3rd INARCH Workshop

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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 addresses five core questions: (1) How do varying mountain measurement standards affect scientific findings worldwide? (2) What effect 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 network of 26 well-instrumented mountain research basins maintained by its members and these are equipped to provide hydrometeorological, cryospheric and hydrological observations at multiple scales. Observations are embedded near the headwaters of larger river basins that supply water for vast downstream populations. The adjacent figure shows a map of INARCH mountain research basins. Sagehen Creek in the Sierra Nevada Mountains, California is the newest.

INARCH has important linkages to the GHP crosscutting project on Cold/Shoulder Season Precipitation Near 0°C and to the recently completed Changing Cold Regions Network RHP (CCRN; see article on page 11). CCRN is being expanded through the Global Water Futures (GWF) Program, which is the largest university-led freshwater research program in the world. INARCH provides a key mechanism for the GWF strategy to engage with the international mountain scientific community and policy makers. It contributes snow measurement information to the World Meteorological Organization (WMO), addresses the United Nations Educational, Scientific and Cultural Organization's (UNESCO) International Hydrological Programme (IHP) efforts to gauge climate change impacts on snow, glaciers and water resources within the framework of the IHP-VIII (2014–2021), and has built direct links with the Third Pole Environment (TPE) Initiative, which is focused on central Asia and the Tibetan Plateau. INARCH supports ANDEX, the new Initiating RHP focused on the Andes Mountains, and the role of mountains as water suppliers for the GEWEX Bread Baskets of the World initiative. INARCH links to the International Association of Hydrological Sciences International Commission for Snow and Ice Hydrology (IAHS-ICSIH) and contributes outreach information to the Mountain Research Initiative led from Bern, Switzerland.

INARCH: International Network for Alpine Research Catchment Hydrology

Austria: 1.Open Air Laboratory (OpAL)
Canada: Canadian Rockies Hydrological Observatory; 2.Marmot Creek Research Basin;3.Peyto Glacier; 4.Quesnel River Research Basin;5.Wolf Creek Research Basin
Chile: 6.Upper Diguillín River Basin 7.Upper Maipo River Basin;
China: 8.Nam Co Monitoring and Research Station for Multisphere Interactions;9.Qomolangma Atmospheric and Environmental Observation and Research Station; 10.Southeast Tibet Observation and Research Station for the Alpine Environment; 11.Upper Heihe River Basin
France: 12. Arve Catchement; 13.Col de Porte Experimental Site; 14.Col du Lac Blanc Experimental Site
Germany:15.Zugspitze Basin and Schneefernerhaus Research Station
Nepal: 16. Langtang Catchment
Norway:17.Finse Alpine Research Centre
Spain:18.Izas Research Basin
Sweden:19.Tarfala Research Catchment
Switzerland: 20.Dischma Research Catchment; 21. Weissfluhjoch Snow Study Site;
USA: 22.Dry Creek Experimental Watershed; 23.Grand Mesa Study Site; 24. Reynolds Creek Experimental Watershed; 25. Senator Beck Basin Study Area; 26. Sagehen Creek, Sierra Nevada.

Current INARCH mountain research basins.

Over the past year, INARCH has participated in several workshops and conferences. John Pomeroy presented an overview of INARCH at the UNESCO-IHP Knowledge Forum on "Water Security and Climate Change: Innovative solutions for sustainable water resources management," which was held in October 2017 in Paris, France. Chris DeBeer represented INARCH at the GHP-TPE Joint Meeting held on 17-20 October 2017 in Kathmandu, Nepal. INARCH members contributed to and led several mountain hydrometeorology sessions at the American Geophysical Union, European Geophysical Union and Canadian Geophysica Union meetings.

An INARCH Special Issue in the journal *Earth System Science Data (ESSD)* is open for submissions until 30 September 2018 on the topic of "hydrometeorological data from mountain and alpine research catchments." Contributions from openly-available, detailed meteorological and hydrological observational archives from long-term research catchments at high temporal, well-instrumented mountain regions around the world are being prepared, and at least 16 submissions are expected from the INARCH project by the special issue co-editors, John Pomeroy (Canada) and Danny Marks (USA).

Several papers will be cross-listed in a CCRN-led special issue of *ESSD* on the topic "water, ecosystem, cryosphere, and climate data from the interior of Western Canada and other cold regions."

The 3rd INARCH Workshop was held at the Schneefernerhaus Environmental Research Station near the summit of Zugspitze, the highest peak in Germany, and provided an excellent opportunity for scientists to explore and discuss specific INARCH scientific topics and priorities. The meeting venue provided breathtaking and inspiring scenery, while also offering a comfortable space to gather as a group. Thirty scientists from the US, Canada, Chile, France, UK, Switzerland, Austria, Germany, Spain, and Norway attended the workshop. Local organizers included Matthias Bernhardt and Karsten Schulz (University of Natural Resources and Life Sciences, Vienna, Austria), and others in the organizing committee included Georg Kaser (University of Innsbruck, Austria), John Pomeroy and Chris DeBeer (University of Saskatchewan, Saskatoon, Canada).

The workshop addressed four themes: (1) snow hydrology, (2) glacier hydrology, (3) alpine measurements including remote sensing and (4) climate models and downscaling for mountains. Each theme was addressed by a keynote speaker and followed by a moderated discussion, along with topical poster sessions with a fast oral introduction to each poster. Keynote speakers included, respectively, Tobias Jonas (WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland), Georg Kaser (University of Innsbruck, Austria), Tom Painter (NASA Jet Propulsion Laboratory, Pasadena, US), and Roy Rasmussen (National Center for Atmospheric Research, Boulder, Boulder, US). Discussions on these topics, workshop statements, and future directions are summarized below. A detailed report written by Robert Sandford (Institute for Water, Environment and Health, United Nations University, Hamilton, Canada) is available on the INARCH website (*http://www.usask.ca/inarch/*) and describes all of the presentations and the progression of events.

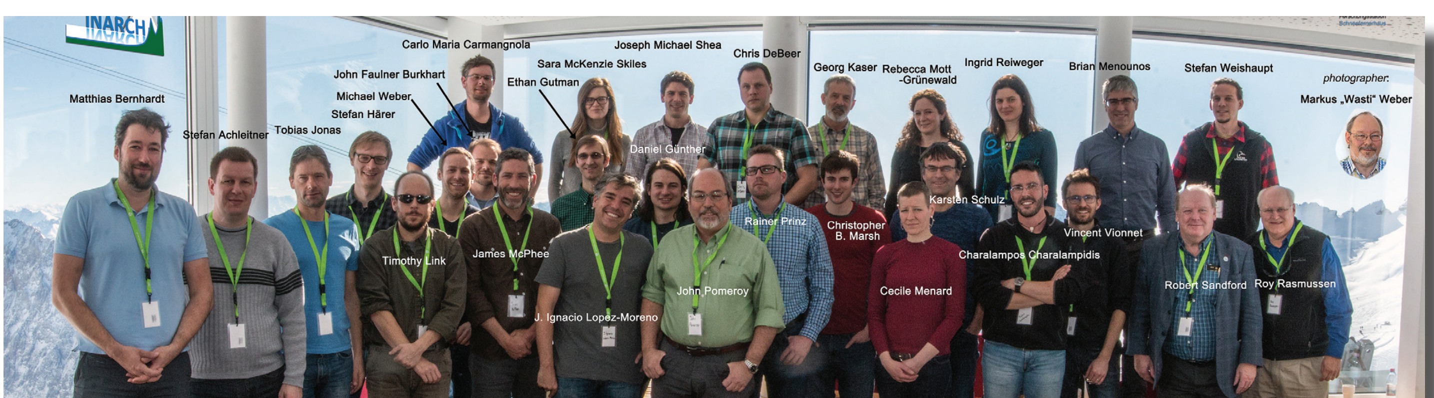
Snow and Glacier Hydrology Discussion

The discussion focused on issues of model input data, model resolution and parameterization, particularly involving the trade-offs between model complexity, computing resources, and the need for different applications; spatial variability and covariance of processes, variables, and fluxes, (e.g., melt energy and snow water equivalent) over multiple scales, and appropriate process representation with proper physics; availability and open access of data and model code; the influences of basin geometry, process sensitivities and responses, and feedbacks; and the need to link this community more closely with the atmospheric modeling community. Specific outcomes from the discussion included:

- Procedures are needed to generate model input data at appropriate scales for the model application—this involves links between atmospheric and surface models.
- There is continued need for detailed validation of individual processes at the process scale.
- Mechanisms are needed to inform large-scale and operational models from small-scale and process advances—advection, vegetation interactions, snow redistribution, human impacts, albedo dynamics, and variable model resolution.
- Scaling of process representations and model structure is needed in models. The same processes and process representations are not applicable to all scales.
- Variations in basin configuration, hypsometry, glacier coverage, ice exposure, and vegetation need to be considered in climate sensitivity studies.
- INARCH supports physical realism, not necessarily complexity, in models.
- Temperature index methods are not considered as scientifically appropriate, physically realistic approaches to snow and ice hydrology prediction, although there may be niche/legacy applications.

Key points and statements were:

- More climate sensitivity and vulnerability studies are needed in INARCH that focus on models driven by perturbed



Participants at the 3rd INARCH Workshop (photo by Markus Weber).

or downscaled climate using INARCH basins and data.

- INARCH will continue to encourage scientifically appropriate, physically realistic approaches to snow and ice hydrology.

Observations Including Remote Sensing Discussion

This involved topics on data quality and fitness, linking surface observations, remote sensing, and modeling initiatives, the value of LiDAR ground surface and snowpack measurements, even if only obtained once, and different remote sensing platforms and sensors and their various applications. Some of the conclusions were:

- There is value in observations from well-instrumented observatories and from remote sensing, model reanalysis and other coupled products.
- Remote sensing advances are providing improved albedo/radiative transfer information for snowpacks and accurate large area estimates of snow and ice surface elevations—digital surface models from airplanes, drones and satellites.
- Snow water equivalent still cannot be remotely sensed in mountains at scales relevant to the hydrology and hydrometeorology interests of INARCH.
- There is value in extending LiDAR or structure from motion estimates of topography and snowpack surface elevations with and without peak snowpacks for INARCH and other basins.
- There is a need to co-locate remote sensing initiatives and INARCH hydrometeorology basins for joint verification, upscaling, parameter identification, modeling and assimilation advances.
- Data quality should be identified and documented before it is used in atmospheric or surface models. Metadata is of high value in interpreting observations.

A resolution was adopted and some key points were:

- INARCH research basin observational data sets will be proposed to the WMO Global Cryosphere Watch (GCW) for inclusion in their global data portal. INARCH will provide input to GCW to inform their development of observational guidelines using current science.
- INARCH will continue to publish data sets and metadata in the *ESSD* special issue.
- INARCH basins will contribute to future coupled surface and remote sensing observational studies including multispectral missions.

Climate Models and Downscaling Discussion

Issues relating to policy climate model runs, the evolution of climate and atmospheric modeling capability and resolution, and the approaches and needs for various applications in different geographic regions were discussed. Key points included:

- Cases where coarse-scale atmospheric models miss events or fail to generate any precipitation signify a fundamental problem for how to handle such situations for bias correction and downscaling purposes. Regarding this, Roy Rasmussen coined the phrase "you cannot statistically correct nothing."
- Dynamical downscaling using nested, multi-scale atmospheric models is strongly preferred over statistical downscaling for mountain snow, ice and hydrology model applications because of its ability to predict precipitation and wind in mountain environments.
- There is a possibility of mountain policy runs—multiple realizations of long-term, high-resolution climate models—with the opportunity to use high resolution weather models nested in climate models. This topic needs exploration and testing.
- Downscaling wind flow over complex terrain can and should employ physically based approaches.

The INARCH statement on this is: Dynamical downscaling is needed to create INARCH mountain policy runs for future climate at scales appropriate for snow and glacier hydrology models.

Future Directions

The deadline for submissions to the INARCH *ESSD* Special Issue is 30 September 2018. The mountain downscaling toolbox portal will soon be completed and posted to the INARCH website at: *http://www.usask.ca/inarch/*. Various important linkages across GEWEX are being pursued, including an LSS-H model comparison and development project that is ongoing and linked to GEWEX-Global Land/Atmosphere System Studies (GLASS) Panel and the GWF RHP, as well as other proposed RHPs. A multiscale climate change vulnerability analysis of cold alpine snow, ice and hydrological systems will be pursued by a collaboration between the University of Saskatchewan and the Spanish National Research Council using the Cold Regions Hydrological Model at INARCH basins. INARCH will also contribute a pre-assessment synthesis article and chapter on high mountains for the Sixth Assessment Report (AR6) report of the Intergovernmental Panel on Climate Change (IPCC). Future INARCH meetings include a convection-permitting atmospheric modeling workshop in Boulder, Colorado, USA on 4-6 September 2018 and a tentative next annual INARCH workshop in Santiago, Chile ahead of the joint GHP-ANDEX meeting in October 2018.

The workshop concluded with a formal statement highlighting the importance of the observatories, the encouragement of process validation to inform large-scale and operational models, the implementation of hybrid downscaling approaches for mountain regions, and the use of these models to explore future integrated Earth system change in these regions.