Recent INARCH Activities and the 4th INARCH Workshop

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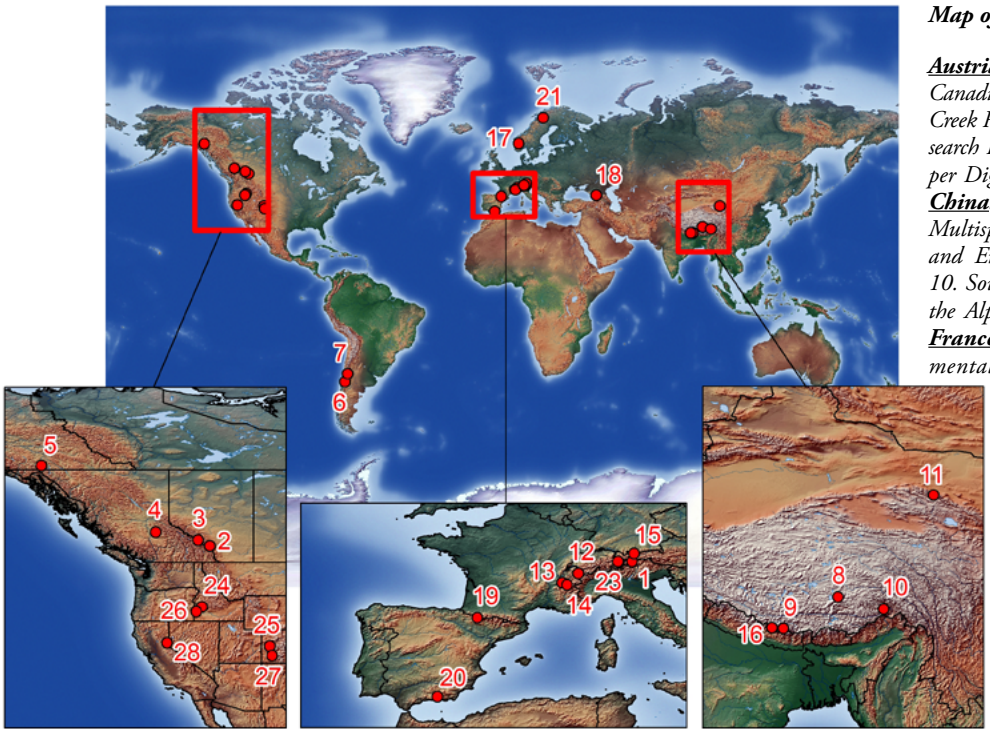
INARCH and Its Recent Activities

The International Network for Alpine Research Catchment Hydrology (INARCH) is a crosscutting project of the GEWEX Hydroclimatology Panel (GHP) with the objectives 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?

In just three years, INARCH has made exceptional progress towards addressing these questions and achieving its goals. This year, the team has grown with the inclusion of new members and research sites in Norway, Russia, Spain, and the USA. Moving forward, INARCH will be developing synthesis papers and other products as outputs of the network and contributing to initiatives beyond GEWEX, such as Future Earth, the World Meteorological Organization (WMO), the Intergovernmental Panel on Climate Change (IPCC), the United Nations Educational, Scientific, and Cultural Organization (UNESCO)'s International Hydrological Programme (IHP), and the United Nations at large through its International Water Action Decade: Water for Sustainable Development, 2018–2028.

Over the past year, there have been several notable areas of activity and progress. John Pomeroy (Canada) and Danny Marks (USA) served as guest editors for an INARCH special issue of Earth System Science Data (ESSD, *https://www.earth-syst-sci-data.net*), covering Hydrometeorological data from mountain and alpine research catchments. The aims of the issue and links to published and in-discussion papers can be found at *https://www.earth-syst-sci-data.net/special_issue871.html*. The issue closed on 30 September 2018, and 19 papers were contributed from around the world, with several more coming into the discussion phase; however, new papers that contribute to this special issue are still welcome by ESSD and will be handled by the special editors if the contributing authors request it.

INARCH convened a special session on Observing and modeling the mountain water cycle using alpine research catchments at the GEWEX Open Science Conference held in Canmore, Alberta, Canada, on 7–10 May, 2018. It addressed topics on:



Map of Current INARCH Mountain Research Basins

***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; **Russia**: 18. Djankuat Research Basin; **Spain**: 19. Izas Research Basin; 20. Guadalfeo Monitoring Network; **Sweden**: 21. Tarfala Research Catchment; **Switzerland**: 22. Dischma Research Catchment; 23. Weissfluhjoch Snow Study Site; **USA**: 24. Dry Creek Experimental Watershed; 25. Grand Mesa Study Site; 26. Reynolds Creek Experimental Watershed; 27. Senator Beck Basin Study Area; 28. Sagehen Creek, Sierra Nevada*

a) convection permitting modeling and high resolution satellite data, b) use of big data techniques and large computers and models, c) hybrid downscaling techniques [e.g., such as the Intermediate Complexity Atmospheric Research (ICAR) model], d) other observational datasets, and e) recent completed field efforts [such as the WMO Solid Precipitation Intercomparison Experiment (SPICE) project on measurement of snow]. The session included eight oral presentations and 11 poster presentations. Dr. John Pomeroy and Dr. Chris DeBeer (Canada) were local organizers for the GEWEX Conference, and Dr. Pomeroy and Bob Sandford also led a tour group to the hydrological apex of the Rocky Mountains: the Columbia Icefield in Banff National Park. Full details on the conference are found at *http://www.gewexevents.org/events/2018conference/*.

The second GEWEX Convection-Permitting Climate Modeling Workshop was held at the National Center for Atmospheric Research (NCAR) Mesa Lab in Boulder, Colorado, USA on 4–6 September, 2018. The meeting was hosted by Roy Rasmussen (USA) and focused on scientific and technical challenges related to convection-permitting climate modeling (horizontal grid spacing ≤4 km). These challenges include model setup, observational datasets, evaluation techniques, computational resources, model intercomparisons, and the use of convection-permitting simulations in impact research. The 3-day workshop's aim was to foster collaborations and synergies to work on this challenging topic as a community, one that includes INARCH. There were oral and poster sessions, several invited talks on key topics, and multiple opportunities for discussions and networking. More information, including an agenda and presentations, can be found at *https://ral.ucar.edu/events/2018/cpcm*.

INARCH 4th Annual Workshop

Most recently, the 4th INARCH Workshop was held by the Faculty of Physical and Mathematical Sciences at the Universidad de Chile and the Hotel Portillo, Chile, high in the Andes Mountains. Twenty four scientists from Chile, Argentina, the USA, Canada, Spain, and France participated in the workshop. Local organizers included James McPhee, Thomas Shaw, and Yohann Videla (Universidad de Chile, Santiago, Chile), while John Pomeroy and Chris DeBeer (University of Saskatchewan, Saskatoon, Canada) also helped plan the workshop.

The meeting focused on reviewing activities, progress, and plans towards INARCH's overall objectives and research questions relating to alpine hydrology. A number of topics were reviewed and discussed, including field observations, catchment data, and emerging methods; snow and glacier hydrology, and climate change; model simulation and data assimilation, big data, and remote sensing; and linkages with various organizations, such as Future Earth's Sustainable Water Futures Programme, the World Meteorological Organization, IHP, the Canadian-led Global Water Futures (GWF) Project, the US-proposed western USA regional hydroclimate project (RHP), and the recently-initiated ANDEX, an RHP for the Andes. An important outcome of the workshop was the development of plans for several key publications based around the INARCH research questions, which will contribute towards the IPCC and its sixth assessment report. The workshop agenda and copies of presentations are available on the INARCH website at *http://www.usask.ca/inarch/index.php*.

Workshop Discussions and Statements

Early discussions focused on field observational practices and the potential for standardization of approaches. Participants agreed that it is not practical or possible to standardize snow measurements around the world, due to inherent variation in snow processes and snowpack characteristics in different environments. However, reporting of uncertainties should be standardized, and stratified landscape sampling techniques should be employed, whereby the landscape is disaggregated into representative types or relatively homogeneous landscape units. This helps to reduce the variance in snow depth and snow water equivalent (SWE) within a landscape unit, improves the confidence of the fit of the SWE distribution, and reduces the necessary field sampling. Best practices for temporal frequency are monthly surveys during the winter accumulation season, and weekly surveys during the spring melt season.

Another key point that emerged in discussions following presentations on snow, glaciers, and climate change was that there is some concern as to how we move towards modeling approaches based on big data, artificial intelligence, and neural networks. We must continue to develop and apply physics-based modeling approaches to capture process interactions and non-linear or unexpected changes in system behavior and response. Further, there is an advantage to predictive modeling in cold regions, as the spatial variability of precipitation inputs (SWE) are better characterized or known than for rainfall, and the timing of snowmelt can be calculated from physically-based relationships from standard meteorological variables and predicted well in advance, whereas rainfall rate prediction is relatively uncertain.

The following statements were developed at the workshop:

- INARCH has identified the importance of the changing high mountain water cycle to global initiatives such as GEWEX, ANDEX, GWF, and the Third Pole Environment (TPE) program and is contributing to a WMO High Mountain Summit and initiative. INARCH supports the idea of an International Year of Snow and Ice and also a year devoted to Mountain Prediction.
- INARCH has published invaluable mountain catchment hydrometeorological datasets from around the world through a special issue of Earth System Science Data with 19 articles. It has expanded to 28 catchments with contributions from 45 scientists based around the world.
- INARCH has identified dramatic snowpack decline and glacial retreat in the Andes and Patagonia as issues of global concern with some of the highest rates of glacial ablation in the world, due to both sublimation and melt. Global warming has influenced mountain mega-droughts in South America, causing hydrological shortages downstream. Complications in glacial modeling due to high

sublimation rates, debris cover, and the occurrence of penitent surfaces require physically-based energy balance techniques for glacier hydrology in the Andes. Mining impacts on some of these glaciers are further accelerating ablation through direct disturbance and dust. An increasing number of glaciers are now debris-covered and so techniques to calculate icemelt under debris are needed in hydrological models. International and national mountain hydrology research programs should prioritize research in the Andes to address these problems.

- The advent of large-area, high resolution atmospheric models at 4 km or less now permits more confident meteorological drivers for advanced snow and glacier hydrology models in complex mountain terrain. The performance of these high resolution atmospheric models needs to be assessed at point and areal scales and spatial datasets for such assessments and for bias-correction should be assembled. Global application of these products to mountains is necessary. High resolution snow and ice hydrology models, including hillslope hydrology processes, require development to take advantage of the more accurate alpine precipitation products that will result.

Participants at the 4th INARCH Meeting

- There is tremendous potential to assimilate high resolution remote sensing products such as snow depth from airborne Light Detection and Ranging (LiDAR) instrumentation, albedo, grain size, and impurities from hyperspectral sensors and visible snowcovered area from multiple platforms into advanced snow hydrology prediction models, and some examples of this are occurring. Efforts are needed to demonstrate how more mountain ranges around the world can be measured by these products and how the outputs can be used together to improve snow prediction models.
- INARCH has quantified the sensitivity of mountain snow hydrology regimes around the world using cold regions hydrological models of virtual alpine basins, driven by reanalysis data, and has shown that decoupling of the snow and hydrological regime with warming is most severe for temperate winter climates with winter precipitation maxima as typified by Mediterranean alpine environments. The results show the controls of both temperature and vapor pressure in determining the sensitivity of mountain snow hydrology to warming. This approach should be extended to examine the sensitivity of mountain glacier hydrology to global warming.
- INARCH continues to examine the performance of alpine snow models in simple alpine environments by comparison of model outputs to diagnostic measurements in INARCH catchments. The next step should be to examine model performance in extreme alpine environments that are more typical of alpine landscapes.

Future Directions

The next major activity for INARCH is to co-organize and contribute to the WMO High Mountain Summit in Geneva, October 2019. Professor Pomeroy is co-chair of the Summit. The Summit is being co-organized with the World Bank Group (WBG)–Global Facility for Disaster Reduction and Recovery (GFDRR), the Food and Agriculture Organization (FAO) of the United Nations, the Mountain Partnership Secretariat, IHP, the Mountain Research Initiative (MRI), the International Association of Cryosphere Sciences (IACS), the International Association of Hydrological Sciences (IAHS), the Chinese Academy of Sciences (CAS)'s TPE program, and has the strong support of Switzerland, Austria, Canada, France, Spain, Italy, and other member nations. The High Mountain Summit seeks to foster international and regional inter-agency collaboration across sectors, scales, and actors by leveraging existing and planned initiatives and projects. This will provide integrated climate service delivery functions along the value chain, addressing the need for reliable information on water and hazard management precipitated by accelerated changes in high mountain cryosphere and ecosystems. The summit objective is to inform and therefore promote sustainable mountain development, and many INARCH participants will attend and contribute. Further information is available at *https://highmountainsummit.wmo.int/en*.

INARCH will continue to build linkages with other GEWEX cross-cuts and RHPs. Of particular importance are ties with the proposed and/or initiating Third Pole Environment cross-cut for the Hindu-Kush-Himalaya region and extended mountain ranges in Asia, the western USA RHP and Water for the Food Baskets of the World initiative, the ANDEX RHP for South America and the Andes, and the Global Water Futures Program in Canada. INARCH members will be well-represented at the upcoming Fall Meeting of the American Geophysical Union in Washington, D.C., in December, as well as the Future Earth–Water Futures session on mountains and climate change in Bangalore, India, in September 2019, and the WMO High Mountain Summit in Geneva in October, 2019, where these links will be further developed. An INARCH meeting is planned for early in 2020.