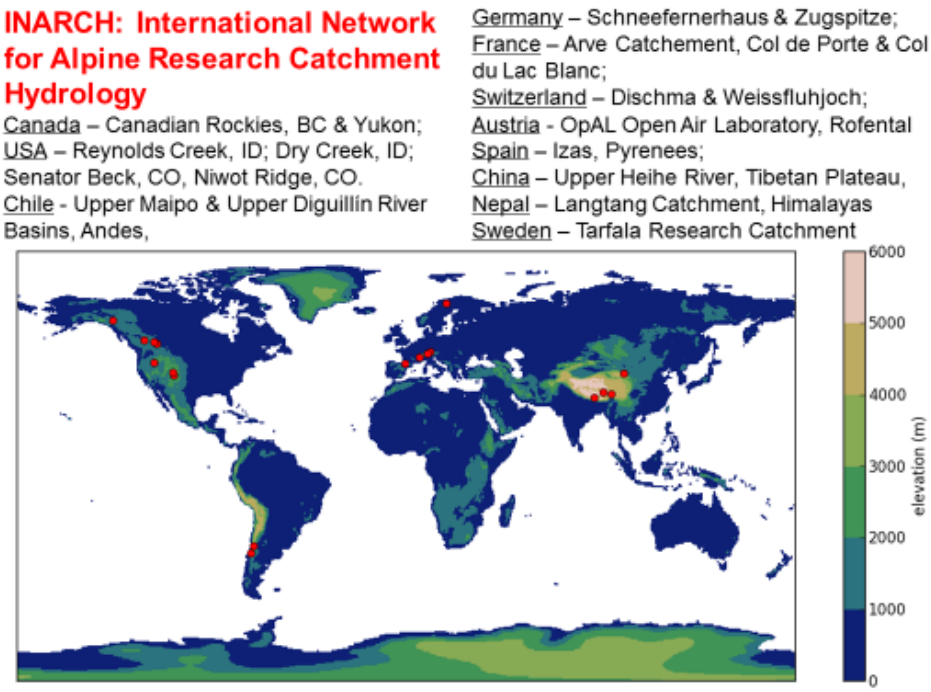
## Project Report for the 2017 GEWEX GHP Meeting

**Cross-cut Project Name:** International Network for Alpine Research Catchment Hydrology (INARCH)
**Reporting Period: November 2016 – October 2017**
**Starting date: January 2015**
**End date: January 2020**
**URL:** www.usask.ca/inarch
**Chair(s) and term dates:** John Pomeroy, University of Saskatchewan, Canada (2015–); co-chair, Matthias Bernhardt, University of Natural Ressources and Life Sciences, Vienna (2017–)

## *Background*

The International Network for Alpine Research Catchment Hydrology (INARCH) is a crosscutting project of the GEWEX Hydroclimatology Panel (GHP) and its objectives are to better understand alpine cold regions hydrological processes, improve their prediction, diagnose their sensitivities to global change and find consistent measurement strategies. INARCH is formulated around addressing five core questions: (1) How do varying mountain measurement standards affect scientific findings around the world? (2) What control does changing atmospheric dynamics have on the predictability, uncertainty and sensitivity of alpine catchment energy and water exchanges? (3) What improvements to alpine energy and water exchange predictability are possible through improved physics, downscaling, data collection and assimilation in models? (4) Do existing mountain model routines have global validity? and (5) How do transient changes in perennial snowpacks, glaciers, ground frost, soil stability and vegetation impact alpine water and energy models?

INARCH has a Secretariat based at the University of Saskatchewan in Canada, composed of Dr. Chris DeBeer as Science Manager, Michael Allchin as webmaster, and Joni Onclin as Network Secretary. The Secretariat is supported by the Centre for Hydrology and the Global Water Futures programme.




INARCH has a network of well-instrumented mountain research basins that INARCH members maintain–all of these research basins have hydrometeorological, cryospheric and hydrological observations at multiple scales over multiple years and have some snow, glacier, hydrological and atmospheric models run at various scales. Observations are embedded near the headwaters of larger river basins that supply water for vast downstream populations.

## *1) Project activities over the last year*

Science Highlights

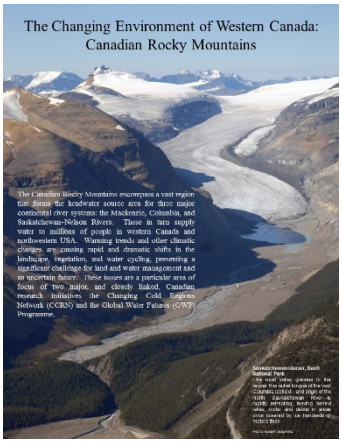
INARCH developed specialised science on downscaling atmospheric models in mountain regions through the activities of a working group on the subject. The working group implemented and tested the new ICAR intermediate

complexity atmospheric research model at high resolution at various mountain locations and also raised the need for "snow drift resolving" atmospheric models in mountains that made a series of presentations to CORDEX 2016 base. INARCH developed a mountain snow hydrology sensitivity intercomparison project and has conducted an intercomparison of the climate change sensitivity of Mediterranean climate (Spain, Morocco, California, Chile) snow hydrology regimes around the world that is published in Environmental Research Letters (see López-Moreno et al., 2017). INARCH has also developed a cold continental climate mountain snow hydrology climate change sensitivity intercomparison that is being published in a series of multi-authored papers.

Science Issues

INARCH's objective is to better understand alpine cold regions hydrological processes, improve their prediction, diagnose their sensitivities to global change and find consistent measurement strategies. Besides contributing to GEWEX, INARCH provides mountain snow and ice water security information for UNESCO's International Hydrological Programme Water Security Project.

Dr. John Pomeroy (Canada), and Dr. Danny Marks (USA) are guest-editing an INARCH special issue of Earth System Science Data, covering **Hydrometeorological data from mountain and alpine research catchments**. The aims of the issue are to respond to an international need to improve the understanding and modelling of mountain snow and ice hydrological processes. Data sets contributed to the special issue will support and promote research on the effects of mountain snowpacks and glaciers on water supply as well as study of variations in energy and water exchange amongst different high-altitude regions. The guest editors invite contributions of openly available detailed meteorological and hydrological observational archives from long-term research catchments at high temporal resolution (at least 5 years of continuous data with hourly sampling intervals for meteorological data, daily precipitation and streamflow, and regular snow and/or glacier mass balance surveys) in well-instrumented mountain regions around the world. Contributors and researchers will use this mountain hydrology data publication special issue for the benefit of global alpine hydrological research. The submission deadline has been extended until **6 April, 2018**. More detailed information and links to papers already submitted can be found at https://www.earth-syst-sci-data.net/special_issue871.html.




Mountain regions globally are increasingly subject to rapid and dramatically changing climate, cryosphere, ecosystems, and water resources. For the situation in the Canadian Rocky Mountains, to facilitate public communication on the importance and use of field observations, the types of changes that are occurring (past and future), and some examples of recent extreme events (floods, drought), a plain-language, illustrated and graphical public information brochure has been developed. This is available at:
http://www.ccrnetwork.ca/outputs/information-products/docs/Rockies_Change.pdf

New projects/activities put in place last year

Downscaling atmospheric models to mountain catchments. INARCH developed a working group on downscaling atmospheric models in mountain regions. To present this science INARCH was well represented at WCRP's International Conference on Regional Climate – CORDEX 2016 in Stockholm over 17-20 May 2016, by Richard Essery (UK), Ethan Gutmann (USA) and Kabir Rasouli (Canada). An overall INARCH presentation by Richard Essery and co-authored by J Pomeroy (Canada), E Gutmann (USA), V. Vionnet (France) and A Winstral (Switzerland) reviewed current thinking on observations and downscaling for alpine hydrological modelling. The presentation is available as a PDF (2.5 Mb).

There is a need to compile data for model testing of the snow and ice sensitivity to climate change in various alpine climates—models driven by perturbed meteorological observations can be used to do this via virtual basins, virtual mountains, etc. Some comparisons (North American Cordillera, Mediterranean) have been initiated.

Workshops and meetings held

**The 2nd INARCH Workshop** was held at the Institut des Géosciences de l'Environnement (IGE) in Grenoble, France, 17–19, October, 2016. This workshop provided an opportunity for scientists to explore and discuss specific issues in mountain snow and ice hydrology highlighted in the first INARCH workshop held in October 2015. The following topics were addressed: (i) Atmospheric downscaling for mountain snow and ice hydrology

modeling; (ii) Availability and suitability of observations from mountain observatories and discussion of the INARCH special issue; and (iii) Sensitivity of the cryospheric and hydrological response of mountain catchments to various representations of a changing climate. A fieldtrip after the workshop visited research sites in the Aiguille du Midi (3842m), near Chamonix, where participants saw and learned about the scientific activities of the CryObs-Clim Observing System, the experimental rain gauge network and related scientific activities, the Taconnaz avalanche path and associated protection, snow measurement techniques and hydrological issues in the Alps, flood defenses (Isabella Zin), the sediment transport station at Pont des Favrands, and water quality issues.

More information on this workshop and a detailed description of the science outcomes are available in the February 2017 issue of GEWEX News, pp 12–14, at:
http://www.gewex.org/gewex-content/files_mf/1489715816Feb2017.pdf

## *2) Planned project activities for next year*

3rd INARCH Workshop, Zugspitze, Germany, 8–9 February, 2018

This workshop will provide a venue to bring scientists together to explore and discuss specific issues in mountain snow and ice hydrology highlighted after the inaugural INARCH workshop in Kananaskis in October 2015 and the second INARCH workshop in Grenoble in October 2016. This will be a 2-day workshop that will address four research themes:

- Snow Hydrology
- Glacier Hydrology
- Alpine Measurements including Remote Sensing
- Climate Models and Downscaling for Mountains

Each theme will be addressed by a keynote speaker and followed by a moderated discussion. These guided discussions will be supplemented by topical poster sessions with a fast oral introduction to each poster. Further details are at: https://words.usask.ca/inarch/2017/09/09/3rd-inarch-workshop-to-be-held-at-schneefernerhaus/.

INARCH session at 2018 GEWEX Open Science Conference, Canmore, AB, Canada, 7–10 May, 2018: Observing and modelling the mountain water cycle using alpine research catchments

INARCH will convene a special session at the upcoming GEWEX Open Science Conference. This will address topics on: a) convective permitting modelling and high resolution satellite data, b) use of big data techniques and large computers and models, c) hybrid downscaling techniques (e.g. such as ICAR), d) other observational datasets, and e) recent completed field efforts (such as the WMO SPICE project on measurement of snow). The details are as follows:

**Convenors**: Pomeroy, J., Bernhardt, M., Marks, D., Vionnet, V.

**Session Description**: Mountains receive and produce a disproportionately large fraction of global precipitation and streamflow, including contributions to floods and essential water supplies for vast downstream areas that include at least one half of humanity. Most mountain regions are undergoing dramatic cryospheric change from global warming. However, research in alpine catchments is complicated by the data scarcity in mountain regions, and that most earth system models have insufficient spatial detail to resolve mountain processes that govern its water cycling; these problems are being addressed by GEWEX's International Network for Alpine Research Catchment Hydrology, INARCH, cross-cut project. This INARCH session welcomes contributions that i) show the value of enhanced mountain hydrometeorological and cryospheric observations and process understanding to inform mountain water cycle modelling, ii) quantify and improve the diagnostic and prognostic potential of models for predicting water and energy cycling in mountain regions, iii) show how improved downscaling methods can drive fine scale "snowdrift resolving" models from large scale atmospheric models, iv) show how changing cryospheric states are influencing water and energy cycling in mountain headwater catchments.

Details on the conference can be found at http://www.gewexevents.org/events/2018conference/, and the full call for papers is here: http://www.gewexevents.org/wp-content/uploads/OSC-abstract_call.pdf.

Other Activities

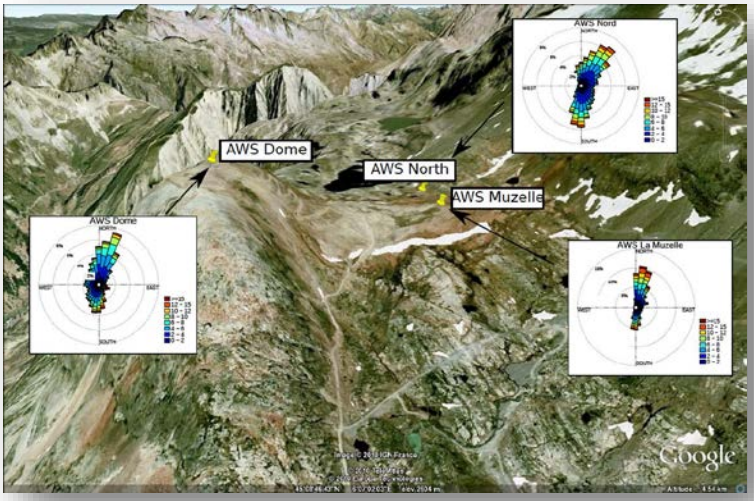
- Participate in snow model comparisons at sites where inputs can measured/defined through links with GLASS (Richard Essery).
- Reduce measurement uncertainty by implementing WMO SPICE recommendations for solid precipitation measurements at all sites and making contact with Global Cryosphere Watch for how to further improve measurement quality
- Develop a downscaling toolbox by examining various techniques for statistical, dynamical and medium complexity downscaling.
- Continue climate sensitivity comparative analysis of various alpine basins using "standard virtual basin" modelling to compare the response of snowcover, snowpack, glaciers and hydrology to variations in temperature and precipitation in various climate regimes.
- The *ESSD* Special Issue will continue to receive submissions until 6 April, 2018, while other journals will be approached for a special INARCH issue on mountain snow and ice hydrology that includes references to downscaling, processes and diagnosis of climate change impacts.
- Updates to the INARCH website (*http://www.usask.ca/inarch/)* will include a downscaling toolbox with a link to methods, as well as metadata for catchments and links to DOI data. A technical document is being planned with UNESCO on "Best Practices in Instrumenting Mountain Research Catchments," as is a policy-relevant publication with UNESCO on "Risks to World Water Security from Changing Mountain Snow and Ice Hydrology."

## *3) Contributions to the GEWEX Science Questions*

GSQ1: Observations and Predictions of Precipitation

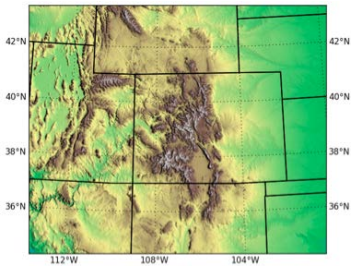
INARCH makes major contributions to GSQ1 by facilitating an active exchange and collaboration between international researchers and forming a network of instrumented mountain catchments to compare instrumentation best practices, suggest improvements in instrumentation, and develop reliable alpine datasets for model testing and numerical experiments. INARCH fosters the sharing and open access of detailed meteorological and hydrological observational archives from long-term research catchments at high temporal resolution (at least 5 years of continuous data with hourly sampling intervals for meteorological data, daily precipitation and streamflow, and regular snow and/or glacier mass balance surveys) in selected heavily instrumented alpine regions. Our 2nd annual INARCH workshop included three oral presentation sessions and one poster presentation session describing progress, advancements, and special activities across the network of mountain research sites—abstracts and presentations are available at http://www.usask.ca/inarch/wkshp2_report.php.

As an example of activities contributing to GSQ1, these images show automatic weather stations and drifting snow measurement inter-comparison at Col du Lac Blanc, French Alps. (Credit: Florence Naaim Bouvet.)

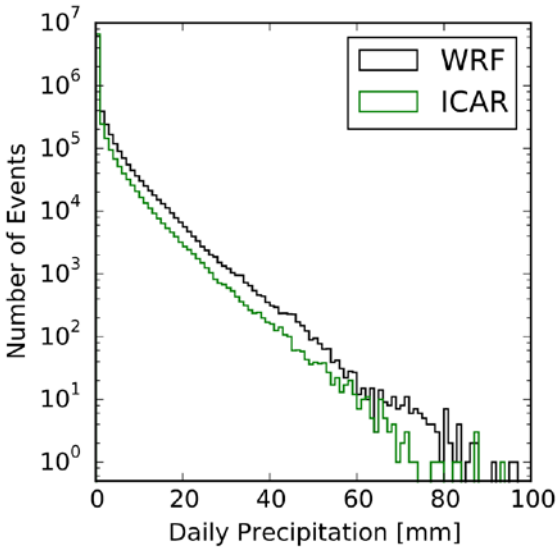


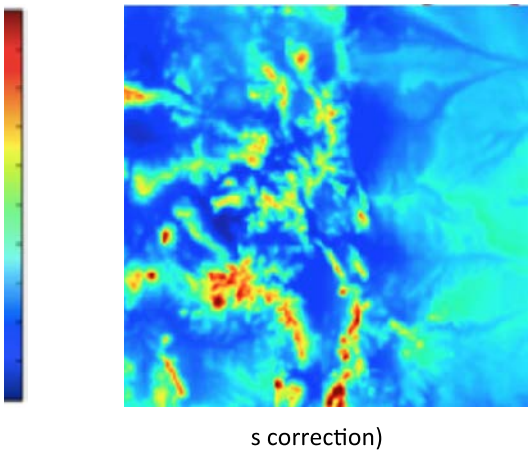

A major focus is directed towards evaluating process descriptions to improve algorithm development; conducting snow, glacier and permafrost hydrology process algorithm intercomparisons; defining optimal parameterisations adapted to the different characteristics of the analysed catchments; and defining structural, initial and boundary conditions. Uncertainty analyses will be conducted to properly quantify the reliability in representing alpine hydrological regimes in models.

INARCH is also focused on evaluation of different downscaling schemes for meteorological models on the basis of different datasets of the test sites. The evaluation is not limited to the regular comparison of different meteorological parameters but also includes parameters like e.g. snowcover extent, snow water equivalent, soil moisture.




Comparison of precipitation simulation over the Colorado Rockies using the Weather Research and Forecasting (WRF) model and the Intermediate Complexity Atmospheric Research (ICAR) model. The two have very similar precipitation distributions, yet ICAR requires ~1% or less of the computational effort of WRF, enabling a pseudo-dynamical downscaling for a wide variety of GCM / scenario combinations. (Credit: Ethan Gutmann.)

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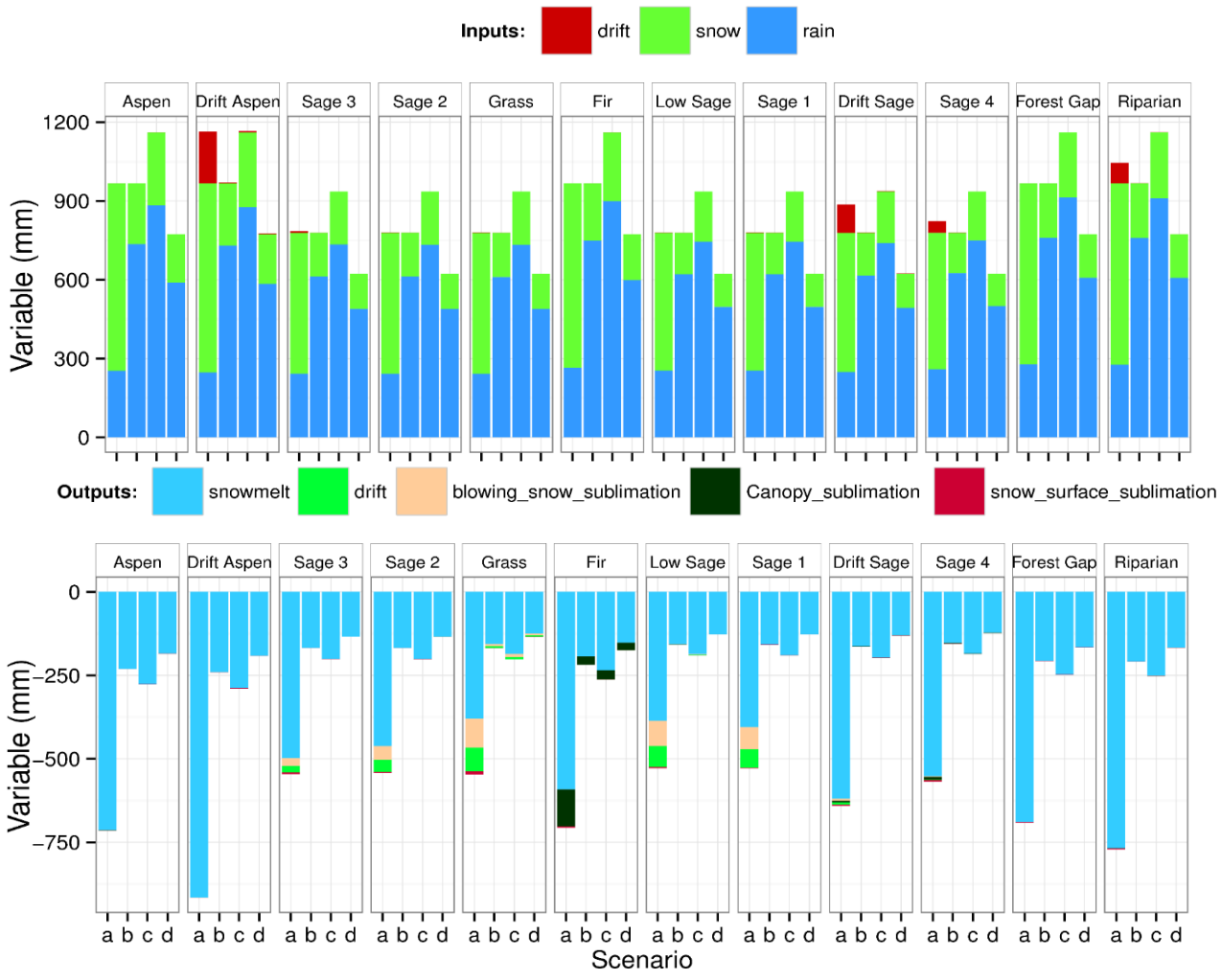
GSQ3: Changes in Extremes

A major effort has been undertaken by the Changing Cold Regions Network (CCRN; www.ccrnetwork.ca) and INARCH that was centered on a comprehensive focal examination of the extreme weather and flooding in southern Alberta in June 2013, focusing on meteorological, hydrological, and water management aspects of the flood. This has led to a collection papers being published in a special issue of *Hydrological Processes*. (See http://ccrnetwork.ca//science/2013-Alberta-flood for further details, information products and links to papers.)


GSQ4: Water and Energy Cycles and Processes

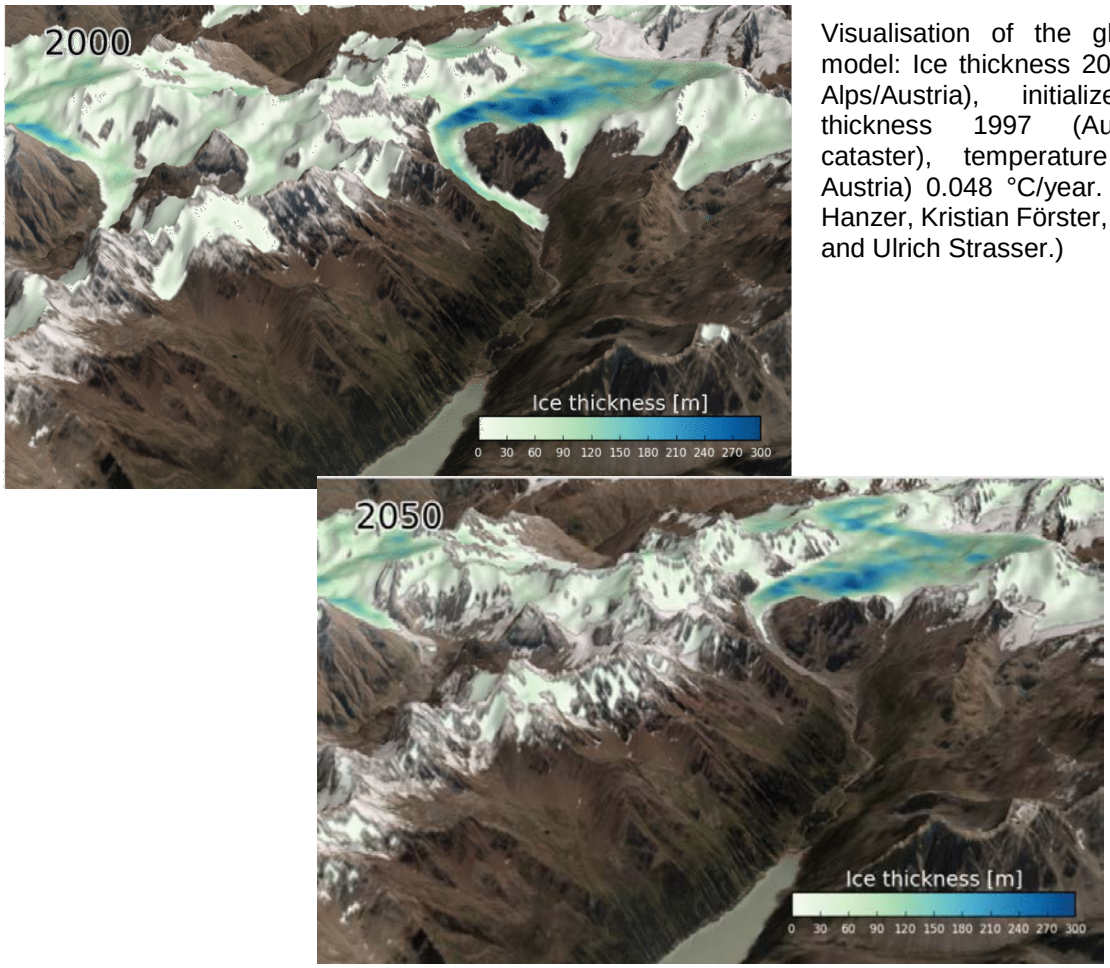
Water and energy cycles in mountain catchments are dominated by snow mass and energy exchange processes such as blowing snow, snow interception, sublimation, and melt. The following example provided by Kabir Rasouli shows how annual fluxes of these processes vary by ecozone in the Reynolds Creek Research Watershed, Reynolds Mountain East sub-basin operated by Dr. Danny Marks of USDA and how sensitive they are to perturbed climate. The four climate scenarios are a) control period of current climate, b) P=100%, T= +5 C, c) P=120%, T=+5C. d) P=80%, T=+5C



## *4) Activities contributing to the WCRP Grand Challenges as identified by the JSC*

Melting Ice and Global Consequences

A major research focus at many of the INARCH research catchments is directed at observing and predicting glacier mass balance and associated area and volumetric changes, and impacts to basin water storage and cycling. Glacier mass balance has been predominantly negative and some areas, such as glaciers in the Rocky Mountains of Canada, have shown record or near record losses in the past few years with an apparent shift to increasingly negative net mass balance.



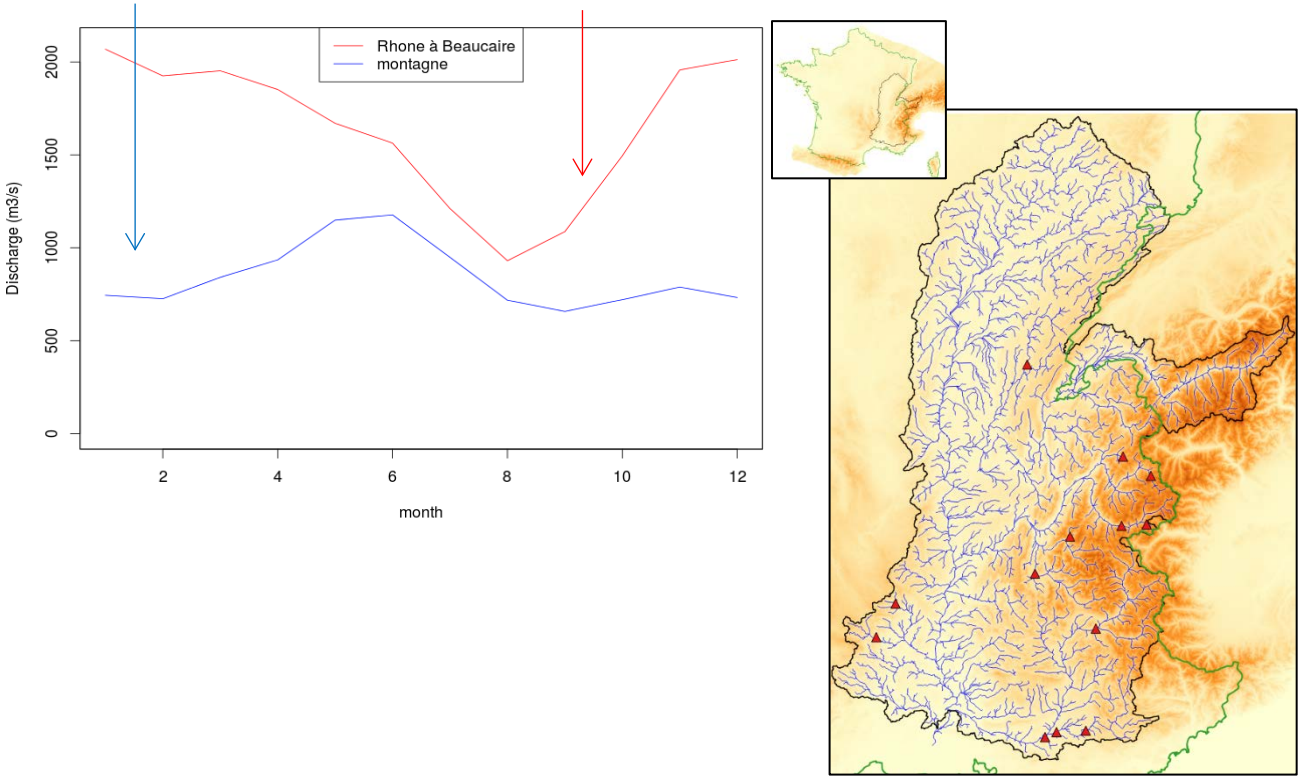

Visualisation of the glacier evolution model: Ice thickness 2000-2050 (Ötztal Alps/Austria), initialized with ice thickness 1997 (Austrian glacier cataster), temperature change (for Austria) 0.048 °C/year. (Credit: Florian Hanzer, Kristian Förster, Thomas Marke, and Ulrich Strasser.)

Climate extremes and water availability

INARCH is focused on conducting cold regions hydrological model sensitivity testing to atmospheric change in various alpine environments and including sensitivity to including the effects of transient changes from glacier mass balance, groundwater changes and vegetation changes. We also aim to demonstrate improvements to model predictability that can be realised from data assimilation, downscaling and model structural improvements.

Mountain regions are the “water towers” for adjacent and downstream regions where population centres exist, conditions generally tend to be drier, and there are multiple demands for water resources. Our last workshop featured a session on modelling the cryospheric and hydrological response of mountain catchments under present and future climate http://www.usask.ca/inarch/wkshp2_report.php.

**Mountain contribution to the total Rhone River discharge, France (Credit : Isabelle Gouttevin)**




## *5) Cooperation with other GHP and WCRP projects (CLIVAR, CliC, SPARC), outside bodies (e,g. iLEAPS) and links to applications*

- Collaboration with UNESCO IHP and information collaboration with SPICE and Global Cryosphere Watch (CliC).
- INARCH is linked to the GEWEX RHP know as the Changing Cold Regions Network (CCRN; www.ccrnetwork.ca); INARCH and CCRN share many common research priorities and objectives.
- The Global Water Futures (GWF; www.globalwaterfutures.ca) Programme is an expanded follow on initiative from CCRN. INARCH will strongly link with the mountain research components of GWF. Distinguished Professor John Pomeroy leads and directs both INARCH and GWF.

## *6) List of key publications*


DeBeer, C. M., & Pomeroy, J. W. (2017). Influence of Snowpack and Melt Energy Heterogeneity on Snow Cover Depletion and Snowmelt Runoff Simulation in a Cold Mountain Environment. *Journal of Hydrology,* doi:10.1016/j.jhydrol.2017.07.051

Li, Y., Szeto, K., Stewart, R. E., Thériault, J. M., Chen, L., Kochtubajda, B., ... & Kurkute, S. (2017). A numerical study of the June 2013 flood-producing extreme rainstorm over southern Alberta. *Journal of Hydrometeorology*, doi: 10.1175/JHM-D-15-0176.1

López-Moreno, J.I., Gascoin, S., Herrero, J., Sproles, E.A., Pons, M., Alonso-González, E., Hanich, L., Boudhar, A., Musselman, K.N., Molotch, N.P., Sickman, J., and Pomeroy, J. (2017). Different sensitivities of snowpacks to warming in Mediterranean climate mountain areas. *Environmental Research Letters*, **12**, https://doi.org/10.1088/1748-9326/aa70cb.

Pomeroy, J., and Vionnet, V., (2017). Report on 2nd INARCH Workshop, 17–19 October 2016, Grenoble, France. In: GEWEX News, Vol. 27, No. 1, February 2017, pp 12–14.