Toward the Development of a Cold Regions Regional-Scale Hydrologic Model
Final Project Report

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1. Summary of results:

In this study, we strove to understand and quantify the processes, mechanisms, timing and magnitude of water pathways in the sub-Arctic boreal forest ecosystem in an attempt to improve our capability to more correctly simulate ecosystem response to a warming climate, and thus the changes in feedback processes that will ultimately affect the regional arctic climate. Specifically, we worked toward quantifying and predicting the spatial and temporal variation in (1) watershed processes, including the relative importance of vegetation water use and the presence/absence of permafrost and active layer dynamics and the pathways of water in a highly heterogeneous (with respect to permafrost and vegetation distribution) sub-arctic watersheds; and (2) to improve the predictive ability of meso- to large-scale hydrologic models by applying a small-scale parameterization scheme that better represents the spatial heterogeneity found in the discontinuous permafrost, boreal forest ecosystem. Our study focused on two primary boreal forest types: coniferous and deciduous dominated ecosystems (CDEs and DDEs, respectively). In a very general sense, near surface permafrost corresponds to CDEs and permafrost-free areas or areas with deeper permafrost correspond with DDEs.

Primary Findings and Significance:

First, this study identified and found solutions to some of the primary challenges in accurately modeling hydrologic processes in the boreal forest ecosystem. The spatial heterogeneity of the boreal forest landscape – which impacts modeling of hydrologic processes – is due to the presence or absence of near surface permafrost, which in turn impacts vegetation cover and species composition, and soil hydraulic and thermal properties. When examining small basins (~6 km^2) this project found that small-scale parameterizations better represent the boreal forest hydrologic processes compared to broad or coarse-scale parameterizations. A small-scale 'ecotype' parameterization scheme was derived from field observations and fine-resolution landscape modeling in two watersheds of contrasting permafrost distribution located in the Caribou-Poker Creeks Research Watershed. The ecotype parameterization scheme was based upon the assumption that in this region, CDEs are located along north-facing slopes and valley bottoms while DDEs are generally found along south-facing slopes. The distribution of CDEs and DDEs were derived from calculation of the slope and aspect of a 30m Digital Elevation Model (DEM). CDEs are assumed to have coniferous vegetation, a thick organic layer, and a reduced hydraulic conductivity. DDEs are assumed to have a deciduous vegetation, a thin organic layer, and a deep damping depth (Figures 1 and 2). The results of the small-scale parameterization model were aggregated into 1 km^2 model elements with hydraulic simulations conducted using the Variable Infiltration Capacity (VIC) model. Compared to using coarse-scale soil and vegetation input parameters, the small-scale parameterization scheme improved the simulated discharge by 50% in the DDE and 10% in the CDE basins (Endalamaw et al, 2017). One finding from this initial work on small versus large scale parameterizations and understanding spatial heterogeneity is that evapotranspiration (ET) is higher in the DDE-regions and ET is decoupled from precipitation but coupled to temperature (Cable et al., 2013). This is because the deciduous trees take up and store snowmelt water, and utilize it throughout the summer. Thus, rainfall is not as important factor for tree water use, but the deciduous vegetation still responds to to air temperature. Additionally, the DDE-regions have low runoff (compared to CDE-regions) due to high infiltration capacity and high tree water use. In the CDE-regions, ET is lower and runoff is higher due to limited soil storage capacity and and low tree water use. The challenge of upscaling from the small-scale basins to a larger-scale basin hydrologic models in the boreal forest still requires capturing the spatial heterogeneity of the ecosystem, often in data-limited areas. We tested our small-scale parameterization scheme by upscaling to the Chena River Basin (~5400 km^2). Using the small-scale parameterization scheme resulted in a 10-20% improvement of simulated stream flow compared to using coarse-scale parameterizations. Simulations using a 5 km^2 model element resolution performed better than simulations using a 10 km^2 model element resolution (Figures 3, 4, and 5). In summary, the spatial heterogeneity of the boreal ecosystem landscapes, including the presence or absence of permafrost and delineation of coniferous and deciduous vegetation, must be represented in hydrologic models to accurately capture the hydrologic processes.

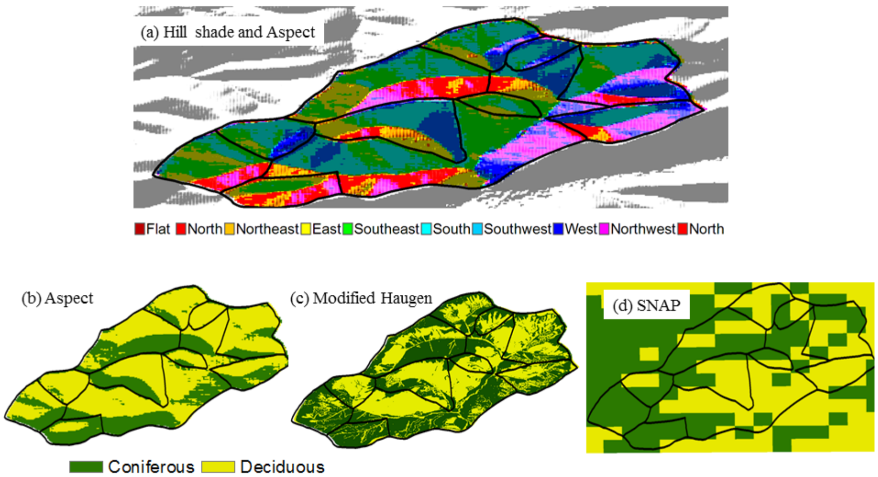

Figure 1: Small-scale parameterization scheme used to delineate DDEs and CDEs. (a) Aspect map derived from a 30m DEM of the Caribou-Poker Creeks Research Watershed; (b) Vegetation composition based upon the small-scale parameterization scheme; (c) Observed vegetation distribution, modified from Haugen et al (1982); (d) Vegetation distribution at 1 km^2 resolution from the Scenarios for Alaska and Arctic Planning (SNAP). The vegetation distribution products from SNAP are for this study, considered to be the large-scale dataset which comparisons are made.

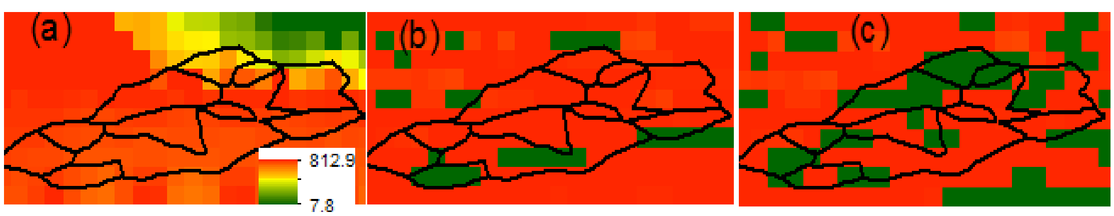

Figure 2: Saturated hydraulic conductivity (mm/day) as derived from (a) the large-scale Food and Agricultural Organization (FAO) soil dataset; (b) based upon observed permafrost (modified from Rieger et al and scaled to 1 km2); and (c) based upon 30m DEM small-scale parameterization scheme. As soil properties are tiled in the VIC model, an entire model cell was assigned hydraulic properties consistent with permafrost if the ratio of permafrost to no-permafrost was found to be 50% or greater.

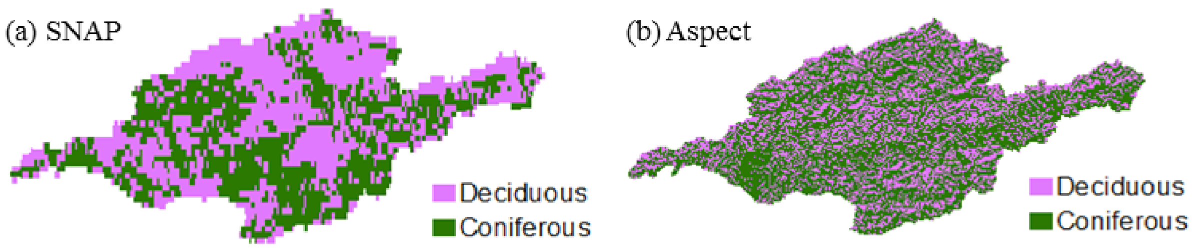

Figure 3: Vegetation cover map of the Chena River Basin; (a) aggregated coniferous and deciduous vegetation distribution from the SNAP land cover data set; and (b) coniferous and deciduous vegetation heterogeneity derived from the 30m DEM fine-scale model parameterization scheme.

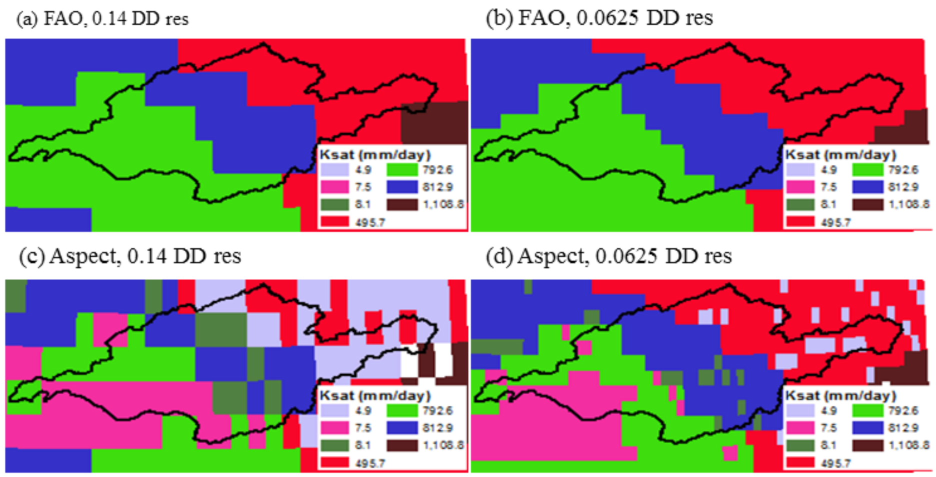

Figure 4: Saturated hydraulic conductivity variation in the Chena River Basin. (a) and (b) represent data extracted from the FAO soil property data set at ~10km^2 and ~5km^2 resolutions; (c) and (d) are modified saturated hydraulic conductivity values derived from the 30m DEM fine-scale parameterization scheme. Note: DD res indicates the model resolution in decimal degrees.

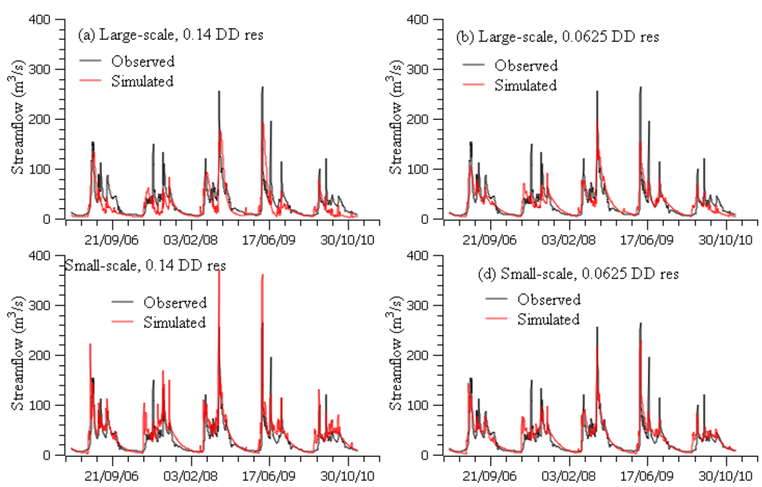

Figure 5: Comparison of simulated and observed stream flow for the Chena River Basin at 5 (left panels) and 10 km^2 (right panels). The R^2 values for panels (a), (b), (c), and (d) are: 0.71, 0.56, 0.77, and 0.62 indicating the small-scale parameterization scheme improves discharge simulations at both the 5 and 10km^2 resolutions, with greater improvements occurring in the 5 km^2 model resolution.

Second, while boreal regions are not often considered to be "dry", a significant part of the Alaskan landscape is dry (~61% of the land area in Alaska including eastern part of the Yukon River basin in

Canada is permafrost free with a deciduous vegetation). The heterogeneity of dry versus wet areas of the boreal forest landscape further challenges the model simulations. This challenge is further complicated with the expected warming and drying climatic trends of this region. Most hydrologic models are designed to be applied to lower latitude systems with the soil properties are generally consistent throughout the year. Through sensitivity analysis of the soil hydraulic parameters that are typically held constant in simulations, this project found that runoff simulations in permafrost free (typically dry soils) are more sensitive to the “residual soil moisture content” property compared to permafrost soils (typically wet soils). In Interior Alaska, drier soils produced more baseflow than from wet soils, which differs from lower latitude systems. This is due to the lack of soil storage capacity in the wet, permafrost soils. As this region is expected to become warmer and drier in the future, this parameter needs to be considered and implemented in future hydrologic modeling projects of the boreal forest, discontinuous permafrost ecosystem.

Third, assessing the impact of climate change on hydrological processes through integrated modeling approaches (e.g. linking results from climate and land surface model outputs to the hydrologic model framework) often do not account for the for the indirect impact of climate on hydrologic processes through changes to the land surface. In the boreal forest, the expected landscape changes include a reduction in near surface permafrost and an increasing deciduous vegetation composition. In this highly heterogeneous landscape, it is critical to include these indirect impacts of climate change when conducting hydrologic simulations into the future. In this study, the effects of changes in direct (temperature and precipitation) and indirect (changes in near surface permafrost distribution and vegetation composition) were quantified. In order to quantify the direct impacts of climate change on the hydrologic system, output from the RCP8.5 CMIP5 model (precipitation and temperature) were used as input to the hydrologic model. In order to explore the indirect effects of climate change, outputs of near surface permafrost distribution (Geophysical Institute Permafrost Laboratory (GIPL) Model) and vegetation distribution (Alaska Frame-based Ecosystem Code (ALFRESCO)) were used as input to the hydrologic model. When considering only the direct effects of climate change, discharge increases significantly compared to current climate conditions. However, when incorporating the indirect impacts (change in permafrost and vegetation distribution), the increase in discharge is moderated due to increases in ET and soil storage capacity (Figure 6). Climate change studies in the boreal forest region, should include the indirect landscape changes that are expected in the future. Ignoring the landscape changes let to an overestimation of discharge by 37%, an underestimation of ET by 40%, and an underestimation of dryness (P-ET) by 9%.

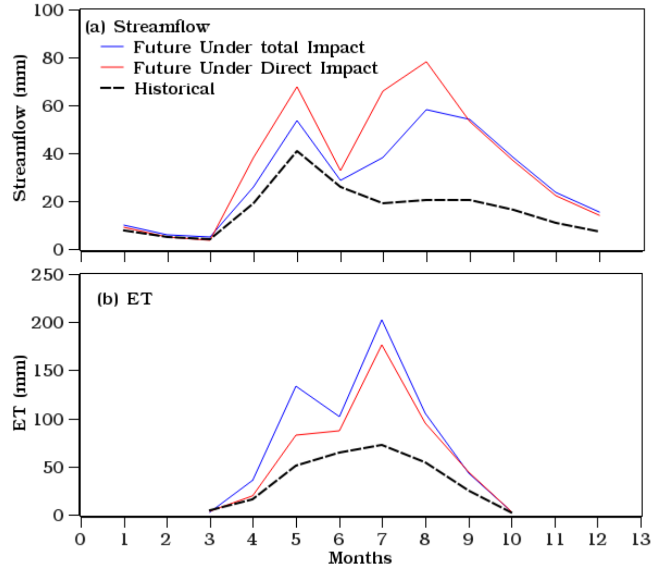

Figure 6: Mean monthly simulations of (a) stream flow and (b) evapotranspiration over the Chena River basin using the VIC model during the baseline historical (1980-2010) and future (2070-2100) time periods. The five model average Global Change Models at RCP8.5 emission scenarios were used to force the model. The simulated total impact considered changes in vegetation cover and permafrost distribution, while the direct impact only considered changes in precipitation and temperature.

Finally, this project highlights the role that vegetation play in boreal forest hydrology, and the importance of considering the differences between deciduous and coniferous vegetation. We found that deciduous trees play a dominant role in hydrologic processes in permafrost-free regions. In the time period between snow melt and leaf-out, deciduous trees took up between 21-25% of the available snow melt water. Over the same period, coniferous vegetation took up <1% of the available snow melt water. Scaling to the Alaskan boreal forest, and including the Yukon River watershed (extending into Canada), between 17.8 -20.9 billion cubic meters of water were removed and stored in the vegetation, equivalent to 8.7 – 10.2% of the annual Yukon River discharge (Young-Robertson et al., 2016). Deciduous trees transpired 0.4 – 2.2 billion cubic meters of water (2-12% of the stored water) immediately following leaf out, leading to more favorable conditions for atmospheric convection/convective storms. The deciduous trees transpire an additional 2.0 – 5.2 billion cubic meters of water (10-30% of the initially stored water) in the period between leaf-out and mid-summer. By 2100, the boreal forest deciduous tree area is expected to increase by 1-15% due to wildfire and other landscape changes, potentially resulting in an additional 0.3 – 3.0 billion cubic meters of snow melt water removed from the hydrologic system. This work highlights the importance of considering and incorporating the vegetation distribution and tree type in hydrologic modeling studies.

Summary:

This project improves meso-scale hydrologic modeling in the boreal forest by: (1) demonstrating the importance of capturing the heterogeneity of the landscape using small-scale datasets and modeling schemes for parameterization in both small and large watersheds; (2) demonstrating that in drier parts of the landscape and as the boreal forest dries with a changing climate, modeling approaches should consider the sensitivity of simulations to soil hydraulic parameters – such as the residual water content – that are usually held constant in simulations; (3) demonstrating that assessing climate change impacts on boreal forest hydrology through multiple model integration must account for direct effect of climate change (temperature and precipitation), and indirect effects from climate impacts on landscape characteristics (permafrost and vegetation distribution). Simulations demonstrated that climate change

will lead to increases in runoff, but will be mitigated by increases in ET, and will result in an overall drying of the landscape; and (4) vegetation plays a signficant role in boreal hydrologic processes in permafrost free areas with deciduous vegetation. This landscape type results in a decoupling of ET and temperature, low runoff, and an overall soil drying.

References:

Cable, J.M., K. Ogle, Bolton, W.R., Bentley, L.P., Romanovsky, V., Iwata, H., Harazono, Y., and Welker, J.: Permafrost thaw affects boreal deciduous plant transpiration through increased soil water, deeper thaw, and warmer soils. Ecohydrology, 7(3): 932-997, 2013.

Endalamaw, A., Bolton, W. R., Young-Robertson, J. M., Morton, D., Hinzman, L., and Nijssen, B.: Towards improved parameterization of a macroscale hydrologic model in a discontinuous permafrost boreal forest ecosystem, Hydrol. Earth Syst. Sci., 21, 4663-4680, https://doi.org/10.5194/hess-21-4663-2017, 2017.

Haugen, R., Slaughter, K., Howe, W., and Dingman, K.E., Hydrology and Climatology of the Caribou-Poker Creeks Research Watershed, Alaska: US Army Corps of Engineers, Cold Regions Research and and Engineering Laboratory Report 82-26, 1982.

Rieger, S., Furbush, C.E., Schoephorster, D.B., Summerfield Jr, H., and Geiger, L.C., Soils of the Caribou-Poker Creeks Research Watershed, Interior Alaska. US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory Report No. CREEL-TR-236, 1972.

Young-Robertson, J.M., Bolton, W.R., Bhatt, U., Cristobal, J., and Thoman, R.,: Deciduous trees are a large and overlooked sink for snowmelt water in the boreal forest. Nature Scientific Reports, 7, Art no. 29504, DOI: 10.1038/srep29504, 2016.

2. Description of Publications and other Products Delivered:

Publications:

Cable, J.M., K. Ogle, Bolton, W.R., Bentley, L.P., Romanovsky, V., Iwata, H., Harazono, Y., and Welker, J.: Permafrost thaw affects boreal deciduous plant transpiration through increased soil water, deeper thaw, and warmer soils. Ecohydrology, 7(3): 932-997, 2013.

Endalamaw, A., Bolton, W. R., Young-Robertson, J. M., Morton, D., Hinzman, L., and Nijssen, B.: Towards improved parameterization of a macroscale hydrologic model in a discontinuous permafrost boreal forest ecosystem, Hydrol. Earth Syst. Sci., 21, 4663-4680, https://doi.org/10.5194/hess-21-4663-2017, 2017.

Young-Robertson, J.M., Raz-Yaseef, N., Cohen, L.R., Rahn, T., Newman, B., Wilson, C., and Wullschleger, S., Evaporation dominates evapotranspiration on Alaska's Arctic Coastal Plain, *Arctic, Antarctic, and Alpine Research*. In revision.

Young-Robertson, J.M., Bolton, W.R., Bhatt, U., Cristobal, J., and Thoman, R.,: Deciduous trees are a large and overlooked sink for snowmelt water in the boreal forest. Nature Scientific Reports, 7, Art no. 29504, DOI: 10.1038/srep29504, 2016.

Young-Robertson, J.M., Ogle, K., and Welker, J., Thawing seasonal ground ice: An important water source for boreal forest plants in Interior Alaska. Ecohydrology, 10(3), DOI: 10.1002/eco.1796, 2017.

Posters:

Bolton. W.R., J.M. Cable, L.D. Hinzman, D. Morton. Development of a Cold Regions Regional-Scale Hydrologic Model Overview. DOE BER Climate and Earth System Modeling Programs PI meeting, Washington DC, 2011.

Bolton, W.R. Endalamaw, A., Young, J., Morton, D., and Hinzman, L., Small-Scale Parameterizations to Improve Stream Flow Simulations Using a Regional-Scale Hydrologic Model in a Sub-Arctic, Boreal Forest Environment, DOE BER Climate and Earth System Modeling Programs PI meeting, Potomac, MD, 2014.

Bolton, W.R., Endalamaw, A., Young-Robertson, J., Nijsseen, B., and Hinzman, L., Improving Meso-Scale Hydrologic Modeling Through Upscaling Small-Scale Parameterizations and Modeling Results in the Alaska Discontinuous Permafrost, Boreal Forest Ecosystem, DOE BER Climate and Earth System Modeling Programs PI Meeting, Potomac, MD, 2016.

Endalamaw, A., Bolton, W.R., Young, J., Morton, D., and Hinzman, L., Toward Improved Parameterization of a Meso-Scale Hydrologic Model in a Discontinuous Permafrost, Boreal Forest Ecosystem, American Geophysical Union Fall Meeting, San Francisco, CA., 2013.

Endalamaw, A., Bolton, W.R., Young-Robertson, J., Morton, D., and Hinzman, L., Meso-Scale Hydrological Modeling from Small-Scale Parameterizations in a Discontinuous Permafrost Watershed in the Boreal Forest Ecosystem, American Geophysical Union Fall Meeting, San Francisco, CA., 2014.

Endalamaw, A., Bolton, W.R., Young-Robertson, J., Morton, D., and Hinzman, L., Sensitivity of Residual Soil Moisture Content in the VIC Model: Soil Property Parameterization for Sub-Arctic Discontinuous Permafrost Watersheds, American Geophysical Union Fall Meeting, San Francisco, CA 2015.

Endalamaw, A., Bolton, W.R., Young-Robertson, J., Morton, D., and Hinzman, L., Improved Parameterization of a Meso-Scale Hydrologic Model in a Discontinuous Permafrost, Boreal Forest Ecosystem, 9th International Conference on Permafrost, Potsdam, Germany, 2016.

Endalamaw, A., Bolton, W.R., Cable, J., Morton, D., and Hinzman, L., Quantifying Direct and Indirect of Future Climate Change on Sub-Arctic Hydrology, American Geophysical Union Fall Meeting, San Francisco, CA, 2016.

Hinzman, L.D., W.R. Bolton, J. Cable, B. Nijssen, D.D. Morton, D.P. Lettenmaier, S.D. Peckham. Quantifying Interdependence Among Processes and Characterizing Dynamic Controls Across Spatial Scales by Linking Climate, Hydrology, and Ecosystem Models. American Geophysical Union Fall Meeting, San Francisco, CA. 2012.

Morton, D, W.R. Bolton, L.D. Hinzman, J. Cable. Computational Development of Cold Regions Regional-Scale Hydrologic Model. DOE BER Climate and Earth System Modeling Programs PI Meeting, Washington DC, 2011.

Morton, D., Bolton, W.R., Endalamaw, A.M., Young, J.M., and Hinzman, L.D., Hydrological Parameter Estimation (HYPE) System for Bayesian Exploration of Parameter Sensitivities in an Arctic Watershed, American Geophysical Union Fall Meeting, San Francisco, CA., 2013.

Young, J., and Bolton, W.R., The Ecohydrology of Boreal Systems. American Geophysical Union Fall Meeting, San Francisco, CA, 2012.

Talks:

B. Bolton. Northern Ecohydrology: Exploring the Timing, Magnitude, and Pathways in Permafrost Affected Environments. Seminar presented to the Land Surface Hydrology Group, University of Washington. 2012.

W.R. Bolton and J.M. Cable. Vegetation Water Use Comparison in a Sub-Arctic, Boreal Forest Environment Using Hydrograph Analysis. The Third International Symposium on Arctic Research (ISAR-3). Tokyo, Japan. 2013.

B. Bolton and J.C. Young. Hydrologic Research in the CPCRW. Bonanza Creek Long Term Ecological Research Symposium and Workshop. 2013.

W. Robert Bolton. Improving Meso-Scale Hydrologic Modeling of the Alaskan Boreal Forest Ecosystem, DOE RGCM High Latitude Climate Webinar, 16 February 2017. 2017.

Endalamaw, A., Meso-Scale Hydrologic Modeling Using Small-Scale Parameterizations in Discontinuous Permafrost Watersheds in the Boreal Forest Ecosystem. International Arctic Research Center Seminar Series, University of Alaska Fairbanks, Fairbanks, AK 2015.

Endalamaw, A., Toward Improved Parameterization of a Meso-Scale Hydrologic Model in a Discontinuous Permafrost, Boreal Forest Ecosystem, Water and Environmental Research Center Seminar Series, University of Alaska Fairbanks, Fairbanks, AK. 2015.

J. Young, Isotope data analysis using Bayesian methods. Advances in Stable Isotope Techniques and Applications Conference. 2012.

J. Young, Deciduous trees put the Eco in Boreal Ecohydrology. Institute of Arctic Biology Life Sciences Seminar and the Water and Environmental Resource Center Seminar, University of Alaska Fairbanks. 2013.

Other Publications:

Endalamaw, A., Development of a Parameterization for Mesoscale Hydrological Modeling and Application to Landscape and Climate Change in the Interior Alaska Boreal Forest Ecosystem, PhD Dissertation, University of Alaska Fairbanks, 2017.

Media Coverage:

Vice News, “Here’s Why Alaska’s Wildfires are Really Bad News fore Everyone,” 16 July 2015, https://news.vice.com/article/heres-why-alaskas-wildfires-are-really-bad-news-for-everyone

Washington Post, “Alaska’s terrifying wildfire season and what it says about climate change,” 26 July 2015, https://www.washingtonpost.com/news/energy-environment/wp/2015/07/26/alaskas-terrifying-wildfire-season-and-what-it-says-about-climate-change/

Deutsche Welle, “Forest Fires in Alaska: A ticking climate time bomb,” 31 August 2015, http://www.dw.com/en/forest-fires-in-alaska-a-ticking-climate-time-bomb/a-18684423

Deutsche Welle, “Fears for Alaska,” 10 September 2015, http://www.dw.com/en/fears-for-alaska/av-18705654