TRACING GLACIAL ICE AND SNOW MELTWATER WITH ISOTOPES

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Abstract

This report describes accomplishments for the two-year project investigating temporal dynamics of glacial ice and snow meltwater, rainfall and base flow contributions to stream flow of Dinwoody Creek in the Wind River Range of western Wyoming. The primary objectives were to 1) characterize diurnal, seasonal and interannual variation in the isotopic composition of water in Dinwoody Creek, 2) quantify the contribution of baseflow and surface runoff to stream discharge using isotopic methods, and 3) partition the surface runoff component of stream discharge into that derived from glacial melt, snowmelt, and summer precipitation. This project involved a collaboration among the University of Wyoming Stable Isotope Facility, directed by the project PI (Williams), Dr. Jessica Cable of the Department of Botany and Dr. Kiona Ogle of the Departments of Botany and Statistics. Dr. Cable led the field and laboratory studies and statistical modeling and will be the primary author of a forthcoming journal article describing the findings from this project to be submitted in June 2009 to *Hydrological Processes*. Dr. Cable was supported part time as a postdoctoral student on this project and was mentored by Drs. Williams and Ogle. Dr. Ogle provided valuable leadership on the statistical modeling used to partition stream flow and quantify the contribution of glacier meltwater.

We estimated the fractional contribution of glacier melt water to flow in Dinwoody Creek on seasonal and interannual time scales. The stable isotope composition of water (oxygen-18 and deuterium) from the Dinwoody Creek watershed and glacier system was determined on a temporally intensive scale in 2007 and 2008. Field sampling of the primary contributors to streamflow, namely snow melt, glacier melt, rain, and baseflow, were collected during the summers of 2007 and 2008. Stream samples were collected every 48 h over the entire melt season from mid-April to late October using an automated stream sampler placed beside an unimpaired USGS gauging station low in the watershed. The data were analyzed with a hierarchical Bayesian framework that allowed integration of temporal and spatial autocorrelation in the isotope data. Glacial melt contributed a significantly large proportion to stream flow in a low flow year (2007) and when stream flow was low during a high flow year (early and late summer 2008). In 2008, a large and persistent snowpack and associated melt dominated stream flow in the middle of the summer. Summer rainfall had minimal contribution to streamflow. Our findings strongly support the assertion that loss of alpine glaciers in the Wind River Range with climate warming will substantially reduce streamflow, but only during periods when snowmelt contributions are low.

Overview and Significance

Widespread glacier recession has been occurring over the past half century and has accelerated since the early 1990's in conjunction with the post 1970's warming trend (Kundzewicz et al. 2007). Continued decline of glacier mass will result in a transient increase in river discharge (Aizen et al. 1997, Kundzewicz et al. 2007). It is estimated that 1/6th of the global population derives much of their water from glacier and snow-fed watersheds (Barnett et al. 2005, Kundzewicz et al. 2007). For example, glacier meltwater contributes to nearly 70% of the Ganges discharge, which supports a large human population (Singh et al. 1997, Singe and Jain

2002, Singh and Bengtsson 2004). The impacts of glacier shrinkage on social, economic, and ecological systems are multi-faceted because the surge of glacier meltwater into rivers will be transient (e.g., Kundzewicz et al. 2007). For the systems depending on the glacier-fed late summer water supply, the post-surge decline in glacier meltwater may be detrimental (Mark et al. 2003, Singh and Bengtsson 2004, Barnett et al. 2005). In conjunction with glacier shrinkage, many of these systems will suffer from altered precipitation regimes, drought, and reduced snowpack, further exacerbating the effects of climate change on water supply (Barnett et al. 2005, Kundzewicz et al. 2007, Stewart 2009). The loss of mountain glaciers in the western U.S., particularly Wyoming, may exacerbate the drought situation faced by water resource planners concerned with allocating water for agricultural and municipal use. The contribution of glacier meltwater to stream discharge in Wyoming is not well quantified.

Stable isotope composition (deuterium [δD] and oxygen 18 [$\delta^{18}O$]) of water have successfully been used as naturally occurring hydrologic tracers to constrain estimates of the contributions of different water sources to stream flow, including snowmelt, glacier meltwater, and groundwater baseflow (Behrens et al. 1971, 1979; Dinçer et al. 1970; Martinec et al. 1974; Rodhe 1981, Hooper and Shoemaker 1986, Obradovic and Sklash 1986, Maulé and Stein 1990). Although there have been a number of important hydrological investigations in Wyoming that have employed isotope tracers (e.g., Schuster et al. 2000, Coplen and Kendall 2000, Naftz et al. 2002, Frost et al. 2002, Frost and Toner 2004, Benjamin et al. 2004), the use of isotopic tracers in studies to identify contributions of rain, snowmelt, groundwater baseflow, and glacier meltwater to stream flow in alpine catchments has received little attention. Potential effects of climate variability, loss of alpine glaciers, and forest disturbances on stream flow are highly uncertain. Stable isotope tracers combined with Bayesian analysis techniques can play a prominent role in reducing this uncertainty. In this study, we used isotopic tracers to distinguish sources of stream discharge in Dinwoody Creek in the Wind River Range by partitioning stream flow into that derived from baseflow, glaciermelt, snowmelt, and summer precipitation. We analyzed the data in a hierarchical Bayesian framework, thereby fully accounting for uncertainty and incorporating temporal and distance autocorrelation.

Objectives

The principal scientific objective of this work was to evaluate isotopic tracers at natural abundances for their ability to distinguish sources of flow in a glacier-fed stream. Specific objectives were to:

1. Characterize seasonal and interannual variation in isotopic composition of a glacier fed stream in the Wind River Range;
2. Quantify the contribution of baseflow and surface runoff to stream discharge using isotopic methods; and
3. Partition the surface runoff component of stream discharge into that derived from glacial melt, snowmelt, and summer precipitation.

Methodology

Using Stable Isotopes for Hydrograph Partitioning. Isotopic tracers are useful for constraining estimates of source contributions to stream flow and are easily employed in remote field locations. Isotopic measurtements can be coupled with stream flow measurements to partition the contributions of different sources. Hydrograph separation using isotope tracers is based on mass conservation for water and tracer (Genereux and Hooper 1998). Successful hydrograph or stream flow separation using isotopes requires that: (1) the isotopic content of the contributors significantly differs from that of the primary glacier-fed river; (2) the contributing sources maintain a constant isotopic content; (3) vadose water does not contribute significantly to stream flow; (4) surface storage contributes minimally to stream flow after a precipitation event occurs.

The first of these requirements is obvious, and the latter requirements to some degree can be dealt with by appropriately sampling the sources of stream flow with enough frequency to either account for this variation or ignore it. Additional isotopic tracers can be included during periods when more than one source contributes to stream flow (e.g., glacier melt and snowmelt). For instance, δD and δ^{18}O together can be measured if the two sources isotopically differ; then partitioning of these sources can be accomplished by examining the isotope data in dual-isotope space.

Alpine glaciers are complex water storage compartments that to some degree behave isotopically like a well mixed lake. Because the current year's snowmelt and summer rain can be trapped within the glacier in fissures to be frozen during winter, the melting of the glacier can release water that has been added from recent inputs together with water stored for decades to centuries. Therefore, it is difficult to predict how the isotopic composition of glacier melt water will differ from the current year's snowmelt or rainfall. However, if one assumes that the glacier mass is an integrator, then melt water from the glacier may be attenuated isotopically relative to seasonal and interannual isotopic variations in meteoric waters. For that reason alone, glacier melt water can be distinguished isotopically from the current year's meteoric inputs. The δD and δ^{18}O compositions of precipitation co-vary but their correlation can be affected by evaporation, sublimation, re-melting, and exchange with atmospheric vapor. The offset due to these fractionation processes can easily be detected in the deuterium excess value of the water sample. Because these processes are likely to play a role in glacier melt and accumulation, both δD and δ^{18}O should be measured as together they may reveal unique signatures of different source waters contributing to stream flow in a snowmelt driven catchment.

Field Sampling of Water. This study was conducted in 2007 and 2008 on Dinwoody Creek, a primary tributary of the Wind River Range fed principally by Dinwoody Glacier (Figure 1). To capture temporal variation in the isotopic composition of Dinwoody Creek, a 24 bottle stream sampler (Teledyne Isco, Inc, Lincoln, NE) was installed beside an unimpaired USGS gauging station (# 06221400, 1981m asl) to collect stream water samples every 2 days at daily peak flow (~ 3 pm) from mid-spring just prior to the onset of

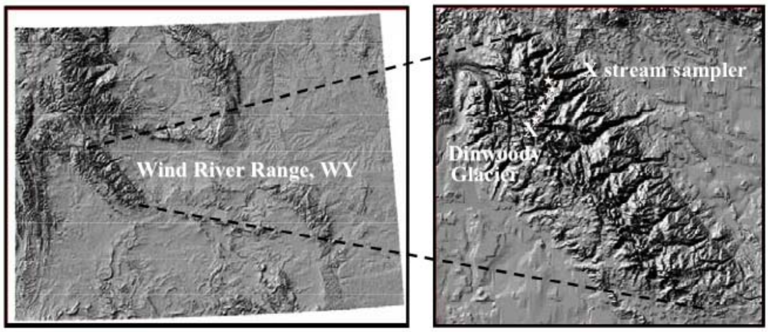

Figure 1. Location of study area, Dinwoody Glacier, and the stream sampler in the Wind River Range, WY. The white stars in the right-hand panel are the sampling locations within the watershed.

snowmelt to late fall. A sample was collected by hand in mid-winter when streamflow was dominated by baseflow. Mineral oil was added to the collection bottles to prevent evaporation and isotopic enrichment. The stream sampler was located 36 km downstream from Dinwoody Glacier and integrated a watershed area of 228 km^2 (USGS), resulting in extensive spatial and temporal integration of watershed isotope and stream flow information. To determine the isotopic signatures of the source waters (rain, snow and glacier meltwater), we conducted summer field trips in both 2007 and 2008. In 2007 and 2008 we sampled in late summer (August) and in 2008 we sampled also in the early summer (early July). The early summer trip was the primary snowmelt period, and the late summer trip coincided with the period of maximum glacier melt. During each trip, we collected glacier meltwater from the tongue of Dinwoody glacier, the current year's snowmelt (through direct sampling of melting snow), and precipitation (through opportunistic sampling). The contribution of glacier water to stream flow was assessed using Bayesian statistical modeling. This aided in hydrograph separation when integrated with data collected at the stream gauge. All samples were analyzed for δD and δ^{18}O composition at the University of Wyoming Stable Isotope Facility.

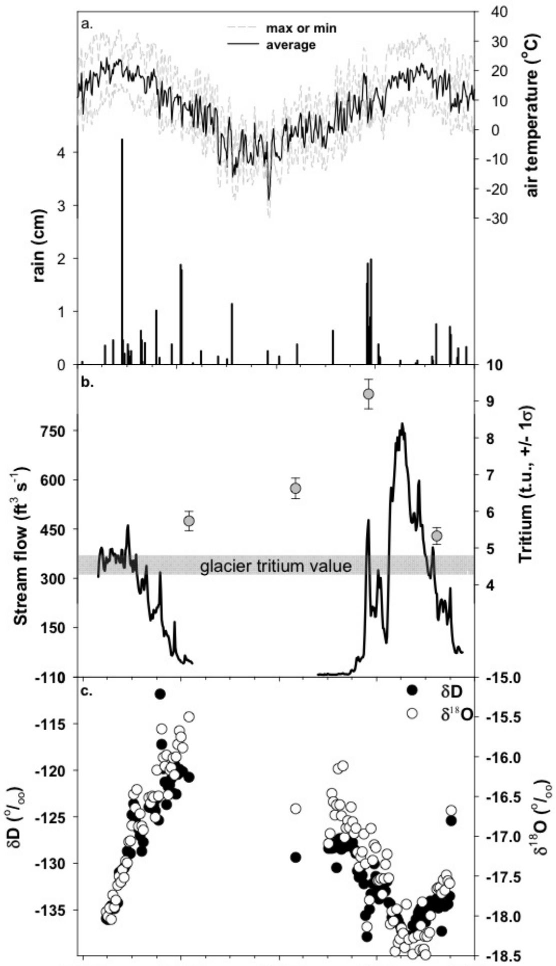

Figure 2. (a) The daily mean, minimum and maximum air temperature and precipitation for Burris, WY (NCDC, 2008). (b) Streamflow recorded at the USGS stream gauge and tritium values collected near the stream gauge. Glacier melt water was collected at the base of the glacier and is represented by the grey bar. (c) Stable isotopes of water collected with the stream sampler placed beside the stream gauge.

Hierarchical Bayesian Analysis. A hierarchical Bayesian (HB) modeling approach (e.g., Berliner 1996; Clark 2005; Ogle and Barber 2008; Wikle 2003) was used to analyze the stable isotope data. The HB method provides a fully consistent statistical framework for analyzing the data within the context of a mixing model. The HB model has three components: (1) the data model that defines the likelihood of the observed data; (2) the mixing model and the models for the fractional contributions of different source waters; and (3) the parameter model that defines the prior distributions for the mixing model parameters and variance terms.

The first part of the data model combines the data likelihoods for observed δD and δ^{18}O data from the source waters. We transformed the δ^{18}O values by multiplying all the data by 2.5 to attain equal variation between the δD and δ^{18}O data. We assume the isotope data (δD and δ^{18}O) from the four water sources fit a multivariate normal distribution model with a mean and a precision covariance matrix. The multivariate normal distribution model accounts for correlation between the δD and $\delta^{18}O$ data. The means for rain (r), glacier (g), and snow (s) source waters and the standard deviations for all four sources (including baseflow) are given by relatively diffuse, non-informative priors that come from a wishart distribution. Baseflow is a mixture of rain, snow, and glacier meltwater, so the mean for baseflow (b) is given by the sum of means for these three sources, each with their own fractional contribution.

The second part of the data model is for the isotope data from Dinwoody Creek. We assume that Dinwoody Creek (stream) isotope data are given by a bivariate normal distribution with a mean and a covariance matrix. The data vary by time (T) and distance from Dinwoody Glacier (D). The mean stable isotope values for the stream are given by a mixing model, which is the sum of the fractional contribution (*p*) of each source multiplied by its isotope value, given by the source mean values. The *p*'s for rain, snow, and glacier were modeled as a function of time, and the *p* for glacier was also modeled as a function of distance from glacier.

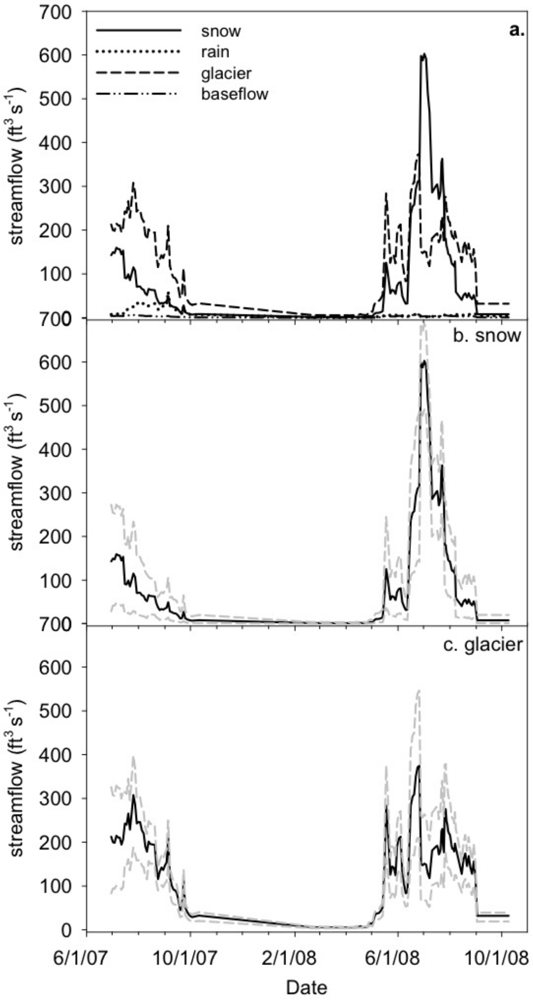

Figure 3. (a) Posterior mean estimates of streamflow contributed by each water source. Posterior mean estimates and 95% credible for the streamflow contributed only by (b) snow melt water and (c) glacier melt water.

The fractional contribution of each source was multiplied by the streamflow ($ft^3\ s^{-1}$) data from the USGS stream gauge to determine the flow of water contributed by each source. We ran four chains for 5000 iterations, and we thinned every 100 while running the model and thinned every 5 after running the model. We discarded the first 400 samples, and this resulted in a total of 3680 samples for calculating the posterior statistics. The model fit the data well ($\delta^{18}O$: $R^2 = 0.77$, observed = 1.2*predicted + 3.2; δD: $R^2 = 0.95$, observed = 1.1*predicted + 13.1).

Results

Air temperatures and rainfall were similar between 2007 and 2008 (Figure 2a). Higher snowfall in 2008 resulted in a more persistent summer snowpack and higher streamflow in the summer of 2008 (Figure 2b). Abrupt increases in tritium values of stream water occurred with the onset of spring streamflow in 2008 (Figure 2b). The stable isotopes of stream water collected at the stream gauge showed distinct seasonal trends, with values becoming more depleted from the beginning to the middle of the summer, and then abruptly becoming more enriched from the middle of the summer into the fall (Figure 2c).

Results from the HB analysis show that glacier melt water dominated streamflow throughout the summer of 2007, followed by snow melt water, rain, and baseflow (Figure 3a). In the summer of 2008, glacier melt water dominated stream flow early (until ~ June 1st) and late in the summer (after August 1st), and snow melt water contributed to the highest stream flow in the mid-summer (Figure 3a-c). This is in accordance with field observations, where a large snowpack was observed in 2008 but not 2007. High stream flow is associated with a higher contribution of snow melt water (Figure 3). Baseflow consisted of 49% snow meltwater, 39.4% glacier meltwater, and 12% rain (Table 1).

Table 1. The mean and 95% credible interval for the percent contribution of snow melt water, rain, and glacier melt water to baseflow.

Source water	Mean [2.5%, 97.5%]
Glacier	39.4 % [0.43 %, 36.8 %]
Rain	12.0 % [0.11 %, 11.5 %]
Snow	48.6 % [0.42 %, 51.2 %]

We show variation in estimates of the contribution of glaciermelt and snowmelt to stream flow, which broadens the potential role of either source throughout the summers of 2007 and 2008 (Figure 3c). We note that although the stable isotope values for glacier and snowmelt water were very similar (Table 2), incorporating time and distance effects into the model constrained estimates of p for all the sources. Further, our conclusions about the differences in the temporal contributions of snow and glacier melt water to stream flow are supported by the tritium data (Figure 2b). The tritium data show promise in distinguishing between snow and glacier meltwater.

Table 2. Predicted estimates of the mean and credible interval for the isotopic value of the water sources.

Isotope	Water source	Mean [2.5%, 97.5%]
δD	Baseflow	-125.1 ‰ [-135.6 ‰, -112.2 ‰]
	Glacier	-134.5 ‰ [-136.8 ‰, -132.0 ‰]
	Rain	-39.57 ‰ [-54.68 ‰, -24.22 ‰]
	Snow	-138.7 ‰ [-142.6 ‰, -135.0 ‰]
$\delta^{18}O$	Baseflow	-16.96 ‰ [-18.31 ‰, -15.22 ‰]
	Glacier	-18.24 ‰ [-18.56 ‰, -17.92 ‰]
	Rain	-5.89 ‰ [-7.46 ‰, -4.25 ‰]
	Snow	-18.65 ‰ [-19.23 ‰, -18.04 ‰]

Conclusions

In this system, interannual variation in streamflow was largely due to differences in snowpack, where the reduced snowpack in 2007 was reflected in lower streamflow compared to 2008. Compared to baseflow and rain water, the large and fairly consistent interannual contributions of glacier meltwater maintained streamflow in low flow years (contributing an average of 59% in 2007), and early and late in the summer (pre and post-snowmelt) in high flow years (contributing an average of 69% early summer and 53% late summer in 2008). ENSO may play a role in affecting the isotope values we observed. The transition between 2006 and 2007 was a warm or El Niño phase and the transition between 2007 and 2008 were a cold or La Niña phase (NOAA, 2009). Thus, the temperature of the sources of moisture for each year may have differed, and impacted the stable isotope composition of the snowpack. Continued reductions in glacial mass in the coming decades will reduce stream flow during critical times, such as dry years and dry parts of the year. Thayyen et al. (2006) also found glacier melt water to sustain streamflow in dry years in a small catchment in the Himalayas. While it is clear that variation in snowpack will increase variation in stream flow and water supply, glacier melt water is a somewhat constant “background” water supply that is declining. This consistency of water for stream flow might be important for water planning in the coming years in Wyoming.

Using a dual stable isotope approach in this study was useful when accounting for temporal and spatial autocorrelation in the isotope data in a hierarchical Bayesian framework. We found that when distance and time were not accounted for, the glaciermelt and snowmelt contributions were not discernable. The HB approach was powerful in this study because we could fully account for variation and estimate uncertainty in the contributions of glaciermelt and snowmelt water to streamflow.

Publication and presentation citations

Cable, J.M., K. Ogle, D.G. Williams, and S. Bachman. 2008. The contribution of glacier meltwater to stream flow in the Wind River Range, WY. *Eos Trans. AGU, 89*(53), Fall Meet. Suppl., C23A-0597.

Cable, J.M., K. Ogle, and D.G. Williams. The contribution of glacier meltwater to streamflow in the Wind River Range, Wyoming: an isotopic and Bayesian analysis approach. (in preparation for *Hydrological Processes*).

Student support information

One postdoc, one graduate student, and one undergraduate student were supported in Year 1 and one postdoc and one part-time technician were supported in year 2 of this project. The postdoc, Dr. Jessica Cable, was supported at 0.25 time from June 2007 to March 2009. One graduate student, Mr. Peter Koenig, was supported on the project in Year 1 from March 2007 to June 2007. Mr. Koenig initiated the field and lab studies. One part-time undergraduate student, Mr. Patrick Juancorena, was supported on the project in Year 1. Mr. Juancorena assited with laboratory work associated with the project. Ms. Sarah Bachman was supported as a part time technician in Year 2 of the project. She assisted with field sampling and laboratory work in Year 2 of the project.

Awards and achievements

Dr. Jessica Cable, the postdoc working on this WWDC project, has successfully acquired $5000 funding from the National Park Service to conduct a parallel study on glaciated basins using isotopic tracers in Grand Teton National Park, WY. The title of her award is: *Using stable isotopes of water to determine the contribution of glacial melt to streamflow and plant water use in Grand Teton National Park*. Dr. Cable is the PI for this new project funded by the UW-NPS Research Center.

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