequestration: The role of light-mediated ?occulation, Limnol. Oceanogr., 53, 2416–2426, 2008.

Von Wachenfeldt, E., Bastviken, D., and Tranvik, L. J.: Microbially induced occulation of allochthonous dissolved organic carbon in lakes, Limnol. Oceanogr., 54, 1811–1818, 2009.

Vorobyev, S. N., Pokrovsky, O. S., Serikova, S., Manasypov, R. M., Krickov, I. V., Shirokova, L. S., Lim, A., Kolesnichenko, L. G., Kirpotin, S. N., and Karlsson, J.: Permafrost boundary shift in western Siberia may not modify dissolved nutrient concentrations in rivers, Water, 9, 985, https://doi.org/10.3390/w9120985, 2017.

Wiegner, T. N., Tubal, R. L., and MacKenzie, R. A.: Bioavailability and export of dissolved organic matter from a tropical river during base- and stormflow conditions, Limnol. Oceanogr., 54, 1233–1242, https://doi.org/10.4319/lo.2009.54.4.1233, 2009.

Woo, M.-K.: Permafrost Hydrology, Springer, Heidelberg Dordrecht London Ney York, https://doi.org/10.1007/978-3-642-23462-0, 2012.

Wrona, F. J., Johansson M., Culp, J. M., Jenkins A., Mård J., Myers-Smith, I. H., Prowse, T. D., Vincent, W. F., and Wookey, P. A.: Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime, J. Geophys. Res.-Biogeo., 121, 650–674, https://doi.org/10.1002/2015JG003133, 2016.

Yang, Q., Zhang, X., Xu, X., Asrar, G. R., Smith, R. A., Shih, J. S., and Duan, S.: Spatial patterns and environmental controls of particulate organic carbon in surface waters in the conterminous United States, Sci. Total. Environ., 554–555, 266–275, https://doi.org/10.1016/j.scitotenv.2016.02.164, 2016.