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Amplified carbon release from vast West Siberian peatlands by 2100

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[1] Extensive new data from previously unstudied Siberian streams and rivers suggest that mobilization of currently frozen, high-latitude soil carbon is likely over the next century in response to predicted Arctic warming. We present dissolved organic carbon (DOC) measurements from ninety-six watersheds in West Siberia, a region that contains the world's largest stores of peat carbon, exports massive volumes of freshwater and DOC to the Arctic Ocean, and is warming faster than the Arctic as a whole. The sample sites span $\sim 10^6$ km^2 over a large climatic gradient (∼55–68°N), providing data on a much broader spatial scale than previous studies and for the first time explicitly examining stream DOC in permafrost peatland environments. Our results show that cold, permafrost-influenced watersheds release little DOC to streams, regardless of the extent of peatland cover. However, we find considerably higher concentrations in warm, permafrost-free watersheds, rising sharply as a function of peatland cover. The two regimes are demarcated by the position of the −2°C mean annual air temperature (MAAT) isotherm, which is also approximately coincident with the permafrost limit. Climate model simulations for the next century predict near-doubling of West Siberian land surface areas with a MAAT warmer than −2°C, suggesting up to ∼700% increases in stream DOC concentrations and ∼2.7–4.3 Tg yr^{-1} (∼29–46%) increases in DOC flux to the Arctic Ocean. **Citation:** Frey, K. E., and L. C. Smith (2005), Amplified carbon release from vast West Siberian peatlands by 2100, *Geophys. Res. Lett.*, *32*, L09401, doi:10.1029/2004GL022025.

1. Introduction

[2] The potential impacts of climate warming on peatland carbon cycling are subject to ongoing debate. Since the Last Glacial Maximum, northern peatlands have behaved primarily as a net sink for atmospheric carbon, storing up to ∼455 Pg C or one-third of the global soil carbon pool [*Gorham*, 1991]. However, the likely fate of this carbon under a warming climate remains a major unanswered question in Arctic science [e.g., *Moore et al.*, 1998]. Previous studies of northern peatlands and soils have focused primarily on the potential for carbon release to the atmosphere through enhanced CO_2 and/or CH_4 gas emissions [*Gorham*, 1991; *Oechel et al.*, 1993]. Recently, the release of DOC to streams and rivers has emerged as an additional and crucial negative term in the carbon balance of peatlands [*Pastor et al.*, 2003; *Billett et al.*, 2004], one that can cause a net carbon loss in peatlands that would otherwise appear to be a net carbon sink [*Billett et al.*, 2004]. Furthermore, this carbon release may be temperature sensitive: DOC concentrations in streams draining peatlands of the United Kingdom rose 65% from 1988–2000, attributed to warming air temperatures [*Freeman et al.*, 2001]. Whether or not such trends may be extrapolated into the future remains contentious [e.g., *Evans et al.*, 2002], but it does appear that high-latitude soils and peatlands are particularly susceptible to temperature-driven increases in DOC production [*Neff and Hooper*, 2002]. The outcome of this debate is critical for understanding the response of northern peatlands to climate warming and also for assessing a potential positive feedback to warming: DOC in part drives large CO_2 emissions from lake and river surfaces to the atmosphere [e.g., *Kling et al.*, 1991] and when delivered to the Arctic Ocean, a significant portion is also rapidly mineralized and returned to the atmosphere [*Hansell et al.*, 2004].

[3] West Siberia contains the most extensive peatlands in the world, storing at least 70.2 Pg C and covering ∼600,000 km^2 [*Sheng et al.*, 2004; *Smith et al.*, 2004]. Furthermore, the region is experiencing rapidly warming air temperatures that are rising faster than the Arctic as a whole [*Serreze et al.*, 2000; *Frey and Smith*, 2003]. The Ob' and Yenisey rivers drain these peatlands en route to the Kara Sea, which consequently receives more dissolved organic matter (DOM) than any other part of the Arctic Ocean [*Opsahl et al.*, 1999]. The Arctic Ocean in turn is an important global sink for terrestrial DOM, receiving more DOM per unit volume than any other ocean basin in the world [*Opsahl et al.*, 1999]. Rivers draining West Siberian peatlands thus provide a globally significant link between a massive pool of terrestrial organic carbon and the adjacent marine environment. The large size ($\sim 2.63 \times 10^6$ km^2) and latitudinal range (∼50–74°N) of West Siberia allows for a significant climatic gradient across the region, with MAATs ranging from −10°C to +2°C and permafrost influencing ∼55% of its area (northwards of ∼60°N; Figure 1).

[4] Until now, the remoteness of West Siberia has constrained most water sampling campaigns to the estuaries and mainstems of the Ob'-Irtysh and Yenisey rivers. Here, we present measurements of stream and river DOC concentration from 96 watersheds distributed throughout West Siberia, both north and south of the permafrost limit (Figure 1). Relationships are established between measured DOC, the percentage of peatland cover, and the MAAT of each watershed. These relationships are subsequently used to (i) explore mechanisms for observed spatial patterns in DOC and (ii) estimate the response of DOC concentrations and fluxes to warming air temperatures predicted by most general

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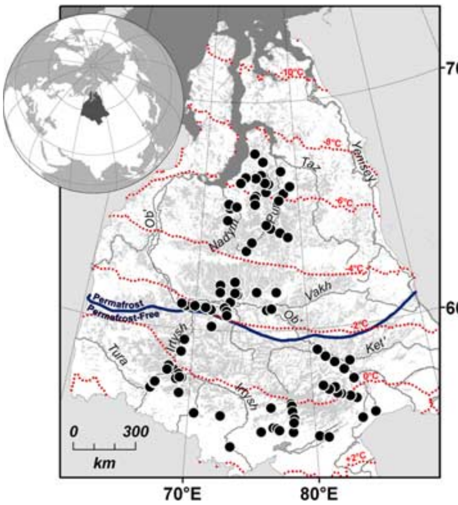

Figure 1. Locations of 96 water samples collected throughout West Siberia. The southern limit of permafrost, mean annual air temperature (MAAT) isotherms, and peatland boundaries (gray polygons) are also shown.

circulation model (GCM) simulations for West Siberia in the next century.

2. Data and Methods

[5] Sampling campaigns were undertaken throughout West Siberia during the late-summer period (mid-July through late August) of 1999, 2000 and 2001. Ninety-six spatially distributed water samples were collected from streams and rivers throughout the region, spanning a latitudinal gradient from ~55–68°N and covering ~10^6 km^2 (Figure 1). Sampled watersheds include 43 cold permafrost-influenced (CPI) and 53 warm permafrost-free (WPF) catchments, with drainage basin areas ranging from 38 km^2 to 2.7 × 10^6 km^2. As such, these measurements are collected at a much larger spatial scale than previous studies [e.g., *Freeman et al.*, 2001; *Pastor et al.*, 2003; *Billett et al.*, 2004] and for the first time explicitly examine stream DOC in permafrost peatland environments. Water samples were filtered in the field through Osmonics® 0.22 micron mixed esters membranes, stored in acid-washed high density polyethylene bottles without head space to minimize degassing and algal growth, and refrigerated at 4°C until analyzed. DOC concentrations were measured on a Shimadzu 5000 TOC-Analyzer in the Department of Ecology and Systematics at Cornell University.

[6] Separation of CPI and WPF watersheds was established using the southern limit of permafrost as mapped by *Brown et al.* [1998]. Watershed areas were delineated with ESRI® ArcGIS™ v. 8.0 using Digital Chart of the World drainage networks, the GTOPO30 digital elevation model, U.S. Tactical Pilotage Charts, U.S. Operational Navigation Charts, and Russian Oblast maps. The percentage of peatland cover contained within each watershed was computed using a comprehensive GIS-based inventory of West Siberian peatlands [*Sheng et al.*, 2004; *Smith et al.*, 2004]. MAAT was calculated for each watershed using gridded climate normals for years 1961–1990 [*New et al.*, 1999]. GCM simulations, including the Geophysical Fluid Dynamics Laboratory R30, the Canadian Center for Climate Modelling and Analysis CGCM2, and the Max Planck Institute für Meteorologie ECHAM4 models were obtained from the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk). Model simulations were averaged over years 2071–2100. Map-based area calculations for all data were performed in the GIS using a Lambert Azimuthal Equal Area map projection.

3. Observations

[7] Measured DOC concentrations in West Siberian streams and rivers reveal a remarkable contrast between CPI and WPF watersheds (Figures 2 and 3). In CPI watersheds, stream DOC concentrations are uniformly low, regardless of the percentage of peatland cover within the watershed. In contrast, DOC concentrations in WPF watersheds rise rapidly as a function of peatland cover (Figure 2). Averaged across all basins, concentrations in WPF watersheds are about triple those for CPI watersheds (33 ± 17 mg L^{-1} vs. 10 ± 6 mg L^{-1}), but even higher contrasts are found in watersheds with extensive peatland cover (e.g., for watersheds with 75% peatland cover, ~55 mg L^{-1} vs. ~10 mg L^{-1}). The transition from low to high DOC concentrations occurs approximately at the position of the −2°C MAAT isotherm (Figure 3), which also coincides with the southern limit of permafrost (Figure 1). Therefore, the −2°C isotherm position and the permafrost limit together mark a critical juncture, south of which watershed DOC concentrations begin rising rapidly as a function of peatland cover.

[8] Our results show (i) uniformly low DOC concentrations in CPI watersheds, regardless of peatland cover (Figure 2); (ii) a strong positive correlation between DOC concentration and peatland cover in WPF watersheds (Figure 2); and (iii) a sharp rise in DOC release to streams where MAAT exceeds −2°C (Figure 3). These findings are particularly interesting because while previous studies have reported that DOC concentrations in a stream are influ-

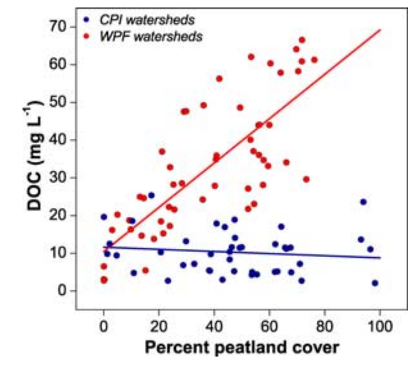

Figure 2. Dependence of DOC concentration on the percent peatland cover ($P_{\%}$) within the sampled watershed. Concentrations in cold permafrost-influenced (CPI) watersheds are uniformly low, with a mean value of 10.29 mg L^{-1} and no statistically significant correlation with $P_{\%}$ ($DOC_{CPI} = -0.03 \cdot P_{\%} + 11.62$; $p = 0.42$; $r^2 = 0.02$). However, concentrations in warm permafrost-free (WPF) watersheds rise significantly with $P_{\%}$ ($DOC_{WPF} = 0.59 \cdot P_{\%} + 10.42$; $p < 0.0001$; $r^2 = 0.60$).

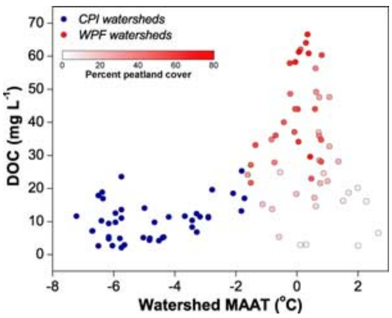

Figure 3. Dependence of DOC concentration on watershed MAAT. A sharp increase in concentrations occurs in watersheds with a MAAT warmer than −2°C. Low concentrations in WPF watersheds are due to sparse peatland coverage.

enced by the percent cover of wetland or peatland within the watershed [e.g., *Hope et al.*, 1994], our data show that cold, permafrost conditions have shut down this process in the northern half of West Siberia. Similarly, although temperature is an established control on peatland DOC production [*Christ and David*, 1996; *Freeman et al.*, 2001; *Neff and Hooper*, 2002], our results show this process to be highly non-linear, with a critical threshold between low and high DOC production occurring at a MAAT of ∼−2°C.

4. Mechanisms

[9] At least two mechanisms may explain the observed contrast in surface water DOC concentrations. First, in permafrost areas, hydrologic transport of DOC from peatlands to their outlet streams may be limited by the presence of ice-rich permafrost. Northern soils most commonly export recently fixed carbon of plant and near-surface soil origin [*Benner et al.*, 2004], suggesting little hydrologic interaction at depth. However, radiocarbon dating has also shown riverine DOC to be much older than previously thought [*Raymond and Bauer*, 2001], suggesting that baseflow from older, deeper peats may also export DOC to streams. If so, ice-rich permafrost may present a physical barrier to infiltration and subsurface flow through peatlands in the northern half of West Siberia, confining the process of DOC production and hydrologic transport to the shallow surface active layer and effectively eliminating large depths of carbon-rich peat (∼1–5 m) [*Sheng et al.*, 2004] as a source of DOC. Thus, the degradation of permafrost in peatlands may amplify DOC export to streams, which in turn could partly depend upon on the DOC sorption ability of newly thawed sub-peat soils [*Moore and Turunen*, 2004]. A second possible mechanism is that DOC increases are driven by warmer air temperatures, through temperature-related processes of DOC production. Warming may increase peat decomposition and thus DOC production by enhancing microbial respiration [*Christ and David*, 1996] and/or the activity of the enzyme phenol oxidase [*Freeman et al.*, 2001]. Furthermore, warming may enhance photosynthesis and aboveground plant biomass, thereby increasing DOC production by providing a larger source pool of organic carbon [*Moore et al.*, 1998]. In future climate scenarios, increases in atmospheric CO_2 concentrations may also boost DOC production by increasing root exudation [*Freeman et al.*, 2004].

[10] Previous field studies have shown that seasonal and interannual variations in riverine DOC concentration can occur. DOC concentrations may be diluted or enhanced by the spring flood [e.g., *Hope et al.*, 1994; *Cauwet and Sidorov*, 1996] or increased through carbon flushing when moist conditions return to previously aerated soils [*Christ and David*, 1996; *Evans et al.*, 2002]. Spring flood effects were mitigated by collecting our samples during late summer (>1 month after freshet) at similar points in the annual hydrograph. We do note that minor carbon flushing effects may occur in West Siberia (suggested by a small positive correlation between DOC and discharge), but the contrast between northern and southern regimes remains robust after subtracting this small trend. Furthermore, repeat samples from the same site in different hydrologic years show little interannual variability in DOC (e.g., 8 vs. 10 mg L^{-1} in a CPI watershed and 22 vs. 27 mg L^{-1} in a WPF watershed). Therefore, while variations in hydrology may play a limited role in the observed DOC variability, their effects are minor relative to the strong contrast seen between WPF and CPI watersheds.

5. Future Warming Scenarios

[11] Regardless of mechanism, our results show that the −2°C MAAT isotherm represents a critical temperature threshold, above which watersheds produce increasing DOC as a function of peatland abundance. A warming Arctic climate may thus lead to increased release of currently sequestered peat carbon through (i) introduction of a new source of DOC from older and deeper areas of the peat column, caused by permafrost degradation; (ii) enhancement of temperature-controlled DOC production processes; or (iii) some combination of the two. However, permafrost degradation would likely lag warming temperatures [*Stendel and Christensen*, 2002], thus delaying DOC increases if

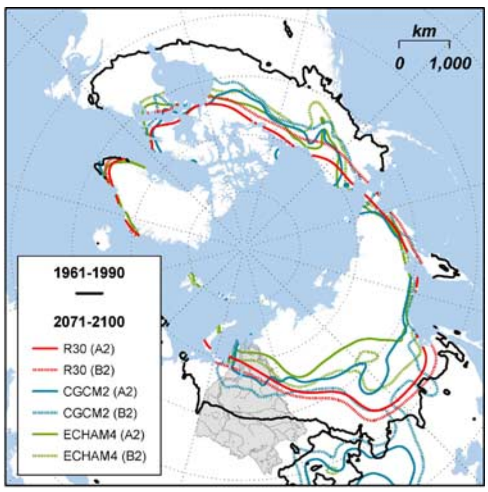

Figure 4. Locations of −2°C MAAT isotherms, based on observational data from 1961–1990 [*New et al.*, 1999] and modelled data from 2071–2100 (using the R30, CGCM2, and ECHAM4 models). Both the A2 (less conservative) and B2 (more conservative) IPCC greenhouse gas emission scenarios are shown for each model.

permafrost were the primary mechanism controlling DOC variability. Climate model simulations nevertheless predict a major northward advance of the −2°C MAAT isotherm by 2100, nearly doubling the West Siberian land surface with air temperatures exceeding this threshold (increasing the area from $\sim 1.3 \times 10^6$ km^2 to $\sim 2.0-2.6 \times 10^6$ km^2, depending on which model is used; Figure 4). Based on the empirical relationships in Figure 2 and these modelled land surface areas, we estimate that West Siberia's regionally averaged (over 2.63×10^6 km^2) stream DOC concentration will rise from its current mean value of ~16 mg L^{-1} to ~21–24 mg L^{-1} by 2100 (a ~29–46% increase; see auxiliary material[1]). For CPI watersheds containing extensive peatland cover, the predicted DOC increase is much greater: The arrival of MAATs above −2°C is expected to produce up to a 670% increase for watersheds containing 100% peat cover (Figure 2). Furthermore, even large rivers are expected to experience significant change. For example, GCM simulations predict that two of the largest CPI river basins in West Siberia (the Nadym and Pur, covering $\sim 6.4 \times 10^4$ km^2 and $\sim 1.2 \times 10^5$ km^2, respectively; Figure 1) will likely be completely south of the −2°C MAAT isotherm by 2100 (Figure 4). As the two watersheds are ~50% covered by peatlands, these major rivers may experience a ~400% increase in DOC concentration (from ~10 to ~40 mg L^{-1}; Figure 2) in the next century.

[12] DOC flux (the product of concentration and river discharge) is important to consider in the global carbon cycle. While our findings suggest the primary control on peatland DOC production is surface air temperature (either directly or through its effects on permafrost), the total terrestrial DOC flux to the Arctic Ocean will also depend on hydrology. Future DOC fluxes from northern peatland watersheds have been predicted both to increase [*Clair et al.*, 1999] and decrease [*Moore et al.*, 1998; *Pastor et al.*, 2003], owing to anticipated wetter and drier conditions, respectively. Our results suggest that the amount of DOC released from northern peatlands to streams will increase remarkably during this century. Assuming the observed late-summer contrasts between CPI and WPF watersheds persist throughout the year and no change in either river discharge or allochthonous, in-channel processes (such as CO_2 evasion), this effect would produce a ~2.7–4.4 Tg yr^{-1} increase in terrestrial DOC flux (from ~9.2 Tg yr^{-1} to ~11.9–13.5 Tg yr^{-1}) from West Siberia to the Arctic Ocean by 2100 (assuming an empirically modelled regional discharge estimate of ~560 km^3 yr^{-1}; see auxiliary material). These estimates are in fact conservative if DOC concentrations peak during spring flood. Furthermore, if the recently observed increases in Siberian precipitation [*Serreze et al.*, 2000; *Frey and Smith*, 2003] and river discharge [*Peterson et al.*, 2002; *Wu et al.*, 2005] continue, even larger increases are likely.

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[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL022025.

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