GHP Working Group (Project) Reports for the 34th GEWEX SSG Meeting 2021

Working Group (Project) Name : The International Network for Alpine Research Catchment Hydrology (INARCH), Phase 2
Reporting Period : 01 January – 31 December 2021
Starting Date : 2021
End Date (where appropriate) : We propose a second term to 2026
URL : https://inarch.usask.ca/ (*note-the URL has recently changed, please update this on GEWEX's website)

Membership

Contact(s) :

INARCH Chair: Distinguished Professor John Pomeroy, Canada Research Chair in Water Resources and Climate Change, Centre for Hydrology, University of Saskatchewan, Canada https://research-groups.usask.ca/hydrology/people/profiles/john-pomeroy.php

INARCH Co-Chair: Professor Juan Ignacio López Moreno, Dep. Procesos Geoambientales y Cambio Global, Instituto Pirenaico de Ecología, C.S.I.C, Spain, http://www.ipe.csic.es/lopez-moreno-j.i.

Science Manager: Dr. Chris DeBeer, Centre for Hydrology, University of Saskatchewan, Canada https://gwf.usask.ca/profiles/people/chris-debeer.php

See INARCH participant list at https://inarch.usask.ca/org-people/participants.php

Working Group Objectives, Goals & Accomplishments during Reporting Period

Overall Working Group Objective(s)

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.

List of Working Group Goals

Adjust yearly

- INARCH Phase II Science Questions
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- 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?

List of 2 to 3 Major Key Results

Adjust yearly with respect to goals

- INARCH has completed our Phase I Science Plan and have a suite of well-instrumented research basins (https://inarch.usask.ca/science-basins/research-basins.php), high-resolution forcing meteorological datasets, and advanced snowdrift-permitting and glacier-resolving hydrological models (https://inarch.usask.ca/science-basins/models-downscaling-tools.php) 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.

Other Science Highlights

Not part of the 2-3 major key results

- New snowdrift-resolving CHM model developed and tested (see https://gwf.usask.ca/articles/2021/news-usask-model-for-predicting-mountain-snowpack-provides-clearer-picture-of-spring-runoff,-impacts-of-climate-change.php).
- Hydroclimatological model AMUNDSEN (which is well documented on the new INARCH web page at "Modelling and Downscaling Tools") is now open source and re-named to „openAMUNDSEN“: see https://github.com/openamundsen/openamundsen#readme and https://github.com/openamundsen/openamundsen
- New modelling work has shed insight on the changes in rain-on-snow in different mountain regions expected under climate warming (see López-Moreno et al., 2021)

Working Group Activities during Reporting Period

List of Working Group Activities and Main Result

- Fieldwork and scientific activities have continued at most INARCH research basins. Presentations at our recent online workshop (https://inarch.usask.ca/news-events/inarch-2021-online-workshop.php#PostersandPresentations) reviewed status and activities at INARCH research basins. It was astonishing to see how much activity has carried on during COVID-19, and this is a testament to the perseverance and innovation of the group. Having local observers was critically important.
- There have been many advancements in model forcing data and modelling applications within INARCH. There is movement towards models that include explicit representation of physical

processes at a higher resolution over larger domains. 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.
- INARCH has presented its results on the importance of high mountain snow and ice hydrology and how this is impacted by climate change to the UN General Assembly, New York through a side event organised by Tadjikistan and opened by the President of the UNGA, and COP26, Glasgow through a session "Cold Regions Warming" organised by Global Water Futures and UNESCO and a plenary talk to a high level side event on snow and ice in climate change organised by UN Water, WMO, UNESCO and the Water and Climate Coalition).

List of New Projects and Activities in Place and Main Objective(s)

- INARCH is submitting a to the GEWEX Hydroclimatology Panel (GHP) for a second term of the network, 2021–2026. See the proposal document for details.

List of New Projects and Activities Being Planned, including Main Objective(s) and Timeline, Lead(s)

- 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.
- 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 will ensure sensors are all working, fly supplementary remote sensing acquisitions, and work together for comparison of processes, data sharing, and model testing in challenging environments. The COPE will be enhanced with both commerically available and novel sensors deployed at multiple sites to directly compare observations and gather a common data set for both instrument and site comparisons. This will expand spatial coverage and allow broader participation, while more advanced technologies can be shared and deployed across sites. A working group is being formed to guide this initiative.

Science Issues and Collaboration during Reporting Period

Contributions to Developing GEWEX Science and the GEWEX Imperatives.

a. Data Sets

- INARCH adopted a philosophy and commitment to open data, with major efforts to compile these data, e.g., ESSD special issue "Hydrometeorological data from mountain and alpine research catchments" with 23 datasets (https://inarch.usask.ca/datasets-outputs/mountain-hydrometeorological-data.php and https://www.earth-syst-sci-data.net/special_issue871.html).

b. Analysis

- INARCH members have carried out many analyses at the mountain research basins and mountain regions more broadly. INARCH has quantified the sensitivity of mountain snow hydrology regimes around the world. INARCH continues to examine the performance of alpine snow models in simple alpine environments by comparison of model outputs to diagnostic measurements.

c. Processes

- Significant advancement in alpine hydro-metyeorological process understanding and representation in models has been achieved by INARCH.

d. Modeling

- The network has developed and advanced the next generation of alpine meteorological and hydrological models, conducted earth system model intercomparisons, proposed new algorithms for modelling and has applied its models to examine sensitivity and responses to climate and landcover change.

e. Application

- We have used the Integrated High Mountain Observation and Prediction Systems (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.

f. Technology Transfer

- INARCH will work with mountain communities and regions and national governments 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.

g. Capacity Building

- INARCH will work with communities and regions 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.

List contributions to the GEWEX Science Goals and plans to include these.

Goal # 1 (GS1): Determine the extent to which Earth's water cycle can be predicted. This Goal is framed around making quantitative progress on three related areas posed in terms of the following questions:

1. Reservoirs:
   What is the rate of expansion of the fast reservoirs (atmosphere and land surfaces), what is its spatial character, what factors determine this and to what extent are these changes predictable?
   INARCH makes valuable contributions to this goal through its work on mountain snowpacks and glaciers and their changes, and to a lesser extent, mountain groundwater and lakes.
2. Flux exchanges:
   To what extent are the fluxes of water between Earth's main reservoirs changing and can these changes be predicted and if so on what time/space scale?

INARCH is focussed on quantifying the sensitivity and changes in the mountain water cycle, including water vapour fluxes driven by sublimation and evapotranspiration, solid fluxes via blowing snow, snow avalanches and glacier ice dynamics and liquid fluxes from meltwater movement through snow and ice, infiltration to frozen and unfrozen soils and mountain runoff generation and streamflow synthesis. Important progress has been made and many scientific publications have resulted.

3. Precipitation Extremes*:*

   How will local rainfall and its extremes change under climate change across the regions of the world?

   We presume you include snowfall in this question. This is a fundamental aspect of INARCH with respect to mountain precipitation with a fundamental question being what is the phase of precipitation and how is it changing from snowfall to rainfall and how are rainfall extremes changing in high mountains.

Goal # 2 (GS2): Quantify the inter-relationships between Earth's energy, water and carbon cycles to advance our understanding of the system and our ability to predict it across scales:

1. Forcing-feedback understanding:

   How can we improve the understanding of climate forcings and feedbacks formed by energy, water and carbon exchanges?

   INARCH contributes through its work at understanding, modelling, and predicting changes in mountain snowcover, glaciers, and landcover, which all have critical importance on surfacce energy balance and climate feedbacks. Examination of ecossytem fluxes and how they are responding to longer snow-free seasons, declining frozen soils and warmer summers and the upward migration of alpine treelines is fundamental to INARCH

2. ABL process representation:

   To what extent are the properties of the atmospheric boundary layer (ABL) defined by sensible and latent energy and water exchanges at the Earth's surface versus within the atmosphere (i.e., horizontal advection and ABL-free atmosphere exchanges)?

   INARCH mountain research basins provide exemplary datasets for characterizing mountain boundary layer meteorology in otherwise data-sparse regions of the world.

3. Understanding Circulation controls:

   To what extent are exchanges between water, energy and carbon determined by the large-scale circulations of the atmosphere and oceans?

   Regional and continental-scale atmospheric modelling (i.e. through collaborations with US National Center for Atmopsheric Research and Global Water Futures for high-resolution WRF simulations) sheds insight on the controls of circulation patterns on mountain hydro-meteorology

4. Land-atmosphere interactions:

   How can we improve the understanding of the role of land surface-atmospheric interactions in the water, energy and carbon budgets across spatiotemporal scales?

   Improved computational capacity, geospatial intelligence and new and improved modelling tools developed in INARCH are helping to bridge scales from site, to headwater basin, river basin, regional and continental, but there remains a critical need for the mountain research observatories and the INARCH hydrometeorological, hydrological and hydroglaciological process studies that are conducted there

Goal # 3 (GS3): Quantify anthropogenic influences on the water cycle and our ability to understand and predict changes to Earth's water cycle.

1. Anthropogenic forcing of continental scale water availability:

To what extent has the changing greenhouse effect modified the water cycle over different regions and continents?

This is a focus for rivers that have mountain headwaters where snow and ice reserves are directly impacted by rising temperatures - these are about 50% of human water supplies around the world.

2. Water management influences:

   To what extent do water management practices and land use change (e.g., deforestation) modify the water cycle on regional to global scales?

   INARCH focusses on landcover change (i.e. glacier loss, forest and vegetation change) in mountain regions, which impact the mountain water cycle and the flow of rivers originating in mountain regions

3. Variability and trends of water availability:

   How do water & land use and climate change affect the variability (including extremes) of the regional and continental water cycle?

   The coupled water and energy cycle is intrinsic to cold regions hydrology that is the core of INARCH. As climate warms, there is further decoupling of snow and hydrological regimes, resulting in increased variability in streamflow.

Other Key Science Questions

List 1 - 3 suggestion that you anticipate your community would want to tackle in the next 5-10 years within the context of a land-atmosphere project

- See our proposal for a second phase of INARCH, 2021-2026, for details

Contributions to WCRP including the WCRP Light House Activities

Briefly list any specific areas of your panel's activities in particular to the WCRP Light House Activities (Digital Earth, Explaining and Predicting Earth System Change, My Climate Risk, Safe Landing Cimates and WCRP Academy) https://www.wcrp-climate.org/lha-overview.

- INARCH's science goals are directly aligned with the Light House Activity, Explaining and Predicting Earth System Change and its overarching objective to design, and take major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning, and prediction of Earth System change on global and regional scales, with a focus on multi-annual to decadal timescales. Our focus is on high mountain regions as headwaters for major river systems of the world.

Cooperation with other WCRP Projects, Outside Bodies and links to applications

e.g. CLIVAR, CliC, SPARC, Future Earth, etc.

- INARCH leads a working group under Future Earth - the Climate Impacts on Global Mountain Water Security working group of the Future Earth, Sustainable Water Futures Programme (SWFP) (https://water-future.org/working_groups/climate-impacts-on-global-mountain-water-security/)
- INARCH will contribute to UNESCO Intergovernmetal 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"
- INARCH co-chaired the WMO High Mountain Summit and will contribute to addressing its 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.
- The Global Water Futures (GWF; www.globalwaterfutures.ca) Program is an expanded follow on initiative from CCRN. INARCH strongly links with the mountain research components of GWF. Distinguished Professor John Pomeroy leads and directs both INARCH and GWF.

Workshops and Meetings

List of Workshops and Meetings Held in 2021

Meeting title, dates and location.

- INARCH held an online global workshop over 3 days, October 18–20, 2021. See the workshop page for further details (https://inarch.usask.ca/news-events/inarch-2021-online-workshop.php).

List of Workshops and Meetings Planned in 2022 and 2023

*Meeting title, dates and location and anticipated travel support needs***.**

- 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.

Other Meetings Attended On Behalf of GEWEX or Panel in 2021

- INARCH research was recently presented by its Chair to a High-Level event of the UN General Assembly in New York and to the World Climate Research Programme's Americas Conference in Washington, DC. At the UNGA, the Permanent Missions of Hungary, Nepal, Pakistan, Russian Federation, and Tajikistan to the UN in cooperation with UNDESA, UNEP, WMO, UNESCO (IHP) and UN-Water held a virtual High-level side event titled, "How changing water availability from ice and snow will impact our societies", on 22 September. Distinguished Professor John Pomeroy participated in a panel discussion and presented recent INARCH research.
- In cooperation with UNESCO, INARCH will contribute to the COP26 meeting in Glasgow with an event at the Cryosphere Pavilion. The objectives are i) artistic impact; ii) scientific coherence; iii) a powerful message for the world leaders that meaningful change is the only way to preserve our cold regions and our planet. The proposal is for an exhibition of paintings and an art-science presentation to highlight the profound impacts which the cryosphere is suffering from climate change in a way which addresses the: physical impacts; importance of feedbacks; related threats to society at large; specific threats to local communities including, especially, Indigenous People and repercussions on their culture; some of the societal and political barriers which have to be overcome; and the imperative of fostering a spirit of optimism around rapid collective action. It is informed by INARCH and collaborators science, predictive models, observations and insights gleaned from two-way engagement with Indigenous communities.
- INARCH is providing a Plenary Talk to a High Level Event of COP26 UN Climate Change Conference, Glasgow, Scotland sponsored by UN-Water, WMO, UNESCO and the Republic of Tadjikistan, "Snow and ice in climate change– how to create resilience against worsening impacts of disasters and changing water availability".

Publications during Reporting Period

List of Key Publications

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- See: https://inarch.usask.ca/datasets-outputs/key-publications.php

- Abrahim, B. N., Cullen, N. J., & Conway, J. P. (2021). A decade of surface meteorology and radiation fluxes at Brewster Glacier in the Southern Alps of New Zealand. International Journal of Climatology.
- Aguilar, C., Pimentel, R., & Polo, M. J. (2021). Two decades of distributed global radiation time series across a mountainous semiarid area (Sierra Nevada, Spain). Earth System Science Data, 13(3), 1335-1359.
- Alonso-González, E., Gutmann, E., Aalstad, K., Fayad, A., Bouchet, M., & Gascoin, S. (2021). Snowpack dynamics in the Lebanese mountains from quasi-dynamically downscaled ERA5 reanalysis updated by assimilating remotely sensed fractional snow-covered area. Hydrology and Earth System Sciences, 25(8), 4455-4471.
- Barandun, M., Callegari, M., Strasser, U., & Notarnicola, C. (2021, September). Towards daily snowline observations on glaciers using multi-source and multi-resolution satellite data. In Microwave Remote Sensing: Data Processing and Applications (Vol. 11861, p. 1186108). SPIE.
- Bhattacharya, A., Bolch, T., Mukherjee, K., King, O., Menounos, B., Kapitsa, V., ... & Yao, T. (2021). High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s. Nature Communications, 12(1), 1-13.
- Capelli, A., Koch, F., Henkel, P., Lamm, M., Appel, F., Marty, C., & Schweizer, J. (2021). GNSS signal-based snow water equivalent determination for different snowpack conditions along a steep elevation gradient. The Cryosphere Discussions, 1-32.
- Conway, J. P., Helgason, W. D., Pomeroy, J. W., & Sicart, J. E. (2021). Icefield breezes: mesoscale diurnal circulation in the atmospheric boundary layer over an outlet of the Columbia Icefield, Canadian Rockies. Journal of Geophysical Research: Atmospheres, 126(6), e2020JD034225.
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- Goger, B., Stiperski, I., Nicholson, L., & Sauter, T. (2021). Large-eddy Simulations of the Atmospheric Boundary Layer over an Alpine Glacier: Impact of Synoptic Flow Direction and Governing Processes. arXiv preprint arXiv:2108.11230.
- Guo, J., Zhang, M., Shang, Q., Liu, F., Wu, A., & Li, X. (2021). River Basin Cyberinfrastructure in the Big Data Era: An Integrated Observational Data Control System in the Heihe River Basin. Sensors, 21(16), 5429.
- Helbig, N., Bühler, Y., Eberhard, L., Deschamps-Berger, C., Gascoin, S., Dumont, M., ... & Jonas, T. (2021). Fractional snow-covered area: scale-independent peak of winter parameterization. The Cryosphere, 15(2), 615-632.
- Helbig, N., Schirmer, M., Magnusson, J., Mäder, F., van Herwijnen, A., Quéno, L., ... & Gascoin, S. (2021). A seasonal algorithm of the snow-covered area fraction for mountainous terrain. The Cryosphere Discussions, 1-28.
- Horak, J., Hofer, M., Gutmann, E., Gohm, A., & Rotach, M. W. (2021). A process-based evaluation of the Intermediate Complexity Atmospheric Research Model (ICAR) 1.0. 1. Geoscientific Model Development, 14(3), 1657-1680.
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- Ikeda, K., Rasmussen, R., Liu, C., Newman, A., Chen, F., Barlage, M., ... & Musselman, K. (2021). Snowfall and snowpack in the Western US as captured by convection permitting climate simulations: current climate and pseudo global warming future climate. Climate Dynamics, 1-25.
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