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Change in winter climate will affect dissolved organic carbon and water fluxes in mid-to-high latitude catchments

Hjalmar Laudon,[1]* Doerthe Tetzlaff,[2] Chris Soulsby,[2] Sean Carey,[3] Jan Seibert,[4] Jim Buttle,[5] Jamie Shanley,[6] Jeffrey J. McDonnell[2,7] and Kevin McGuire[8]

[1] *Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Umeå, Sweden*
[2] *Northern Rivers Institute, School of Geosciences, University of Aberdeen, Scotland, UK*
[3] *School of Geography and Earth Sciences, McMaster University, Hamilton, Ontario, Canada*
[4] *Department of Geography, University of Zurich, Zurich, Switzerland*
[5] *Department of Geography, Trent University, Peterborough, Ontario, Canada*
[6] *US Geological Survey, Montpelier, USA*
[7] *Global Institute for Water Security, National Hydrology Research Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*
[8] *Virginia Water Resources Research Center and Department of Forest Resources and Environmental Conservation, Virginia Tech, Blacksburg, Virginia, USA*

Abstract:

There is a growing awareness that mid-to-high latitude regions will be strongly affected by climate change. These changes are predicted to be especially pronounced during winter, particularly at higher latitudes. To test how water quality in northern catchments could be affected by warmer winter climates, we assembled long-term data from eight well-studied catchments in Sweden, Scotland, Canada and the USA across a climatic gradient spanning from −2 to +9 °C in mean annual temperature and between −11.6 and + 6.1 °C in average winter temperature. We used the climatic gradient combined with inter-annual variability among catchments to examine how warmer winters could affect the seasonality (seasonal timing) and synchroneity (coupling) of water and dissolved organic carbon (DOC) fluxes. In general, sites with colder winters (less than −5 °C) experienced an export concentrated in spring, whereas sites with warmer winters (>0 °C) displayed a more evenly distributed export across all seasons. Catchments with warmer winters also displayed less synchroneity between water and DOC flux during winter compared with colder sites, whereas the opposite was found for the spring. Patterns from the climatic gradient were supported by inter-annual variability at individual sites where both seasonality and synchroneity in the spring were related to the temperature during the preceding winter. Our findings suggest that one likely consequence of warmer winters in northern regions is that the proportion of the annual DOC and water export will increase during winter and decrease during spring and summer. This is of importance as it is the latter seasons during which downstream utilization of both water and DOC often is largest. Copyright © 2012 John Wiley & Sons, Ltd.

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INTRODUCTION

Export of water and dissolved solutes from snow-covered catchments is of critical concern for downstream aquatic ecosystems and human water use in many areas of the world. Melting of the snow pack that accumulates over winter often constitutes a major proportion of the annual water yield (Barnett *et al*., 2005). From a global perspective, some of the largest changes in the hydrological regime have been predicted for snow-dominated regions in mid-to-high latitudes, where a warmer climate can result in a fundamental alteration to the distribution and duration of snow cover, and hence in the snow pack's ability to contribute water to the stream (Nijssen *et al*., 2001). Despite the importance of seasonal snow cover and freezing conditions in many northern areas, the winter season is generally the period least studied and understood (Campbell *et al*., 2005). This poor understanding of the role of winter processes is especially challenging as this is the period where the effects of climate change are expected to be most strongly expressed (IPCC, 2007) and where the most clear observational evidence of change already exists (Huntington *et al*., 2009; Harpold *et al*., 2012).

Dissolved organic carbon (DOC) is an important natural constituent affecting fundamental aspects of the biogeochemistry and ecology of freshwaters (e.g. Hruska *et al*., 2003; Berggren *et al*., 2010). A recent increase in surface water DOC across large regions of the northern hemisphere (Monteith *et al*., 2007; Dawson *et al*., 2008; Haaland *et al*., 2010) has resulted in increasing research efforts to better understand the regulation and transport mechanisms of DOC. Increasing water purification costs for drinking water and the formation of mutagenic chlorinated organic by-products (McDonald and Komulainen, 2005) are direct consequences of elevated DOC levels, but ecosystem responses to this increase can also be expected (Karlsson *et al*., 2009). Thus, an improved understanding of the underlying mechanisms of DOC regulation is of fundamental importance for our ability to predict future shifts in the chemistry and ecology of aquatic ecosystems in mid-to-high latitudes.

The conceptual understanding of stream water DOC regulation has largely been developed in the temperate

*Correspondence to: Hjalmar Laudon, Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Umeå, Sweden. E-mail: Hjalmar.Laudon@slu.se

regions of the world (e.g. Mulholland, 1992). Recently, however, more attention has been focused on northern regions, particularly the northern temperate, boreal and sub-arctic biomes where the DOC concentrations of streams, rivers and lakes often are substantially higher (Laudon *et al*., 2012). This increased attention is partly motivated by a global carbon cycling perspective that recognizes the large carbon storage in these mid-to-high latitude regions (Cole *et al*., 2007; Nilsson *et al*., 2008). In addition, climate change scenarios predict that some of the most significant changes will be in northern regions of the world (IPCC, 2007). These regions are particularly sensitive to climate perturbations during winter as relatively small changes in temperature determine the form of precipitation, magnitude and timing of snowmelt, and extent of soil frost and active soil layers (Stieglitz *et al*., 2003).

Most previous research on mechanisms that regulate surface water DOC in northern regions has been based on individual well-studied catchments (e.g., Hinton *et al*., 1998; Billett *et al*., 2006; Petrone *et al*., 2006; Eimers *et al*., 2008a) or on larger regional monitoring datasets (Evans *et al*., 2006; Clair *et al*., 2008; Erlandsson *et al*., 2008). Although a major advantage of individual research catchments is the large amount of ancillary data that can provide mechanistic explanations, a disadvantage is that the results can be difficult to extrapolate outside the study region because of limited geographic representation. Conversely, a limitation of environmental monitoring is that the data collection commonly is not designed to answer process-based questions, which can impede the inference of causal relationships (Lovett *et al*., 2007).

Here, we synthesize catchment data across eight well-studied research catchments in Sweden, Scotland, Canada and the USA to explore the seasonality and synchroneity of water and DOC flux. Seasonality and synchroneity of water and DOC fluxes are fundamental aspects of streams and rivers with important implications for ecosystem functioning and understanding the regulating mechanisms of DOC. The seasonality, or the seasonal timing and distribution, of the fluxes is not only important for such downstream utilization as hydropower or drinking water production but also for downstream ecosystems that have adapted over millennia to recurring seasonal patterns. Synchroneity, on the other hand, refers to the coupling of water and DOC fluxes in time; the degree to which these fluxes are in (or out) of phase reveals how sources of DOC production are connected/disconnected to catchment streams at different times of the year.

We test the hypothesis that winter air temperature is a first-order control on the seasonality and synchroneity of water and DOC fluxes in mid-to-high latitude streams. This entailed the examination of results from field observations from our eight catchments that cover a large gradient of hydro-climatic conditions across the northern region, spanning annual average temperatures from −2 to +9 °C and annual precipitation from less than 500 to greater than 2600 mm. Our objective was to contribute to more robust predictions of how a change in winter climatic conditions will alter the seasonality and synchroneity of DOC export in mid-to-high latitude catchments by combining the natural climatic gradient among catchments with inter-annual variability of the individual streams for inferring future climate-driven trends.

STUDY SITES

The eight catchments included in our analysis (one in Sweden, three in Scotland, two in Canada and two in the USA) are part of the Northern Watershed Ecosystem Response to Climate Change (North-Watch) programme (www.abdn.ac.uk/northwatch) and are well-investigated long-term research catchments in the mid-to-high latitudes (Figure 1). There is an extensive set of publications on the hydrological and biogeochemical functioning of these individual catchments based on rich stream, soil, vegetation and climatic datasets. A comparative examination of the hydroclimatic controls on catchment hydrology of these North-Watch sites has recently been presented by Carey *et al*. (2010). Here, only a short description of the study sites, sorted by mean annual temperature, is given in Table I.

Granger catchment in the Wolf Creek Research Basin in Yukon, Canada, is the coldest of the catchments and is currently one of the most studied permafrost catchments in terms of hydrology and biogeochemistry (McCartney *et al*., 2006). The climate is continental subarctic, with a mean annual temperature (*T*), precipitation (*P*) and discharge (*Q*) of −2.2 °C, 478 mm and 352 mm, respectively. Permafrost underlies approximately 70% of the catchment area (Carey, 2003). Svartberget (catchment 7) in the Krycklan catchment is in the boreal forest in Sweden (Buffam *et al*., 2007). It is the most northerly study site, with a milder and wetter climate than Wolf Creek and *T*, *P* and *Q* of 2.4 °C, 651 mm and 327 mm, respectively. There is no permafrost, but soil frost depth can reach to 60 cm during winter (Mellander *et al*., 2007). The forested W-9 catchment at Sleepers River, Vermont, USA, has a humid continental climate

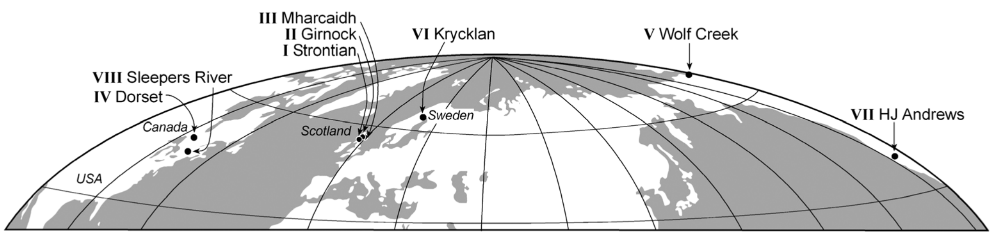

Figure 1. Location of the study catchments: I Strontian; II Mharcaidh; III Girnock; IV Krycklan; V Sleepers River; VII Dorset, VII HJ Andrews, VIII Wolf Creek

Table I. Catchment characteristics, analytical details and methods at each study site

Site	Country		Catchment area (km^2)	Mean annual (and winter) temperature (°C)	Mean annual precipitation (mm)	Mean annual discharge (mm)	Runoff ratio	Data record	Yearly samples	Analytical method	Analysis
Wolf Creek	Canada	62°32′N, 135°11′W	7.6	−2.2 (−11.6)	478	352	0.74	2001–2008	32	Colourimetrically (Technicon Autoanalyzer)	DOC
Krycklan	Sweden	64°14′N, 19°46′E	0.5	2.4 (−6.8)	651	327	0.49	1987–2008	32	Combustion (Shimadzu TOC- 5000)	TOC and DOC
Sleepers River	USA	44°29′N, 72°9′W	0.41	4.7 (−7.0)	1256	743	0.59	1991–2007	52	Combustion (Shimadzu TOC- 5000)	DOC
Dorset	Canada	45°00′N, 75°00′W	1.2	4.9 (−6.1)	980	577	0.55	1978–2008	40	Colourimetrically	DOC
Mharcaidh	Scotland	57°6′N, 3°50′W	10	5.7 (3.4)	1222	873	0.72	1987–2008	35	Colourimetrically (Skalar Sans)	DOC
Girnock	Scotland	57°2′N, 3°06′W	30	6.7 (5.0)	1059	603	0.57	2005–2008	31	Colourimetrically (Skalar Sans)	DOC
Strontian	Scotland	56°45′N, 5°36′W	8	9.1 (6.1)	2632	2213	0.84	1991–2002	15	Colourimetrically (Skalar Sans)	DOC
HJ Andrews	USA	44°12′N, 122°09′W	5.8	9.2 (3.6)	2150	1744	0.80	2003–2006	20	Combustion (Shimadzu 5000 TOC)	DOC

TOC, total organic carbon.

(Shanley *et al*., 2004), with *T*, *P* and *Q* of 4.7 °C, 1256 mm and 743 mm, respectively. Soil frost is intermittent and is usually <10 cm in the forest (Shanley and Chalmers, 1999). Harp Lake 4 in Dorset, Ontario, Canada, is at the transition to the southern Boreal ecozone (Eimers *et al*., 2008b). It has a humid continental climate similar to Sleepers River with a *T*, *P* and *Q* of 4.9 °C, 980 mm and 577 mm, respectively. Soil frost occurs rarely, except in wetlands where it is common each winter. In Scotland, the Allt' a Mharcaidh site is located in the subarctic Cairngorms region (Soulsby *et al*., 1997). *T*, *P* and *Q* are 5.7 °C, 1222 mm and 873 mm, respectively. The Girnock catchment (Tetzlaff *et al*., 2007) has a *T*, *P* and *Q* of 6.7 °C, 1059 mm and 603 mm, respectively. Strontian is located in the maritime northwest of Scotland and is the wettest of the study catchments. *T*, *P* and *Q* are 9.1 °C, 2632 mm and 2213 mm, respectively. Mack Creek, in the HJ Andrews research forest in the western Cascades of Oregon in the USA (Hood *et al*., 2006) is a steep, high-relief catchment. It is the warmest of the study catchments with a *T*, *P* and *Q* of 9.2 °C, 2158 mm and 1744 mm, respectively.

METHODS

Datasets of *T*, *P* and *Q* at each of the eight sites include more than 10 years of continuous daily record, excluding the Mharcaidh catchment, which has a 4 year record and where data from the nearby Girnock catchment was used to interpolate missing winter temperatures. For Dorset winter, temperature data were missing for the last 5 years. DOC data were collected within the individual research programmes and span from four to over 20 years (Table I). To standardize the comparison, only data from the last 10 years (1998 to 2008) were used. Only periods where climate, hydrology and DOC observation data were available (or could be calculated from nearby stations) and were included in the seasonality and synchroneity analysis. This resulted in a total of 10 years from Krycklan, Sleepers River and Allt' a Mharcaidh, 6 years from Strontian, 5 years from Dorset and Wolf Creek, and 3 years from Girnock and HJ Andrews. In Krycklan, the DOC concentration has for some years been measured as total organic carbon (Table I), but all data are referred to as DOC because the difference between DOC and total organic carbon is not statistically significant at that site (see Laudon *et al*., 2011 *for details*).

Export of DOC was calculated by linear interpolation of individual sampling occasions to daily values and multiplication with discharge to give daily flux in kg C ha^{-1} following Ågren *et al*. (2007). Mean annual and seasonal (winter, spring, summer and autumn) flux values were calculated and compared with mean annual and seasonal climate (Table II). Synchroneity was calculated as the mean monthly and seasonal difference in the annual proportion of water and DOC flux. Similar to the long-term average values of seasonality and synchroneity for each catchment, seasonal values were also determined for each year individually.

Table II. Annual and seasonal export of water and DOC

Site	Annual export		Winter export		Spring export		Summer export		Autumn export	
	Discharge mm yr^{-1}	DOC kg ha^{-1} yr^{-1}	Discharge mm yr^{-1}	DOC kg ha^{-1} yr^{-1}	Discharge mm yr^{-1}	DOC kg ha^{-1} yr^{-1}	Discharge mm yr^{-1}	DOC kg ha^{-1} yr^{-1}	Discharge mm yr^{-1}	DOC kg ha^{-1} yr^{-1}
Wolf Creek	352 (123)	15 (5)	25 (13)	0 (1)	163 (57)	12 (2)	125 (45)	2 (1)	38 (20)	0 (1)
Krycklan	327 (143)	71 (34)	21 (14)	4 (2)	171 (50)	31 (12)	76 (70)	22 (20)	60 (36)	14 (2)
Sleepers River	743 (156)	14 (4)	133 (57)	2 (1)	360 (75)	7 (2)	73 (45)	2 (1)	177 (116)	3 (1)
Dorset	577 (150)	60 (9)	156 (60)	11 (5)	262 (120)	21 (10)	31 (50)	8 (9)	128(100)	19 (18)
Mharcaidh	873(192)	48 (16)	287 (86)	13 (6)	159 (35)	6 (3)	131 (60)	10 (4)	296 (133)	18 (10)
Girnock	603 (60)	28 (9)	259 (60)	10 (6)	102 (25)	4 (3)	112 (115)	8 (10)	130 (36)	6 (3)
Strontian	2213(508)	143 (37)	715 (321)	26 (12)	217 (80)	13 (8)	509 (229)	50 (25)	773 (340)	54 (25)
HJ Andrews	1743(350)	15 (6)	675 (310)	5 (2)	472 (122)	4 (2)	87 (17)	1 (1)	509 (213)	5 (3)

Numbers in parenthesis denotes one standard deviation.

Seasonality was defined as the proportion of annual export of water (Equation (1), Table III) and DOC (Equation (2), Table III) occurring during winter (defined as January–March), spring (April–June), summer (July–September) and autumn (October–December) and synchroneity as the similarity in proportion of the annual flux of water and DOC occurring each season and month (Equation (2), Table III).

RESULTS

The seasonality of runoff and DOC export varied markedly across the study sites (Figure 2). Colder sites (less than $-5\,°C$ mean winter temperature, represented by Wolf Creek, Krycklan, Sleepers and Dorset) had a large proportion of annual export during spring (40–80%; Figure 3), with more limited export during winter (2–19%), summer (15–30%) and autumn (3–32%). Warmer sites ($>0\,°C$ mean winter temperature, represented by Mharcaidh, Girnock, Strontian and HJ Andrews) exported a larger portion of their annual DOC load during autumn (20–40%) and winter (20–35%). Spring export was small (7–20%) at these warmer sites (Figure 3), and summer export was highly variable (3–35%). Mean winter temperature was positively correlated to winter DOC export ($r^2 = 0.65$; $p = 0.01$) and negatively correlated with spring DOC export ($r^2 = 0.85$; $p = 0.001$, Figure 3) across all sites.

Similar to the pattern for average seasonal values (Figure 3) across sites, a larger fraction of the annual export occurred during spring at most individual catchments during years with colder winters (Figure 4). Although there were no significant correlations for individual catchments, combining all data from all sites gave a weak but significant correlation between the inter-annual variation in winter temperature and spring DOC export ($r^2 = 0.15$; $p = 0.006$).

There was a general synchroneity between DOC and water export at all sites (Figure 2). The timing of the largest deviation from this synchroneity varied across sites, but there was generally a lower relative DOC to water export during winter and spring and higher relative DOC to water export during summer and autumn. Synchroneity during both winter and spring was significantly correlated to mean winter temperature (Figure 5). Synchroneity decreased during winter with warmer mean winter temperature ($r^2 = 0.73$; $p < 0.01$), whereas it increased during spring ($r^2 = 0.64$; $p = 0.01$). One exception to this general pattern was Wolf Creek that had higher DOC export relative to discharge during spring. Even with Wolf Creek excluded from the regression, the synchroneity during spring was significantly correlated with winter mean temperature ($r^2 = 0.59$; $p = 0.04$). Hence, catchments with colder winters experienced a stronger synchroneity between DOC and water flux during winter and a weaker synchroneity during spring.

Similar to the long-term average seasonal pattern, the between-year variability in synchroneity was positively related to warmer winter temperatures during individual years during spring ($r^2 = 0.26$; $p < 0.001$, Figure 6) but less so during winter ($r^2 = 0.11$, $p = 0.09$, not shown). The

Table III. Calculation of seasonality of water and DOC fluxes as well as synchroneity

Characteristic	Calculation
Seasonality for water fluxes, evaluated for a certain month or season.	$\frac{Q_{(\text{seasonal or monthly})}}{Q_{(\text{annual})}}$ (1)
Seasonality for DOC fluxes, evaluated for a certain month or season.	$\frac{C_{(\text{seasonal or monthly})}}{C_{(\text{annual})}}$ (2)
Synchroneity for water and DOC fluxes, evaluated for a certain month or season.	$\frac{Q_{(\text{seasonal or monthly})}}{Q_{(\text{annual})}} - \frac{C_{(\text{seasonal or monthly})}}{C_{(\text{annual})}}$ (3)

$Q_{(\text{seasonal or monthly})}$ (m^3) is the sum of discharge during the respective seasons (or month) and Q_{annual} (m^3) is the annual sum of discharge. Similarly, $C_{(\text{seasonal or monthly})}$ (kg) and C_{annual} (kg) are the DOC fluxes during the respective season (or month) and the annual sum.

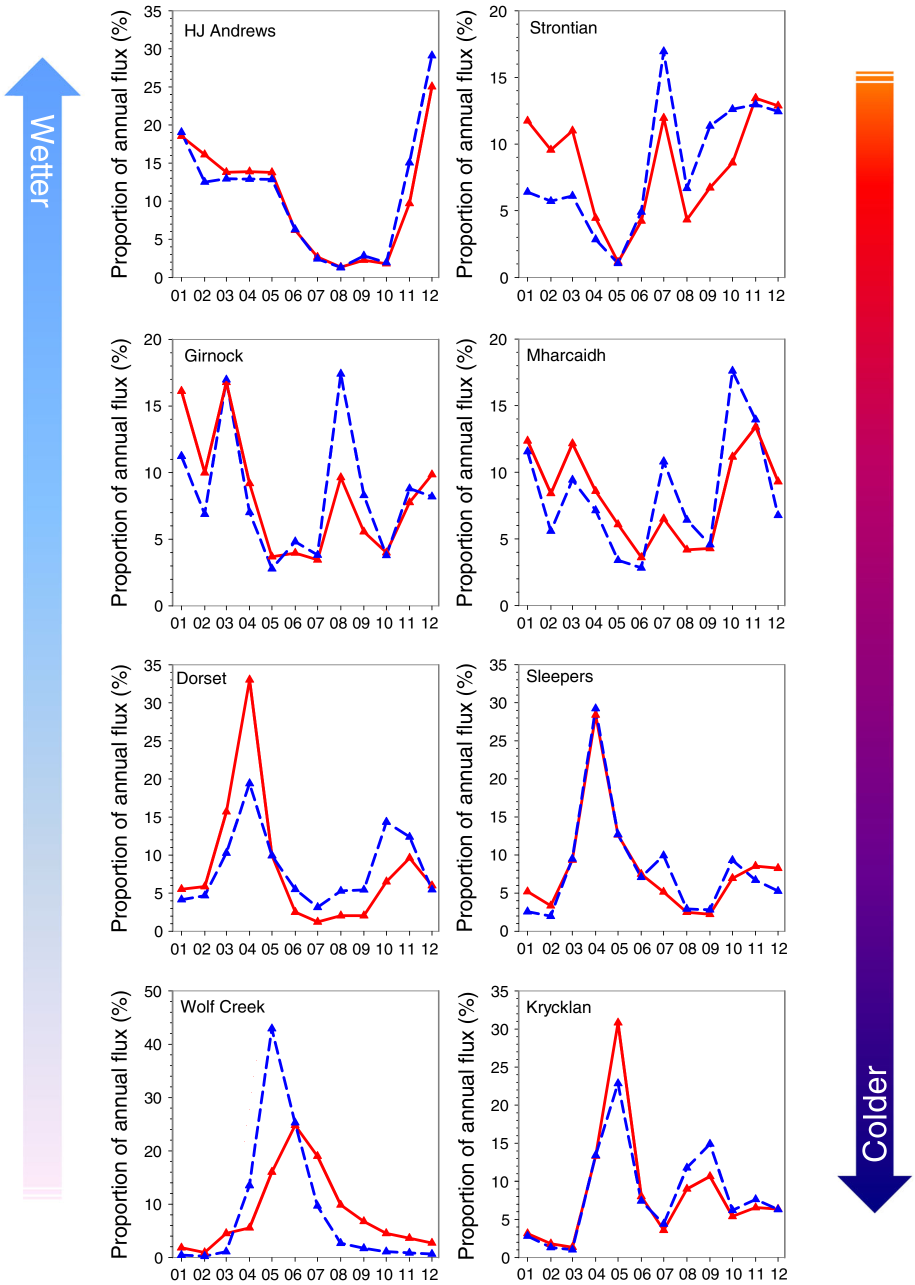

Figure 2. Seasonality and synchroneity of discharge and DOC export for the eight study sites. The similarity in water (blue dashed line) and DOC (red solid line) flux is the measure of synchroneity. Sites are ordered according to mean air temperature and precipitation, with the warmest and wettest sites at the top and coldest and driest sites at the bottom of the figure

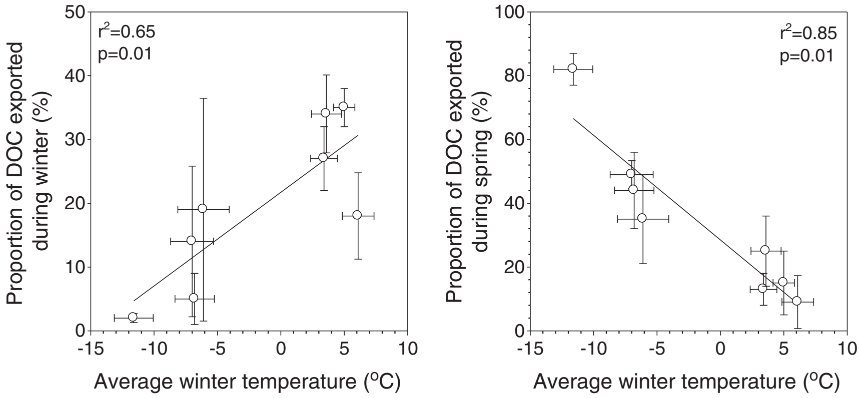

Figure 3. Correlation of mean winter temperature (January–March) and the percentage of seasonal DOC export from the eight sites. Error bars denote one standard deviation of winter temperature and seasonal DOC export

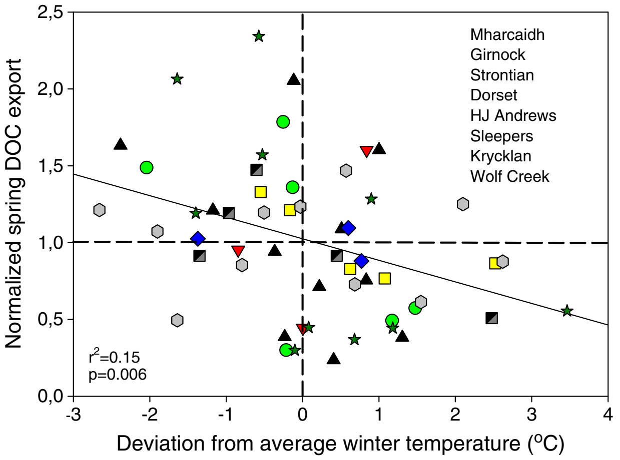

Figure 4. Normalized spring DOC flux relative to the normalized average winter temperature for each catchment. Both the spring export and the deviation from average winter temperature are normalized to the average of all available data for each site. The regression line includes all available data from the eight sites

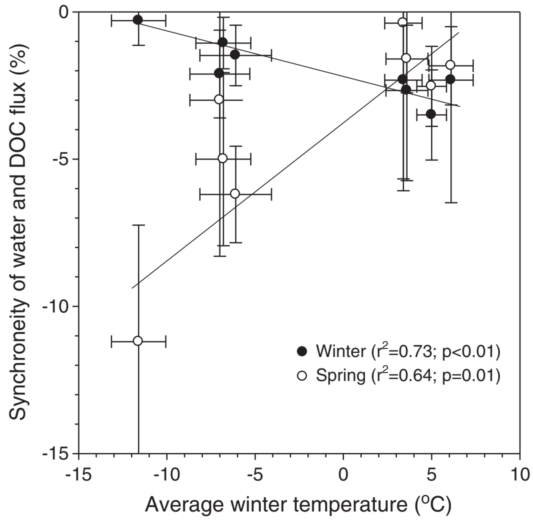

Figure 5. Synchroneity in water and DOC flux during winter and spring in the eight study catchments. Zero synchroneity suggests perfect synchroneity between water and DOC flux. Error bars denote one standard deviation of winter temperature and seasonal DOC export

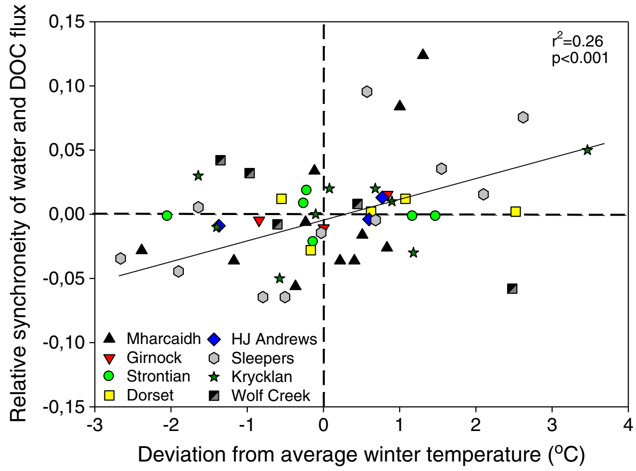

Figure 6. Inter-annual variability in the synchroneity in water and DOC fluxes for the eight study sites during the spring. Both the synchroneity and the deviation from average winter temperature are normalized to the average available data for each site. The regression line includes all data from all sites

relationship between winter temperature and the synchroneity of water and DOC flux observed for all sites combined (Figure 6) was significant for only one site (Sleepers River).

DISCUSSION

On the basis of time series of stream water and DOC fluxes from catchments along a large-scale climatic gradient, we analysed how their seasonality and synchroneity may be affected by the variability and changes in winter climatic conditions. Despite the weak correlations with winter temperature for the individual sites, the combined normalized values (Figures 4 and 6) indicate decreased seasonality and increased synchroneity during the spring associated with warmer winters. These results are corroborated by the large climatic gradient demonstrating a similar pattern across all catchments. The analysis suggests that although the interannual variability in climate may explain individual catchment response to short-term fluctuations, the climate gradient offers a framework for understanding the possible trajectory of individual system response to more lasting and large-scale changes in the future.

Most previous studies on water and DOC fluxes from northern regions have been carried out using data from major rivers in North America (Rember and Trefry, 2004; Striegl *et al*., 2005) and Eurasia (Alling *et al*., 2010; Pokrovsky *et al*., 2010). These large systems often integrate a multitude of landscape types and processes over large, sometimes sub-continental, regions. In contrast, the small relatively homogenous catchments included in this study provide a tighter connection between terrestrial and aquatic processes that allows a more mechanistic understanding of the underlying processes (Tetzlaff *et al*., 2009). Such smaller systems are usually characterized by shorter travel time for water and solutes between the soil/stream interface, thus minimizing the influence of internal stream processes. What is measured can hence be seen as an integrated signal of the terrestrial sources that contribute to stream water quality.

In this work, we placed a special emphasis on the role of winters as they are defining features of mid-to-high latitude regions and are integral for much of the ecological and biogeochemical functioning of high latitude regions (Haei *et al*., 2010; Kreyling, 2010). It has previously been established that cold winter conditions increase root mortality (Tierney *et al*., 2001), elevate soil nitrate levels (Fitzhugh *et al*., 2001), affect soil CO_2 production (Öquist and Laudon, 2008) and influence soil organic matter decomposition rates (Schimel and Mikan, 2005; Haei *et al*., 2012) as well as microbial water availability (Sparrman *et al*., 2004). Although we are now beginning to understand some of the fundamental aspects of winter processes for soil ecosystems, much less is known about how freshwater ecosystems could be affected.

The correlation between mean winter temperature and winter and spring DOC fluxes both within (Figure 3) and among catchments (Figure 4) in this study indicates that winter conditions influence the seasonality of DOC export. While in general agreement with other northern studies (Finlay *et al*., 2006; Ågren *et al*., 2007; Eimers *et al*., 2008a), these results show a more direct link between winter climatic conditions and the seasonality of DOC export across this climatic gradient. We attribute this seasonality primarily to the large seasonal water storage in the snow pack over winter and the subsequent release during spring in most of the catchments investigated. A likely consequence of warmer future winters would hence be that the seasonality in these snow-covered systems could move from a spring dominated export to a greater relative DOC export during winter.

Undoubtedly, climatic factors other than winter temperature also affect the production of DOC and subsequent transport to the stream. Variable soil moisture conditions can cause large intra-annual and inter-annual variability in DOC export (Köhler *et al*., 2008). Higher temperatures also enhance DOC production rates, resulting in greater DOC concentrations for a given flow in summer and autumn compared with winter and spring (Moore *et al*., 2008; Seibert *et al*., 2009). The seasonal dependence of DOC production is manifested in the study catchments as temporal variability in the synchroneity between water and DOC fluxes. Although most sites follow the conceptual model of higher DOC production in later stages of the growing season, the divergence of Wolf Creek from this pattern was likely related to the increasing active layer depth above permafrost (Striegl *et al*., 2005; Petrone *et al*., 2006). The strong connectivity between the organic soil DOC sources and stream when the soil was frozen subsequently weakened and a thickening active layer in later summer and autumn resulted in longer subsurface flow pathways (Carey, 2003).

The role of connectivity of organic-rich soils and streams is receiving increasing interest (Clark *et al*., 2010; Laudon *et al*., 2011; Tank *et al*., 2012). Although it is clear that stream-connected peatlands play a fundamental role in controlling stream water DOC in many northern catchments (Dillon and Molot, 1997; Creed *et al*., 2003; Laudon *et al*., 2004), forested areas on mineral soils can also contribute significant sources of DOC to streams (Ågren *et al*., 2007). All catchments examined here have relatively low percent wetland coverage ($<15\%$) indicating that other sources of DOC may be important at these sites. However, because areas of low wetland percentage dominate most landscapes, they often have a proportionately larger role in exporting DOC than organic dominated catchments in most areas, despite generally lower concentrations. Increasing evidence is emerging that organic-rich riparian soils are of fundamental importance for stream water DOC (Findlay *et al*., 2001; McGlynn and McDonnell, 2003; Bishop *et al*., 2004; Petrone *et al*., 2007; Seibert *et al*., 2009). However, hydrologically connected organic topsoil layers or small local patches of organic soils can also be potential sources of DOC in some areas (Boyer *et al*., 2000).

Seasonal variability in the connectivity between the terrestrial sources of DOC and the stream has not only been reported from the permafrost site at Wolf Creek but also from catchments with seasonal soil frost. For example, concrete soil frost conditions in the Krycklan sub-catchments cause overland flow during snow melt, short-circuiting the normal subsurface hydrologic connection between soil and stream (Laudon *et al*., 2007). This effect is especially manifested in wetland dominated systems, causing a larger deviation in the synchroneity between water and DOC flux (Berggren *et al*., 2007; Ågren *et al*., 2008). Soil frost has also been reported at Sleepers River during relatively cold and snow-poor winters (Shanley and Chalmers, 1999), augmenting the negative correlation between synchroneity and harsher winter conditions (Figures 5 and 6).

The weak synchroneity of water and DOC flux found for the colder sites during spring is likely related to flushing of DOC that has either built up during winter or has remained from the previous autumn, and that cannot be replaced until the soils are thawed when the conditions for production are more favourable. Little is known about DOC production under winter conditions; however, recent evidence suggests that colder winters with more extensive soil frost also can enhance DOC levels in snowmelt waters in some catchments by physical disruption of cells and other soil organic matter or by slowing the mineralization rate (Haei *et al*., 2012). Thus, although colder winter conditions can augment DOC export in individual catchments (Ågren *et al*., 2010), this trans-regional study suggests that colder winter conditions systematically shift the synchroneity of the water/DOC relationship toward relatively higher DOC export during summer and autumn.

In this work, we consider changes in air temperature only. As large changes in precipitation are also predicted in these northern regions (IPCC, 2007), the consequences of warmer winter temperatures on DOC and water fluxes that we predict will likely be confounded by other concurrent processes. Such changes include alterations in the timing and amount of precipitation, evapotranspiration, runoff and changes in the vegetation cover (Jones *et al*., 2012). However, by isolating winter temperature, which presumably is one of the major driving variables determining the timing and magnitude of snow melt discharge as well as DOC production, we can begin to understand the major mechanisms determining the seasonality and synchroneity of water and DOC flux in northern regions.

The consequences of future climate change scenarios in northern catchments could be substantial. Results from this study lead us to hypothesize that with warmer winters, many northern catchments will move from a strongly seasonal behaviour to a more evenly distributed export of water and DOC in the future. They also suggest that water and DOC fluxes may become less synchronous during winter and more synchronous during spring (Figure 7). Hence, warmer winters in the future could have important implications for stream-connected ecosystems that have adapted over several millennia to strong seasonal variability in these fluxes. These effects are likely to be most prominent for regions that presently are at, or just below, the 0 °C isotherm during winter.

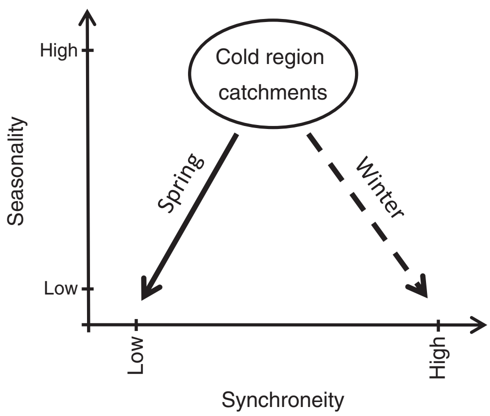

Figure 7. Conceptual model of the future mid-to-high latitude catchments. As winters become warmer, DOC export will be less seasonally concentrated. The dominant flux period will shift from spring to an export that is more evenly distributed throughout the year. We hypothesize that another consequence of a warmer climate is that the synchroneity (coupling) between the export of water and DOC will decrease during spring and increase during winter

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