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Catchment-scale carbon exports across a subarctic landscape gradient

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Abstract

Climatic change is currently enhancing permafrost thawing and hydrological cycling in subarctic and arctic catchments with major consequences for the carbon export to aquatic ecosystems. We studied stream water carbon export in several tundra dominated catchments in northern Sweden. There were clear seasonal differences in both dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) concentrations. The highest DOC concentrations occurred during the spring freshet while the highest DIC concentrations were always observed during winter baseflow conditions for the six catchments considered in this study. In these subarctic catchments, DIC accounted for at least about half of the annual mass of C exported. Further, there was a direct relationship between both hydrologic flow pathway length and the maximum flow to minimum flow ratio (which serves as a proxy for fractioning between surface and subsurface flow pathways) and annual carbon fluxes for these six catchments. Further, these relationships were more prevalent for annual DIC exports than annual DOC exports in this region. These results highlight that there can be large regional differences in high latitude ecosystems and emphasize the importance of proper representation of subsurface hydrogeological conditions. This is particularly relevant in subarctic environments were thawing permafrost and changes to subsurface ice due to global warming can influence stream water fluxes of C. The large proportion of stream water DIC flux also has implications on regional C budgets and needs to be considered in order to understand climate induced feedback mechanisms across the landscape.

1 Introduction

Tundra soils at northern latitudes contain 30–50 % of the global soil stocks of C (Gorham, 1991; Tarnocai et al., 2009) representing a pool at least twice as large as that of the atmosphere. This pool may potentially be released either as CO_2 (Dutta et al., 2006; Shaver et al., 2006; Lee et al., 2010) or by increased leaching losses of dissolved C (Frey and Smith, 2005; Dutta et al., 2006; Frey and McClelland, 2009) due to the polar amplification of climate change and changes in precipitation patterns seen in the past decades. Changes have already manifested in northern latitude ecosystems in the form of thawing permafrost (Osterkamp, 2007; Sjöberg et al., 2013), changes in hydrology (Peterson et al., 2002; Déry et al., 2005) and vegetation cover (Sturm et al., 2001); all potentially affecting C dynamics. At a landscape level, leaching losses of soil C is an important component of the landscape C budget since it can contribute to a large part of the net C loss mainly attributed to lake respiration of terrestrial C (Cole et al., 2007; Karlsson et al., 2009). Lake dissolved organic carbon (DOC) concentrations in high latitude ecosystems have been shown to relate positively to terrestrial net primary production (NPP) (Jansson et al., 2008) and a warmer climate is likely to increase NPP (Kimball et al., 2007) and eventually enhance terrestrial DOC losses. Changes in temperature and hydrology could also liberate large amounts of previously inactive carbon; for instance due to permafrost thawing (Schuur et al., 2009; Dorrepaal et al., 2009) or priming effects related to vegetation changes (Fontaine et al., 2007).

Many tundra soils underlain by continuous or discontinuous permafrost are today experiencing an increase in the active layer (Osterkamp, 2007) due to global warming. This may have profound effects not only on C losses but also on the forms of C lost. For instance, although there are indications of increased losses of DOC (Frey and Smith, 2005) from northern latitude ecosystems changes in hydrological flow pathways may also alter the proportion between organic and dissolved inorganic carbon (DIC) export (Lyon et al., 2010a; Jantze et al., 2013). Loss of permafrost areas due to degradation (Zimov et al., 2006; Klaminder et al., 2009) or a deepening of the active layer may increase the importance of subsurface flow pathways (Striegl et al., 2005; Walvoord and Striegl, 2007; Lyon et al., 2009, 2010b). Striegl et al. (2005) found, for instance, that the summer DOC export decreased in the Yukon River. They attributed this decreased export to increased groundwater flow pathways, residence times and mineralization of DOC in the active layer. Walwoord and Striegl (2007) also found an upward trend in the groundwater contribution and thus DIC to stream flow in the Yukon river basin. They

BGD
10, 7953–7988, 2013

proposed that the increase in groundwater contributions were caused predominately by climate warming and permafrost thawing (e.g. Lyon and Destouni, 2010) that enhances infiltration and supports deeper flow pathways.

These observations may have large consequences for not only landscape C budgets but also for the ecosystem functioning of the recipient aquatic ecosystems. Changes in the terrestrial DOC export to high latitude lake ecosystems can alter light conditions within lakes and thus affect the relative contribution of the benthic and pelagic primary production as well as overall biomass production (Karlsson et al., 2009; Ask et al., 2009). Shifts in hydrologic flow pathways may also alter the C quality and thus its bioavailability to aquatic bacteria (Roehm et al., 2009). An increased export of DIC, mainly HCO_3^- and CO_2 (g), may result in a negative feedback for atmospheric CO_2 since HCO_3^- can be retained once it reaches the ocean (Berner and Berner, 1996). Since about two-thirds of the C found in HCO_3^- originates from respired soil CO_2 globally (Berner and Berner, 1996) this is an important sink for terrestrial C and may counteract (to some extent) increased DOC leaching and respiration. At a more local scale an increased groundwater contribution may also play a significant part in CO_2 losses due to degassing from aquatic ecosystems. Northern aquatic streams and lakes are generally supersaturated with CO_2 (Kling et al., 1991; Jonsson et al., 2003; Giesler et al., 2013) and a large part of this CO_2 can be related to terrestrial soil respiration (Humborg et al., 2010). A degassing of this CO_2 may thus contribute to a significant part of the landscape C budget. In fact, the overall C budget of tundra landscapes depends on whether organic carbon is respired in soils or in streams and lakes. Soil pCO_2 is transformed partly to alkalinity (HCO_3^- and CO_3^{2-}) and will mainly be outgassed to the atmosphere in running waters and lakes. The CO_2 sink-source function of the aquatic continuum from soil water through groundwater and surface waters is, thus, largely controlled by groundwater pH and the extent of alkalinity formation versus surface water CO_2 outgassing which is controlled by stream water pH and the gas transfer coefficient.

BGD
10, 7953–7988, 2013

In northern latitudes, such as the Swedish subarctic region, the distribution of hydrologic flow pathways can be seen as an important factor for catchment-scale C export. Lyon et al. (2010a) demonstrated this connection between flow pathway distribution and the travel time of water through a catchment and carbon export for the subarctic Abiskojokken catchment in northern Sweden using a detailed distributed modeling approach. Jantze et al. (2013) followed up on this model-based analysis to provide a detailed mechanistic framework for estimation of C export relevant for catchment-scale transport. While such studies offer promise for estimation of future C loads through simulation, basic knowledge of how hydrologic responses will shift in the future due to climatic changes in arctic and sub-arctic areas is necessary. Such knowledge, however, is still lacking since research into the hydrologic processes in northern, cold regions is rather limited (Woo et al., 2008). Further, knowledge of the coupled response of hydrology and C export across scales and conditions is sparse for northern environments due to their inherent remoteness.

To address these potential knowledge gaps, we investigated the annual catchment-scale C export from six subarctic catchments spanning landscape conditions across northern Sweden. We hypothesize that, while regional differences exist, terrestrial hydrology provides a dominant control of annual C export. The coupling of C export and hydrologic response across this gradient potentially provides a space-for-time proxy to allow us to consider the role of climatic change in large-scale C export for this landscape.

2 Methods

2.1 Study sites

We selected six streams across a subarctic landscape gradient in northern Sweden (68° 21′ 36″ N, 18° 46′ 48″ E) located between the towns of Kiruna and Abisko (Fig. 1). The catchments and their streams are all north-facing and draining into the upper reaches of the Torne river system (Table 1). The long-term mean annual temperature in Abisko is about −1 °C (1961–1990; Åkerman and Johansson, 2008) but has been above 0 °C in more recent decades (Callaghan et al., 2010). Precipitation in the region is around 300 mm yr^{-1} in Abisko increasing eastward to about 424 mm yr^{-1} at Bergfors located about 16 km northwest of the outlet of stream 1 considered in this study (1961–1990; Åkerman and Johansson, 2008). The vegetation in the region is dominated by deciduous forest at lower altitudes (*Betula pubescens Ehrh.* spp. *czerepanovii*) and dwarf shrub heath tundra at altitudes above approximately 550 m. The permafrost in the Abisko region is considered discontinuous and has a non-random patchy distribution determined by site-specific factors that affect the microclimate (Johansson et al., 2006). Permafrost is found at lower altitudes on north-facing slopes and does exist as low as 350 m a.s.l (Johansson et al., 2006; Åkerman and Johansson, 2008). Permafrost thickness increases with altitude from one or a few meters to many tens of meters and is common in the tundra zone (Johansson et al., 2006).

2.2 Stream water sampling and hydrological measurements

For each of the six catchments, grab samples of water were taken from mid-April 2008 to the end of April 2009. Samples were taken more intensely during the spring freshet (2 to 3 to times per week) and weekly thereafter. From December to April only monthly samples were taken. These water samples were collected and stored for various future analyses. The water samples collected for DOC analyses were filtered (0.45 µm Millex HA filter, Millipore) and thereafter acidified with hydrochloric acid. Water samples collected for silica analyses (only streams 1, 2, 4 and 5) were filtered through a 0.22 µm Whatman Nucleopore filter and acidified with nitric acid. These samples collected for DOC and silica analyses were stored in a cooler until further analyses. The water samples collected for alkalinity measurements were kept untreated in a cooler until analyses. Water samples collected for analysis of CO_2 concentration were collected in 60 mL plastic syringes. Three syringes with 30 mL of water and no air space were collected for each stream at each sampling occasion. The samples were analyzed within 4 h after sampling.

Stream flow hydrographs were developed for each of the six catchments considered in this study. For stream 6 (Abiskojokka) considered in the study of Lyon et al. (2010a) and Jantze et al. (2013), daily stream flows for the entire hydrologic year 1 May 2008 through 30 April 2009 were measured by and available through the Swedish Meteorological and Hydrological Institute (SMHI; Gage ID 957). For the remaining sites, daily stream flow was observed from 1 May 2008 through 1 October 2008. Flow estimates were based on stage changes in the streams measured using Hobo water level loggers and empirical rating curves. The daily stream flows for the remainder of the hydrologic year were approximated by scaling observed stream flows from stream 6 to each individual catchment using catchment area ratios. The influence of this approximation is assumed to be minimal since the 7 months where flows were approximated account for only about 10 % of the annual flow (considering long term observations at stream 6) and this low flow winter period is noticeably less dynamic compared to the spring freshet and summer high flows (Lyon et al., 2010a).

2.3 Chemical analysis and load estimates

DOC was measured on a total organic carbon (TOC) analyzer (Shimadzu TOC-VcPH total organic carbon analyzer) coupled to a nitrogen module (total nitrogen analyzer) by the catalytic combustion technique. Silica was analyzed on an ICP-OES, Varian Vista Ax providing an accuracy and precision better than 4 % based on certified standard measurements. Alkalinity was measured using a Mettler Toledo automated titration system using a Metrohm Aquatrode Plus (6.0257/000) pH electrode (Metrohm AG, Switzerland). The samples were titrated to a pH 4.0 with 0.1 M HCl and then back-titrated to 5.6 using 0.1 M NaOH. Alkalinity was calculated from the difference in the amount of NaOH and HCl used and the sample volume. Analysis of CO_2 concentration was done using a headspace equilibration technique (Cole et al., 1994). A 30 mL gas headspace was created, where after the syringes were shaken vigorously for 1 min

BGD
10, 7953–7988, 2013

and then left standing for 1 min for equilibration of the gas and water phases. The concentrations of CO_2 in the head-space were analyzed using an infrared gas analyzer (EGM-4; PP-Systems Inc.). The CO_2 concentration in the water was calculated according to Åberg et al. (2007). DIC was calculated from alkalinity and pCO_2 values using PHREEQCI (Parkhurst and Appelo, 1999).

Annual DOC and DIC loads were estimated as the product of daily concentrations and stream flows. Since DOC and DIC concentrations were measured at non-uniform time intervals, linear interpolation was used to approximate daily concentrations from the observed concentrations. These daily concentrations where then multiplied by daily average flow amounts to estimate DOC and DIC mass flux coming from each of the catchments monitored in this study. These mass fluxes were summed to estimate annual load of DOC and DIC coming from each catchment. Further, the annual average flow weighted concentrations were determined to provide reference.

2.4 Hydrological characteristics in relation to DOC and DIC loads

As previous studies have explored the connection between hydrology and chemical fluxes in this region (i.e. Lyon et al., 2010a), we considered several simple hydrological and terrain analysis to capture the potential spatial variability of terrestrial hydrology and explore their relation to the annual DOC and DIC loads from these six catchments. The selection of characteristics considered was guided by previous work in the region (e.g. Lyon et al., 2010a; Karlsson, 2010) and other cold-region research. Daily stream flow data for each stream were analyzed to determine several basic statistics. These were the total annual flow, annual runoff (specific discharge), average daily flow rate, maximum daily flow rate and minimum daily flow rate (Table 1). In addition, the ratio of maximum to minimum daily flow was calculated for each catchment as these has been seen to be a good proxy for the ratio between fast and slow flows within subarctic landscapes (i.e. Ye et al., 2009).

Basic terrain analysis was also considered as a proxy of terrestrial hydrology (Table 2). A raster digital elevation model (DEM) with a pixel resolution of 50 m was used for analysis of topographic characteristics. Flow direction was calculated using a D8 routing algorithm (O'Callaghan and Mark, 1984). Basic topographic features including catchment area, average elevation, average slope, average aspect and flow pathway lengths were calculated for each catchment within the System for Automated Geoscientific Analyses (SAGA) Geographical Information System (GIS). Flow pathway lengths here are the average length of all the estimated hydrologic flow pathways delineated from the DEM over an entire catchment. In addition, we considered the ratio of flow pathway lengths to gradients (i.e. land surface slopes) as this potential serves as a good proxy for hydrologic flux through the landscape and has been seen to be a dominate control of the residence time of water within catchments (i.e. McGuire et al., 2005; Lyon et al., 2010b).

2.5 Long-term chemistry in relation to DOC and DIC loads

To put the catchment sampling and observed DOC and DIC loads in perspective and test the ability of the six catchments monitored in this study to potentially serve as a space-for-time proxy, we compare the annual average values measured in this current study with existing long-term sampling. Publically available long-term monthly stream water chemical data (including alkalinity, cations/anions, and total organic carbon (TOC) are available for stream 6 for the period 1982 to 2011 and for stream 3 for the period 2000–2006 through a systematic monitoring program carried out by the Swedish University of Agricultural Sciences (SLU), Department of Environmental Assessment.

We have used the DOC and DIC concentrations collected in this current study in combination with the publically available long-term monthly chemistry data to develop long-term monthly concentrations of DOC and DIC. For stream 6, there was a strong 1 : 1 relation between the long-term monitoring of monthly TOC and the detailed DOC observations ($r^2 = 0.950$), such that DOC can be considered essentially equivalent to TOC for this system. For long-term DIC, there was further a strong linear relationship between the long-term monitoring observations of alkalinity and the detailed DIC

BGD
10, 7953–7988, 2013

observations (r^2 = 0.996). Similar relationships were established for stream 3. The DIC relationships were used to translate the available long-term monthly alkalinity values into long-term monthly DIC concentrations while the DOC relationships were used to translate long-term monthly TOC into long-term monthly DOC concentrations.

3 Results

3.1 Observed variations in stream water DIC and DOC

Stream water concentrations of DOC and DIC showed opposite temporal patterns across all streams considered in this study (Fig. 2). The variations amongst the six streams were remarkably similar although the range of streamflow across the catchments was widely dissimilar due to variations in catchment size (ranging from 5.2 km^2 to 565.3 km^2). DOC concentrations were generally highest at the first snowmelt peak of the spring freshet although peaks in DOC concentration also were noted during later high flow events. The increase in DOC concentration from baseflow to the first snow melt peak was between 6 to 11-fold with the highest increase occurring in streams 3 and 4. DIC concentrations, on the other hand, were highest during the winter with the highest concentrations observed in late spring (Fig. 2). During the spring freshet concentrations decreased and the lowest concentrations were generally observed during peak flow conditions. Flow-weighted annual DOC concentrations showed more variability across the six catchments than the flow-weighted annual DIC concentrations (Table 3). The opposite is true, however, when considering the annual DOC loads compared to the annual DIC loads. DIC loads ranged from 1.02 to 3.26 $g\,C\,m^2$ while DOC loads ranged from 0.82 to 2.29 $g\,C\,m^2$ across the six catchments.

BGD
10, 7953–7988, 2013

3.2 Relating observed C fluxes to hydrology

We explored linear relationships between several predicting variables and the annual DOC and DIC exports for the six monitored catchments in this study (Table 4). Of the predicting variables considered, DOC annual load was found to have a significant ($p < 0.10$) linear relationship only with the total runoff (specific discharge) across these catchments. While not significant, relatively good linear relationships were found between annual DOC load and both flow pathway lengths and maximum flow to minimum flow ratios. For annual DIC loads, significant ($p < 0.10$) linear correlations were found for flow pathway length, total runoff, and maximum flow to minimum flow ratio.

3.3 Comparing to long-term trends in DOC and DIC

For the available long-term data, we estimated trends with linear regression and estimated a seasonal component by assuming an additive value for each month (i.e. 12 values per year, to catch the seasonality of the concentrations). This resulted in models where fits were compared to observed data. The quality of these fits is reported as MAPE (mean absolute percentage error), MAD (mean absolute deviation) and MSD (mean square deviation). We found an increasing linear trend for DIC concentration in stream 6 (Fig. 3, Table 5). The increase corresponded to about 9 % for the 28 yr of measurements. The trend was mainly related to an increase during the autumn/early winter months (Fig. 4). Also stream 3 showed an increase in DIC concentration of around 9 % for the six years of measurement (Fig. 3). Conductivity showed the same patterns as DIC (Fig. 3) and weathering products such as Ca, Mg, and K were always strongly related to DIC and showed similar increasing trends for both streams (Table 6; data only shown for stream 6). No clear trends in DOC concentration were found for the streams and the fitted values in the time series analyses were poorly explained (Table 5). Further, considering the long-term annual DOC and DIC loads, Jantze et al. (2013) reported no significant trends in the total annual mass flux of either DIC or DOC over the periods considered but a significant decreasing trend in

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
BGD
10, 7953–7988, 2013
Catchment-scale carbon exports across a subarctic landscape gradient
R. Giesler et al.

total annual discharge for stream 6. Together, this decreasing trend in discharge and increasing trend in DIC concentration can be shown to be consistent with increasing water travel times through the landscape using a mechanistic modeling approach like that outlined in Lyon et al. (2010a) and Jantze et al. (2013).

The temporal variations in DOC and DIC concentrations observed in the six streams were consistent with the long-term average values for stream 6 (Lyon et al., 2010a). Overall, DIC accounted for 57 % of the total carbon export on average in the six streams monitored ranging from 49 % for stream 5 and 64 % for stream 6. This value is comparable to the long-term average of about 61 % DIC for stream 6 and stream 3. In addition, silica concentrations were always positively and significantly ($p < 0.001$) correlated to DIC concentrations for the individual streams (Fig. 5).

Based on long-term chemistry data (here 1982 to 2011), there was clear relationship between annual DIC load and total flow in stream 6 such that higher total annual flow leads to higher mass flux (Fig. 6). Counter to this, there was not a strong relationship of increasing DOC export with higher flows.

4 Discussion and concluding remarks

4.1 Long-term chemistry in relation to DOC and DIC loads

Overall, annual measurements for the six streams showed that DIC is a substantial component of the C flux in the subarctic ecosystems. The DIC accounted (on average) for more than half of the stream water C export. This separates these subarctic catchment-stream systems from Scandinavian boreal forest streams, for which previous reports have shown that DIC accounts for only about 19 % of the total C export (Wallin et al., 2010). A higher proportion of DIC to the total C flux is also found in the large Siberian Rivers, especially in the east (Raymond et al., 2007). We also found strong relationships between stream water DIC loads and both hydrologic maximum to minimum flow ratios and flow pathway lengths (Table 4). These relationships hold (albeit to a lesser extent) for annual DOC loads in this landscape. This likely indicates that both flow pathways and the speed that water travels through the landscape varies across these systems influencing DIC export to a first order while other factors (i.e. biological) potentially influence DOC export. This is consistent with previous mechanistically-based modeling work (e.g. Jantze et al., 2013).

Further, comparison between the annual DOC and DIC loads and the long-term observations (Fig. 6), the catchments considered here potentially offer a space-for-time proxy (a particularly strong proxy with regards to the geogenic-derived DIC) as they cover a range of expected cryogenic influences and subsequent groundwater-surface water interactions. This is consistent with the view of geogenic-derived inorganic carbon loading across the entire catchment (Basu et al., 2010; Jantze et al., 2013) while additional factors (e.g. biological) in addition to the amount of water moving through the catchment potentially influence the annual export of DOC. This is further supported as the annual DIC loads for the six catchments considered in this study provide a continuation of this linear relationship between DIC and discharge such that they are more-or-less consistent with the mass fluxes estimated from the long-term data at stream 6. Counter to this, while there is some consistency, it is not possible to relate the DOC export from the six catchments to the long-term DOC relationship between annual load and annual stream flow. There is a clear potential for non-linear behavior and considerable scatter that does not allow for directly relating annual discharge to DOC export based on the data considered here.

The variations in hydrologic response (e.g. maximum to minimum flow ratios in Table 1) demonstrate an effective widening and deepening of subsurface flow paths across these catchments. In subarctic environments, such subsurface pathways can be seen as a main effect of variations in permafrost and ice saturation within the subsurface as shown by recent simulation studies of Frampton et al. (2011) and Sjöberg et al. (2013) coupled with geological variations. We also found positive trends in stream water DIC concentrations indicating that previous temperature increases may have affected – deepened and extended – flow pathways within the catchments. For the largest

BGD
10, 7953–7988, 2013

catchment (stream 6), Lyon et al. (2009) characterized long-term thaw of permafrost at the catchment scale over the past century. It is also well documented that there has been an increase in the active layer in most low-altitude permafrost mires in the region during the past 20 yr (Callaghan et al., 2010; Johansson et al., 2006; Åkerman and Johansson, 2008).

Taken together, these long-term trends highlight the change in subsurface ice condition and permafrost expected across this landscape. Below we therefore suggest that the observed variations in C fluxes potentially offer a space-for-time proxy consistent with changes in permafrost conditions in the catchments rather than to other environmental variables. This is a challenging hypothesis since it implies that permafrost thawing leads not only to a positive feedback to atmospheric CO_2 but also to alkalinity formation that binds atmospheric CO_2 for geological time scales and, as such, should be considered in region-to-global scale analysis.

4.2 Seasonal patterns in stream water DOC and DIC

The observed seasonal variation in stream water DIC and DOC concentrations coincides with a source shift from a subsurface dominated flow during baseflow conditions, i.e. autumn/winter, to surface dominated flow pathways during the spring freshet. This is in accordance with hydrograph separations between shallow and deep groundwater from stream 6 (Lyon et al., 2010a) and with the observations of increased silica concentrations during baseflow conditions (Fig. 5). Silica is likely to reflect weathering inputs to the streams and should increase with a more groundwater dominated flow as has been observed in many arctic streams and rivers (Frey et al., 2007 and reference therein). The reverse is true for stream water DOC concentration which increases during the snowmelt when shallower groundwater flow pathways dominate (Lyon et al., 2010a). Such shifts are commonly observed in watersheds with seasonal snowpacks in arctic (Carey, 2003), alpine (Hood et al., 2005) and boreal streams (Laudon et al., 2004) and our data are in line with these results.

The extent and distribution of permafrost is typically seen to influence stream water DOC fluxes. Carey (2003) found that the spring freshet contributes to more than 50 % of the DOC export, as well as to the spring snowmelt contribution of DOC (69 %) in the high-permafrost area of the Yukon Territory, Canada. Also in Alaskan permafrost areas, the spring freshet was found to account for 51 % of the annual DOC export in a high-permafrost watershed, while it was otherwise less than 20 % of the annual DOC flux in low-permafrost watersheds (Petrone et al., 2006; MacLean et al., 1999). The increase in stream water DOC concentrations from baseflow to the snowmelt peak further differed between high-permafrost and low-permafrost catchments, with the increase being a 12-fold in the former compared to a 6-fold in the latter (Petrone et al., 2006). Carey (2003) suggested that permafrost dominated hillslopes potentially have a larger DOC reservoir and that permafrost dominated hillslopes are more effective at delivering DOC to the stream due to increased lateral flow. We found similar differences in the DOC increase going from baseflow conditions to the spring snowmelt as Petrone et al. (2006) and our data resemble mostly the high-permafrost area behavior found in these previous Canadian and Alaskan studies.

There is, however, currently no detailed information available on the areal extent of the permafrost in our studied catchments. Mountain permafrost determined mainly by air temperatures is found approximately above 880 m a.s.l (Jeckel, 1988; Johansson et al., 2006), but can probably occur at lower elevations on north-facing slopes that are less exposed to solar radiation (Johansson et al., 2006). The extent of the permafrost is also dependent of the snow depth which is a critical factor for permafrost formation (King, 1986; Seppälä, 1986). This may be important in areas with less winter precipitation such as the Miellajokka (stream 5) catchment that receives less snow than areas more westward or eastward (Klaminder et al., 2009; Åkerman and Johansson, 2008). Clearly, there is need for detailed subsurface and geophysical investigations to better control detailed estimates of permafrost distributions; however, to a first order, one can assume that the gradient of elevations covered in this current study sufficiently span a range of permafrost conditions in this region on the border between discontinuous

BGD
10, 7953–7988, 2013

and sporadic permafrost. This is reflected in the variations of hydrologic responses across the catchments (specifically, maximum to minimum ratios) consistent with those seen over long periods of time regionally (Sjöberg et al., 2013).

4.3 The role of shifting flow pathways for DIC and DOC export

We hypothesized that the observed temperature increase in the Abisko region during the last decades (e.g. Callaghan et al., 2010) should affect stream water C concentrations similar to previous observations from the Yukon River (Walvoord and Striegl, 2007) and other arctic streams (Frey and McClelland, 2009). Our long-term data does indeed suggest that there has been an increase in stream water DIC concentrations and that these changes are mainly related to the autumn period (Fig. 5). There are a number of arguments favoring that the observed changes are related to changes in water flow pathways such as those seen in space across the gradient of catchments considered here (Tables 1 and 2) and in time from the long-term monitoring. For instance, recession flow analysis based on long-term flow records from stream 6 suggests that there has been an increase in the effective aquifer depth in the catchment that could be related to permafrost thaw (Lyon et al., 2009) while analysis of the annual flows matching the period considered here show decreases in annual total flows (Jantze et al., 2013). There are no direct observations of active layer changes from upland soils in the area but it seems likely that these also are affected similar to the observations from the permafrost mires (e.g. Callaghan et al., 2010). The increase in DIC especially during the autumn months (Fig. 5) is in line with this assumption since the active layer is deepest during this time period (Åkerman and Johansson, 2008). We interpret this change in DIC as a result of an increased contribution of deeper groundwater like those indicated by the detailed generic simulations of Frampton et al. (2011) of permafrost thawing effects on flow and flow pathways under long-term climate change, rather than to changes in external inputs (e.g. Sjöberg et al., 2013).

There is not a concomitant decrease in DOC as has been observed from several studies from other permafrost influenced watersheds (Striegl et al., 2005; Walvoord

BGD
10, 7953–7988, 2013

and Striegl, 2007; McClelland et al., 2007). Such a decrease has been attributed to increase in hydrological residence time and microbial breakdown of DOC that would otherwise be released to streams (Striegl et al., 2005). This current study found a lack of connection between traditional residence time proxies (like flow pathway length to gradient ratio) and DOC loads across sites (Table 4), but this is likely attributed to the lack of subsurface information (hydrological conductivity) in these proxies. Therefore, this proxy fails to capture the speed at which water effectively move through the terrestrial system. The lack of clear connection between DOC and flows (Fig. 6) could also be attributed to increased interactions between DOC and mineral surfaces due to sorption. The latter process is probably important and contributes to the build-up of mineral soil C with higher precipitation, i.e. increased soil infiltration in tundra soils (Klaminder et al., 2009). This suggests that DOC concentrations may be less sensitive to shifts in flow pathways as opposed to other factors. A possible explanation to this insensitivity might be that the relative difference in DOC release is minor in the mineral soil in contrast to the surface soils that contribute to the DOC release during the spring freshet. As such, the ability of the six catchments considered in this study to provide a space-for-time proxy with regards to DOC export is less effective than it is for DIC export.

4.4 Implications for the regional C export

It is clear that DIC is a major component of the stream water C export in the studied streams and similar proportions between inorganic and organic C have also been found for Arctic streams in Alaska (Striegl et al., 2007). In landscape C budgets both organic and inorganic C stream fluxes should be considered since they seem to be of the same magnitude in high-latitude ecosystems and both their origin and their effect on the net ecosystem exchange of C is largely the same. With the assumption that most of the DOC we see in streams is of terrestrial origin, the DOC is a result of degradation of plant or microbial residues or direct inputs via root exudation (Giesler et al., 2006). Both degradation of soil organic matter and root respiration (Berner and Berner, 1996)

BGD
10, 7953–7988, 2013

will contribute to the formation of carbonic acid (H_2CO_3), and promote weathering and thus formation of the DIC (Berner and Berner, 1996; Humborg et al., 2010). Hence, at least part of the DIC and DOC can be attributed to terrestrial C, which within rather recent times has been fixed via plant photosynthesis, with the remaining part of DIC originating from carbonate weathering.

Part of the DIC formed will end up in oceans where it may precipitate and will be a net sink for atmospheric CO_2 (Humborg et al., 2010). However, part of the DIC may also be degassed and thus counteract its effect as a sink for atmospheric CO_2 (Wallin et al., 2010; Humborg et al., 2010). Further, exported organic C inputs are minimized by heterotrophic bacteria in lakes and streams (Karlsson et al., 2007), contributing to a net release of CO_2 to the atmosphere (Cole et al., 2007). At a landscape level the flux of CO_2 from aquatic ecosystems in our study area has been estimated to be the most important net source of CO_2 (Christensen et al., 2007). The overall effect of DIC on landscape C budgets is, however, still unclear and further studies are needed to elucidate its role for CO_2 emissions from the aquatic ecosystems as well as the partitioning between the contribution from carbonate versus silicate weathering; the latter contributing to DIC formed from respiratory CO_2 compared to the former where carbonate also contributes to the DIC formation.

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Catchment-scale carbon exports across a subarctic landscape gradient

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Table 1. Stream flow characteristics for the six catchments considered in this study.

Stream	Total Flow (10^6 m^3)	Total Runoff (mm)	Daily Flow ($m^3 s^{-1}$)	Max Daily Flow ($m^3 s^{-1}$)	Min Daily Flow ($m^3 s^{-1}$)	Max/Min Flow (–)
1	8.3	519	0.3	2.37	0.19	12.43
2	5.0	962	0.2	0.46	0.12	3.69
3	81.2	816	2.5	17.97	2.07	8.69
4	2.8	480	0.5	0.51	0.03	18.63
5	20.3	394	0.6	16.76	0.41	40.39
6	342.6	606	10.6	84.63	5.27	16.07

BGD
10, 7953–7988, 2013

Catchment-scale carbon exports across a subarctic landscape gradient

R. Giesler et al.

Table 2. Terrain characteristics for the six catchments considered in this study.

Stream	Common Name	Area (km^2)	Elevation Range (m)	Elevation (m)	Slope (deg)	Aspect (% North)	Flow Pathway Length (m)	Flow Pathway Length/Gradient ($m\,m^{-1}$)
1	Homojokka	15.9	475–1013	575	5.6	11	762	16 567
2	–	5.2	362–811	651	9.2	36	999	7178
3	Pessijokka	99.5	360–1734	967	10	16	833	6319
4	–	5.8	366–928	756	9.5	33	754	4537
5	Miellajokka	51.5	384–1731	955	14.5	41	704	4688
6	Abiskojokka	565.3	374–1793	956	13.1	22	816	4754

BGD
10, 7953–7988, 2013

Table 3. Flow-weighted annual DOC and DIC concentrations and mass fluxes for the six catchments considered in this study.

Stream	Flow-weighted Concentrations DOC	DIC	Mass Fluxes DOC	DIC
	($mg\,dm^{-3}$)	($mg\,dm^{-3}$)	($g\,C\,m^2$)	($g\,C\,m^2$)
1	4.7	3.1	1.79	2.07
2	3.4	2.9	2.29	3.26
3	4.0	3.0	2.11	3.18
4	3.2	2.4	0.95	1.19
5	3.2	2.2	1.07	1.02
6	1.6	2.4	0.82	1.43

BGD
10, 7953–7988, 2013

Table 4. R^2 for linear relationships between hydrological and terrain characteristics (as predicting variables) and DIC and DOC mass fluxes for the six catchments considered in this study. Significant ($p < 0.10$) trends are in bold.

Predicting variable	DOC	DIC
Area	0.24	0.06
Elevation	0.17	0.06
Slope	0.32	0.21
Aspect	0.07	0.10
Flow Pathway Length	0.46	**0.64**
Flow Pathway Length/Gradient	0.18	0.06
Total Flow	0.20	0.04
Total Runoff	**0.62**	**0.85**
Daily Flow	0.22	0.04
Max Daily Flow	0.27	0.08
Min Daily Flow	0.13	0.01
Max/Min Flow	0.44	**0.64**

BGD
10, 7953–7988, 2013

Table 5. Time series analyses (fitted trend and seasonal component) for stream 3 (2000–2006) and 6 (1982–2010). Here, MAPE is Mean Absolute Percentage Error; MAD is Mean Absolute Deviation; and MSD is Mean Square Deviation.

	Stream 6			Stream 3		
	DOC	DIC	Cond	DOC	DIC	Cond
Yearly trend	−0.005	0.012	0.039	0.059	0.070	0.105
MAPE (%)	41.9	11.2	9.0	25.9	9.3	8.1
MAD	0.53	0.03	0.42	0.39	0.03	0.40
MSD	0.617	0.001	0.341	0.316	0.002	0.370

BGD
10, 7953–7988, 2013

Table 6. Pearson correlation between stream water solutes from stream 6 (Abiskojokka).

	DIC	Cond	Ca	Mg
DIC				
Cond	0.97[b]			
Ca	0.97[b]	0.99[b]		
Mg	0.95[b]	0.99[b]	0.98[b]	
Na	0.61[b]	0.63[a]	0.57[a]	0.59[a]

[a] Denoting significance at 0.01 level.
[b] Denoting significance at 0.001 level.

BGD
10, 7953–7988, 2013

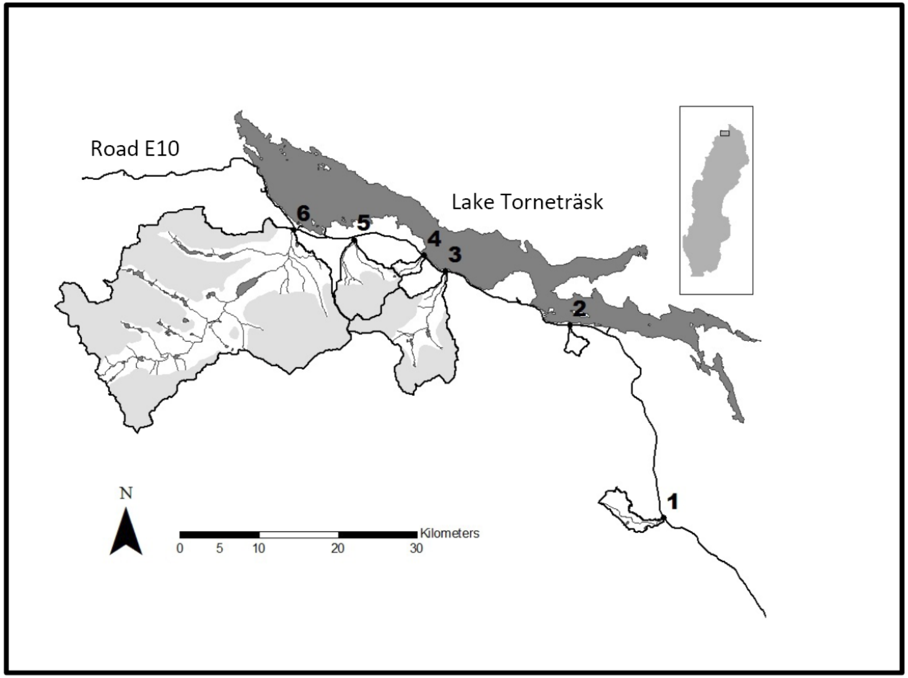

Fig. 1. The six catchments studied in the Abisko region. The grey areas are those above 880 m where mountain permafrost can occur more frequently.

BGD
10, 7953–7988, 2013

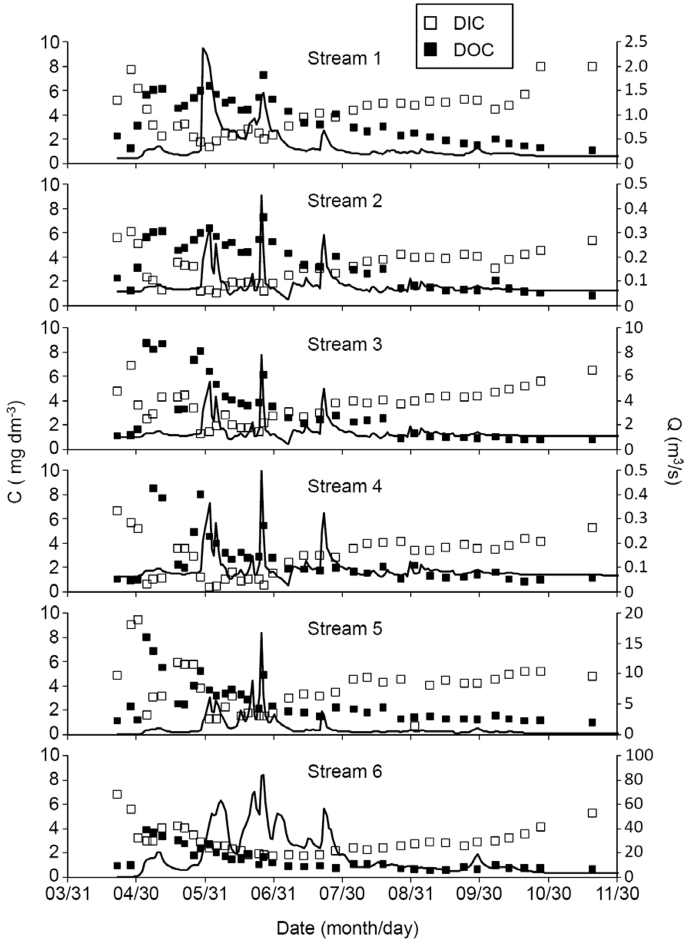

Fig. 2. Annual variation (2008) in stream water DOC and DIC concentrations in the six streams studied. The black line shows stream water flow.

BGD
10, 7953–7988, 2013

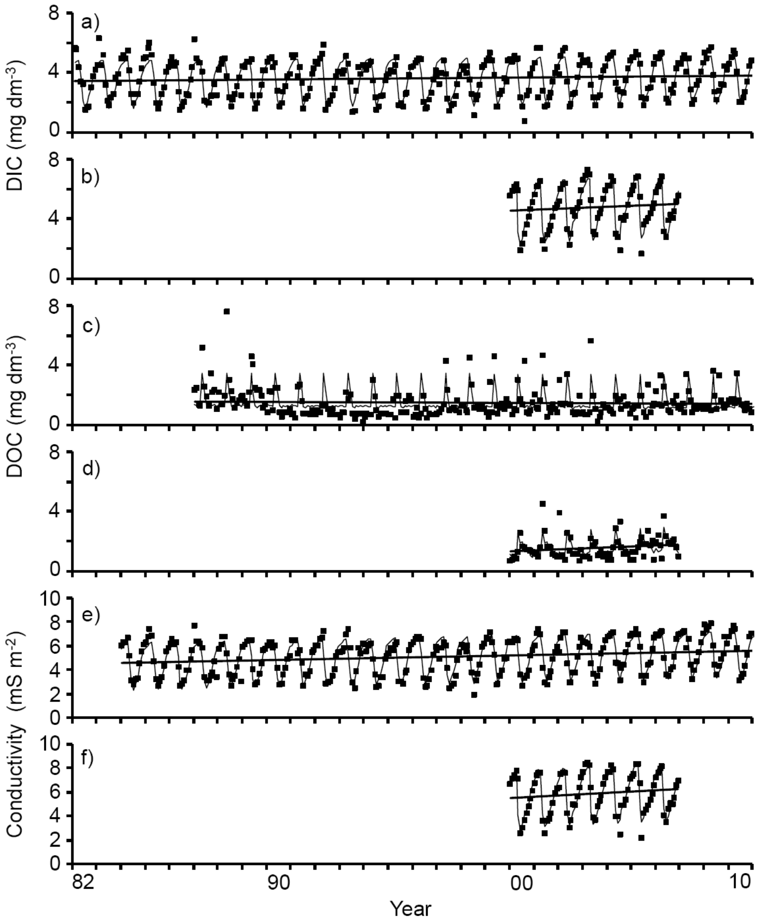

Fig. 3. Long-term trends for stream 6 (Abiskojokka) and stream 3 (Pessijokka) in DIC (**a** and **b**), DOC (**c** and **d**) and conductivity (**e** and **f**).

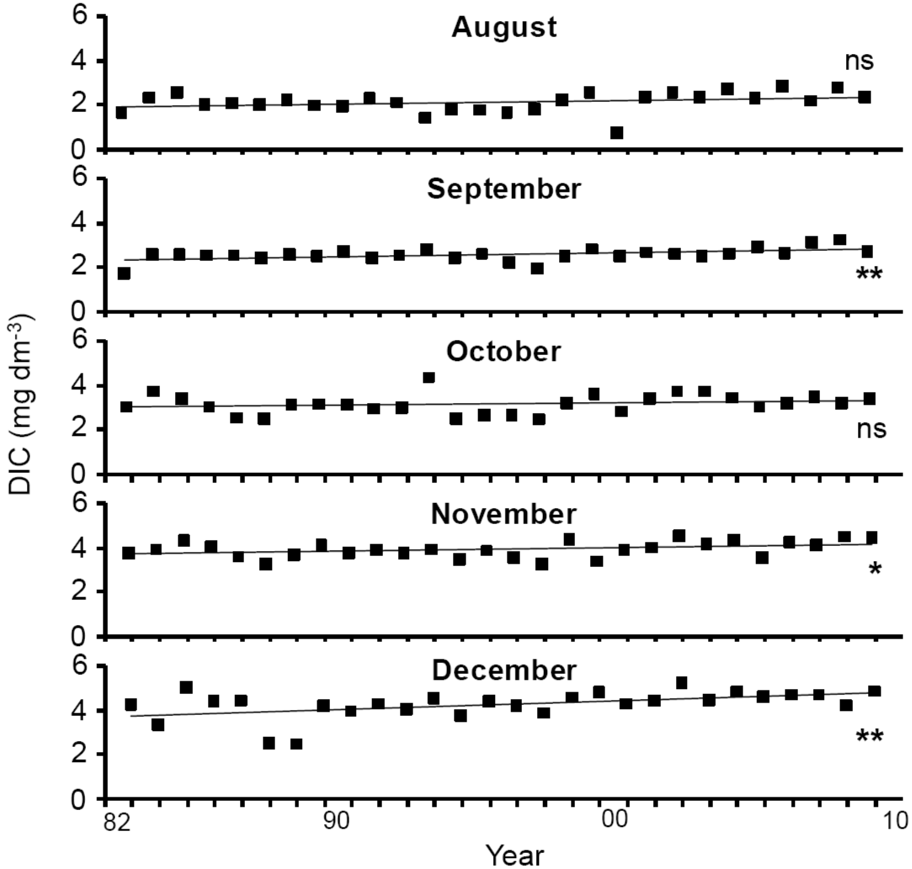

Fig. 4. Long-term trends in stream water DIC concentrations (stream 6) for separate months. Only autumn/early winter months are shown since no significant trends were found during other the other parts of the year. Here, * denotes significant trend at 0.05 level and ** at 0.01 level.

BGD
10, 7953–7988, 2013

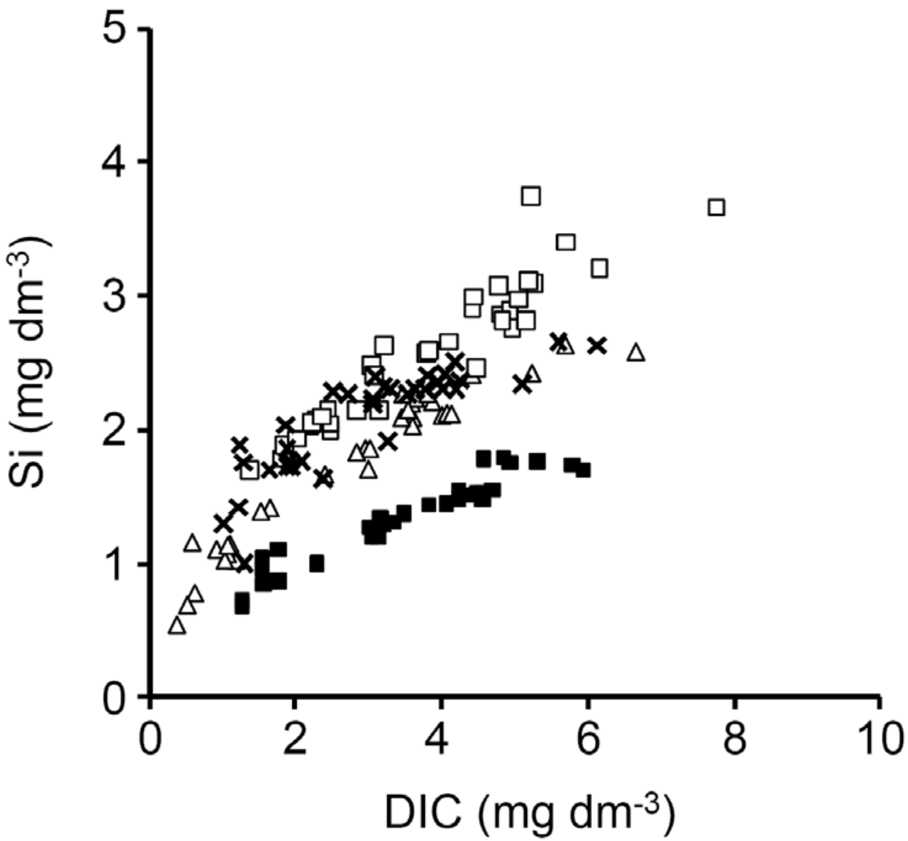

Fig. 5. The relationship between stream water concentrations of dissolved silica (Si) and DIC in stream 1 (open squares), stream 2 (crosses), stream 4 (open triangles), and stream 5 (filled squares).

BGD
10, 7953–7988, 2013

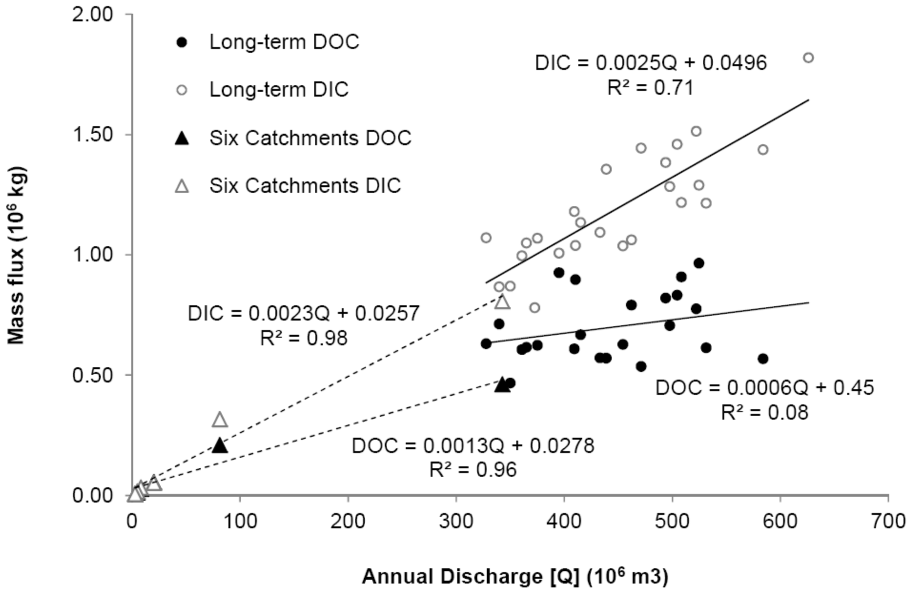

Fig. 6. Annual DOC and DIC loads in relation to total annual stream flow for stream 6 (Abiskojokka) based on available long-term data (here, filled circles are DOC loads and open circles are DIC loads) in comparison to the range of values observed for the six catchments considered in this study (here, filled triangles are DOC and open triangle are DIC). Solid trend lines are fit to the long-term data for stream 6 while dashed trend lines are fit to the annual data for the six catchments.

BGD
10, 7953–7988, 2013