GHP Working Group (Project) Reports for the 35th GEWEX SSG Meeting 2023

Working Group (Project) Name : The International Network for Alpine Catchment Hydrology (INARCH), Phase 2
Reporting Period : 01 January – 31 December 2022
Starting Date : 2021
End Date (where appropriate) : 2026
URL : https://inarch.usask.ca/

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)

To better:

* measure and understand high mountain atmopheric, 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

- Our phase II proposal to GEWEX contains details on our vision, objectives, and science questions.
- A major goal for the next 18-24 months is to carry out a common observing period experiment (COPE), focusing on obtaining high-quality measurements, to the extent possible, across most of the INARCH basins (https://inarch.usask.ca/science-basins/cope.php).

List of 2 to 3 Major Key Results

Adjust yearly with respect to goals

- During the COPE we will 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 has been formed to guide this initiative (https://inarch.usask.ca/science-basins/cope.php#COPEsteeringcommittee). We are now compiling all of the information we have received from across the network and are developing a meta-data catalogue and data management system for COPE (https://gwfnet.net/cope).

Other Science Highlights

Not part of the 2-3 major key results

- Activities at the Rofental, Ötztal Alps (Austria)
- Participation in the ongoing "Alpsnow“ project funded by ESA (ESA Alpine Regional Initiative AlpSnow EXPRO+ for the development of innovative EO-based products for serving scientific and operational needs in the Alpine region): Integration of remote sensing products in openAMUNDSEN modelling of the Rofental catchment (https://alpsnow.enveo.at)
- documentation of INARCH model openAMUNDSEN (https://doc.openamundsen.org/)
- all three climate/snow stations in operational work, data online at https://doi.pangaea.de/10.1594/PANGAEA.876120 and https://www.pangaea.de/?q=%40ref104365

- The European Space Agency AlpSnow project is a contribution to INARCH aimed at developing and implementing algorithms for mountain snow products from EO data, and demonstrating their use for scientific and operational applications. The parameters assessed include snow extent, snow surface albedo and grain size, snow water equivalent, snow depth, snow wetness and melt phases. Five test areas, including the Dischma and Rofental INARCH research basins, are being used for validating the retrieval algorithms. Copernicus satellite data (Sentinel-1 SAR, Sentinel-2 and Sentinel-3) and third-party missions (such as PRISMA, TerraSAR-X, SAOCOM SAR) are used. The retrieval of fractional snow extent is based on Sentinel-2 and Landsat-8/9, and can be combined with medium resolution products from Sentinel-3 with daily coverage. The prototype algorithms account for topographic effects on solar illumination, especially for snow detection in shaded areas and exploiting the full spectral capabilities of optical sensors. A semi-empirical approach and an approximation of atmospheric radiative transfer for albedo and surface grain size are being evaluated for alpine terrain. Melt monitoring using SAR is mature and robust, but the method has now been extended to provide information on the different phases of melt. Direct measurement of SWE change with repeat pass L-Band SAR is being evaluated in preparation for the Copernicus-2 ROSE-L mission. A second approach for SWE retrieval assimilates EO-products (snow extent, wet snow, albedo) into operational snow pack models to improve the spatial distribution and conditions of the snow cover. Differencing of DEMs from TanDEM-X single pass datasets is being tested to measure snow depth. In the next steps, algorithms will be selected for production of multiyear timeseries.

Working Group Activities during Reporting Period

List of Working Group Activities and Main Result

- Initialization of COPE and ongoing fieldwork activities at most INARCH basins.
- Continuation of model develop, application, and testing across INARCH research basins

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

- INARCH has submitted a proposal for phase II activities (submitted to and approved by GHP). There has been some feedback to the proposal and we adress it briefly here:

- GHP comment: While the proposal emphasizes on co-designing solutions with stakeholders and local communities, it is important that the procedure and mechanisms to facilitate such links are outlined.
- INARCH response: We did indeed note that we must work with communities to develop plans to predict future water scenarios, build capacity, and enhance forecasting systems. We will build on existing and new relationships between our members and local partners and user groups. We are already engaged in buidling stronger links with local water management and government bodies in central Asia and in the Himalayan headwaters of the Ganges River. Given that INARCH has no funding, we must leverage other activities and sources of fuding to achieve our collective aims. Ideally, we will engage directly with local stakeholders through workshops and knowledge/technology transfer opportunities. Where feasible, we will reach out to gather user perspectives and concerns, and to be able to tailor our specific approach and deliverables to meet their needs. In-person meetings would facilitate reporting to communities and provide opportunities to share results, solutions and tools, but may be limited by funds to host such events.

- GHP comment: The link of this CC with other activities in the GHP, as well as broader GEWEX and WCRP, in particular lighthouse activities, is not very clear. In addition there are possibilities for collaborations with non-WCRP, e.g. the USGS Next Generation Water Observing System (NGWOS). The panel suggests that the INARCH-II team thinks about tangible and impactful collaboration within the GHP and beyond.
- INARCH response: We feel this is important as well. Key linkages in GHP that we must strengthen moving forward are with the Third Pole Environment Programme and ANDEX. INARCH does have strong connections to UNESCO's Integovernmeltal Hydrological Programme and to the World Meteorological Organization.

- GHP comment: While the numbers of observatories and involved researchers have increased from phase I to phase II, there are still gaps in certain regions, e.g. Andes. There are active climate stations above 5,000 m altitude in different parts of south America for example in Argentina IANIGLA (https://www.mendoza.conicet.gov.ar/portal/ianigla/) in Bolivia Bolivian Mountain Institute (http://www.bolivian-mountains.org/index.php) and in Ecuador INAMHI (http://www.inamhi.gob.ec/). Such links can be extremely important for giving INARCH-II a global leadership.
- INARCH response: We welcome broader participation and collaboration in the network, and would consider adding more sites to the global network of research sites (provided they meet our basic criteria). Thank you for pointing out these potential linkages, and indeed there has been some contact with the IANIGLA group. We have also recently added the Salcca-Sibinacocha basin in the Andes of Peru as a site participating in COPE.

- GHP comment: The proposal would have benefited from more details about specific future plans beyond 2022.
- INARCH response: The COPE is a major undertaking that will continue until 2024. For COPE we plan to take a variety of different models and apply them in different basins to see how they work,

make sure we have the proper forcing information, try different forcing, at different scales, see what corrections are needed for those forcings, calculate snow and ice dynamics and hydrological dynamics at the surface, and look at these diagnostically with available measurements from ice and snow changes, to soil moisture, streamflow, and turbulent fluxes, as available. This has not been done globally in alpine regions and could be potentially very powerful. This will likely be an ongoing effort well beyond the end of the field data collection component of COPE. We will have a chance to discuss and develop more concrete plans for further newtowkr activities at our upcoming workshop in the fall of 2022.

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

- COPE and the follow-on model testing and evaluation, sensitivity analyses, and diagnostic and predictive modelling will be a major endeavor over the next several years of INARCH.

Science Issues and Collaboration during Reporting Period

Contributions to Developing GEWEX Science and the GEWEX Imperatives.

a. Data Sets
   - https://inarch.usask.ca/datasets-outputs/mountain-hydrometeorological-data.php

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.
   - https://inarch.usask.ca/science-basins/cope.php#Modellingsoftwaretools

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.
   - https://inarch.usask.ca/science-basins/models-downscaling-tools.php

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

- NARCH 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 contributes 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 is contributing 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 2022
Meeting title, dates and location.

- We held the INARCH 2021 Online Workshop virtually over October 18–20, 2021 to review the status and activities at INARCH's mountain research basins, recent advances in modelling, and the combined use of modelling and observations, as well as to define a collective vision and refined our plans for a second phase of the program. A summary of the workshop and pdf copies of the presentations are available at https://inarch.usask.ca/news-events/inarch-2021-online-workshop.php.

List of Workshops and Meetings Planned in 2023 and 2024
*Meeting title, dates and location and anticipated travel support needs***.**

- INARCH plans to hold the next in-person workshop in the Spanish Pyrenees at a small village called Baños de Panticosa (Panticosa hot springs) on October 18-20, 2022. Participants will arrive in Zaragoza and meet on Oct 17 before departing to Banos de Panticosa on Oct 18. Participants will return to Zaragoza on Oct 20. (https://inarch.usask.ca/news-events/inarch-workshop-2022.php).

Other Meetings Attended On Behalf of GEWEX or Panel in 2022

- We presented INARCH studies on the impacts of climate change on mountain snow and ice to three sessions at the World Leaders Summit COP26 Cryosphere at COP26 in Glasgow at the World Leaders Summit COP26 Cryosphere – ICCI – International Cryosphere Climate Initiative (https://iccinet.org/cop26cryospherepavilion/world-leaders-summit-cop26-cryosphere/) on Nov 1, 2021. All are available to watch on the Youtube link provided on the page. There was very strong interest at COP26 on declining mountain snow and ice and its impacts on downstream water resources.
- INARCH Chair, John Pomeroy, presented to the SINTER: Snow International (http://depts.washington.edu/sinter/index.html) group at their quarterly meeting on May 27, 2022. The theme of the seminar was observation networks, and Dr. Pomeroy described INARCH, the COPE, and our Phase II plans and activities.

Publications during Reporting Period

List of Key Publications

- Some notable recent publications are:
- Aubry-Wake, C., Bertoncini, A., & Pomeroy, J. W. (2022). Fire and Ice: The Impact of Wildfire-Affected Albedo and Irradiance on Glacier Melt. Earth's Future, 10(4), e2022EF002685. https://doi.org/10.1029/2022EF002685
- Capelli, A., Koch, F., Henkel, P., Lamm, M., Appel, F., Marty, C., & Schweizer, J. (2022). GNSS signal-based snow water equivalent determination for different snowpack conditions along a steep elevation gradient. The Cryosphere, 16(2), 505-531.
- Kiewiet, L., Trujillo, E., Hedrick, A., Havens, S., Hale, K., Seyfried, M., Kampf, S., & Godsey, S. E. (2022). Effects of spatial and temporal variability in surface water inputs on streamflow generation and cessation in the rain–snow transition zone. Hydrology and Earth System Sciences, 26(10), 2779–2796. https://doi.org/10.5194/hess-26-2779-2022
- Pradhananga, D., & Pomeroy, J. W. (2022). Diagnosing changes in glacier hydrology from physical principles using a hydrological model with snow redistribution, sublimation, firnification and energy balance ablation algorithms. Journal of Hydrology, 608, 127545. https://doi.org/10.1016/j.jhydrol.2022.127545
- Sanmiguel-Vallelado, A., McPhee, J., Carreño, P. E. O., Morán-Tejeda, E., Camarero, J. J., & López-Moreno, J. I. (2022). Sensitivity of forest–snow interactions to climate forcing: Local variability in a Pyrenean valley. Journal of Hydrology, 605, 127311. https://doi.org/10.1016/j.jhydrol.2021.127311

All publications are listed here: https://inarch.usask.ca/datasets-outputs/key-publications.php