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Coloured Dissolved Organic Matter Variability in Tundra Lakes of the Central Lena River Delta (N-Siberia)

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Abstract: In this study, we investigate the optical group of Coloured Dissolved Organic Matter (CDOM) in surface water bodies in the central Lena Delta, Arctic Siberia. Within the framework of Russian-German expeditions we sampled surface water from lakes and the Lena River during summers 2013 to 2016. Main study objects were lakes on Samoylov Island, a Holocene river terrace, and on Kurungnakh Island, an erosional remnant of the Late Pleistocene Yedoma formation. Supplementary samples were taken from the Lena River Olenekskaya branch bordering Kurungnakh and Samoylov. We investigated absorption and the type of CDOM. The magnitude of CDOM is given by its absorption, the type and freshness or source of CDOM is revealed by the CDOM Slope (S) value in the ultraviolet and the visible wavelength regions of CDOM absorption.

Results show different characteristics for thermokarst lakes on Samoylov and Kurungnakh Island in contrast to oxbow lakes on Samoylov. The type of pristine tundra thermokarst lakes on Samoylov Island shows lowest CDOM by absorption and no fresh terrestrial matter characterization. Some thermokarst lakes on Samoylov and on Kurungnakh show fresher terrestrial CDOM with equivalent low CDOM Slope ratio (Sr) values ≤1. We assume that on the Holocene river terrace of Samoylov, the lakes with CDOM Sr values ≤1 and higher CDOM absorption are influenced by the Lena River spring flood. The Lena River spring flood with high water level brings fresh terrestrial-derived CDOM in through flooding the lakes that are on lower topographic levels. The lake group that seems to be influenced by the Lena spring flood in every year are the floodplain lakes and oxbow lakes showing highest CDOM early in summer. The thermokarst lakes on Kurungnakh on the Yedoma plateau do not seem to be influenced by the Lena River spring flood. They show low to medium CDOM absorption.

We could define three different lake class types according to the event scale of terrestrial input: (1) pristine thermokarst tundra lakes on the Holocene terrace, (2) topographically low-lying lakes episodically influenced by the Lena River spring flood, and (3) thermokarst lakes on the Yedoma upland with steep topography and shore erosion processes to bring in terrestrial matter into the lakes.

Our study represents the first CDOM data collection and the first assessment of CDOM regimes in the lakes in the Lena River delta. This assessment sets reference conditions facilitating detecting future trends of CDOM over time.

Zuammenfassung: In dieser Studie untersuchen wir die optisch definierte Gruppe „Coloured Dissolved Organic Matter" (CDOM) in Oberflächengewässern im zentralen Lena Delta (Arktisches Sibirien). Die Seen im Lena Delta und die Flussarme der Lena wurden intensiv in den Sommern 2013 bis 2016 im Rahmen der Russisch-Deutschen Kooperation beprobt. Die Untersuchungsobjekte sind vor allem ausgesuchte Seen auf der Insel Samoylov, einer holozänen Flussterrasse, und auf der Insel Kurungnakh, einer spätpleistozänen Flussterrasse mit Yedoma-Deckschichten. Darüberhinaus wurde der Olenek beprobt, ein Nebenarm im Lena Delta, welcher entlang der Inseln Kurungnakh und Samoylov fließt. Wir untersuchten die CDOM-Absorption und den CDOM-Typus. Die CDOM-Größe ist gegeben durch die Absorption, den Typus und Frische-Status von CDOM. Die Herkunft wird durch den CDOM-Kurvenanstieg (S) im Ultraviolett und im sichtbaren Wellenlängenbereich der CDOM-Absorption ausgedrückt.

Die Ergebnisse zeigen, dass die Thermokarstseen auf Samoylov und auf Kurungnakh andere CDOM-Charakteristiken haben als die Altarm-Seen und der See auf der Überflutungsebene auf Samoylov. Der Typus „unbeeinflusster Tundra-See" auf Samoylov zeigt die niedrigste CDOM-Absorption und keine Anzeichen von frischem terrestrischen Materialeintrag. Einige der Thermokarstseen auf Samoylov und Kurungnakh zeigen Hinweise auf frisches terrestrisches Material mit einem entsprechend niedrigen CDOM Slope-Ratio (Sr) Wert ≤1. Wir nehmen an, dass auf der Holozänen Flussterrasse von Samoylov die Seen, welche einen CDOM Sr Wert ≤1 und hohes CDOM haben, vom Frühjahrshochwasser der Lena beeinflusst sind. Das Frühjahrshochwasser der Lena mit hohem Wasserstand bringt frisches terrestrisches CDOM in die Wasserkörper, indem die Seen auf den topographisch niedriger liegenden Bereichen geflutet werden. Die Seen, die auf Samoylov eindeutig jedes Jahr vom Frühjahrshochwasser beeinflusst werden, sind der See auf der Überflutungsebene und die Altarm-Seen, welche auch die höchsten CDOM-Absorptionswerte im Frühsommer zeigen. Dagegen sind die Thermokarstseen auf Kurungnakh auf dem Yedoma-Plateau nicht vom Frühjahrshochwasser beeinflusst. Diese Seen zeigen niedrige bis mittlere CDOM-Absorption.

In dieser Studie gelang es uns, über den terrigenen Eintrag als beeinflussendem Faktor drei verschiedene Seentypen zu definieren: (1) Thermokarst-Seen auf der Holozänen Terrasse; (2) topographisch niedriger liegende Seen die episodisch mit Lena Frühjahrs Hochwasser geflutet werden, und (3) Thermokarst Seen auf dem Yedoma Hochland mit steiler Topographie und Ufer-Erosionsprozessen die terrigene Organik in die Seen bringen.

Unsere Studie repräsentiert die erste CDOM Daten-Kompilation und die erste Einschätzung der CDOM Größenordnungen in den Seen des Lena Deltas. Diese erste Einschätzung ist auch die Referenz um zukünftige CDOM Trend-Entwicklungen abchätzen zu können.

INTRODUCTION

Lateral carbon fluxes from plant and soils into aquatic systems are an important component of the terrestrial carbon cycling linking terrestrial and aquatic systems. Carbon moves from land to water and from water to the atmosphere, while the land and atmosphere exchange carbon in both directions. Lateral carbon fluxes occur as particulate and dissolved carbon fluxes. Tranvik et al. (2009) describe inland waters as important participants in the carbon cycle, actively processing the carbon derived from terrestrial ecosystems that then makes its way into the atmosphere. The vertical carbon fluxes from inland waters occur via gas exchange due to microbial mineralization and photo-oxidation of the aquatic carbon pool. Kling et al. (1991) describe how Arctic lakes and streams act as gas conduits to the atmosphere. The authors measured carbon dioxide, CO_2, in aquatic ecosystems across Alaska tundra ecosystems and could show that CO_2 was released from the freshwater bodies to the atmosphere whereas the tundra landscape acted as sink for CO_2. Kling et al. (1991) also could show that CO_2 emission rates from lakes were proportional to the input and lake

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mineralization of the terrestrial organic carbon input. Lakes are a prominent landscape feature in the Arctic. Changes in the input of terrestrial organic carbon will change the ecosystem services and the Arctic tundra landscape carbon net exchange. Algesten et al. (2004) rise the question how future changes will change terrestrial carbon cycling between terrestrial and aquatic systems for boreal environments.

A highly reactive component of the terrestrial carbon cycling is the component of Dissolved Organic Matter (DOM) in soils and aquatic systems. Optical measurements of absorbance and fluorescence are increasingly used to investigate the magnitude, sources and composition of aquatic DOM. Coloured Dissolved Organic Matter (CDOM) is the operationally defined group of chromophores first introduced as "Gelbstoff" by Kalle (1949). Optical measurements and units are absorption-related (e.g. specific absorption coefficient per meter; the logarithmic slope value (S), across specific regions of the optical spectrum) or fluorescence-related (e.g., excitation and emission spectra).

CDOM is a major light absorbing constituent in natural surface waters (Bricaud et al. 1981, Davies-Colley & Vant 1987). The main source of allochthonous CDOM in terrestrial surface waters are humic and fulvic substances derived from terrestrial vegetation and soil in the catchment. The main contributors for autochthonous CDOM in lakes are phytoplankton, aquatic plants, and benthic algae (Thurmann 1985). Terrigenous CDOM has more aromatic molecules and is more "coloured", but highly susceptible to photodegradation processes (Helms et al. 2008). Sobek et al. (2007) describe how catchment and lake properties determine the DOM regime within particular lakes. Vincent et al. (1998) and Laurion et al. (1997) intensively investigated DOM in subarctic and arctic fresh water bodies in Canada from discontinuous to continuous permafrost and from taiga to tundra landscapes. They found that the land cover is a major source determining the magnitude of organic matter input into the lakes; lakes in tundra north of tree line are characterized by low organic matter regimes decreasing as the distance from tree line increases (Vincent & Pienitz 1996). To our knowledge, only few published studies and datasets on DOM in lakes are available for Siberian tundra permafrost landscapes, such as in Manasypov et al. (2015), Skorospekhova et al. (2016) and Dvornikov et al. (2016, 2017) who investigated lake-rich tundra permafrost landscapes in Yamal and Gydan Peninsula, East of the Yamal Peninsula. In the Lena Delta, Abnizova et al. (2012) were the first to investigate carbon cycling in lakes and ponds and found that the inorganic carbon was the major source for vertical carbon fluxes. Abnizova et al. (2012) used for their study on the dissolved carbon fraction the chemically defined group of Dissolved Organic Carbon (DOC).

Our study presents the first assessment on the quantity and quality of the optical group of CDOM in fresh water bodies in the Lena Delta. The author team collected the water samples, processed the samples for CDOM and assembled the CDOM data collection. The data collection could be only possible in the frame of Joint Russian-German expeditions specifically within the CarboPerm project framework that took place in the Lena Delta and the logistical support of the modern research basis "Samoylov Station" (Hubberten & Grigoriev 2014) providing the opportunity to sample in surface water bodies through several summer seasons.

We used our CDOM data collection to investigate if the spatial variability of CDOM is linked to different lake types. Is the terrestrial imprint significant and what event scale, i.e., what processes are involved to bring terrestrial DOM into the different lake systems?

STUDY AREA

The Lena Delta located in the subarctic tundra zone in Eastern Siberia is the biggest delta in the Arctic. The Lena Delta is underlain by continuous permafrost and can be subdivided into three geomorphological terraces (Grigoriev 1993, Schwamborn et al. 2002, Morgenstern et al. 2008, 2011, 2013, Pavlova & Dorozhkina 2000). The 1st Holocene terrace and active floodplain are characterized by flat relief and active interaction with Lena River during flood time. The 2nd terrace in the north-west Lena Delta is composed of Pleistocene alluvial sandy sediments. The 3rd Lena Delta terrace is mainly in the south west Lena Delta and represents the highest terrace with heights of 30 to 55 m above sea level (a.s.l.; Morgenstern et al. 2011). The 3rd terrace has at the base fluvial sandy sediments but is mostly composed by ice rich Yedoma (Schirrmeister et al. 2003). The 3rd terrace is also called the Ice Complex (Schirrmeister et al. 2011, Kaplina et al. 2009).

In this study, we investigate different lake types situated in different stratigraphic-geomorphological units in the central Lena Delta: thermokarst lakes on the 3rd terrace (Late Pleistocene Yedoma formation), thermokarst lakes and oxbow lakes on the Holocene terrace, and on the floodplain of Samoylov Island (Fig. 1).

Samoylov Island has a western low-lying part that is the modern floodplain which is flooded every year by the Lena River spring flood. The floodplain contains one permanent lake body with a maximum depth of around 1.5 m with emergent vegetation. The eastern part of Samoylov is the Holocene river terrace with an elevation of 10 to 16 m a.s.l. The Holocene river terrace is polygonal wet tundra and contains large thermokarst lakes (larger than 10 ha), shallow (around 1-1.5 m depth) and also deeper tundra ponds (>1.5 m), and water-filled polygonal cracks (Muster et al. 2012, 2013). Relatively large oxbow lakes (up to a few 100 m in diameter) are also present on Samoylov. The ground ice setting from the Holocene terrace originates in more flat-bottomed lakes. The low-relief terrain also contributes to coalescence of lakes causing noncircular shapes and irregular margin outlines for some of the lakes. Samoylov Island and its lakes are described in Boike et al. (2013, 2015). The investigated aquatic ecosystems are representative of most of the typical freshwater habitats in the vast Lena Delta area as described in Abramova et al. (2017). Chetverova et al. (2018) describe in detail the hydrochemistry and hydromorphometry of the thermokarst and oxbow lakes in the Lena Delta with a focus on Samoylov Island.

Kurungnakh Island has an elevation of 30 to 60 m a.s.l; its plateau and its lakes are not reached by the Lena River spring flood. The lakes of the deep ground ice environment of the Yedoma are the first generation of the large deep thermokarst lakes and second generation of the Alas lakes in Alas depressions (Morgenstern et al. 2011). Lakes on lower morpho-

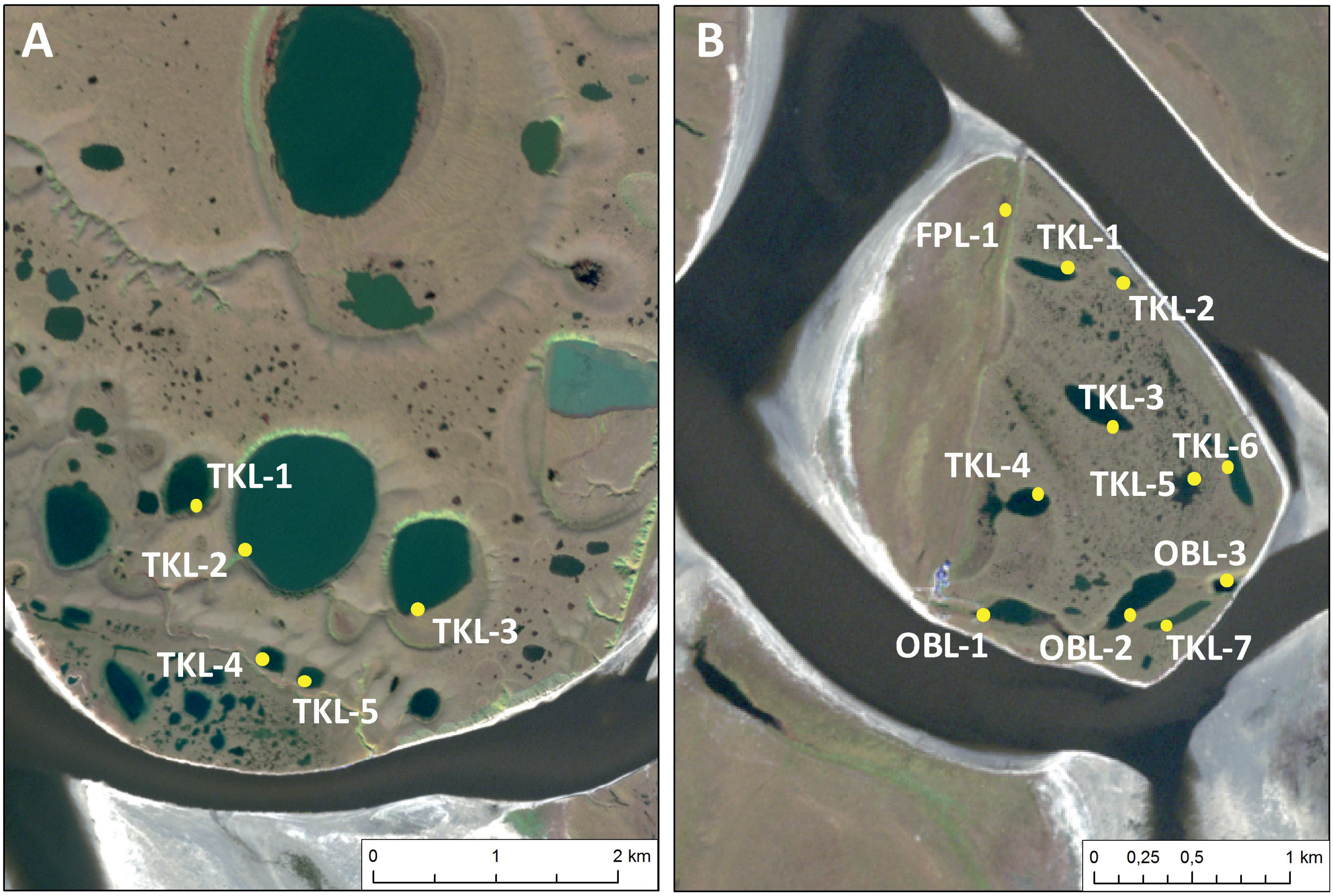

Fig. 1: Subset of central Lena Delta with (A) study sites on Kurungnakh (Yedoma upland) and (B) Samoylov (Holocene river terrace and modern floodplain). Sample sites are indicated with yellow points, codes are explained in Tables 1a,b. The Samoylov Station lays west of OBL-1 in image (B). Background images of (A) and (B) are Sentinel 2 satellite acquisitions in early September 2016 in quasi-true colour RGB composites.

Abb. 1: Ausschnitt des zentrales Lena Deltas mit den Inseln (A) Kurungnakh (Yedoma) und (B) Samoylov (Holozäne Flussterrasse und Überflutungsebene). Gelbe Punkte stellen die Proben-Lokationen dar; Erläuterung der Kodierung siehe in Tabelle 1. Die Forschungsstation Samoylov liegt westlich (links) von OBL-1 im Bild (B). Hintergrundbilder in (A) und (B) sind quasi Echtfarben-Darstellungen von Sentinel-2 Satelliten Akquisitionen von September 2016.

logical level on Kurungnakh can be influenced by the Lena River spring flood due to the flood wave moving over 100 m inland.

This type of Arctic lakes in the Lena Delta is subject to lake ice cover until early summer and by this monomictic with stratified conditions below the lake ice and mixed conditions during summer months. Table 1 shows the investigated lakes and characteristics with their geomorphological and hydrological lake type setting according to Xenopoulos et al. (2003). Hydrological lake type classification separates the lakes according to if they are closed systems or have inlets and/or outlets or are flow-through systems: seepage lakes are closed systems with no apparent surface inlet or outlets, seepage-inlet lakes have inlets, and no apparent surface outlets, headwater type of lakes has outlets and no apparent surface inlets and drainage lakes have inlets and outlets.

The naming of the lakes on Samoylov and Kurungnakh is according to the geomorphological classification (Tab. 1). The thermokarst lakes on Samoylov are named SA_TKL-1 to 5, the oxbow lakes SA_OBL-1 to 3, the Samoylov floodplain lake is named SAM_FPL-1. The thermokarst lakes on Kurungnakh are named accordingly KU_TKL-1 to 5.

DATA AND METHODS

Field Work

We sampled from 2013 to 2016 thermokarst lakes, the three oxbow lakes on Samoylov Island and the southern thermokarst lakes on Kurungnakh. We took the samples from the lakes either from the shore, or from the shallows of the lake or from boat. We sampled the Lena River from early summer to late summer from boat and from the shores specifically frequently with few days interval in 2014.

Water samples were filtrated in the field trough 0.7 µm pore-size glass fiber filter for CDOM and through 0.45 µm pore-size cellulose acetate filter for major ions and trace elements. Water samples for major ions and trace elements were collected, stored and transported in 20-60 ml plastic bottles pre-cleaned by nitric acid (1:1 diluted HNO_3). Water samples for cations were acidified in the field with 50-100 µl of 65 % HNO_3. Water samples for CDOM were stored and transported in brown glass bottles and kept cool and dark without freezing.

a)

name of lake working name	short name (code)	geomor-phol. setting	geomor-phol. lake type	hydrological lake type
Oxbow Lake 1 Banya Lake 1	SA_OBL-1	1st terrace	oxbow	drainage
Oxbow Lake 2 Banya Lake 2	SA_OBL-2	1st terrace	oxbow	drainage
Oxbow Lake 3 Banya Lake 3	SA_OBL-3	1st terrace	oxbow	drainage
Floodplain Lake 1	SA_FPL-1	flood plain	riparian	drainage
Thermokarst Lake 1 North Lake	SA_TKL-1	1st terrace	thermokarst	headwater
Thermokarst Lake 2 NE Lake	SA_TKL-2	1st terrace	thermokarst	headwater
Thermokarst Lake 3 Molo Lake	SA_TKL-3	1st terrace	thermokarst	seepage
Thermokarst Lake 4 Fish Lake	SA_TKL-4	1st terrace	thermokarst	headwater
Thermokarst Lake 5 Shallow Lake	SA_TKL-5	1st terrace	thermokarst	seepage
Thermokarst Lake 6 East Lake	SA_TKL-6	1st terrace	thermokarst	seepage
Thermokarst Lake 7 South Lake	SA_TKL-7	1st terrace	thermokarst	headwater

b)

Thermokarst Lake 1 West Lucky Lake	KU_TKL-1	3rd terrace	thermokarst	headwater
Thermokarst Lake 2 Lucky Lake	KU_TKL-2	3rd terrace	thermokarst	drainage
Thermokarst Lake 3 Oval Lake	KU_TKL-3	3rd terrace	thermokarst	headwater
Thermokarst Lake 4 SW Lake	KU_TKL-4	lower terrace	thermokarst	headwater
Thermokarst Lake 5 (SE Lake)	KU_TKL-5	lower terrace	thermokarst	headwater

Tab. 1: Investigated lakes on **a)** Samoylov Island (SA) and on **b)** Kurungnakg Island (KU) with name, short name code and hydrological lake type.

Tab. 1: Die untersuchten Seen auf der **a)** Samoylov Insel (SA) und auf der **b)** Kurungnakg Insel mit Namen, Kodierung und Zuornung zu Seentypus.

Measurement and analyses of CDOM

CDOM was measured using the dual-beam spectrometer SPECORD 200 at the Otto Schmidt Laboratory (OSL), of the Arctic and Antarctic Research Institute, (AARI), in St. Petersburg. Absorbance (A) spectra of CDOM were measured between 200 m and 750 nm with 1 nm spectral resolution. For measurements of A we used two 5 cm length quartz cuvettes – one was filled with the water sample, the second one was filled with purified water as the blank reference for water without CDOM. Water samples and blanks of purified water were always measured at the same temperature. The water samples that were stored cold were given time to adapt to room temperature.

A is either expressed as the natural logarithm (ln) to the base e or the logarithm to the base 10 (log). WinASPECT program connected to spectrometer SPECORD 200 stores A as logarithm to the base 10. A with base 10 logarithm was transformed to CDOM absorption per meter, a_{CDOM} [m^{-1}], using the factor 2.303 transforming from log to ln and by the cuvette length (l) in meter using the equation

$$a_{CDOM}(\lambda) = \frac{2.303*A}{l} \ [m^{-1}] \qquad (1)$$

The spectral S, (e.g., Twardowski et al. 2009) was calculated within the wavelength ranges of 275 nm to 295 nm, 350 nm to 400 nm, and 300 nm to 500 nm using the equation

$$a_{CDOM}(\lambda) = a_{CDOM}(\lambda_0)e^{-S(\lambda-\lambda_0)} \ [m^{-1}], \qquad (2)$$

where wavelength = λ; specific wavelength = λ0.

According to Helms et al. (2008), the UV/VIS spectral slape ratio Sr, can be used as a fast and reproducible method for characterizing CDOM in natural waters and is defined by equation:

$$S_r = S_{275-295}/S_{350-400} \qquad (3)$$

Measurement and analyses of inorganic ionic and trace element composition

We analysed the water samples for major ions and trace element concentration at the OSL and at the hydrochemical analytical laboratory of the Alfred Wegener Institute (AWI, Potsdam) using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) for Calcium (Ca), Potassium (K), magnesium (Mg), sodium (Na), chloride (Cl), sulphate (SO4) and bicarbonate (HCO3), and for the trace elements (Al, B, Ba, Br, Cd, Co, Cu, Fe, Hg, Li, Mn, Mo, Ni, P, Pb, Si, Sr, Ti, Zn) (see also Chetverova et al. 2018, this volume).

RESULTS

CDOM in the Lena Delta tundra lakes and in the Lena River

Optical parameters and indices of CDOM from the joint Russian-German sampling activities in 2013 to 2016 are published together with the location (coordinates in decimal degree) and the sampling date in the PANGAEA research data repository in Skorospekhova et al. (2017). The CarboPerm WebGIS database (Haas et al. 2016) visualizes the sample locations of the Lena River discharge measurements from Fedorova et al. (2013, 2015) and the CDOM data collection from this study (Skorospekhova et al. 2017). Table 2 provides an overview on the selected CDOM parameters from the main lakes on Samoylov Island and Kurungnakh: $a_{CDOM}(440)$, the S value deduced from the ultraviolet (UV) and visible (VIS), and the UV/VIS Sr.

Measured $a_{CDOM}(440)$ in summer season for these 16 lakes ranges from 0.23 to 5.12 m^{-1} (median value 0.96 ±1.09 m^{-1}, n = 67). That are much lower CDOM absorption coefficients than measured in the Lena River. Instead of highest $a_{CDOM}(440)$ value during the river spring flood was measured on May 31, 2014, with a_{CDOM} (440) = 9.16 m^{-1}. The CDOM magnitude decreases during June to $a_{CDOM}(440)$ values of 5-6 m^{-1}, decreasing further in July–August and September to 2-3 m^{-1} (Tab. 2). Through three years, 2015 was characterized by higher CDOM absorption coefficients among lakes in the summer season, however not the full group of same lakes was sampled from year to year, therefore a direct comparison of median values is not possible between the years. The median values demonstrate the low CDOM regimes of the lakes in the central Lena Delta: $a_{CDOM}(440)$ median value is 0.94 ±1.03 m^{-1} (n = 29) in 2014, $a_{CDOM}(440)$ median value is 1.08 ±1.22 m^{-1} (n = 23), and 0.87 ±0.97 m^{-1} (n = 15).

The group of oxbow lakes and the floodplain lake on Samoylov are characterized by higher $a_{CDOM}(440)$ (1.16 to 5.12 m^{-1}, median value 2.72 ±1.18 m^{-1}, n = 17, 2014–2016) (Fig. 2) than the group of thermokarst lakes on the Holocene Samoylov terrace (0.38 to 1.32 m^{-1}, median value 0.85 ±0.23 m^{-1}, n = 37, 2014–2016) and the thermokarst lakes on Kurungnakh (0.23 to 1.78 m^{-1}, median value 0.65 ±0.42 m^{-1}, n = 13, 2014–2015) (Fig. 3). The drainage lake type on Samoylov is characterized by higher CDOM compared to the other lake types of headwater or seepage lakes: the oxbow lakes SA_OBL-1,2,3 and the floodplain lake SA_FPL-1 on Samoylov show three times higher CDOM than the other lakes on Samoylov Island.

The median of S values in the visible wavelength range, S(VIS), S(300-500) for thermokarst lakes on Samoylov Island remains the same through 2014 to 2016 (S(VIS) = 0.016 nm^{-1}) with a small deviation among years with 0.016 nm^{-1} for 2014 and 2016 and 0.017 nm^{-1} for 2015. In contrast, including also ponds and small water bodies, and the thermokarst lakes on Kurungakh Island, S(300-500) value shows a wide value range

Name of lake	short name (code)	$a_{CDOM}(440)$ (min - max)	S (300-500) (min-max)	Sr slope ratio (min-max)	slope ratio Sr type
Samoylov, Oxbow Lake 1 (Banya Lake 1)	SA_OBL-1	1.81 - 2.72	0.0.15 - 0.017	1 – 1.1	<1.2
Samoylov, Oxbow Lake 2 (Banya Lake 2)	SA_OBL-2	1.16 - 2.95	0.0.15 - 0.017	0.9 – 1.2	<1.2
Samoylov, Oxbow Lake 3 (Banya Lake 3)	SA_OBL-3	3.12 - 5.12	0.0.15 - 0.018	0.9 – 1	<1.2
Samoylov, Floodplain Lake 1	SA_FPL-1	1.58	0.015	1	<1.2
Samoylov, Thermokarst Lake 6 (East Lake)	SA_TKL-6	0.75 - 1.05	0.0.14 - 0.018	1.1 – 1.3	~1.2
Samoylov, Thermokarst Lake 4 (Fish Lake)	SA_TKL-4	0.82 - 1.32	0.016 - 0.018	1.1 – 1.3	~1.2
Samoylov, Thermokarst Lake 3 (Molo Lake)	SA_TKL-3	0.38 - 0.54	0.013 - 0.017	1.3 – 1.7	>1.2
Samoylov, Thermokarst Lake 1 (North Lake)	SA_TKL-1	0.43 - 0.76	0.014 - 0.022	1.1 – 1.4	~1.2
Samoylov, Thermokarst Lake 2 (North-East Lake)	SA_TKL-2	0.65 - 0.9	0.015 -0.017	1.2 – 1.4	>1.2
Samoylov, Thermokarst Lake 5 (Shallow Lake)	SA_TKL-5	0.5 - 1.14	0.015 -0.017	1.2 – 1.3	>1.2
Samoylov, Thermokarst Lake 7 (South Lake)	SA_TKL-7	0.94 - 1.04	0.017 -0.019	1.2 – 1,4	>1.2
Kurungnakh, Thermokarst Lake 2 (Lucky Lake)	KU_TKL-2	0.64 - 1.04	0.018- 0.021	1.1 – 1.3	~1.2
Kurungnakh, Thermokarst Lake 3 (Oval Lake)	KU_TKL-3	0.53 - 1.08	0.016 - 0.024	1.1 – 1.2	<1.2
Kurungnakh, Thermokarst Lake 4 (South West Lake)	KU_TKL-4	0.31 - 0.42	0.016 - 0.017	1.4	>1.2
Kurungnakh, Thermokarst Lake 5 (South East Lake)	KU_TKL-5	0.23 - 1.78	0.010 - 0.022	1.2 – 1.9	>1.2
Kurungnakh, Thermokarst Lake 1 (lake West of Lucky Lake)	KU_TKL-1	0.76	0.012	1.5	>1.2

Tab. 2: Value range of CDOM parameters for aCDOM(440), S(300-500), Slope ratio (Sr) and the Slope ratio type of lakes on Samoylov Island and Kurungnakh Island.

Tab. 2: Wertebereich von CDOM Parametern für aCDOM(440), S(300-500), Slope ratio (Sr) und den „slope ratio" Typen der Seen auf der Samoylov und der Kurungnakh Insel.

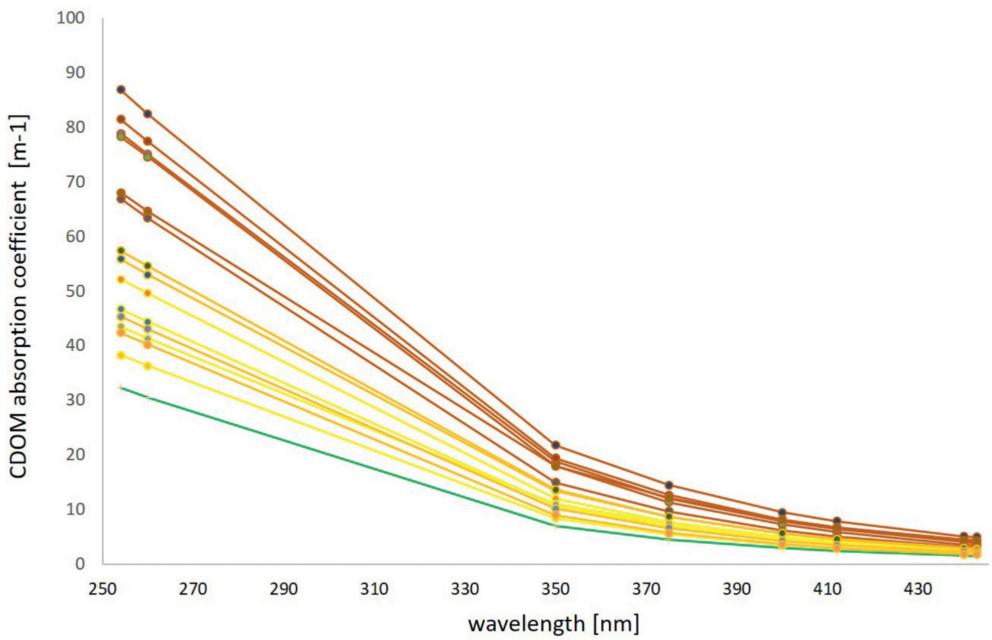

Fig. 2: CDOM absorption coefficient (m^{-1}), for discrete measurements at 254, 260, 350, 375, 400, 412, 440, 443 nm (PANGAEA data publication, SKOROSPEKHOVA et al. 2017) in the group of oxbow lakes and floodplain lake on Samoylov Island. Green colour: floodplain lake SA_FLP; yellow: SA_OBL-1; orange: SA_OBL-2; ocker: SA_OBL-3.

Abb. 2: CDOM Absorptionskoeffizient (m^{-1}) an diskreten Messungen bei 254, 260, 350, 375, 400, 412, 440, 443 nm (aus PANGAEA Datenpublikation: SKOROSPEKHOVA et al. 2017) für die Gruppe der Altarm-Seen und des Sees auf der Überflutungsebene der Samoylov Insel; grün: See auf Überflutungsebene SA_FPL-1; gelb: SA_OBL-1; orange: SA_OBL-2; ocker: SA_OBL-3.

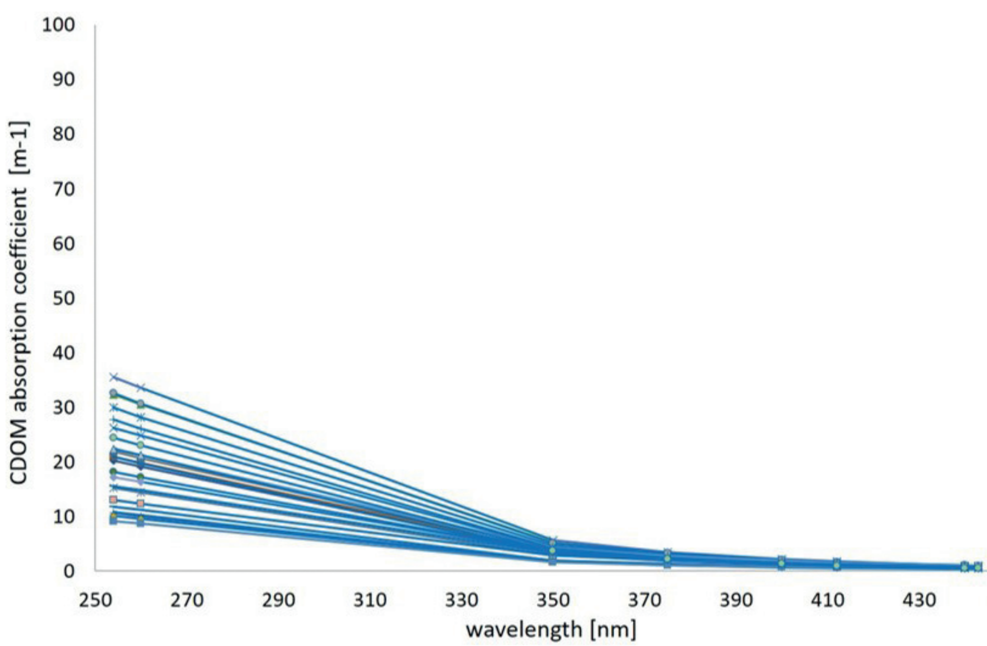

Fig. 3: CDOM absorption coefficient (m^{-1}) for discrete measurements at 254, 260, 350, 375, 400, 412, 440, 443 nm (PANGAEA data publication, SKOROSPEKHOVA et al. 2017) for the group of tundra lakes on Kurungnakh Island and Samoylov Island (blue colour tones).

Abb. 3: CDOM Absorptionskoeffizient in (m^{-1}) an diskreten Messungen bei 254, 260, 350, 375, 400, 412, 440, 443 nm (aus PANGAEA Datenpublikation: SKOROPECHOVA et al. 2017) für die Gruppe der Tundra-Seen auf der Kurungnakh Insel und der Samoylov Insel (blaue Farbtöne).

from 0.010 to 0.024 nm^{-1}. The value range of S(300-500) of the Lena River samples varies from 0.014 to 0.017 nm^{-1} showing the typical value range of terrestrial influenced surface waters. The median value of S(300-500) = 0.016 nm^{-1} of the different groups of lakes is the same for the group of oxbow lakes as well as for the group of thermokarst lakes located on Samoylov Island. The data also show that there is no significant influence of the hydrological type on the S(300-500) values: either for closed systems or seepage or headwater systems. The main variation for thermokarst lakes is due to high S(300-500) for some of the thermokarst lakes such as SA_TKL-1 north of Samoylov Station, and KU_TKL-3 on Kurungnakh Island.

Main findings related to S values of the UV wavelength region S(275-295) are that they show considerable difference among lakes located on different topographical levels. Median value of S(275-295) equals 0.017 nm^{-1} for the group of oxbow lakes, in contrast to S(275-295) = 0.022 nm^{-1} for the thermokarst lakes on Samoylov and 0.024 nm^{-1} for the thermokarst lakes on Kurungnakh Island. Precisely the wide range of the S in the UV wavelength region, S(275-295) regulates Sr. We found lowest values of Sr = 0.8 to 0.9 in the drained lake type representing a remaining pond on Kurungnakh. Typical values for the Lena River are Sr values from 0.8 to 1. All oxbow lakes and the floodplain lake on Samoylov Island show Sr values around 1 or ≤1.2. SA_TKL-1,4, and 6 lakes on Samoylov Island and KU_TKL-2 and 3 lakes on Kurungnakh Island have transitional Sr values around Sr = 1.2. All other studied lakes show high Sr values >1.2. On Samoylov Island the maximum Sr values with a range from 1.3 to 1.7 characterize SA_TKL-5 in the central part of the island. Hence, Sr is lower among oxbow lakes of Samoylov Island (median Sr = 1), and higher for thermokarst lakes on Samoylov (median Sr = 1.2) and thermokarst lakes on Kurungnakh Island (median Sr = 1.3).

DISCUSSION

Influence of landscape forms and Lena River spring flood

The spectral characteristics of CDOM such as S in the UV and visible wavelength ranges, S(UV) and S(VIS), can be used to investigate CDOM freshness and CDOM sources. S(VIS) = 0.014 to 0.017 nm^{-1} is a typical range for CDOM S values in fresh water bodies (e.g., Helms et al. 2008). Deviations of S(UV) from S(VIS) can indicate different types and processes on surface water CDOM. S values of S(VIS) in the wavelength range between 300 to 500 nm or 350 to 400 nm higher than 0.02 nm^{-1} is indicative for dominance of autochthonous DOM, i.e. CDOM coming from lysis and degradation of phytoplankton and also is in the same way indicative for photobleaching of terrestrial (allochthonous) DOM. For deeper investigation on CDOM type and CDOM sources fluorescence-based investigations would be needed. The UV/VIS value, Sr = 1 is the typical Sr value for freshwater surface waters. Sr <1 points to fresh and humic-rich terrestrial organic matter, whereas Sr >1.2 may indicate photo-degradation.

The lowest CDOM absorption coefficients are observed in the lakes of the 3rd terrace on Kurungnakh and on the higher elevated central and northern parts of Samoylov Island. These lakes also show Sr ≥1.2. The maximum Sr (1.3 to 1.7) of this type of lakes was found in SA_TKL-5 in the central part of the island that is also the deepest thermokarst lake on Samoylov. These lakes represent pristine tundra lakes with small lake catchments with low morphology. Input of continuous fresh terrestrial organic matter from snow melt processes and river floods seem to be low in the central part of the Holocene Samoylov terrace because this group of lakes have low CDOM and high S values as indication of no fresh terrestrial material. The organic matter in lake SA_TKL-5 seems to show the highest photobleaching regarding the high Sr with low fresh organic matter input.

SA_OBL-1,2,3, and SA_FPL-1 are lakes on Samoylov with lower S values around 1 and higher CDOM than in all other lakes. This group of oxbow lakes and floodplain lake shows highest CDOM in the early summer. The lowest-lying oxbow lake SA_OBL-3 contains the highest CDOM. In most years, CDOM S gets higher during summer months indicating less coloured CDOM and also, we observe that the CDOM magnitude gets lower. In several of the lakes on Samoylov Island, CDOM seems to become degraded through the summer months, because in some of the years the S value range indicates slightly less coloured CDOM and CDOM absorption tends to decrease in the months following the spring flood.

Similar dynamics we also found for some of the dissolved mineral components in the lakes on Samoylov Island. The Lena River spring flood seems to protrude over and under the lake ice (pers. comm. of rangers from the Lena Delta Reservate). Concentration of dissolved nutrients, e.g., silicates and phosphates are higher in the Lena River than in the lakes on Samoylov Island (Chetverova et al. 2013). The highest concentrations of silicates (>1,000 mg l^{-1}) characterize the floodplain lake and oxbow lakes, specifically, SA_OBL-3 that is annually flooded in spring. Chetverova et al. (2018) describe that maximum concentrations of phosphates were measured in the middle of July when lake ice cover and the ground ice in soil active layer are melting with concentrations of silicates about 500 mg l^{-1} in thermokarst lakes (SA_TKL-3 and 6). The seasonal dynamics for nutrients is similarly to CDOM and shows a slight decrease of concentrations during summer season in most of the years.

The Lena River spring flood may also reach the lakes SA_TKL 2,4,5, and 6 with lowering S(UV) value to a range from 0.020 to 0.022 nm^{-1}. Thermokarst lakes with no terrestrial organic matter input show S(UV) values up to 0.024 nm^{-1}. We know that the floodplain and the oxbow lakes on Samoylov Island are regularly flooded by the Lena River during the period of the spring flood with high water level. Abramova et al. (2017) and Osudar et al. (2016) show that the Lena River has a strong influence on the structure of the pelagic zooplankton and bacterial communities in lake water bodies within its delta. The highest zooplankton diversity occurred in those lakes that were regularly influenced by river water during spring floods. The permanent floodplain waterbodies on the delta islands have accumulated invasive species (Abramova et al. (2017). The Lena River spring flood brings also fresh terrestrial-derived CDOM into the lower-lying lakes on Samoylov. We assume that the floodplain lake SA_FPL-1 and the lowest laying oxbow lake SA_OBL-3 are regularly intensively flooded and the higher-lying oxbow lakes SA_OBL-1 and 2 less intense.

Thermokarst lakes KU_TKL-1 and 2 on Kurungnakh are the largest of the studied lakes. Catchments of KU_TKL-1 and 2 are located on the Late Pleistocene terrace and are much larger and contain steeper slopes than the thermokarst lakes on Samoylov. Yet, KU_TKL-1 and 2 contain low to moderate CDOM. KU_TKL-1 partly shows lower S(UV) indicating some fresh terrestrial matter input. The coastal slopes and cliffs of these lakes partly have outcrop of Later Pleistocene material potentially providing ancient organic matter input into the lakes.

In the tundra landscape of the central Lena Delta, lateral fluxes of inorganic N and P from the land into the aquatic systems are exceedingly low (Chetverova et al. 2017) that is also valid for the lateral carbon fluxes that we show in this study using CDOM. Like this, the central Lena Delta tundra landscape is characterized by thermokarst lakes with low CDOM and nutrient regimes. Hobbie et al. (2014) describe these low lateral nutrient and carbon fluxes also from the tundra landscape of the Toolik Lake region, North Slope, Alaska. The Toolik Lake catchment is large with steep morphology and intense snow melt in spring (Hobbie et al. 2014). Extinction coefficients measured in Toolik Lake in summer (wavelengths 395 nm, 380 nm) were around 4 and 5 m^{-1}, respectively. We can compare extinction coefficients versus the CDOM absorption in magnitude in case of transparent lake water. Extinction includes both optical processes, scattering and absorption, and is measured on non-filtrated samples. However, if particle scattering is a minor process determining the extinction coefficient such as in the oligotrophic Toolik Lake system the extinction coefficient is determined by CDOM. If we compare the magnitude of extinction to the magnitude of CDOM absorption $a_{CDOM}(400)$, $a_{CDOM}(375)$, of the Lena Delta lakes this magnitude is most equal to the group of oxbow lakes on the Holocene Samoylov terrace that have the hydrological connectivity to the Lena River in spring.

For the central Yamal region, DVORNIKOV et al. (2017) found that flooding in spring from the Mordy-Yakha River network enriches the group of lakes in CDOM on the lower topographic levels (n = 7, mean $a_{CDOM}(440)$ = 3.8 m^{-1}) that is similar to the group of oxbow lakes and the floodplain lake on Samoylov (n = 17, $a_{CDOM}(440)$ = 1.16-5.12 m^{-1}, 2014–2016). Whereas in the Yamal permafrost landscape also thermokarst lakes on higher topographical level that are not influenced by the spring flood are enriched in CDOM: in Yamal, the activation of thermocirques led to a large input of terrestrial organic matter resulting in high CDOM (n = 15, mean $a_{CDOM}(440)$ = 5.3 m^{-1}). This is of a much higher CDOM magnitude than the group of thermokarst lakes on the Holocene Samoylov terrace (n = 37, $a_{CDOM}(440)$ = 0.38-1.32 m^{-1}, 2014–2016) and the thermoskarst lakes on Kurungnakh (n = 13, $a_{CDOM}(440)$ = 0.23-1.78 m^{-1}, 2014–2015).

Arctic tundra landscapes are considered to be a sink for atmospheric carbon dioxide during summer months that is also true for the central Lena Delta during July and August (KUTZBACH et al. 2007). Whereas the waterbodies emit CO_2 proportionally to the organic carbon regime and the mineralization of the terrestrial organic carbon in the lakes (KLING et al. 1991). Because the thermokarst lakes of the tundra landscape of the Lena Delta contain low CDOM the organic carbon source for CO_2 vertical fluxes from water to the atmosphere is limited. In fact, ABIZNOVA et al. (2012) could show that the considerable CO_2 emission from thermokarst lakes on Samoylow was predominantly driven by the dissolved inorganic carbon pool much less then by the low organic carbon pool.

CONCLUSIONS

The central Lena Delta and the logistic support by the Samoylov Research Station offered the unique opportunity to investigate CDOM across different type of lakes in a lowland permafrost tundra landscape with abundant freshwater bodies on different terrace levels and catchment types. To our knowledge there are no publications on CDOM in freshwater bodies in the Lena Delta, the largest delta in the Arctic. We show for the first time a compilation of CDOM values, ranges and CDOM dynamics in the lake types of the central Lena Delta.

CDOM results show different characteristics for thermokarst lakes on Samoylov Island and Kurungnakh Island in contrast to the floodplain lake and the oxbow lakes on Samoylov Island. We assume that the Lena River spring flood with high water level brings fresh terrestrial-derived CDOM in through flooding the lakes that are on lowest topographic levels. This group that is intensively influenced by the Lena spring flood contains the floodplain lakes and the group of oxbow lakes with higher CDOM than the thermokarst lakes.

The type of pristine tundra lakes on the Holocene terrace of Samoylov Island shows lowest CDOM by absorption and no fresh terrestrial matter characterization visible in the CDOM S and Sr values. Some of the thermokarst lakes on Samoylov Island and on Kurungnakh Island show relative fresher terrestrial CDOM input than others. The large Yedoma thermokarst lakes on Kurungnakh are not influenced by the Lena River spring flood.

This first assessment of CDOM regimes of the lakes in the Lena River delta can be used to determine reference conditions and to facilitate detecting future trends in organic geochemistry over time by accounting for variation among the three different lake class types according to the event scale of terrestrial input: (1) pristine thermokarst tundra lakes on the Holocene terrace; (2) topographically low-lying lakes episodically influenced by the Lena River spring flood, and (3) thermokarst lakes on the Yedoma upland with steep topography and shore erosion processes to bring in terrestrial matter into the lakes.

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