JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, G03001, doi:10.1029/2009JG000971, 2009

Effects of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska

Eran Hood[1] and Logan Berner[1]

Received 10 February 2009; revised 3 April 2009; accepted 1 May 2009; published 21 July 2009.

[1] Runoff from mountain glaciers and icecaps is a critical control on physical and chemical conditions of aquatic ecosystems in glaciated watersheds. To date, there has been little research on the biogeochemistry of proglacial streams. Here we use a space for time substitution to evaluate how stream water physical conditions and concentrations of carbon, nitrogen, and phosphorus may be altered by diminishing glacial coverage. For a full annual hydrograph, we sampled six watersheds in southeastern Alaska that ranged in glacier coverage from 0 to 55%. We found that during the summer runoff season (May–October), stream water temperature and specific conductivity were negatively correlated with the percentage of the watershed covered by glacial ice, while stream water turbidity showed a significant positive correlation. Stream water concentrations of dissolved organic carbon (DOC) were typically low (0.5–3.0 mg C L^{-1}) and showed a significant trend toward higher concentrations as watershed glacier coverage decreased. Concentrations of dissolved organic nitrogen (DON) and dissolved inorganic nitrogen also increased significantly with decreasing glacial coverage. In contrast, concentrations of soluble reactive phosphorus decreased with lower glacial coverage. Interestingly, we found that the DOC:DON ratio of stream water dissolved organic matter (DOM) decreased with increasing glacier coverage, suggesting that glaciers may be a source of N-rich DOM. During winter low flows (November–April) there were few differences in stream water physical and biogeochemical conditions across the six watersheds as glacial inputs diminished and streamflow was dominated by groundwater. Our findings suggest that in southeastern Alaska ongoing glacial recession and the associated land cover change will impact physical and biogeochemical conditions in coastal streams, with implications for salmon spawning habitat, aquatic ecosystem productivity, and fluxes of reactive nutrients to downstream nearshore marine ecosystems.

Citation: Hood, E., and L. Berner (2009), Effects of changing glacial coverage on the physical and biogeochemical properties of coastal streams in southeastern Alaska, *J. Geophys. Res.*, *114*, G03001, doi:10.1029/2009JG000971.

1. Introduction

[2] Mountain glaciers and ice caps cover about 525,000 km^2 of the Earth's surface and runoff from these cryospheric reservoirs can have a profound impact on the physical and chemical characteristics of receiving streams and rivers. The major ion chemistry of glacial runoff has been studied extensively in an effort to understand subglacial hydrological and chemical weathering processes [e.g., *Tranter et al.*, 2002; *Hodson et al.*, 2002; *Brown*, 2002, and references therein]. Additionally, ecological studies in proglacial streams have shown these aquatic ecosystems typically have low primary productivity [*Robinson et al.*, 2001] and low macroinvertebrate species richness [*Milner et al.*, 2000; *Friberg et al.*, 2001] compared to nonglacial streams because of low water temperatures and high levels of turbidity and physical disturbance. However, very little research has been devoted to evaluating how runoff from glaciers affects downstream riverine concentrations of carbon, nitrogen, and phosphorus, which strongly influence primary and heterotrophic productivity in freshwater aquatic ecosystems [*Hodson et al.*, 2005].

[3] Developing an understanding of the biogeochemistry of glacial streams is important because mountain glaciers are rapidly receding and thinning in many areas of the world [*Dyurgerov and Meier*, 2000]. One area where glacial recession has been particularly dramatic is southeastern Alaska, which contains large volumes of ice in low-elevation maritime environments [*Arendt et al.*, 2002]. Over the last 50 years, approximately 95% of glaciers fed by the Juneau and Stikine ice fields on the Alaska panhandle have thinned and retreated, with rates of thinning as high as 6–8 m/a [*Larsen et al.*, 2007]. Over timescales of decades to centuries, these reductions in glacial volume and areal extent have the potential to alter the physicochemical

[1]Environmental Science Program, University of Alaska Southeast, Juneau, Alaska, USA.

0148-0227/09/2009JG000971$09.00

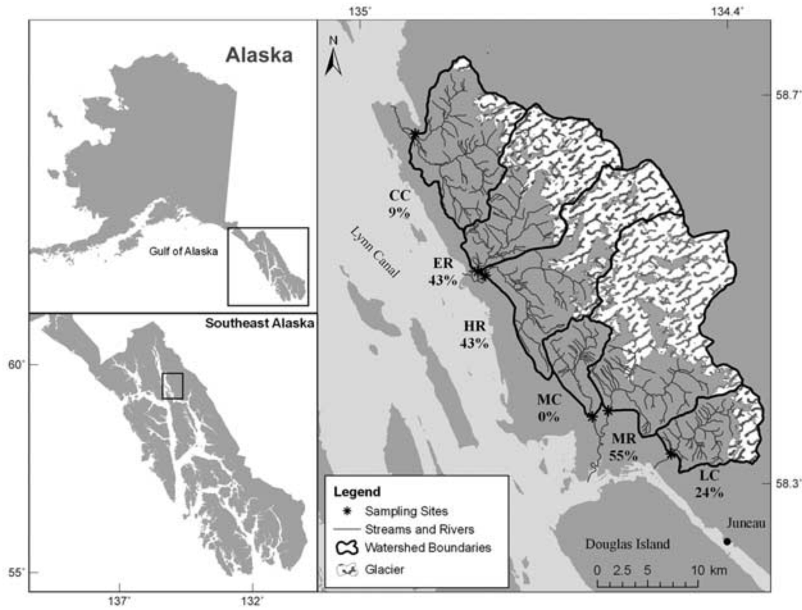

Figure 1. Map of six study watersheds near Juneau, Alaska. The two letter abbreviation and the percentage of the watershed covered by glacial ice are shown for each watershed.

properties of downstream aquatic ecosystems by changing watershed land cover and decreasing the proportion of streamflow derived from glacial runoff.

[4] The relationship between glacial recession and changes in physical and chemical properties of glacial rivers is difficult to evaluate because there are few continuous, long-term data on the hydrochemistry of glacial streams. As a result, several studies have utilized colocated watersheds in various stages of deglaciation to evaluate the impact of changing glacial area on proglacial streams. For example, *Milner et al.* [2000] studied 15 streams ranging in age from 25 to 200 years since deglaciation in Glacier Bay, Alaska to document changes in stream development as well as microcrustacean and macroinvertebrate diversity associated with watershed evolution following deglaciation. *Lafreniere and Sharp* [2005] compared adjacent glacial and nonglacial watersheds in Alberta, Canada to evaluate the influence of physical catchment properties on stream water hydrochemistry and solute fluxes derived from glacial runoff. Finally, *Collins* [2006] evaluated how basin water yields were impacted by differences in glacial area across five watersheds located in the Swiss Alps. However, none of these studies evaluated how runoff from glaciers influences the physical and biogeochemical properties of proglacial streams over the entire annual range of the hydrograph, including the potentially productive transition periods between summer high flows and winter low flows.

[5] The purpose of this study was to evaluate how changing glacial coverage within watersheds in southeastern Alaska affects the physical characteristics of stream water as well as concentrations of C, N, and P in proglacial stream ecosystems. We used a space for time substitution consisting of six adjacent watersheds draining the Juneau Icefield that ranged in glacier coverage from 0 to 55%. This gradient in watershed glacial coverage allowed us to evaluate how increasing forest cover and decreasing glacial runoff associated with watershed deglaciation will alter the physicochemical properties of stream water across the full range of the annual hydrograph. This question is of particular importance in southeastern Alaska because many glacial streams provide spawning habitat for salmon and influence downstream nearshore marine ecosystems via discharges of water, sediment and nutrients.

2. Methods

2.1. Site Description

[6] Our research watersheds are located in coastal southeastern Alaska near Juneau on the western edge of the 3800 km^2 Juneau Icefield, the fifth largest ice field in North America. Juneau has a moderate maritime climate with mean monthly temperatures ranging from -2°C to 14°C. Mean annual precipitation at sea level is 1400 mm, much of which falls as rain during large frontal storms in the fall. Winter snowfall ranges from an average of 0.4 m of water equivalent (w.e.) at sea level to more than 10 m w.e. at higher elevations on the ice field [*Miller and Pelto*, 1999]. The study sites are at the outlet streams of six adjacent watersheds on the western margin of the ice field (Figure 1). The six study watersheds range in area from approximately 35 to 200 km^2 and extend from near sea level to the margin or interior of the ice field at an elevation of 1400–1910 m (Table 1). These watersheds share a similar bedrock lithology composed mainly of Cretaceous and Tertiary high-temperature metamorphic rocks and igneous plutons (mainly granite and tonalite) of the central pluton-gneiss belt that extends along the southeastern Alaska coast [*Stowell*, 2006]. All of the study watersheds contain high-elevation reaches with alpine tundra, exposed bedrock, and relatively thin (<1 m) soils [*Nowacki et al.*, 2001]. The lower elevations of the watersheds are blanketed by spruce-hemlock forest extending to the coast and contain abundant wetlands in low-lying areas and along slope breaks. Three

Table 1. Watershed Characteristics for the Six Study Watersheds

Watershed	Abbreviation	Watershed Size (km^2)	Elevation Range (m)	Glacier Cover (%)	Forest Cover (%)
Montana Creek	MC	37	24–1400	0	51
Cowee Creek	CC	108	32–1570	9	44
Lemon Creek	LC	59	22–1410	25	15
Herbert River	HR	158	17–1860	38	20
Eagle River	ER	123	15–1910	43	18
Mendenhall River	MR	231	20–1890	55	6

of the watersheds: Montana Creek, Lemon Creek, and Mendenhall River have continuous stream gages maintained by the U.S. Geological Survey (USGS), and all six watersheds have runs of spawning salmon that return during late July through early September. The Mendenhall and Eagle watersheds also contain proglacial lakes.

[7] The watersheds chosen for this study are representative of numerous watersheds draining the west slope of the coast range in British Columbia and southeastern Alaska. Watershed coverage of glacial ice across the six study watersheds ranges from 0% in the Montana Creek watershed, which contains some semipermanent snowfields at high elevations, to a maximum of 55% in the Mendenhall River watershed (Figure 1). This gradient in glacial coverage is driven primarily by differences in elevation and proximity to the ocean. Glacial coverage in the study watersheds is changing rapidly. For example, the Mendenhall Glacier has retreated by an average of more than 30 m a^{-1} over the last 50 years [*Motyka et al.*, 2002] and glacier ice thinning rates in the five watersheds containing glaciers have been estimated at 2–5 m a^{-1} at lower elevations [*Larsen et al.*, 2007].

2.2. Watershed Characterization

[8] The six watersheds were delineated to the sampling site using ArcGIS 9.1 Hydrology tools in conjunction with a 20 m digital elevation model (DEM). Watershed areas were calculated using Hawth's Tools (H. Beyer, Hawth's Analysis Tools for ArcGIS, available at http://www.spatialecology.com/htools, 2004). Glacial extent within each watershed was determined using a 50 category Image Analysis unsupervised classification. The classification was based on a ratio of Landsat-7ETM bands four and five from a summer 2001 scene. The band ratio has been shown effective for threshold classifications of clean ice [*Paul et al.*, 2003]. The presence of lateral and medial moraines complicated the classification, as debris obscured the underlying ice. Pixels classified as rock that were surrounded by glacier were recoded as ice after visual inspection. Additionally, patches of ice smaller than 0.5 km^2 were taken as remnant snowfield and removed. No formal error assessment of the classification was conducted; however visual comparison with high-resolution digital orthoquads confirmed the accuracy of our glacier delineations.

2.3. Sample Collection, Field Parameters, and Chemical Analyses

[9] The six study watersheds were sampled during the period May 2006 to April 2007. Sampling was conducted weekly from May–November and approximately biweekly during low flows in winter and spring (December–April). On each sample date, the six watersheds were sampled consecutively during a 5 h period to minimize the variability in streamflow conditions. At each site, water temperature and specific conductivity were measured at a well mixed section of the stream using a YSI 556 multiprobe unit. A 25 ml grab sample for isotopic analyses and two 150 ml grab samples for chemical analyses were collected. Isotope samples were collected and stored in narrow mouth glass bottles with conical polyseal lids. Samples for nutrient analyses were collected in acid-washed, high-density poly ethylene (HDPE) bottles. One stream sample was collected at each site as a composite of three individual samples, and all samples were filtered in the field using precombusted Whatman GF/F, glass fiber filters (0.7 μm). Water samples were packed in a cooler and transported to the lab where they were refrigerated (isotopic samples) or frozen (chemical samples) until analysis, which occurred within three months after sample collection. Finally, a depth integrated 500 ml grab sample was collected at a wadable point in the stream. This sample was returned to the lab in a cooler and analyzed for turbidity using a Hach 2100P turbidometer after being agitated to resuspend settled sediment.

[10] Concentrations of DOC and total dissolved nitrogen (TDN) were determined by high-temperature catalytic oxidation using a Shimadzu TOC-V Organic Carbon and Total Nitrogen Analyzer in Juneau, Alaska. Nitrate nitrogen (NO_3-N) was measured on a Dionex DX 500 Ion Chromatograph (IC), ammonium nitrogen (NH_4-N) was measured on a Lachat 4000 flow injection analyzer, and soluble reactive phosphorus (SRP) was measured as the orthophosphate ion (PO_4^{3-}) using a Lachat QuikChem 8000 employing spectrophotometric detection at the University of Colorado Mountain Research Station. Dissolved organic nitrogen (DON) was calculated as TDN minus inorganic N (NO_3-N + NH_4-N). The $\delta^{18}O$ of stream water was analyzed at the Institute of Arctic and Alpine Research Stable Isotope Lab in Boulder, Colorado and all $\delta^{18}O$ values are expressed relative to Vienna-standard mean ocean water (VSMOW). Streamflow data were obtained from the USGS gages on Montana and Lemon Creeks and Mendenhall River, and stream water $\delta^{18}O$ values were measured only on these three streams.

3. Results

3.1. Physical Hydrology

[11] Discharge in the three gaged watersheds reflected the relative contributions of precipitation and glacier meltwater to streamflow. Discharge on Montana Creek ranged from <1 to 36 m^3 s^{-1} with numerous rainfall peaks, particularly during fall when large frontal storms come onshore from the Gulf of Alaska (Figure 2a). The hydrograph in Lemon Creek, which contains intermediate (25%) glacial coverage, was influenced strongly by glacier melt in midsummer

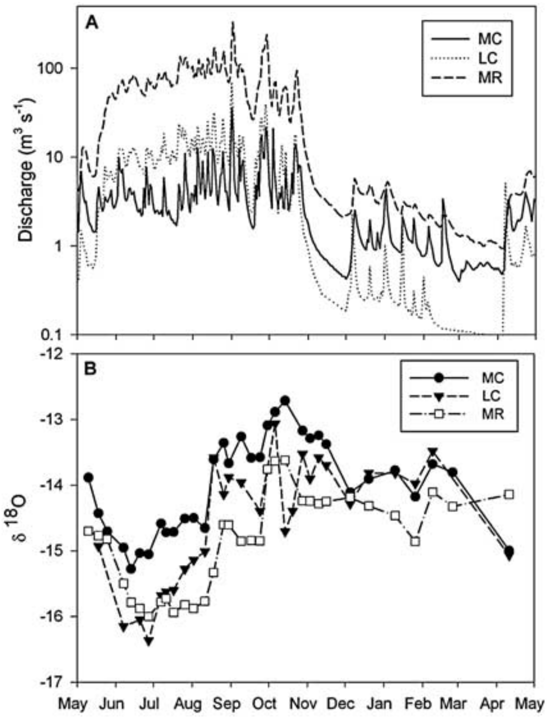

Figure 2. (a) Discharge and (b) $\delta^{18}O$ of stream water for the three gaged basins: MC, LC, and MR.

months but also showed rainfall generated peaks similar to those seen on Montana Creek. Discharge for Lemon Creek ranged from <1 to 71 m^3 s^{-1}. The hydrograph in the heavily (55%) glaciated Mendenhall River watershed tracked closely with air temperature consistent with the idea that it is dominated by glacier meltwater in the summer months [*Motyka et al.*, 2002]. Discharge ranged from 1 to 317 m^3 s^{-1} and, similar to Montana and Lemon, the annual peak occurred during a large frontal storm that produced 12.8 cm of rainfall over five days in late September. Overall, rainfall-driven discharge peaks were less pronounced and accounted for a smaller proportion of total streamflow as watershed glacial coverage increased.

[12] The $\delta^{18}O$ value for precipitation typically decreases with increasing elevation and decreasing air temperature leaving snow and glacier ice depleted in $\delta^{18}O$. The $\delta^{18}O$ values of stream water in MC, LC, and MR reflected seasonal differences in the source of streamflow in the three streams. All of the streams showed a sharp decrease in $\delta^{18}O$ in early May coincident with snowmelt (Figure 2b). By mid June when snowmelt had largely ended, stream water $\delta^{18}O$ in Montana Creek began to increase reflecting proportionally larger inputs from rainfall and groundwater. In contrast, stream water $\delta^{18}O$ in Lemon and Mendenhall were depleted well into the summer and showed minima in July before the onset of the rainy season in August. For most of the summer, the $\delta^{18}O$ for stream water was most enriched in Montana and most depleted in Mendenhall suggesting that $\delta^{18}O$ was a reliable indicator of the proportion of stream water derived from glacier meltwater. Stream water $\delta^{18}O$ peaked in October during the height of the rainy season and near the end of the glacier melt season. During the winter, Mendenhall stream water $\delta^{18}O$ values remained somewhat depleted compared to the other two streams because of inputs of water from proglacial Mendenhall Lake.

3.2. Stream Water Physical Characteristics

[13] For comparing physical and chemical stream water characteristics to watershed glacial coverage, we defined two seasons: (1) summer (May–October) when the mean elevation-weighted air temperature in all six watersheds was above 0°C and precipitation was dominated by rainfall and (2) winter (November–April) when the mean elevation-weighted air temperature was below the freezing point of water in all six watersheds and precipitation was dominated by snowfall. Stream water temperature strongly reflected inputs of glacial meltwater during summer with the highest temperatures in the Montana and Cowee Creeks and the lowest temperatures in the more glaciated Herbert, Eagle and Mendenhall Rivers (Figure 3a). During winter, stream temperatures remained near freezing in all three watersheds. Mean stream water temperatures during summer were strongly negatively correlated with watershed glacier coverage; however, there was no correlation between stream water temperatures and glacier coverage in the winter (Figure 3b).

[14] Specific conductivity of stream water ranged from approximately 10–60 microseimens/cm across all six watersheds (Figure 4a). During summer, specific conductivity was lower and less variable as watershed glacier coverage increased across the six watersheds. Montana Creek, the nonglacial watershed, had the highest conductivity during summer but decreased sharply during Septem-

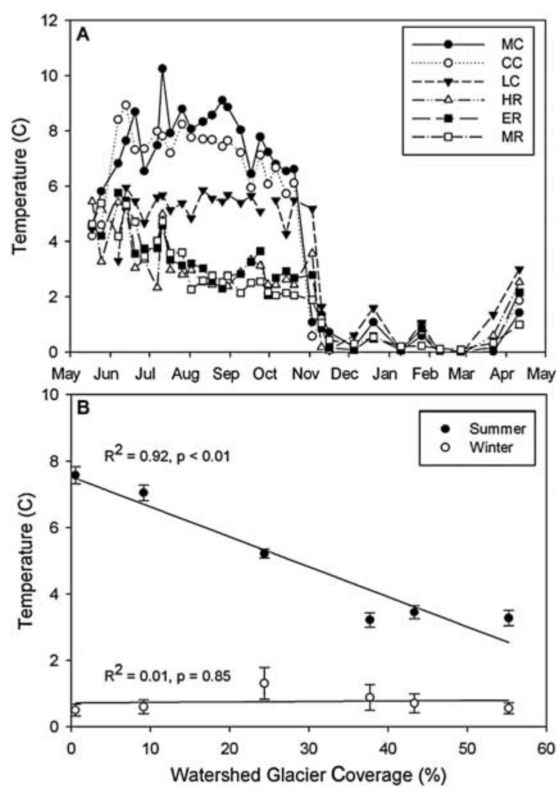

Figure 3. (a) Time series of stream water temperature for the six watersheds and (b) regressions comparing mean stream water temperature (±SE) for the summer and winter seasons to watershed glacial coverage.

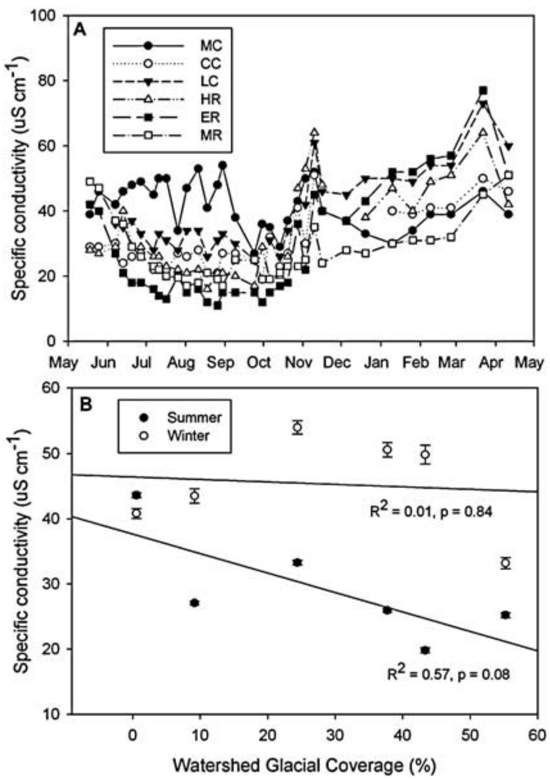

Figure 4. (a) Time series of stream water specific conductivity for the six watersheds and (b) regressions comparing mean stream water specific conductivity (±SE) for the summer and winter seasons to watershed glacial coverage.

ber and October at the peak of the rainy season. For the entire summer, average stream water conductivity was significantly negatively correlated with watershed glacial coverage; however, there was no correlation during winter (Figure 4b). Stream water conductivity was significantly higher in all of the watersheds during winter (*t* test; $p < 0.02$) except Montana Creek where there was no significant difference between the seasons (*t* test; $p = 0.38$).

[15] Stream water turbidity was substantially lower throughout the year in Montana and Cowee Creeks, which contain little to no glacial coverage (Figure 5a). Herbert River, which is heavily glaciated and does not have a proglacial lake, had the highest turbidities of the six watersheds during much of the summer. Mendenhall and Eagle Rivers, which contain proglacial lakes, had the highest turbidities during winter. The annual maxima in stream water turbidities occurred during the fall rainy months in all six watersheds. Mean stream water turbidity for the summer months had a strong positive correlation with watershed glacial coverage (Figure 5b). For the winter, stream water turbidities were significantly lower in all six watersheds (*t* test; $p \leq 0.05$ for all streams) and were not significantly correlated with glacial coverage (Figure 5b). Moreover, only the streams with proglacial lakes showed elevated winter turbidities.

3.3. Stream Water Nutrient Concentrations

[16] Concentrations of DOC in stream water ranged from <0.5 mg C L^{-1} to 5 mg C L^{-1} for all streams (Figure 6a). During summer, DOC concentrations were higher and more variable in streams with less glacier coverage. In streams with higher inputs of glacial meltwater, concentrations of DOC were consistently low during summer and higher and more variable during the winter months (Figure 6a). Mean stream water DOC concentrations were strongly negatively correlated with watershed glacial coverage in summer and less strongly correlated during winter. Concentrations of DOC were significantly higher during winter months in all six watersheds (*t* test; $p < 0.04$ for all streams).

[17] Stream water concentrations of DON were typically below 0.2 mg N L^{-1} for all streams with the exception of Montana and Cowee Creeks which showed higher values during salmon spawning in August and early September (Figure 7a). Similar to DOC concentrations, concentrations of DON were inversely correlated with watershed glacier coverage during summer; however the correlation during winter was not significant (Figure 7b). The heavily glaciated streams tended toward higher DON concentrations in the winter while the less glaciated streams typically had higher DON concentrations in summer, particularly during the salmon spawning season. Interestingly, after removing the salmon-affected samples (6 dates in late summer) from Montana and Cowee Creeks, the slope for the decrease in DON was significantly lower than the slope for the decrease in DOC across the watershed sequence in summer (*F* test; $p < 0.05$). This is consistent with the fact that during the summer runoff season the C:N ratio of stream water DOM decreased from ∼40 to <20 as watershed glacier coverage increased across the six watersheds.

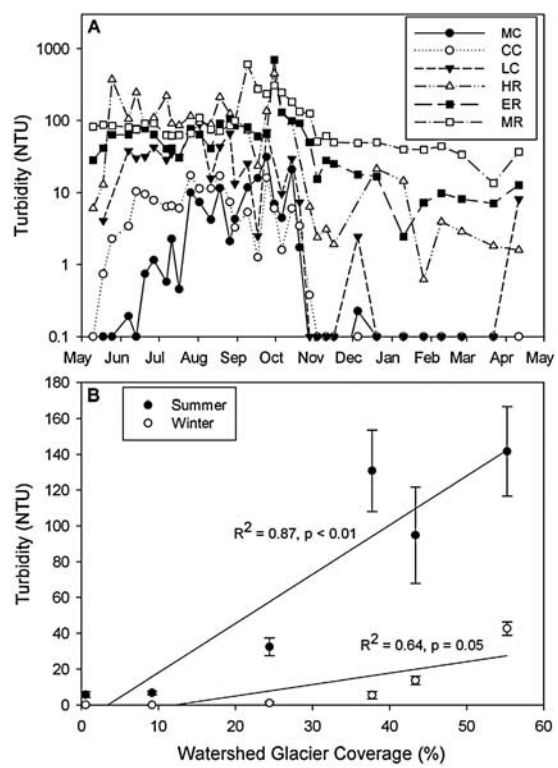

Figure 5. (a) Time series of stream water turbidity for the six watersheds and (b) regressions comparing mean stream water turbidity (±SE) for the summer and winter seasons to watershed glacial coverage.

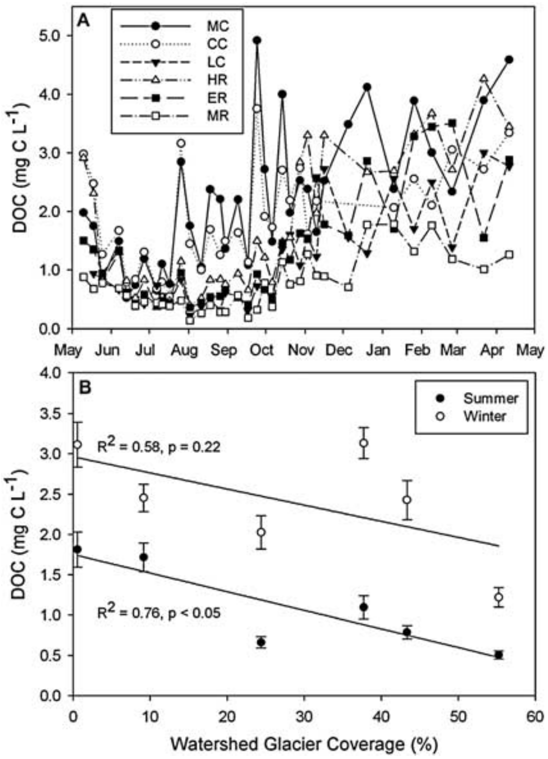

Figure 6. (a) Time series of stream water concentrations of DOC for the six watersheds and (b) regressions comparing mean stream water DOC (±SE) for the summer and winter seasons to watershed glacial coverage.

[18] Concentrations of DIN in stream water ranged from <0.05 mg N L^{-1} to 0.37 mg N L^{-1} for all streams (Figure 8a). Concentrations of DIN decreased during snowmelt in May and remained low through July in all streams. During August and September, DIN concentrations increased sharply in Cowee and Montana, both of which have substantial runs of spawning salmon. During summer months, there was a strong negative correlation between watershed glacial coverage and DIN concentrations (Figure 8b). The correlation between these variables was less strong in winter, and winter concentrations of DIN were significantly higher than summer DIN concentrations in all watersheds (*t* test; $p < 0.01$) except Cowee Creek (*t* test; $p = 0.12$). The increase in winter DIN concentrations was particularly pronounced in the Lemon Creek watershed, which was intermediate in terms of watershed glacial coverage.

[19] Concentrations of SRP in stream water were relatively low (<0.05 mg P L^{-1}) in all watersheds, and were near or below detection limits for much of the peak growing season (July–September; Figure 9a). The highest concentrations of SRP occurred in the heavily glaciated watersheds (Herbert, Eagle, and Mendenhall) throughout the year. The only exception to this was the elevated concentrations of SRP evident in Cowee Creek during salmon spawning in August. Concentrations of SRP were strongly positively correlated with watershed glacial coverage in summer and less strongly correlated in winter (Figure 9b). Concentrations of SRP did not differ significantly between summer and winter in any of the watersheds except HR which had significantly lower concentrations of SRP in winter.

4. Discussion

4.1. Streamflow and Physical Stream Water Parameters

[20] The three gauged streams along our watershed sequence were consistent with previous studies in showing that as watershed glacial coverage decreases there is a shift from a temperature driven hydrograph dominated by glacial meltwater toward a precipitation driven hydrograph dominated by runoff from snowmelt and rainfall [*Kyle and Brabets*, 2001; *Neal et al.*, 2002; *Collins*, 2006]. Previous research has also shown that the δ^{18}O value of stream water can be used as a relative indicator of the contribution of glacier runoff to streamflow since meltwater from snow and glacial ice is depleted in δ^{18}O compared to other streamflow sources such as precipitation and groundwater [*Rietti-Shati et al.*, 2000; *Stichler and Schoterer*, 2000]. Thus, the increasingly depleted δ^{18}O values for stream water moving from Montana (nonglacial) to Mendenhall River (heavily glaciated) are further evidence that the importance of glacial runoff as a source of streamflow decreases with watershed glacial coverage across this sequence of watersheds. One implication of these findings are that as glaciers recede in areal extent and contribute less to streamflow, runoff will be come more episodic and streams more prone to extreme low flows during drier periods in summer. In the near term, the fact that specific discharge for the summer season increased

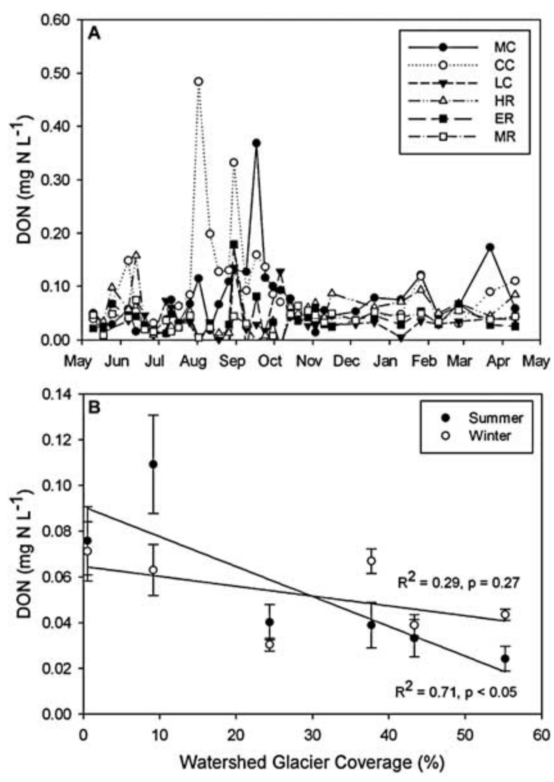

Figure 7. (a) Time series of stream water concentrations of DON for the six watersheds and (b) regressions comparing mean stream water DON (±SE) for the summer and winter seasons to watershed glacial coverage.

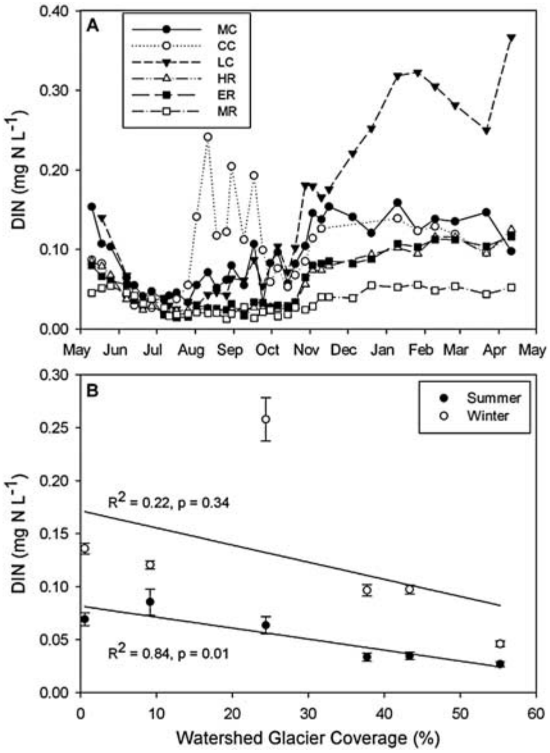

Figure 8. (a) Time series of stream water concentrations of DIN for the six watersheds and (b) regressions comparing mean stream water DIN (±SE) for the summer and winter seasons to watershed glacial coverage.

from 2.2 m in MC to 4.9 m in MR suggests that continued warming and concomitant loss of glacier ice has the potential to increase mean summer and annual discharge in these watersheds. This supposition is consistent with time series records of discharge for glacial rivers in Alaska and Europe that show increasing discharge trends during the second half of the twentieth century [*Neal et al.*, 2002; *Collins*, 2006].

4.2. Physical Properties of Stream Water

[21] Glacial rivers typically have summer temperatures below 10°C and summer turbidity levels exceeding 30 NTU [*Milner and Petts*, 1994]. The streams in our study fell into three categories in terms of their summer temperature and turbidity regimes. The heavily glaciated streams (MR, ER, and HR) all had very cold water temperatures (<5°C) that decreased through the summer and had consistently high turbidity levels (>50 NTU). Lemon Creek, which is intermediate in terms of glacier coverage, had sufficient inputs of glacier meltwater to prevent stream water temperatures from rising with summer air temperatures and maintained elevated turbidity levels. Finally, CC and MC with little to no glacial coverage showed increasing stream water temperatures during summer and low turbidity levels. These findings are consistent with previous research showing that glacial coverage within a watershed has a strong influence on stream temperature, turbidity, and suspended sediment concentrations [*Milner et al.*, 2000; *Kyle and Brabets*, 2001; *Füreder et al.*, 2001]. Interestingly, water temperatures in MC (no glacier) and CC (low glacial coverage) diverged several times during the summer, particularly during August, when inputs of glacial meltwater buffered CC from temperature increases evident in MC. This finding suggests that the presence of even relatively small glaciers may be important for stabilizing stream temperatures during warm, dry periods in summer.

[22] Summer and fall stream water temperatures are an important issue in southeast Alaska because the region contains more than 4000 anadramous salmon streams [*Halupka et al.*, 2002]. Pacific salmon have a water temperature range of about 5–15°C for the incubation and rearing stages of their freshwater life cycle [*Groot and Margolis*, 1991]. In this context, our data show that moderate levels of watershed glacial coverage (5–30%) could become increasingly important for maintaining optimum stream water physical conditions for spawning salmon given that mean annual stream water temperatures in the Pacific Northwest and Alaska are predicted to rise between 1 and 7°C under a 2 × CO_2 climate scenario [*Mohseni et al.*, 1999; *Kyle and Brabets*, 2001].

[23] The presence of proglacial lakes can have a strong moderating effect on the downstream impacts of glacial runoff. In particular, these lakes attenuate summer peak flows, increase water temperatures, and decrease levels of suspended sediment [*Dorava and Milner*, 2000; *Milner et al.*, 2000]. In our study only the two most heavily glaciated watersheds (ER and MR) have substantial proglacial lakes that contribute glacial meltwater to streamflow throughout the year. During summer, the presence of these lakes appeared to result in slightly higher water temperatures

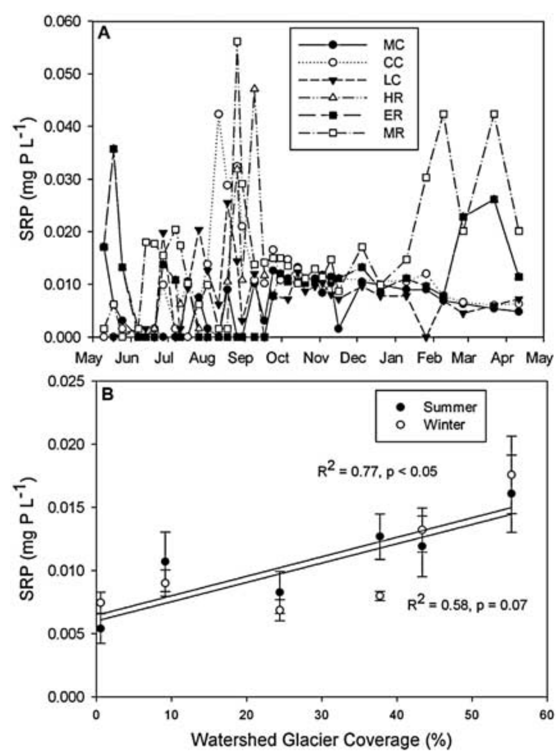

Figure 9. (a) Time series of stream water concentrations of SRP for the six watersheds and (b) regressions comparing mean stream water SRP (±SE) for the summer and winter seasons to watershed glacial coverage.

and lower levels of turbidity when compared to HR, which has lower glacial coverage but no proglacial lake. The lakes were also important for maintaining the glacial character of their two rivers during winter. In particular, MR was much more turbid and had a lower ionic strength in winter compared to the other streams.

[24] Most previous studies of the physicochemical properties of glacial streams have focused exclusively on the summer melt season [*Collins*, 1999; *Hodson et al.*, 2002; *Lafreniere and Sharp*, 2005] (but see *Tockner et al.* [2002]). Our results indicate that during winter, stream water physical properties are similar for glacial and nonglacial streams because streamflow in the glacial watersheds is dominated by groundwater inputs [*Malard et al.*, 1999; *Tockner et al.*, 2002]. Our data from the winter low-flow season suggest that glacial streams in temperate forest watersheds generally have significantly higher levels of dissolved ions, including nutrients, and significantly lower turbidity levels during winter months compared to summer months. Previous research has found that macroinvertebrate densities and taxon richness are highest in the spring and fall transition periods between winter low flows and summer glacier melt [*Burgherr and Ward*, 2001; *Tockner et al.*, 2002]. These transition periods are characterized by relatively warm water temperatures and an absence of the highly turbid flows that scour the streambed during the summer runoff season. Our data suggest that these productive transition periods will increase in duration as glacier coverage within a watershed decreases.

4.3. Stream Water Nutrient Concentrations

[25] The concentrations of DOC that we report for the heavily glaciated rivers (HR, ER, and MR) are consistent with previous studies showing that DOC is typically less than 1 mg C L^{-1} during the summer runoff season in glacial rivers [*Tockner et al.*, 2002; *Lafreniere and Sharp*, 2004; *Barker et al.*, 2006]. As watershed glacier coverage decreased below 10%, summer DOC concentrations increased substantially, suggesting that as forest soils replace glacier ice, there is increased flushing of soluble organic matter from temperate rain forest soils into streams. In particular, the sharp peaks in DOC evident in the less glaciated watersheds (MC and CC) in summer and fall provide evidence that during high-flow events, DOC is being rapidly mobilized from abundant peatland and forested wetland soils via overland flow paths [*Fellman et al.*, 2009]. This finding indicates that terrestrial ecosystem processes play an increasingly important role in determining stream water nutrient concentrations as the landscape ages after glacial recession. This is consistent with the model of physicochemical evolution for lakes [*Engstrom et al.*, 2000] and streams [*Milner et al.*, 2007] developed along landscape chronosequences undergoing deglaciation in nearby Glacier Bay. Interestingly, DOC concentrations increased in all watersheds during winter indicating that there was a relative increase in the proportion of DOC-rich hillslope and riparian groundwater entering the stream during winter low flows. This is consistent with the seasonal differences reported for the Roseg glacier watershed in Austria, where hillslope groundwater with relatively elevated concentrations of dissolved organic C and N dominated streamflow during winter months [*Tockner et al.*, 2002]. At our sites the elevated winter concentrations of organic C and N are also likely influenced by the occurrence of intermittent winter rains that flush dissolved organic material from forest soils into the streams at lower elevations below the glaciers.

[26] The nitrogen concentrations we report are consistent with previous results from glacial rivers as was the fact that stream water DIN concentrations were generally higher than DON concentrations [*Hodson et al.*, 2005; *Lafreniere and Sharp*, 2005]. Concentrations of both forms of N decreased with increasing glacier coverage; however, the decrease in DIN with increasing glacier coverage differs from the results of *Lafreniere and Sharp* [2005], who reported that a glaciated watershed in the Canadian Rockies had higher concentrations of nitrate compared to a colocated unglaciated watershed. This finding was attributed to the lack of vegetated soils (and thus N retention) in the glacial catchment. Across our watershed sequence, it appears that the increased terrestrial nitrogen capital associated with the loss of glacial ice resulted in generally higher concentrations of both organic and inorganic N in stream water.

[27] Concentrations of DIN in stream water were generally highest in the moderately glaciated LC catchment, particularly during winter and spring when vegetation was dormant. A relatively large proportion of the LC watershed has undergone deglaciation since the end of the Little Ice Age [*Miller and Pelto*, 1999], and much of the recently deglaciated portion of the watershed has been colonized by transitional vegetation species such as *Dryas drummondii* and *Alnus sinuate* (Sitka alder) that commonly persist for up to a century following deglaciation in southeastern Alaska [*Chapin et al.*, 1994]. These N-fixing species enhance nitrogen mineralization and soil N pools in terrestrial ecosystems [*Hobbie et al.*, 1998] and can contribute abundant nitrate to stream water [*Compton et al.*, 2003], which would be consistent with the elevated stream water DIN concentrations in LC. Elevated concentrations of both DIN and DON also occurred in the least glaciated watersheds (MC and CC) during and immediately after salmon spawning season (August–September). The increase in DIN in both streams was driven primarily by elevated concentrations of NH_4-N, which is consistent with inputs of N from live and dead spawning salmon [*Gende et al.*, 2002]. Similarly, the increased levels of stream water DON are consistent with inputs of N-rich DOM from salmon [*Hood et al.*, 2007; *Sarica et al.*, 2004].

[28] The fact that concentrations of DON decreased less quickly than concentrations of DOC across the watershed sequence suggests that there is a shift in DOM precursor material toward a predominance of more N-rich DOM in the heavily glaciated watersheds. This N-rich DOM in glacial runoff is likely derived from microbial populations that exist in both supraglacial and subglacial ecosystems [*Skidmore et al.*, 2000; *Hodson et al.*, 2005, 2008; *Anesio et al.*, 2009] and are thought to contribute DOM to proglacial streams [*Lafreniere and Sharp*, 2004; *Barker et al.*, 2006]. Moreover, the shift in the ratio of DOC to DON across the six watersheds was also evident in the ratio of annual riverine fluxes of DOC and DON in the Montana, Lemon and Mendenhall watersheds [*Hood and Scott*, 2008].

[29] The increase in concentrations of phosphorus as glacier cover increased in the six watersheds is consistent with the idea that the action of glaciers can enhance

phosphorus release via rock weathering. Glacial watersheds typically have high concentrations of total P in stream water, most of which is associated with poorly weathered calcite/apatite-rich mineral phases [*Hodson et al.*, 2004]. The increase in concentrations of SRP with glacier coverage suggests that some portion of the P liberated by weathering in the more heavily glaciated catchments occurs in dissolved, reactive forms. Because P is a limiting nutrient in many freshwater aquatic ecosystems, it is also likely that lower in-stream uptake of P contributes to the higher concentrations of SRP in the heavily glaciated watersheds because primary productivity is strongly limited by scouring and light availability in turbid glacial streams [*Robinson et al.*, 2001]. The elevated concentrations of SRP in CC during August also show that salmon can contribute substantial reactive P during the spawning period [e.g., *Mitchell and Lamberti*, 2005].

4.4. Implications of Glacier Loss for Watershed Biogeochemistry

[30] Our findings indicate that changes in land cover and hydrologic flow paths associated with the loss of glaciers in temperate forest watersheds could have pronounced impacts on stream water C, N, and P concentrations. In particular, concentrations of C and N appear to increase with increased routing of water through forest soils as opposed to glacier ice and till, while concentrations of P decrease. Changes in inputs of glacial meltwater also appear to have important indirect effects on nutrient dynamics in coastal streams. For example, higher watershed glacial coverage increases specific discharge and stream water turbidity and decreases stream water temperature, all of which influence the magnitude of runs of spawning salmon in coastal streams [*Dorava and Milner*, 2000]. Recent research on Auke Creek, a nonglacial salmon stream in southeastern Alaska, has shown that average stream water temperature during pink salmon incubation increased significantly during 1972–2005, causing an earlier outmigration of salmon fry [*Taylor*, 2008]. This change in the timing of outmigration increases the potential for the fry to become mismatched with optimum environmental conditions during their early marine life history. In this context, our results suggest that inputs of glacier meltwater could help stabilize stream water temperatures within a range that is optimal for salmon as climate change increases summer temperatures in low-lying coastal watersheds. The effect of climate change on salmon viability in southeastern Alaska has critical implications for watershed biogeochemistry because of the influence of spawning salmon on stream water nutrient concentrations [*Mitchell and Lamberti*, 2005; *Hood et al.*, 2007], nutrient yields [*Moore et al.*, 2007], and aquatic ecosystem productivity [*Chaloner and Wipfli*, 2002] in coastal streams.

[31] The issue of land cover change is critical for high-latitude watersheds because of the relatively large projected increases in temperature at high latitudes in coming decades [*Serreze et al.*, 2000]. Previous research has shown that permafrost degradation is altering organic and inorganic nutrient dynamics in northern rivers [*Streigl et al.*, 2005; *Frey et al.*, 2007]. Our results indicate that land cover changes resulting from glacial recession have similarly important implications for stream water biogeochemistry in watersheds along the Gulf of Alaska. In particular, watershed glacier extent affects stream water concentrations of C, N, and P by (1) altering inputs of glacier versus forest-derived runoff that differ in their concentrations of reactive nutrients and (2) changing stream water physical properties such as temperature and turbidity that influence instream processing and retention of nutrients via biotic and abiotic pathways. Moreover, the changes in water yields associated with the loss of glaciers combined with changes in concentrations of C, N, and P have the potential to dramatically alter the magnitude and timing of fluxes of reactive nutrients to downstream freshwater and nearshore marine ecosystems [*Hood and Scott*, 2008]. Taken together, our findings highlight the importance of developing a better understanding of how changes in glacier coverage will alter the physical and biogeochemical properties of streams in areas like the Gulf of Alaska that are experiencing rapid glacial recession.

[32] **Acknowledgments.** Josh Jones provided valuable assistance with field and lab work. Chris Seibold at the Kiowa Lab in the University of Colorado Mountain Research Station provided major ion chemistry analyses. Bruce Vaughn at the Institute of Arctic and Alpine Research Stable Isotope Laboratory provided isotopic analyses. Sonia Nagorski, Jason Fellman, and two anonymous reviewers provided helpful comments on the manuscript. This work was supported by a Research Experience for Undergraduates Program grant from the U.S. National Science Foundation to UAS (NSF-0553000) and a University of Alaska Southeast Chancellor's Fund grant to E.H.

References

Anesio, A. M., A. J. Hodson, A. Fritz, R. Psenner, and B. Sattler (2009), High microbial activity on glaciers: Importance to the global carbon cycle, *Global Change Biol.*, doi:10.1111/j.1365-2486.2008.01758.x.

Arendt, A. A., K. A. Echelmeyer, W. D. Harrison, C. S. Lingle, and V. B. Valentine (2002), Rapid wastage of Alaska glaciers and their contribution to rising sea level, *Science*, *297*, 382–386.

Barker, J. D., M. J. Sharp, S. J. Fitzsimons, and R. J. Turner (2006), Abundance and dynamics of dissolved organic carbon in glacier systems, *Arct. Antarct. Alp. Res.*, *38*, 163–172.

Brown, G. (2002), Glacier meltwater hydrochemistry, *Appl. Geochem.*, *17*, 855–883, doi:10.1016/S0883-2927(01)00123-8.

Burgherr, P., and J. V. Ward (2001), Longitudinal and seasonal distribution patterns of the benthic fauna of an alpine glacial stream (Val Roseg, Swiss Alps), *Freshwater Biol.*, *46*, 1705–1721.

Chaloner, D., and M. S. Wipfli (2002), Influence of decomposing Pacific salmon carcasses on macroinvertebrate growth and standing stock in southeastern Alaska streams, *J. N. Am. Benthol. Soc.*, *21*, 430–442.

Chapin, F. S., L. Walker, C. Fastie, and L. Sharman (1994), Mechanisms of primary succession following deglaciation at Glacier Bay, Alaska, *Ecol. Monogr.*, *62*, 149–175.

Collins, D. N. (1999), Seasonal variation of solute concentration in melt waters draining from an alpine glacier, *Ann. Glaciol.*, *2*, 11–16.

Collins, D. N. (2006), Climatic variation and runoff in mountain basins with differing proportions of glacier cover, *Nord. Hydrol.*, *37*, 315–326.

Compton, J. E., M. R. Church, S. T. Larned, and W. E. Hogsett (2003), Nitrogen export from forested watersheds in the Oregon Coast Range: The role of N2-fixing red alder, *Ecosystems*, *6*, 773–785.

Dorava, J., and A. Milner (2000), Role of lake regulation to glacier-fed rivers in enhancing salmon productivity: The Cook Inlet watershed, south-central Alaska, USA, *Hydrol. Process.*, *14*, 3149–3159.

Dyurgerov, M., and M. Meier (2000), Twentieth century climate change: Evidence from small glaciers, *Proc. Natl. Acad. Sci. U. S. A.*, *97*, 1406–1411.

Engstrom, D. R., S. C. Fritz, J. E. Almendinger, and S. Juggins (2000), Chemical and biological trends during lake evolution in recently deglaciated terrain, *Nature*, *408*, 161–166.

Fellman, J., E. Hood, R. T. Edwards, and D. D'Amore (2009), Changes in the concentration, biodegradability and fluorescent properties of dissolved organic matter during stormflows in coastal temperate watersheds, *J. Geophys. Res.*, *114*, G01021, doi:10.1029/2008JG000790.

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

Friberg, N., A. M. Milner, L. M. Svendsen, C. Lindegaard, and S. E. Larsen (2001), Macroinvertebrate stream communities along regional and physico-chemical gradients in Western Greenland, *Freshwater Biol.*, *46*(12), 1753–1764, doi:10.1046/j.1365-2427.2001.00857.

Füreder, L., C. Schütz, M. Wallinger, and R. Burger (2001), Physico-chemistry and aquatic insects of a glacier-fed and a spring-fed alpine stream, *Freshwater Biol.*, *46*, 1673–1690, doi:10.1046/j.1365-2427.2001.00862.x.

Gende, S. M., R. T. Edwards, M. F. Willson, and M. S. Wipfli (2002), Pacific salmon in aquatic and terrestrial ecosystems, *BioScience*, *52*, 917–928.

Groot, C., and L. Margolis (Eds.) (1991), *Pacific Salmon Life Histories*, 564 pp., Univ. of B. C. Press, Vancouver, B. C., Canada.

Halupka, K. C., M. B. Bryant, M. F. Willson, and F. H. Everest (2002), Biological characteristics and population status of anadromous salmon in southeast Alaska, *Gen. Tech. Rep. PNW-468*, Pac. Northwest Res. Stn., U.S. Dep. of Agric. For. Serv., Juneau, Alaska.

Hobbie, E., S. Macko, and H. Shugart (1998), Patterns in N dynamics and N isotopes during primary succession in Glacier Bay, Alaska, *Chem. Geol.*, *152*, 3–11.

Hodson, A., M. Tranter, A. Gurnell, M. Clark, and J. O. Hagen (2002), The hydrochemistry of Bayelva, a high Arctic proglacial stream in Svalbard, *J. Hydrol. Amsterdam*, *257*, 91–114.

Hodson, A., P. Mumford, and D. Lister (2004), Suspended sediment and phosphorus in proglacial rivers: Bioavailability and potential impacts upon the P status of ice-marginal receiving waters, *Hydrol. Process.*, *18*, 2409–2422.

Hodson, A. J., P. N. Mumford, J. Kohler, and P. M. Wynn (2005), The High Arctic glacial ecosystem: New insights from nutrient budgets, *Biogeochemistry*, *72*, 233–256.

Hodson, A., A. M. Anesio, M. Tranter, A. Fountain, M. Osborn, J. Priscu, J. Laybourn-Parry, and B. Sattler (2008), Glacial ecosystems, *Ecol. Monogr.*, *78*, 41–67.

Hood, E., and D. T. Scott (2008), Riverine organic matter and nutrients in southeast Alaska affected by glacial coverage, *Nature Geosci.*, *1*, 583–587.

Hood, E., J. Fellman, and R. T. Edwards (2007), Salmon influences on dissolved organic matter in a coastal temperate brownwater stream: An application of fluorescence spectroscopy, *Limnol. Oceanogr.*, *52*, 1580–1587.

Kyle, R. E., and T. P. Brabets (2001), Water temperature of streams in the Cook Inlet basin, Alaska, and implications of climate change, *U.S. Geol. Surv. Water Resour. Invest. Rep., 01-4109*.

Lafreniere, M., and M. J. Sharp (2004), The concentration and spectrofluorometric properties of DOC from glacial and non-glacial catchments, *Arct. Antarct. Alp. Res.*, *36*, 156–165.

Lafreniere, M. J., and M. J. Sharp (2005), A comparison of solute fluxes and sources from glacial and non-glacial catchments over contrasting melt seasons, *Hydrol. Process.*, *19*, 2991–3012.

Larsen, C. F., R. J. Motyka, A. A. Arendt, K. A. Echelmeyer, and P. E. Geissler (2007), Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise, *J. Geophys. Res.*, *112*, F01007, doi:10.1029/2006JF000586.

Malard, F., K. Tockner, and J. V. Ward (1999), Shifting dominance of subcatchment water sources and flow paths in a glacial flood plain (Val Roseg, Switzerland), *Arct. Antarct. Alp. Res.*, *31*, 135–150.

Miller, M. M., and M. S. Pelto (1999), Mass balance measurements on the Lemon Creek Glacier, Juneau Icefield, 1953–1998, *Geogr. Ann. A.*, *81*, 671–681.

Milner, A. M., and G. Petts (1994), Glacier rivers: Physical habitat and ecology, *Freshwater Biol.*, *32*, 295–307.

Milner, A. M., E. E. Knudsen, C. Soiseth, A. L. Robertson, D. Schell, I. T. Phillips, and K. Magnusson (2000), Colonization and development of stream communities across a 200-year gradient in Glacier Bay National Park, Alaska, U.S.A, *Can. J. Fish. Aquat. Sci.*, *57*, 2319–2335.

Milner, A. M., C. L. Fastie, F. S. Chapin, D. R. Engstrom, and L. C. Sharman (2007), Interactions and linkages among ecosystems during landscape evolution, *BioScience*, *57*, 237–247.

Mitchell, N. L., and G. A. Lamberti (2005), Responses in dissolved nutrients and epilithon abundance to spawning salmon in southeast Alaska streams, *Limnol. Oceanogr.*, *50*, 217–227.

Mohseni, O., T. R. Erickson, and H. G. Stefan (1999), Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario, *Water Resour. Res.*, *35*, 3723–3733.

Moore, J. W., D. E. Schindler, J. L. Carter, J. Fox, J. Griffiths, and G. W. Holtgrieve (2007), Biotic control of stream fluxes: Spawning salmon drive nutrient and matter export, *Ecology*, *88*, 1278–1291.

Motyka, R., S. O'Neel, C. Connor, and K. Echelmeyer (2002), Twentieth century thinning of Mendenhall Glacier, Alaska, and its relationship to climate, lake calving, and glacier run-off, *Global Planet. Change*, *35*, 93–112.

Neal, E. G., M. T. Walter, and C. Coffeen (2002), Linking the Pacific decadal oscillation to seasonal stream discharge patterns in southeast Alaska, *J. Hydrol. Amsterdam*, *263*, 188–197.

Nowacki, G., M. Shephard, P. Krosse, W. Pawuk Fisher, G. Baichtal, J. Brew, D. Kissinger, and E. Brock (2001), Ecological subsections of southeast Alaska and neighboring areas of Canada, *Gen. Tech. Rep. R10-TP-75*, U.S. Dep. of Agric., Juneau, Alaska.

Paul, F., A. Kaeaeb, M. Maisch, M. Hoelzle, and W. Haeberli (2003), Glacier monitoring from LandSAT TM: Problems and perspectives, *Geophys. Res. Abstr.*, *5*, 04,417.

Rietti-Shati, M., R. Yam, K. Wibjorn, and A. Shemesh (2000), Stable isotope composition of tropical high-altitude fresh-waters on Mt. Kenya, equatorial East Africa, *Chem. Geol.*, *166*, 341–350.

Robinson, C., U. Uehlinger, and M. Hieber (2001), Spatio-temporal variation in macroinvertebrate assemblages of glacial streams in the Swiss Alps, *Freshwater Biol.*, *46*, 1663–1672.

Sarica, J., M. Amyot, L. Hare, M.-R. Doyon, and L. W. Stanfield (2004), Salmon-derived mercury and nutrients in a Lake Ontario spawning stream, *Limnol. Oceanogr.*, *49*, 891–899.

Serreze, M. C., J. E. Walsh, F. S. Chapin, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry (2000), Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*, 159–207.

Skidmore, M., J. M. Foght, and M. J. Sharp (2000), Microbial life beneath a high arctic glacier, *Appl. Environ. Microbiol.*, *66*, 3214–3220.

Stichler, W., and U. Schoterer (2000), From accumulation to discharge: Modification of stable isotopes during glacial and post-glacial processes, *Hydrol. Process.*, *14*, 1423–1438.

Stowell, H. H. (2006), *Geology of Southeast Alaska: Rock and Ice in Motion*, 140 pp., Univ. of Alaska Press, Fairbanks.

Streigl, R. G., G. R. Aiken, M. M. Dornblaser, P. A. Raymond, and K. P. Wickland (2005), A decrease in discharge-normalized DOC export by the Yukon River during summer through autumn, *Geophys. Res. Lett.*, *32*, L21413, doi:10.1029/2005GL024413.

Taylor, S. G. (2008), Climate warming causes phonological shift in Pink Salmon, Oncorhynchus gorbuscha, behavior at Auke Creek, Alaska, *Global Change Biol.*, *14*, 229–235.

Tockner, K., F. Malard, U. Uehlinger, and J. V. Ward (2002), Nutrients and organic matter in a glacial river-floodplain system (Val Roseg, Switzerland), *Limnol. Oceanogr.*, *47*(1), 266–277.

Tranter, M., M. J. Sharp, H. R. Lamb, G. H. Brown, B. P. Hubbard, and I. C. Willis (2002), Geochemical weathering at the bed of the Haut Glacier d'Arolla, Switzerland—A new model, *Hydrol. Process.*, *16*, 959–993.

L. Berner and E. Hood, Environmental Science Program, University of Alaska Southeast, 11120 Glacier Highway, Juneau, AK 99801, USA. (eran.hood@uas.alaska.edu)