Template for Project Reports for the GEWEX GHP Meeting

Full Panel, Project or Working Group Name (Acronym): International Network for Alpine Research Catchment Hydrology (INARCH)
Reporting Period: November 2017 – October 2018
Starting date: January 2015
End date: January 2020
URL: www.usask.ca/inarch
Chair(s) and term dates: John Pomeroy, University of Saskatchewan, Canada (2015–); co-chair, Matthias Bernhardt, University of Natural Resources and Life Sciences, Vienna (2017–)

1) Regional Hydroclimate Project (RHP) or Cross-Cut (CC) activities over the last year

Science highlights

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 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?

INARCH is more than halfway through its term and 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 Spain, Norway, and USA. Moving forward INARCH will be developing syntheses papers and other products as outputs of the network and contributing to initiatives beyond GEWEX, such as Future Earth, the World Meteorological Organization, the Intergovernmental Panel on Climate Change, UNESCO's International Hydrological Programme, and the UN at large through its International Water Action Decade: Water for Sustainable Development, 2018–2028.

Science issues

Dr. John Pomeroy (Canada), and Dr. Danny Marks (USA) served as guest editors for an INARCH special issue of Earth System Science Data, covering **Hydrometeorological data from mountain and alpine research catchments**. The aims of the issue and links to published and in-discussion papers are found at https://www.earth-syst-sci-data.net/special_issue871.html. The issue closed on 30 September 2018, and there have been 18 papers contributed from around the world.

New projects/activities put in place last year

Dr. Juan Ignacio López Moreno (Spain) led a major effort using bias-corrected reanalysis data and the Cold Regions Hydrological Model to simulate snowpack and streamflow regimes of idealized catchments in 44 mountain regions of the world. The simulations illustrate the existence of complex behaviour, with very strong regional differences in the sensitivity of snow accumulation and duration to climate warming. As temperature increases, the river regime timing tends to synchronize to their precipitation regimes, and the contribution of snowmelt to annual runoff is reduced. However, annual runoff is not strongly affected by changes in the seasonal snowpack. Overall, the result show increased decoupling of snow regimes, snow hydrology and basin hydrology with increased warming, but with substantial regional variations in how this occurs. There are substantial regional variations in the magnitude of these changes in the hydrograph, which are not always well related with the observed sensitivity of snowpack. Identifying the drivers of the variable response of snowpack and snow hydrology can help explain the desynchronization of snowpack

and streamflow regimes with warming. This permits identification of the most vulnerable mountain areas to projected climate change. This work will be submitted for publication soon.

Workshops and meetings held

The third annual INARCH workshop was held at Zugspitze, Germany, on 8–9 February, 2018. The meeting brought together a group of 30 scientists from the US, Canada, Chile, France, UK, Switzerland, Austria, Germany, Spain, and Norway. This was a very fruitful meeting were a number of statements and resolutions were adopted, significant progress was shown, and future directions were mapped out. A full report is available in the Feb–May 2018 issue of GEWEX News on pages 16–18 https://www.gewex.org/gewex-content/uploads/2018/08/Feb-May2018.pdf. The meeting page on the INARCH website contains further information and a detailed summary written by Bob Sandford (Canada) http://www.usask.ca/inarch/wkshp3_report.php.

INARCH convened a special session on *Observing and modelling the mountain water cycle using alpine research catchments* at the GEWEX Open Science Conference held in Canmore, Alberta, Canada, on 7–10 May, 2018. This addressed topics on: a) convective permitting modelling and high resolution satellite data, b) use of big data techniques and large computers and models, c) hybrid downscaling techniques (e.g. such as ICAR), d) other observational datasets, and e) recent completed field efforts (such as the WMO 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 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 Modelling Workshop was held at the NCAR MESA lab in Boulder, Colorado, USA on 4–6 September, 2018. The meeting was hosted by Dr. Roy Rasmussen (USA). The workshop focused on scientific and technical challenges related to convection-permitting climate modelling (horizontal grid spacing ≤4 km). These challenges include the model setup, observational datasets, evaluation techniques, computational resources, model intercomparisons, and the use of convection-permitting simulations in impact research. The 3-day meeting's aim was to foster collaborations and synergies to work on this challenging topic as a community. 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.

2) Planed RHP or CC activities for next year

Planed new scientific activities

INARCH will continue working towards its overarching goals and initiatives such as the development of a downscaling toolbox with a link to methods, as well as metadata for catchments and links to DOI data; participation in snow model comparisons at sites where inputs can measured/defined through links with GLASS; and continuing climate sensitivity comparative analysis of various alpine basins using “standard virtual basin” modelling to compare the response of snowcover, snowpack, glaciers and hydrology to variations in temperature and precipitation in various climate regimes.

INARCH will contribute pre-assessment syntheses to support the IPCC AR6 WG1 (Physical Science Basis) and AR6 WG2 (Impacts, Vulnerability and Adaptation, including Cross Chapter Paper on Mountains). We will provide synthesis/review on key problems/issues (as a central focus thematic), and comparing those observations/phenomena/issues/impacts across mountain regions, taking a 'regional' or 'global' approach in the review to provide a sense of differences within and across regions.

INARCH is contributing to the ***WMO High Mountain Summit*** in Geneva, Feb 2019 with Professor Pomeroy as 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 of the United Nations (FAO), the Mountain Partnership Secretariat, the United Nations Educational, Scientific and Cultural Organization (UNESCO) – International Hydrological Programme (IHP), the Mountain Research Initiative (MRI), the International Association of Cryosphere Sciences (IACS), the International Association of Hydrological Sciences (IAHS), the Third Pole Environment program (TPE) of the Chinese

Academy of Sciences (CAS), and with the strong support of Switzerland, Austria, Canada, France, Spain, Italy, and other Members. 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, for providing 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, with the objective to inform, and therefore, promote Sustainable Mountain Development.

The central theme of the Summit will be "Addressing the information needs for adequate adaptation strategies of the coupled human and environmental systems, experiencing changes in high mountain regions". The outcomes of the Summit will seek to:

1) Mobilize public and private sectors leaders to help leverage funding in support of relevant initiatives, including commitments for funding agreed next steps.

2) Promote collaboration for new and ongoing initiatives, by developing a roadmap for enhancing and strengthening the provision of hydro-meteorological, climate, and prediction services for mountain regions, for optimizing cryosphere and high mountain observations, and advancing the scientific research agenda to address emerging gaps.

3) Leverage the knowledge, expertise, and influence of relevant stakeholders, for coordinating upscaling of end-to-end services, for increasing interagency engagements, including identifying barriers and proposing enabling factors.

The Summit will conclude with:

- A statement and call for action, reflecting the Summit outcomes, and express support for agreed initiatives, in line with the 2030 Agenda.
- The launch of a limited number of flagship projects, using as examples, existing and functioning value chains.

The Conference will contribute to aligning the efforts of WMO and its partners towards enhancing climate and hydro-meteorological knowledge available to all United Nations Member Countries, towards meeting the related SDGs.

Planed workshops or meetings

INARCH will hold its fourth annual workshop on 24–26 October, 2018 in Santiago and Portillo, Chile. The workshop is organized and will be hosted by Dr. James McPhee (Chile). The workshop will bring together this network to follow up on activities, progress, and plans towards its overall objective and its research questions relating to alpine hydrology. A number of topics will be reviewed and discussed, including field observations, catchment data and emerging methods, snow hydrology, glacier hydrology, model simulation and data assimilation, and the interface of science to policy. Regional initiatives and linkages with various external organizations, such as the WMO High Mountain Summit, Future Earth's Sustainable Water Futures Programme and UNESCO's International Hydrological Programme, as well as the Canadian-led Global Water Futures Project and the recently proposed and initiating ANDEX RHP for the Andes, will be discussed. Further information is at https://www.gewexevents.org/events/2018-andex-ghp-inarch-meeting/.

3) Contributions to the GEWEX Science Questions

GSQ1: Observations and Predictions of Precipitation

- INARCH makes major contributions to GSQ1 by facilitating an active exchange and collaboration between international researchers and forming a network of instrumented mountain catchments to compare instrumentation best practices, suggest improvements in instrumentation, and develop reliable alpine datasets for model testing and numerical experiments.
    - **INARCH Workshop Statement 2018: INARCH's global mountain observatories are providing a unique set of published, archived, high quality, surface, model and remote sensing datasets that will be made available to WMO-GCW and other global initiatives including remote sensing.**

- Development of a downscaling toolbox by examining various techniques for statistical, dynamical and medium complexity downscaling on the basis of different datasets of the test sites. The evaluation is not limited to the regular comparison of different meteorological parameters but also includes parameters like e.g. snowcover extent, snow water equivalent, soil moisture.
- INARCH, through its membership and collaboration with NCAR, are pursuing high resolution, convention permitting Weather Research and Forecasting (WRF) model simulations over the North American domain, in both historical and future pseudo-global warming model. (see https://ral.ucar.edu/events/2018/cpcm; Li et al., 2017; Liu et al., 2017; Prein et al., 2017a, 2017b)

GSQ3: Changes in Extremes

- INARCH focuses on extreme events (floods, droughts, wildfire) and their impacts on mountain regions (e.g. a major effort was dedicated to an examination of the 2013 flooding events in western Canada; see http://ccrnetwork.ca//science/2013-Alberta-flood/index.php for a description and links to published papers). Other recent work has focused on drought in Chile (Garreaud et al., 2017).

GSQ4: Water and Energy Cycles and Processes

- Water and energy cycles in mountain catchments are dominated by snow mass and energy exchange processes such as blowing snow, snow interception, sublimation, and melt. The network has conducted extensive diagnostic work on water and energy exchanges, hydrological processes, and their sensitivity and response to climate change, using the global network of high alpine (as well as other cold region) research catchments. See Aksamit and Pomeroy (2018), Conway et al. (2018), Krogh and Pomeroy (2018), López-Moreno et al. (2017), MacDonald et al. (2018), Musselman et al. (2017), and Wayand et al. (2018).
    - **INARCH Workshop Statement 2018: INARCH encourages process validation and description to inform large scale and operational model advances, acknowledging the need to demonstrate improved predictions of the water security impacts of global change in mountain regions.**

4) Activities contributing to the WCRP Grand Challenges as identified by the JSC

Melting Ice and Global Consequences

- A major research focus at many of the INARCH research catchments is directed at observing and predicting glacier mass balance and associated area and volumetric changes, and impacts to basin water storage and cycling. Glacier mass balance has been predominantly negative and some areas, such as glaciers in the Rocky Mountains of Canada, have shown record or near record losses in the past few years with an apparent shift to increasingly negative net mass balance. Here, forest fires have resulted in deposition of ash and other debris onto glacier surfaces, reducing their albedo and accelerating their melt. See *Wildfire season: Is this the new normal?* By Mark Ferguson https://phys.org/news/2018-09-wildfire-season.html
- See *'It's not impossible': Western Canada's risk of water shortages rising* by Erin Collins of the CBC https://www.cbc.ca/news/canada/calgary/africa-capetown-water-shortage-drought-canada-rockies-glacier-1.4564616
- A major review paper was published, including some INARCH members as co-authors, examining the current and future state of the European mountain cryosphere (Beniston et al., 2018).

Climate extremes and water availability

- INARCH is focused on conducting cold regions hydrological model sensitivity testing to atmospheric change in various alpine environments and including sensitivity to including the effects of transient changes from glacier mass balance, groundwater changes and vegetation changes. We also aim to demonstrate improvements to model predictability that can be realised from data assimilation, downscaling and model structural improvements. See the work described above by Dr. Juan Ignacio López Moreno, and also López Moreno et al. (2017).
- High resolution WRF modelling will allow unprecedented fine-scale and process oriented simulations

of historical and future precipitation (pseudo-global warming), that will allow examination of how weather systems and storms in the recent past climate would unfold under a warmer climate in future. See http://ccrnetwork.ca//science/PGW/index.php; Li et al. (2017), Prein et al. (2017b).

- **INARCH Workshop Statement 2018: INARCH is implementing hybrid downscaling with moderate (km) scale dynamical downscaling from atmospheric models followed by fine (<100s m) scale downscaling (dynamical, empirical) to *snowdrift resolving* scales for improved snow and ice hydrology prediction in support of mountain climate change policy runs.**
- **INARCH will use these model runs to predict the response of mountain snow, ice and hydrology to climate change, taking into account transient vegetation cover, basin geometry and hydrological and cryospheric storage.**

5) Cooperation with other GHP and WCRP projects (CLIVAR, CliC, SPARC), outside bodies (e,g. iLEAPS) and links to applications

- Collaboration with UNESCO IHP and information collaboration with SPICE and Global Cryosphere Watch (CliC).
- Contribution to developing the WMO High Mountain Summit
- INARCH is linked to the GEWEX RHP known as the Changing Cold Regions Network (CCRN; www.ccrnetwork.ca; completed in March 2018). INARCH and CCRN share many common research priorities and objectives.
- 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.

6) List of key publications

*See ESSD special issue on Hydrometeorological data from mountain and alpine research catchments https://www.earth-syst-sci-data.net/special_issue871.html.

- Aksamit, Nikolas O., and John W. Pomeroy. "The effect of coherent structures in the atmospheric surface layer on blowing-snow transport." Boundary-Layer Meteorology 167, no. 2 (2018): 211-233.
- Beniston, Martin, Daniel Farinotti, Markus Stoffel, Liss M. Andreassen, Erika Coppola, Nicolas Eckert, Adriano Fantini et al. "The European mountain cryosphere: a review of its current state, trends, and future challenges." *Cryosphere* 12, no. 2 (2018): 759-794.
- Conway, Jonathan P., John W. Pomeroy, Warren D. Helgason, and Nicholas J. Kinar. "Challenges in modelling turbulent heat fluxes to snowpacks in forest clearings." *Journal of Hydrometeorology* 2018 (2018).
- Garreaud, René D., Camila Alvarez-Garreton, Jonathan Barichivich, Juan Pablo Boisier, Duncan Christie, Mauricio Galleguillos, Carlos LeQuesne, James McPhee, and Mauricio Zambrano-Bigiarini. "The 2010-2015 megadrought in central Chile: impacts on regional hydroclimate and vegetation." *Hydrology & Earth System Sciences* 21, no. 12 (2017).
- Krogh, Sebastian A., and John W. Pomeroy. "Recent changes to the hydrological cycle of an Arctic basin at the tundra–taiga transition." *Hydrology and Earth System Sciences* 22, no. 7 (2018): 3993-4014.
- Li, Yanping, Kit Szeto, Ronald E. Stewart, Julie M. Thériault, Liang Chen, Bohdan Kochtubajda, Anthony Liu et al. "A numerical study of the June 2013 flood-producing extreme rainstorm over southern Alberta." *Journal of Hydrometeorology* 18, no. 8 (2017): 2057-2078.
- Liu, Changhai, Kyoko Ikeda, Roy Rasmussen, Mike Barlage, Andrew J. Newman, Andreas F. Prein, Fei Chen et al. "Continental-scale convection-permitting modeling of the current and future climate

of North America." *Climate Dynamics* 49, no. 1-2 (2017): 71-95.

- López-Moreno, Juan I., S. Gascoin, J. Herrero, E. A. Sproles, M. Pons, E. Alonso-González, L. Hanich et al. "Different sensitivities of snowpacks to warming in Mediterranean climate mountain areas." *Environmental Research Letters* 12, no. 7 (2017): 074006.
- MacDonald, Matthew K., John W. Pomeroy, and Richard LH Essery. "Water and energy fluxes over northern prairies as affected by chinook winds and winter precipitation." Agricultural and Forest Meteorology 248 (2018): 372-385.
- Mernild, Sebastian H., Glen E. Liston, Christopher A. Hiemstra, Jeppe K. Malmros, Jacob C. Yde, and James McPhee. "The Andes Cordillera. Part I: snow distribution, properties, and trends (1979–2014)." *International Journal of Climatology* 37, no. 4 (2017): 1680-1698.
- Mernild, Sebastian H., Glen E. Liston, Christopher A. Hiemstra, Jacob C. Yde, James McPhee, and Jeppe K. Malmros. "The Andes Cordillera. Part II: Rio Olivares Basin snow conditions (1979–2014), central Chile." *International Journal of Climatology* 37, no. 4 (2017): 1699-1715.
- Musselman, Keith N., Martyn P. Clark, Changhai Liu, Kyoko Ikeda, and Roy Rasmussen. "Slower snowmelt in a warmer world." *Nature Climate Change* 7, no. 3 (2017): 214.
- Prein, Andreas F., Changhai Liu, Kyoko Ikeda, Randy Bullock, Roy M. Rasmussen, Greg J. Holland, and Martyn Clark. "Simulating North American mesoscale convective systems with a convection-permitting climate model." *Climate Dynamics* (2017a): 1-16.
- Prein, Andreas F., Roy M. Rasmussen, Kyoko Ikeda, Changhai Liu, Martyn P. Clark, and Greg J. Holland. "The future intensification of hourly precipitation extremes." *Nature Climate Change* 7, no. 1 (2017b): 48.
- Wayand, Nicholas E., Christopher B. Marsh, Joseph M. Shea, and John W. Pomeroy. "Globally scalable alpine snow metrics." Remote Sensing of Environment 213 (2018): 61-72.