The International Network for Alpine Research Catchment Hydrology (INARCH)

Proposal to the GEWEX Hydroclimatology Panel (GHP) for a second term of INARCH, 2021–2026

Website: https://inarch.usask.ca/

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Background

INARCH began as a GHP cross-cutting project in 2015 and since then has grown to a network of 50 research scientists with wide-ranging expertise from around the world, and 29 experimental research basins in 14 countries covering key mountain regions on most continents. Since its inception, INARCH has made significant advances in understanding and predictive modelling of the high mountain water cycle, contributing significantly to multiple international science initiatives, organizations, and other stakeholders (see https://inarch.usask.ca/science-basins/phase-i-achievements.php). The network adopted a philosophy and commitment to open data, with major efforts to compile these data in a special issue of the journal Earth System Science Data titled "Hydrometeorological data from mountain and alpine research catchments" with 23 datasets (https://essd.copernicus.org/articles/special_issue871.html). Throughout its time as a cross-cutting project, the network has remained engaged and scientifically active, and while the COVID-19 pandemic has resulted in a hiatus in in-person meetings and some fieldwork, a considerable amount of progress has still been made, as shown during an online workshop held recently (https://inarch.usask.ca/news-events/inarch-2021-online-workshop.php). This is a testament to the perseverance and innovation of the group. In recent months the INARCH leadership has been considering future directions for the program and potential science questions following from the progress made during the first term of INARCH (2015–2020). The recent online workshop was held to refine the specific science questions and develop a collective vision and plans for a second term of the network. This proposal describes this vision and summarizes the plans that were made.

Participants

The membership of INARCH has undergone change since the network began and remains open to join for those interested in linking with INARCH whose research is aligned and who focus on alpine research catchment hydro-meteorology. Participants during the first term are listed on the archived website here https://gwfnet.net/sites/inarch/participants.html. Moving forward, INARCH participants are listed at https://inarch.usask.ca/org-people/, although the network is broader than this, with many other affiliated researchers, post-doctoral fellows, and students contributing to the overarching program goals and deliverables, and participating in workshops.

At present, the participants are:
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Motivation

The motivation for INARCH was clearly articulated in the original proposal and remains true now. In brief, this includes:

- "In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality" – IPCC AR4 (2014) WG II report;
- Alpine catchments receive and produce a disproportionately large fraction of global precipitation and runoff;
- Snowfall does not equal accumulation on the ground;
- Snow, ice, and phase change domination of alpine hydrology means that it is especially sensitive to temperature change;
- Alpine regions are data scarce.

According to the 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (https://www.ipcc.ch/srocc/) chapter on High Mountain Areas, "*Snow cover, glaciers and permafrost are projected to continue to decline in almost all regions throughout the 21st century*" and "*river runoff in snow dominated and glacier-fed river basins will change further in amount and seasonality in response to projected snow cover and glacier decline with negative impacts on agriculture, hydropower and water quality in some regions*." The challenges are intensifying and call for immediate action globally. The World Meteorological Organization (WMO) High Mountain Summit (https://highmountainsummit.wmo.int/en), held in Geneva in October 2019 issued a call for action that included the following:

- The high mountain regions are the home of the cryosphere, and source of global freshwater that are transmitted by rivers to much of the world. Preservation of ecosystem function and services from these regions is essential to global water, food and energy security. Climate change and development are creating an unprecedented crisis in our high mountain earth system that threatens the sustainability of the planet. There is great urgency to take global action now to build capacity, invest in infrastructure and make mountain and downstream communities safer and more sustainable. This action must be informed by science, local knowledge and based on transdisciplinary approaches to integrated observations and predictions.
- We, the participants at the WMO High Mountain Summit 2019, hereby commit to the goal that people who live in mountains and downstream should have open access to hydrological, cryospheric, meteorological, and climate information services to help them adapt to and manage the threats imposed by escalating climate change. To meet this goal we commit to an Integrated High Mountain Observation and Prediction Initiative, organized as collective, intensive campaigns of analysis and forecasting demonstration projects in key high mountains and headwaters around the world. The Initiative will co-design solutions, build capacity and suggest investments with information users, providers and producers to address the front lines of climate, cryospheric, and hydrological change in support of natural hazard risk management and adaptation in mountain regions and downstream. We urge the relevant organisations to collaborate and specifically organize as a matter of urgency, intense observation and prediction campaigns in a WMO Year of Mountain Prediction. The Initiative will contribute to the desired International Year of Mountains, and Year of Snow and Ice and will be co-produced and supported by a consortium of national institutions, international initiatives, user groups, researchers and science networks from policy, operations, practice and scientific research under the convening leadership of WMO.

Principal research questions to be addressed

INARCH has completed our Phase I Science Plan and have a suite of well-instrumented research basins, high-resolution forcing meteorological datasets, and advanced snowdrift-permitting and glacier-resolving hydrological models that are exemplars of Integrated High Mountain Observation and Prediction Systems (IHMOPS). We have used the IHMOPS to improve our scientific understanding, and evaluate observed changes, data and models around the world. The models are being used to estimate the sensitivity of the high mountain cryosphere and hydrology to climate change.

A New Vision for INARCH

Moving forward, this includes the following issues and priorities:

- Improve mountain hydrometeorological and related observations, understanding and predictions to help adapt to rapid climate change.
- Implement recommendations from the WMO High Mountain Summit—integrated observation and prediction systems. How can we build up integrated prediction systems around these research basins and apply them to the larger earth systems that derive from mountains, and what does it take to do that?
- Science for society. Can we contribute to the development of 'fit-for-purpose' hydrological, meteorological and climate information services in high mountain catchments?
- Mountain systems include human-water interactions and complex ecological interactions – how can we address this in our models? Can we use these to develop solutions to help achieve water sustainability in high mountain river basins and downstream?

We need to:

- provide common and archived observations for basin diagnosis and modelling through a Common Observation Period Experiment (COPE);
- enhance basin observations with novel and more sensors;
- Improve, downscale and correct atmospheric forcing datasets using basin observations;
- develop, improve, compare, and apply multiscale high-fidelity cryosphere-hydrological-water management models to river basins originating in high mountains;
- work with communities to develop plans to predict future water scenarios, build capacity, enhance forecasting systems, answer questions on water futures and evaluate the sustainability of proposed water management solutions.

INARCH Phase II Objectives

To better:

- measure and understand high mountain atmospheric, hydrological, cryospheric, biological and human-water interaction processes,
- improve their prediction as coupled systems,
- diagnose their sensitivities to climate change and propose how they may be managed to promote water sustainability under global change.

INARCH Phase II Science Questions

1. How different are the observation and measurement approaches amongst INARCH basins and do we expect distinctive differences in our understanding of basin response and hydrological predictability because of the sampling schemes, and data quality and quantity?
2. How do the predictability, uncertainty and sensitivity of energy and water exchanges vary with changing atmospheric thermodynamics, ecosystem structure and water management in various high mountain regions of the Earth?
3. What improvements to high mountain energy and water exchange predictability are possible through improved physics in, coupling of, and downscaling of models in complex terrain, and improved and expanded approaches to data collection and assimilation?
4. To what extent do existing model routines have global validity, are transferable, and meaningful in different mountain environments for providing service to society?
5. Can mountain systems be predicted and managed to find solutions to help achieve water sustainability in river basins under climate change?

Eventually contribute to answering - How have mountain atmospheric-cryospheric-hydrological-ecosystem-human systems co-evolved to their current states and how will they respond to climate change over the next century?

Data requirements

As in Phase I, data requirements for this project will primarily be met by:

i. 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 selected heavily instrumented alpine regions;
ii. atmospheric model reanalyses;
iii. downscaled climate model as well as regional climate model outputs.

Instrumented sites, catchments and domains that investigators wish to make available to this project will be reviewed upon application as to how well they meet these requirements and encouraged to develop comprehensive high-quality datasets. The ideal is for sites to be Integrated High Mountain Observing and Predicting Systems (IHMOPS). The INARCH classification scheme for IHMOPS is:

CLASS A: sites receiving technology transfer and developing towards CLASS B to E.

CLASS B: Single measurement points with highly accurate driving data and snow or glacier data,

CLASS C: gauged catchments that contain Class B sites and detailed vegetation coverage, soils, topography, snowcovered area, glacier mass balance or permafrost information,

CLASS D: domains for which high resolution gridded meteorological data is available that includes CLASS C sites,

CLASS E: the same as CLASS D but gridded meteorological data is also available as climate change scenarios.

High resolution atmospheric model runs (~2.5 km and finer) will be needed by this project for domains centered around IHMOPS sites and for regional to continental-scale analyses and model forcing. Collaboration with the US National Center for Atmospheric Research (NCAR) is expected to yield historic and future 21st century high resolution and detailed Weather Research and Forecasting (WRF) model pseudo-global warming and dynamic global warming outputs for North and South America, and eventually, other mountain regions globally.

Project methodology

The project methodology, as outlined in the original proposal for INARCH as a GHP cross-cutting project, will be the same. In brief (see original proposal for details), this includes forming and maintaining a network of instrumented mountain research catchments, evaluating and improving model physical process algorithms, conducting model sensitivity analyses, demonstrating improvements to model predictability, initializing regional modelling initiatives, evaluating downscaling schemes, fostering research and development, and facilitating education and training programmes to enhance capacity.

The mountain research sites have been and will continue to be core to INARCH. These are listed below and shown in Fig. 1.

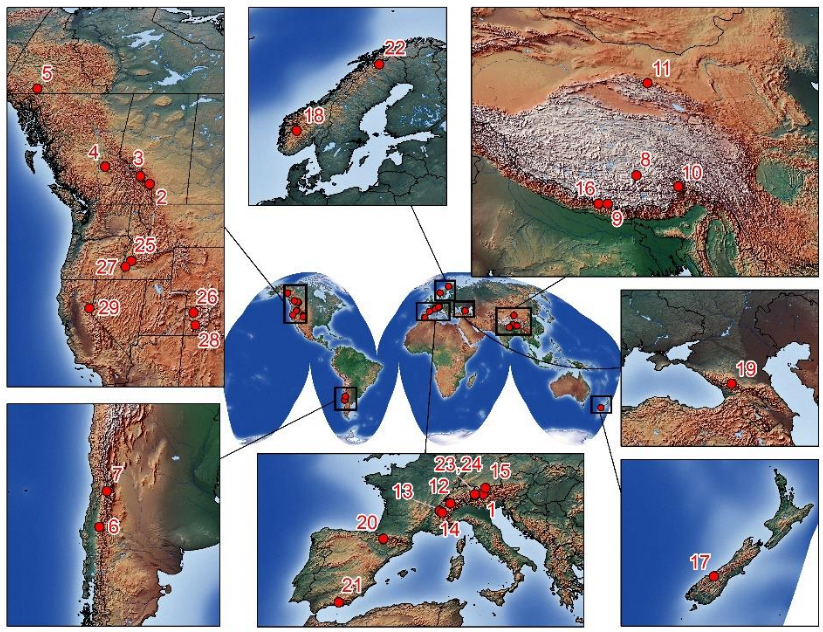

Figure 1. *Current Integrated High Mountain Observing and Predicting Systems (IHMOPS) in INARCH*

Austria **1. Rofental Open Air Laboratory (OpAL)**;
Canada **2. Marmot Creek Research Basin**; **3. Peyto Glacier**; **4. Quesnel River Research Basin**; **5. Wolf Creek Research Basin**;
Chile **6.** Upper Diguillín; **7.** Upper Maipo;
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. Schneefernerhaus and Research Catchment**;
Nepal **16. Langtang Catchment**;
New Zealand **17. Brewster Glacier**;
Norway **18. Finse Alpine Research Centre**;
Russia **19. Djankuat Research Basin**;
Spain **20. Izas Research Basin**; **21. Guadalfeo Monitoring Network**;
Sweden **22. Tarfala Research Catchment**;
Switzerland **23. Dischma Research Catchment**; **24. Weissfluhjoch Snow Study Site**;
United States of America **25. Dry Creek Experimental Watershed**; **26. Grand Mesa Study Site**; **27. Reynolds Creek Experimental Watershed**; **28. Senator Beck Basin Study Area**; **29. Sagehen Creek, Sierra Nevada**.

As we move towards models that include explicit representation of physical processes at a higher resolution over larger domains, the question is what are the insights, lessons, information that can be useful from the research catchments feeding into these large-scale projects? What would be meaningful from this group? Notwithstanding the availability of high-resolution and broad spatial coverage of remotely sensed observations, the experimental data that reveals insight on process understanding is still crucial. Improved computational capacity is helping to bridge scales, but this does not replace the need for high quality; there is a need to ensure that the models follow trusted observations and this is necessary to improve the models. We will take some of the well-instrumented INARCH sites and begin to apply the spatial models together to better understand their differences, what the models do and what they include, and how they might evolve together. The future is likely model-agnostic (e.g., there are many models, often incorporating the same process algorithms) and so looking at these together we can better understand how they operate. Comparing model routines at different sites under a common framework will be useful and worthwhile.

INARCH will use the mountain observatory sites towards many of our science questions. We will explore coupling remote sensing datasets with mountain observatory data, developing and/or utilizing more computationally intensive spatial data assimilation procedures to run on these sophisticated model frameworks, and evaluating and incorporating improved remote sensing datasets. There is need for improved data assimilation in a more "spatially aware" framework e.g., when dealing with mass transfer between grid cells or computational units—especially critical for the snow community. Operational methods for forecasting are called for by society and these will include forecasting systems that are aided by data assimilation.

Collaboration Mechanisms

INARCH will continue to follow the same collaboration mechanisms as it has in past. This includes focused workshops to promote scientific integration, joint field and modelling experiments, joint development of open-access modelling and downscaling tools, promoting development of other alpine catchments, climate change sensitivity experiments, and model and process algorithm evaluation and intercomparisons. INARCH will contribute to UNESCO Intergovernmental Hydrological Programme efforts on climate change impacts on snow, glacier and water resources within the framework IHP-IX (2022–2029), "Science for a Water Secure World in a Changing Environment", and we will contribute to the WMO High Mountain Summit call for action, in particular, the observation and prediction aspects of the Integrated High Mountain Observation, Prediction and Services Initiative. It will be imperative for INARCH to show leadership and provide guidance for governments to implement this.

New ideas emerged at our recent online workshop. INARCH will plan to carry out a period focusing on obtaining high-quality measurements to the extent possible, defining this as starting in 2022 to coincide with the start of the snow season in the southern hemisphere, and carrying on until 2024. During this common observing period experiment (COPE) we would ensure sensors are all working, fly supplementary UAV acquisitions, and work together for comparison of processes, data sharing, and model testing in challenging environments. The COPE will be enhanced with a suite of new and low-cost and more advanced sensors and drones to build and deploy at multiple sites to directly compare observations and gather a common data set (both instrument and site comparisons). Other sensors that are common across multiple sites (more expensive commercially available sensors) could also be compared. This will expand spatial coverage and allow broader participation, while more advanced technologies can be shared and deployed across sites. A working group will be formed to guide this initiative.

INARCH has advanced despite COVID-19, but we have new ideas that need deep discussion, and need to reconvene in person at an alpine research site in 2022. We plan to hold the next in-person workshop in Benasque, Spain, where detailed preparations were made for the meeting in March 2020 that was cancelled due to COVID-19. We must include hybrid options for virtual participation as well. For future meetings, we should consider the carbon footprint of travel and try, to the extent possible, to take advantage of other major meetings or events where travel is already occurring. Meeting in Asia would be desirable at some point in the future.