International Network for Alpine Research Catchment Hydrology

Summary and Overview of INARCH

Phase I Achievements and Phase II Ambitions

John Pomeroy, INARCH Chair

Chris DeBeer, INARCH Science Manager

Contributions from Chris Marsh, Zhibang Lv, Ignacio Lopez Moreno

SINTER: Snow International Meeting

May 27, 2022

https://inarch.usask.ca

GEWEX INARCH

About INARCH

- A cross-cut project of the World Climate Research Programme's (WCRP) Global Energy and Water Exchanges (GEWEX) Hydroclimatology Panel (GHP) to:
  - better understand alpine cold regions hydrological processes,
  - improve their prediction, and
  - find consistent measurement strategies.
- A network of 50 research scientists, 29 experimental research basins in 14 countries.
- INARCH completed its initial 5-year term.
- A second term, 2021–2026, with refined science questions and activities has been proposed and GEWEX-GHP has endorsed this.

Participants

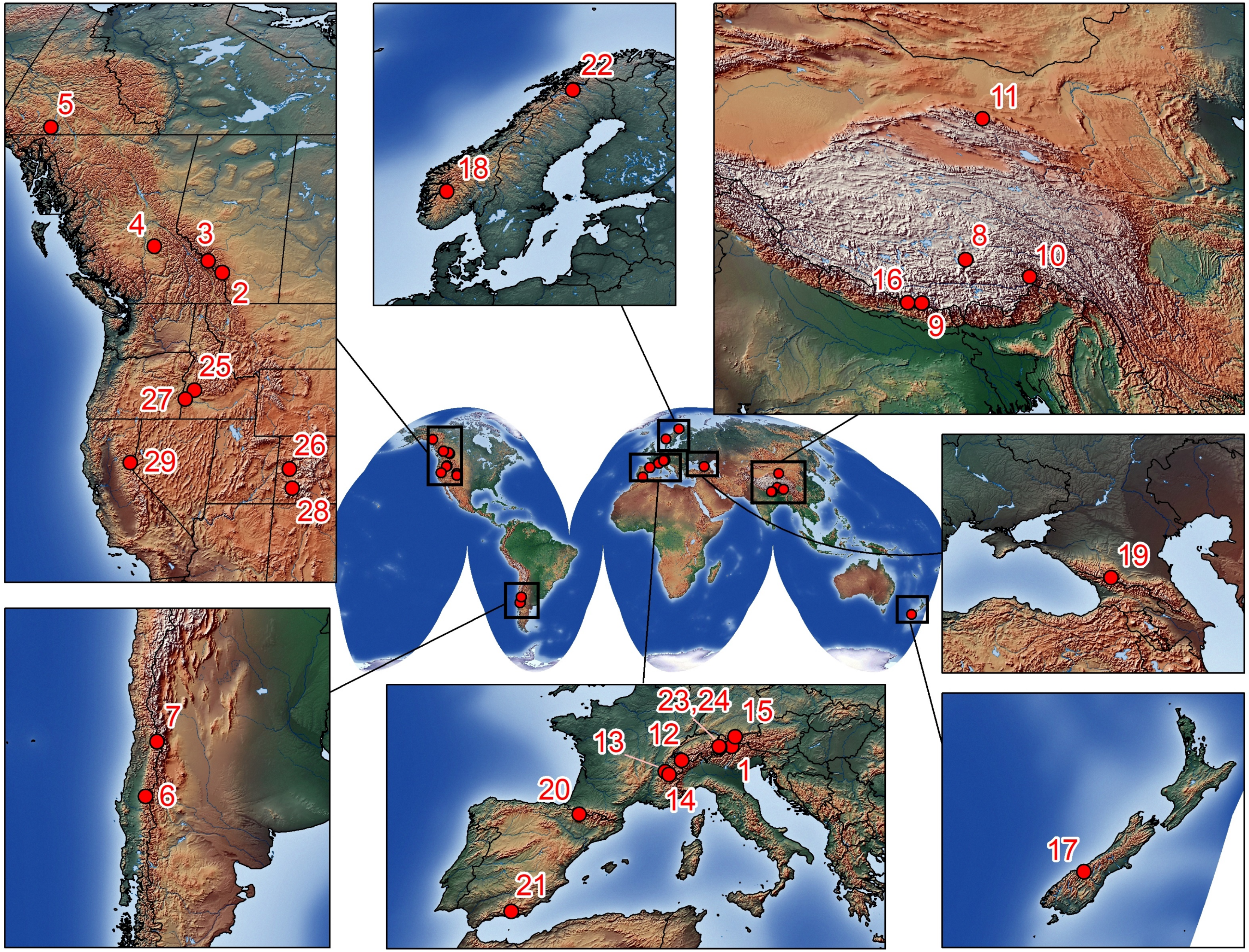
Participants

https://inarch.usask.ca/org-people/participants.php

- John Burkhart, University of Oslo, Norway
- Wouter Buytaert, Imperial College London, England
- Sean Carey, McMaster University, Canada
- Jono Conway, National Institute of Water & Atmospheric Research, New Zealand
- Nicolas Cullen, University of Otago, New Zealand
- Chris DeBeer, University of Saskatchewan, Canada
- Stephen Dery, University of Northern British Columbia, Canada
- Marie Dumont, Centre National de Recherches Météorologiques (UMR CNRS & Météo-France), Centre d'Etudes de la Neige, France
- Richard Essery, University of Edinburgh, Scotland
- Simon Gascoin, Université de Toulouse, France
- Alexander Gelfan, Water Problems Institute, Russian Academy of Sciences, Russia
- Isabelle Gouttevin, Centre National de Recherches Météorologiques, Météo-France, France
- Ethan Gutmann, National Center for Atmospheric Research, USA
- Adrian Harpold, University of Nevada, Reno, USA
- Walter Immerzeel, Utrecht University, Netherlands
- Peter Jansson, Stockholm University, Sweden
- Tobia Jonas, WSL Institute for Snow and Avalanche Research SLF, Switzerland
- Georg Kaser, University of Innsbruck, Austria
- Franziska Koch, University of Natural Resources and Life Sciences Vienna, Austria
- Sebastian Krogh, Universidad de Concepción, Chile
- Vincenzo Levizzani, National Research Council of Italy (CNR-ISAC), Italy
- Xin Li, Chinese Academy of Sciences (CAS), China
- Ignacio Lopez Moreno, Spanish National Research Council (CSIC), Spain
- Yaoming Ma, Chinese Academy of Sciences (CAS), China
- Danny Marks, US Department of Agriculture, USA
- James McPhee, University of Chile, Chile
- Pablo Mendoza, Universidad de Chile, Chile
- Brian Menounos, University of Northern British Columbia, Canada
- Anil Mishra, International Hydrological Programme, UNESCO, France
- Samuel Morin, Centre National de Recherches Météorologiques, Météo-France, France
- Florence Naaim-Bouvet, Institut National de Recherche en Sciences et Technologies pour l'Environnement et l'Agriculture (IRSTEA), France
- Francesca Pellicciotti, Eidgenössische Technische Hochschule (ETH), Switzerland
- María José Polo Gómez, University of Córdoba, Spain
- John Pomeroy, University of Saskatchewan, Canada
- Dhiraj Pradhananga, Tribhuvan University, Nepal
- Rainer Prinz, Universität Innsbruck, Austria
- Roy Rasmussen, US National Center for Atmospheric Research, USA
- Ekaterina Rets, Institute of Water Problems, Russian Academy of Science, Russia
- Gunhild Rosqvist, Stockholm University, Sweden
- Nick Rutter, University of Northumbria, England
- Robert Sandford, United Nations University Institute for Water, Environment and Health, Canada
- Karsten Schulz, University of Natural Resources and Life Sciences (BOKU), Austria
- Jean-Emmanuel Sicart, Institut de Recherche pour le Développement, France
- Delphine Six, Université Joseph Fourier, France
- Sara (McKenzie) Skiles, University of Utah, USA
- Ulrich Strasser, University of Innsbruck, Austria
- Julie Thériault, Université du Québec à Montréal, Canada
- Vincent Vionnet, Environment and Climate Change Canada, Canada
- Isabella Zin, Laboratoire d'étude des Transferts en Hydrologie et Environnement (LTHE), France

INARCH Basins

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.



https://inarch.usask.ca/science-basins/research-basins.php

Data Requirements

Surface based data requirements for INARCH will primarily be met by:

1. 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
2. atmospheric model reanalyses
3. downscaled climate model as well as regional climate model outputs

INARCH Phase I Achievements

- INARCH has grown to a network of 50 research scientists with wide-ranging expertise from around the world
- 29 experimental research basins in 14 countries covering most continents and mountain regions of the world
- significant advances in understanding and predictive modelling of the high mountain water cycle, contributing significantly to multiple international science initiatives, organizations, and other stakeholders
- 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.

WORLD METEOROLOGICAL ORGANIZATION

WEATHER CLIMATE WATER

High Mountain Summit

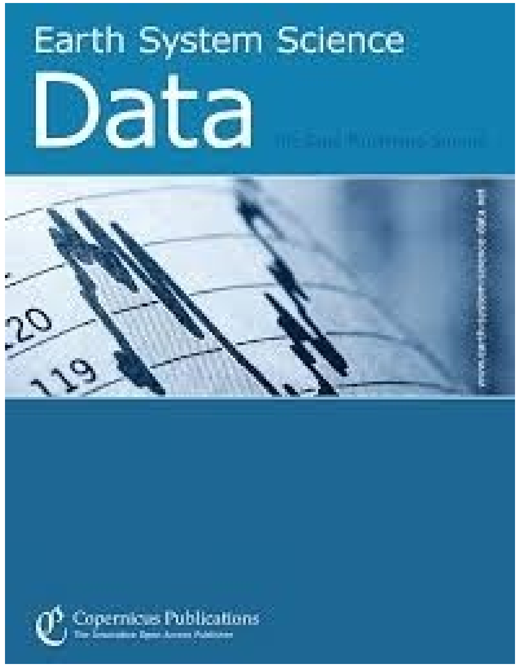
Call for Action, Geneva, October 2019

- Climate change and development are creating an **unprecedented crisis in our high mountain earth system** that threatens the sustainability of the planet.
- People living in mountains and those living downstream shall have **open access to and use of 'fit-for-purpose' hydrological, meteorological and climate information**.
- **Integrated High Mountain Observation, Prediction and Services Initiative**, organized as collective, intensive campaigns of analysis and forecasting demonstration projects in key high mountains and headwaters around the world. .

Earth System Science Data Special Issue

- Hydrometeorological data from mountain and alpine research catchments
- https://www.earth-syst-sci-data.net/special_issue871.html
- Guest Editors: J.W. Pomeroy, D.G. Marks
- 23 data papers contributed and more coming in

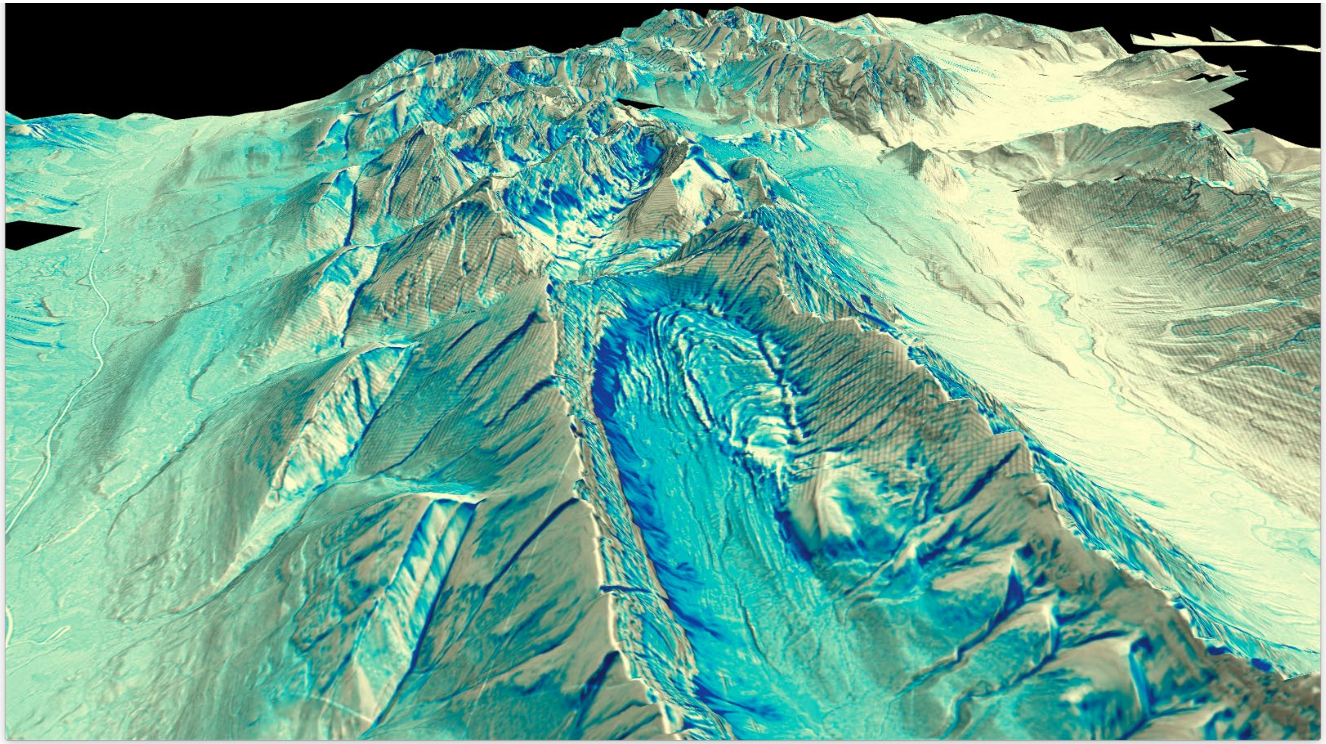
"Data sets contributed to the special issue should support and promote research on the effects of mountain snowpacks and glaciers on water supply as well as study of variations in energy and water exchange amongst different high-altitude regions in well-instrumented mountain regions around the world."



GEWEX INARCH

INARCH Snow Hydrology Modelling

- Water models need to account for the substantial spatial and temporal **heterogeneity in mass and energy fluxes, especially in mountains**
- Heterogeneity of the seasonal snowpack motivates the use of **"snowdrift permitting"** (0.1m – 200m) scales for distributed predictive models (Vionnet, et al., 2021)



5-m 3D map of snow depth derived from **airborne Lidar** over the Kananaskis region (Alberta), Canada on 27 April 2018

CRHM Modelling of Virtual Alpine Basin Climate Warming Sensitivity

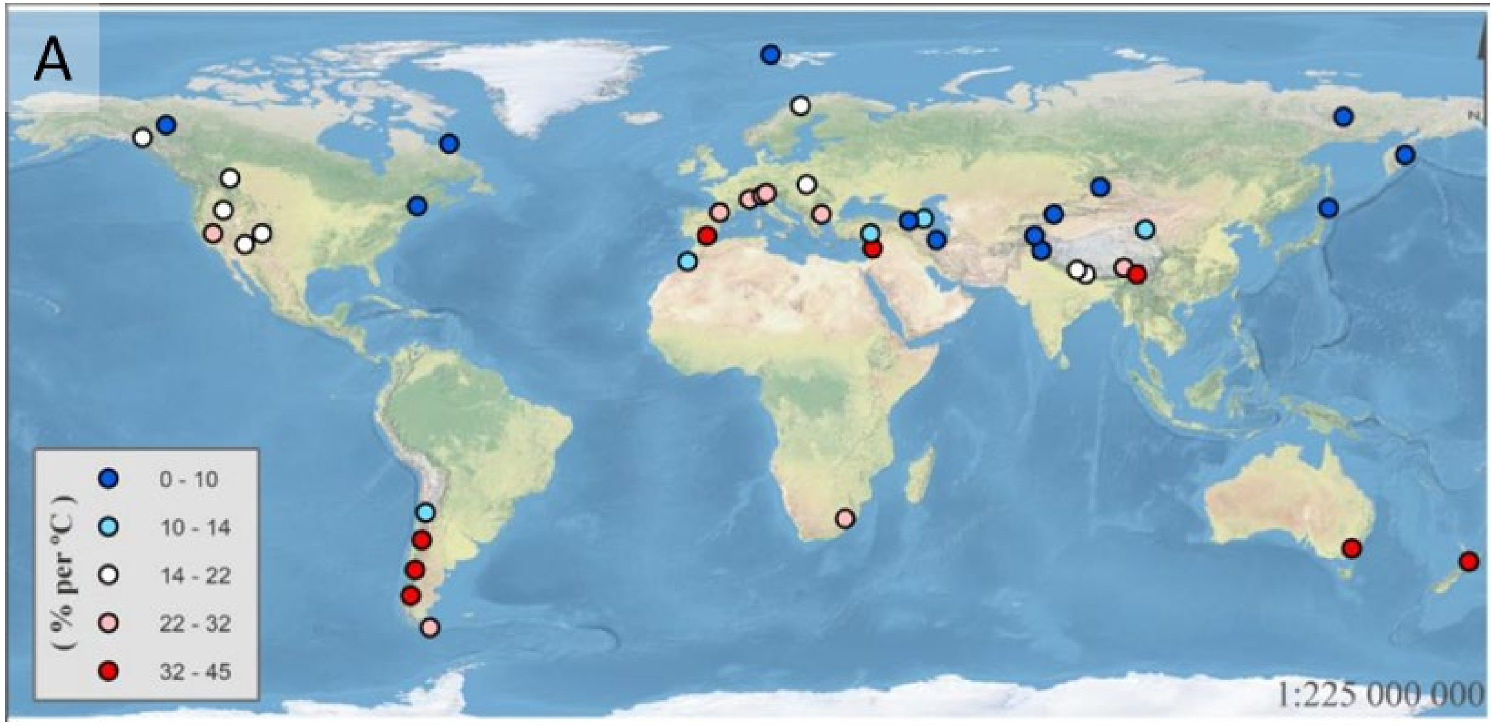
Sensitivity (decrease in % change per ºC of warming) of

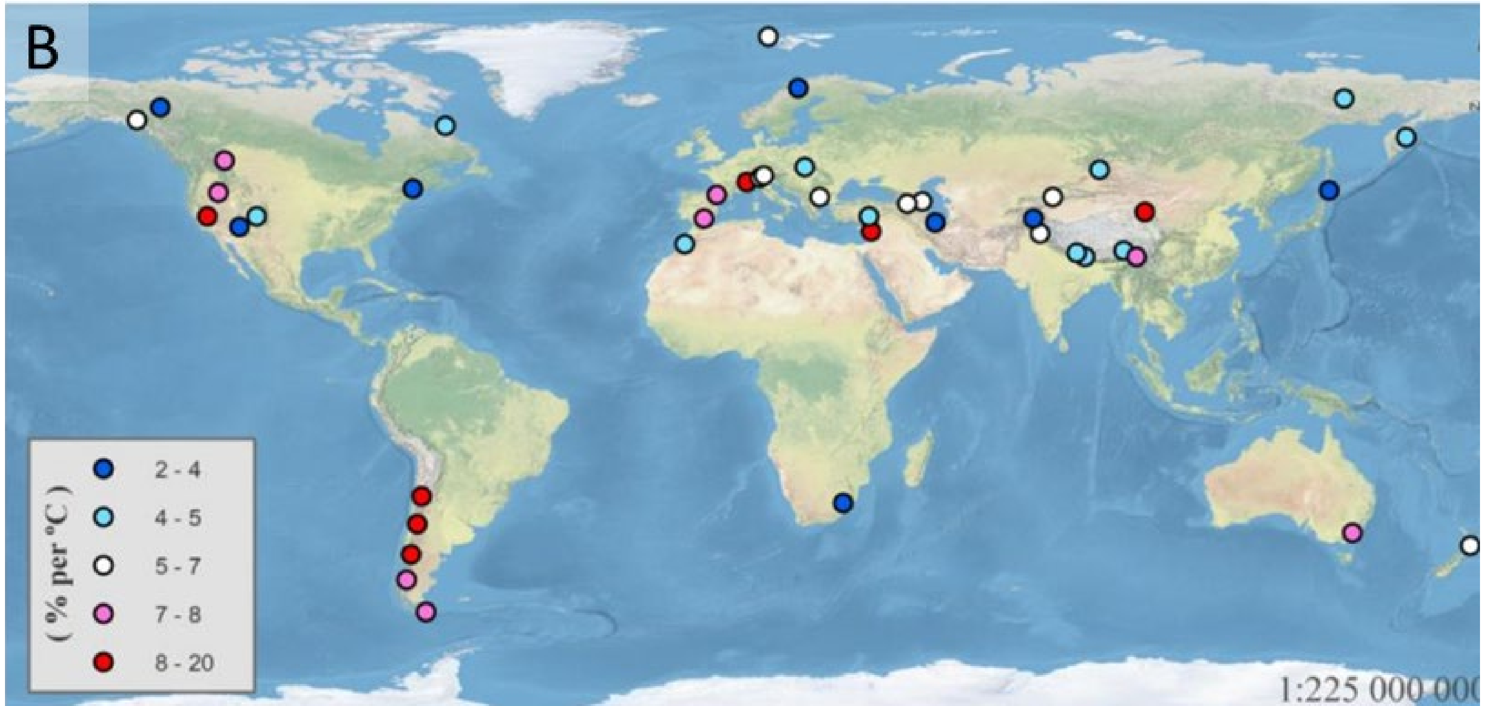
(A) mean annual peak snow water equivalent and

(B) the annual snowmelt rate

(López-Moreno et al., 2020).

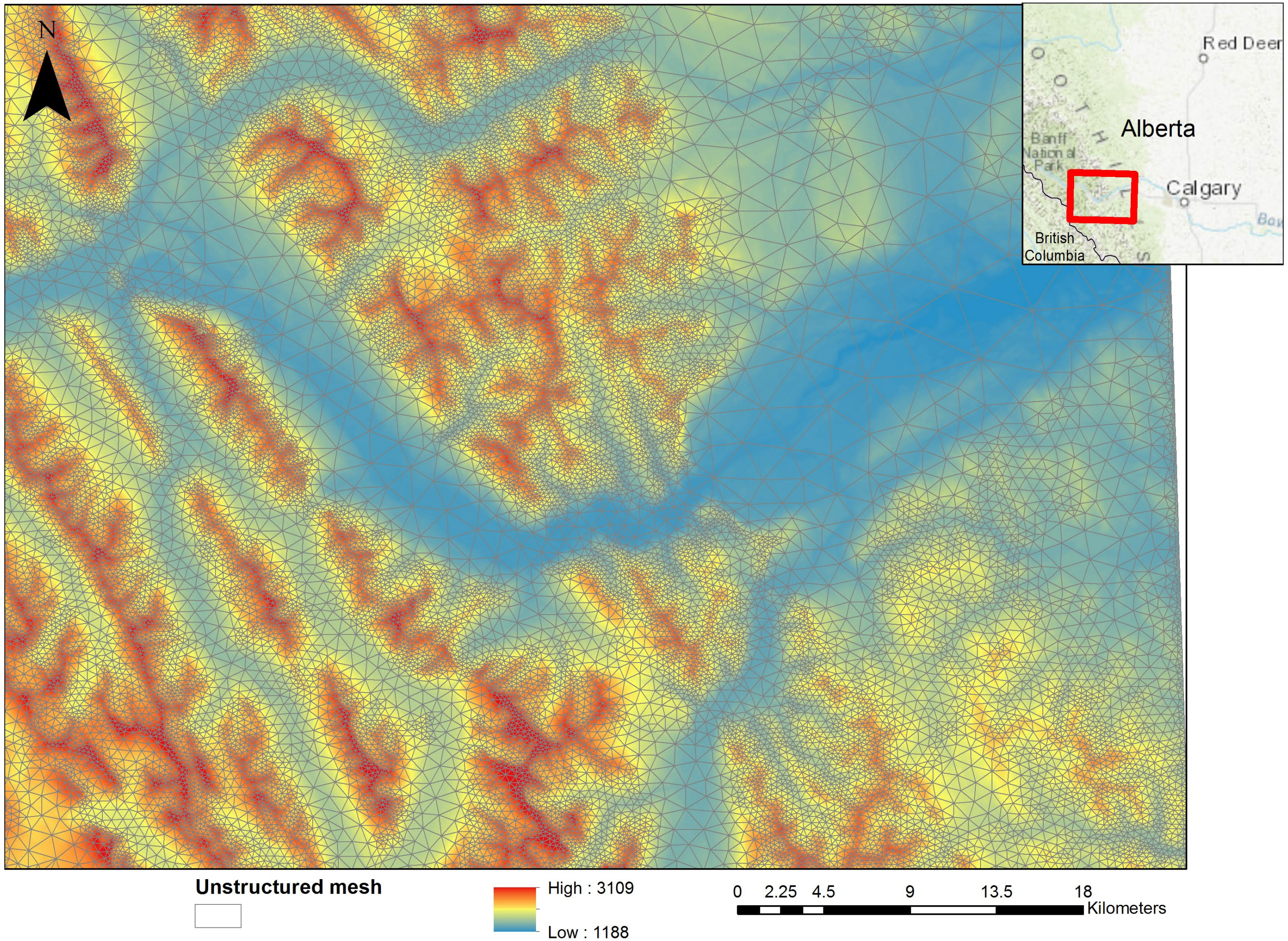
Cold Regions Hydrological Model with snow redistribution, radiation to slopes, energy balance snowmelt





Canadian Hydrological Model (CHM)

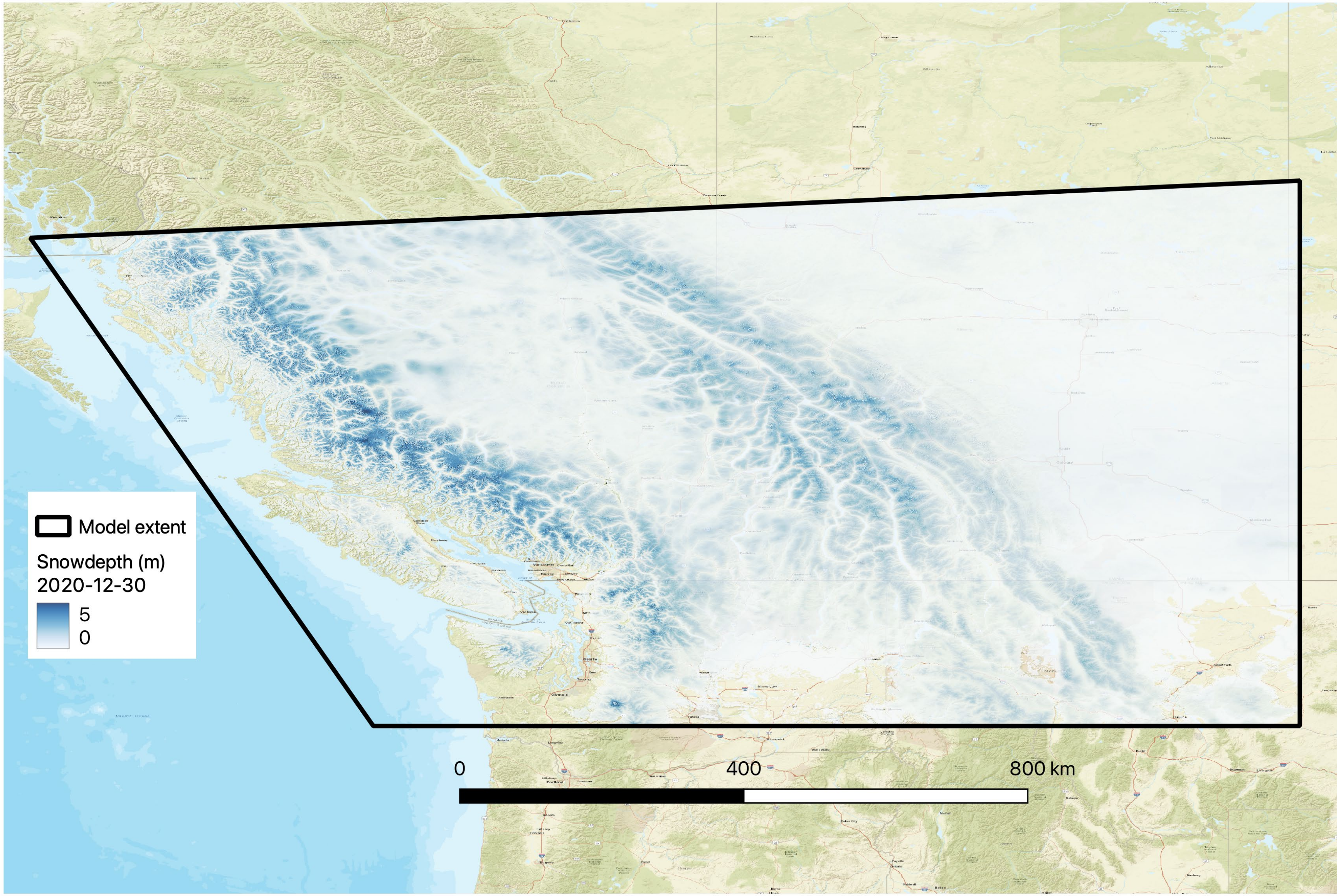
- **Variable resolution triangular mesh** depending on topography, soils, vegetation
- Large decrease in computational and data demands over rectangular gridded models
- Algorithms for downscaling meteorological data
- CHM currently accounts for:
  - **slope** and **aspect**; terrain **shading**
  - **Variable wind** fields
  - **gravitational redistribution (avalanches)**
  - **blowing snow (**redistribution + sublimation**)**
  - **Snow interception and sublimation** from forest canopies
  - **energy balance** snowmelt as impacted by complex terrain and forest cover
  - Snowmelt runoff



Marsh et al. (2019)

Large extent snowpack modelling

- ~1.3M km^2
- 3B raster cells reduced to 34M triangles
  - Minimum 50m length scale
  - Elevation + canopy + water
- Downscale ECCC HRDPS 2.5 km forcing
  - 1hr time step
- Oct 2020 – June 2021
- Blowing snow, avalanching, canopy interactions, energy balance snow model
- 800 CPUs, ~20hrs wallclock

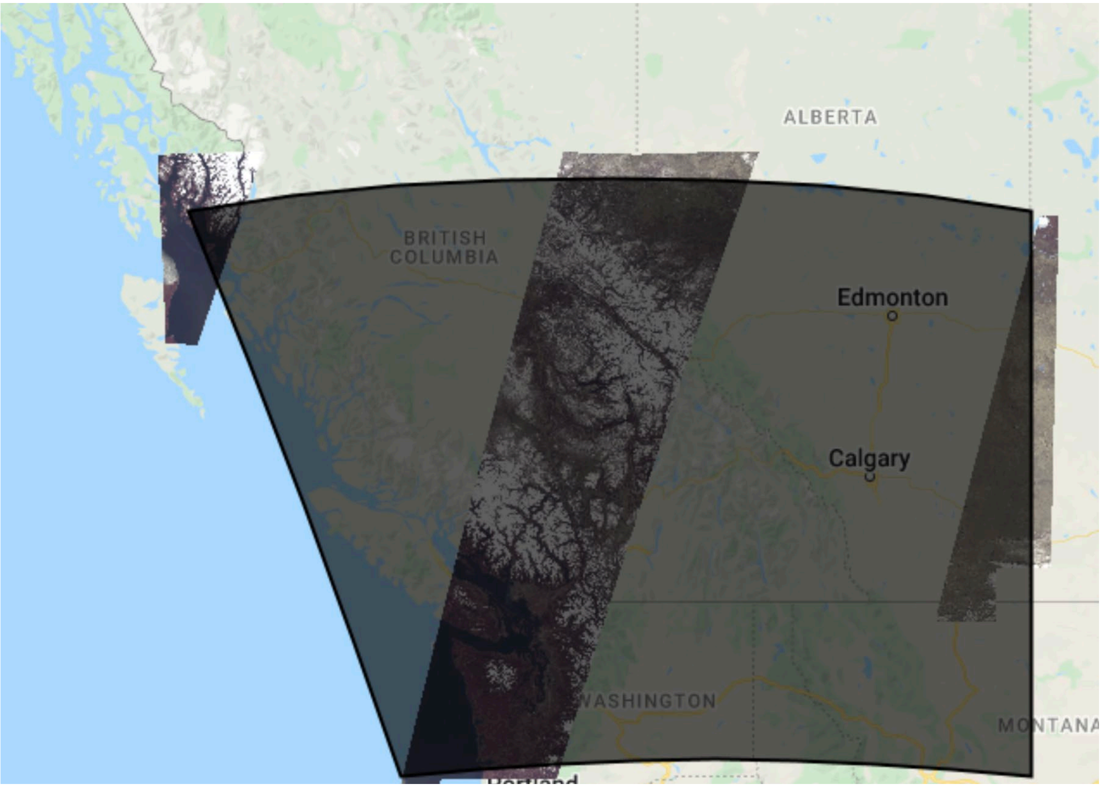


www.snowcast.ca

Predicted Snowcovered Area Evaluation

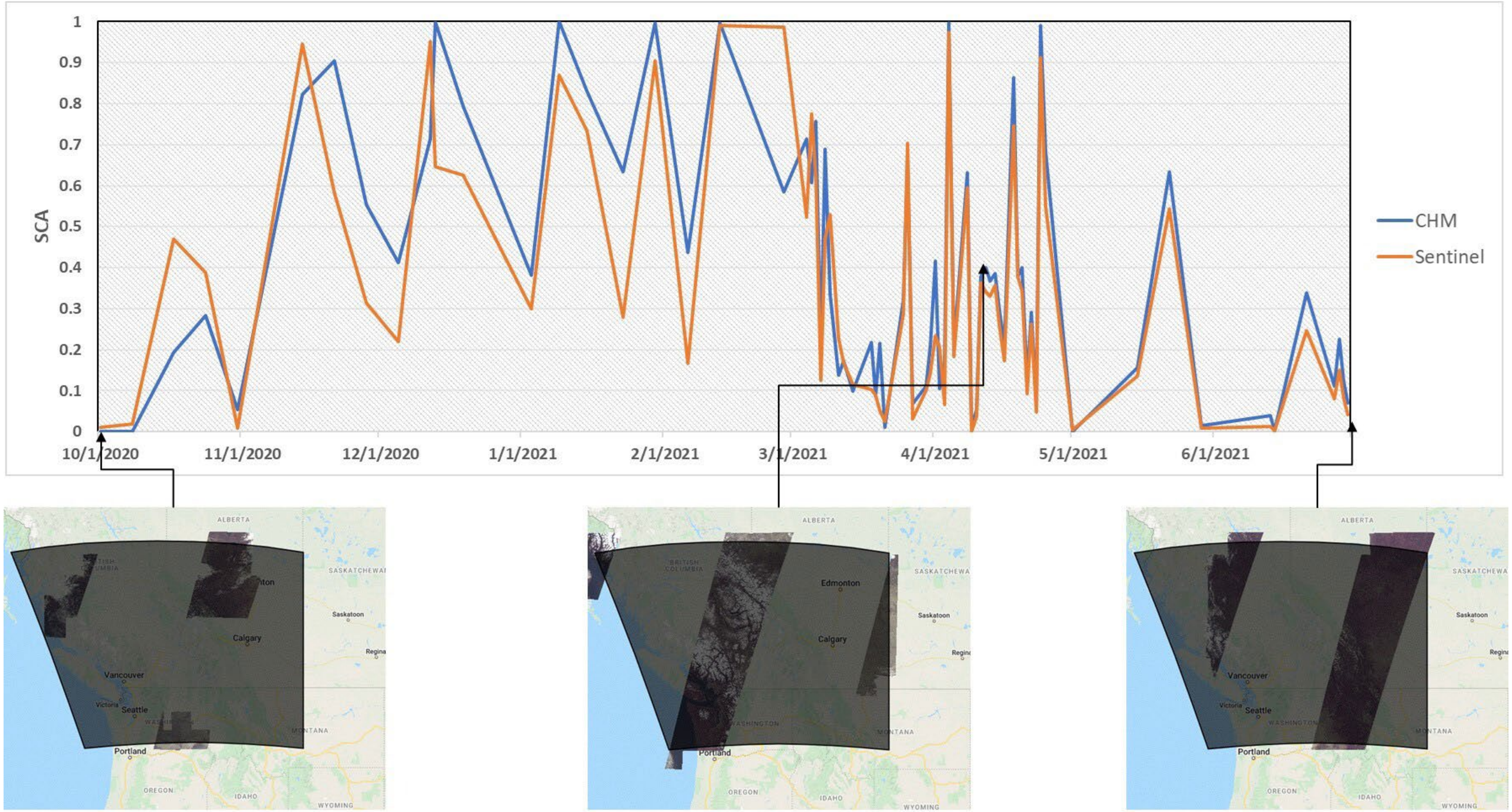
1. Weekly SCA from Sentinel2 resampled to 150 m
2. Corresponding grid cells of HRDPS-CHM output extracted to match weekly extent of S2 images

- Note: each week will have a different set of images
- LandSat 8 images were not available for this evaluation period



CHM domain in grey, weekly acquisitions shown

CHM Forecast Compared to Sentinel Snow Covered Area



Oct.. 1 2020

Apr. 15 2021

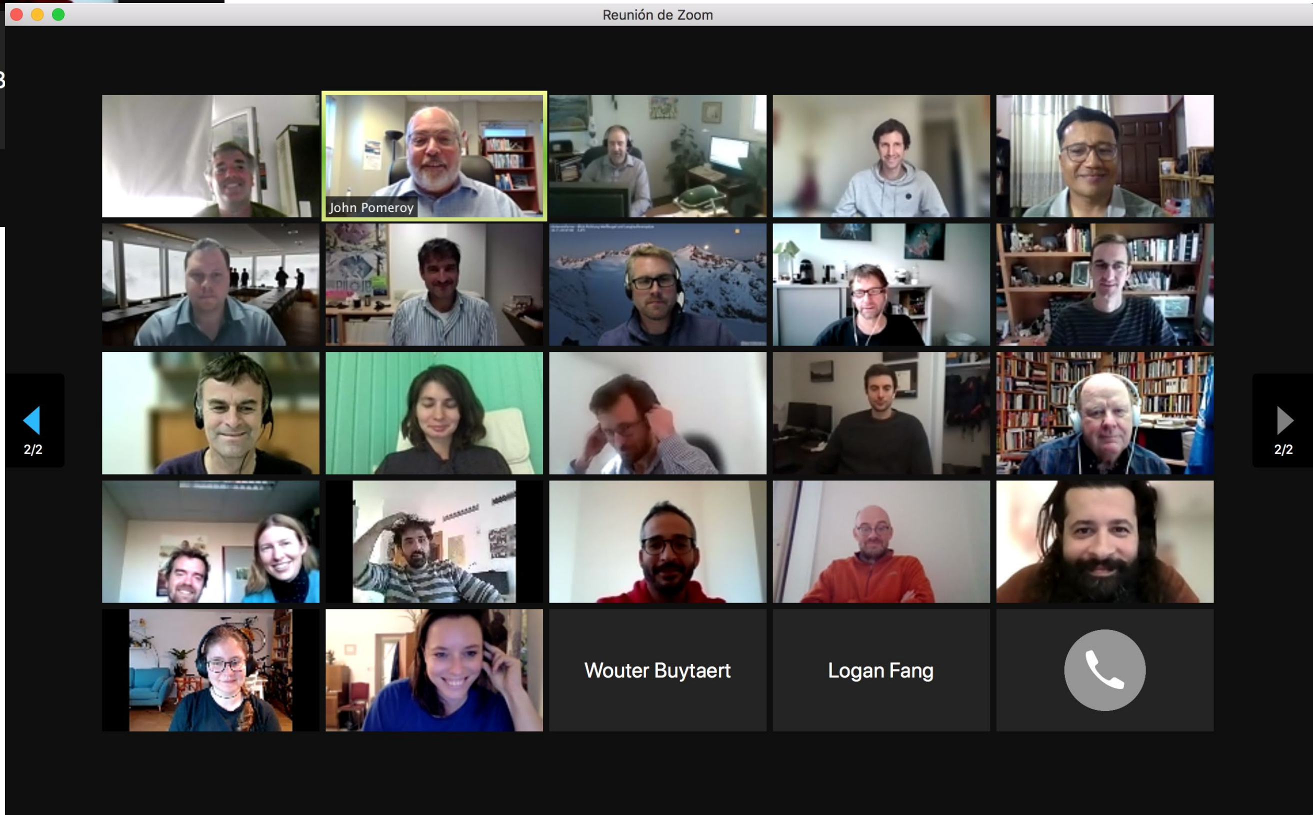
Jun. 30 2021

Regional Snowpack Simulation

INARCH Online 2021

Held virtually on Zoom, October 18–20, 2021

Significant INARCH progress was shown; see the website for full details: https://inarch.usask.ca/news-events/inarch-2021-online-workshop.php



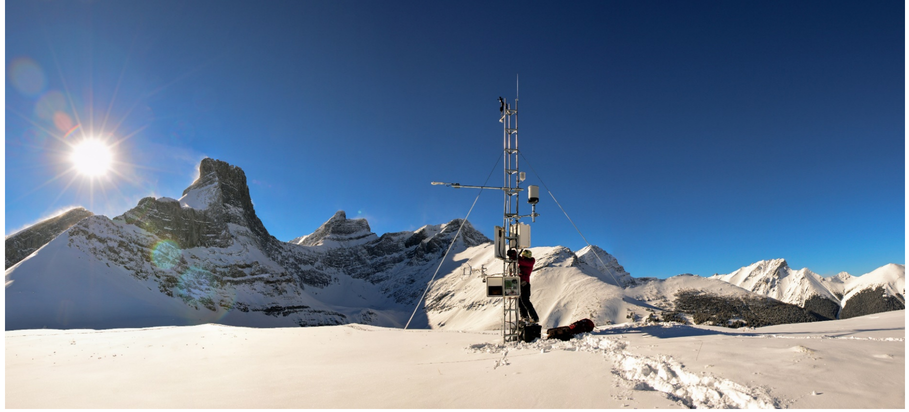
INARCH Workshop Statement 2021

- We have completed our Phase 1 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.
- 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.

A New INARCH Vision

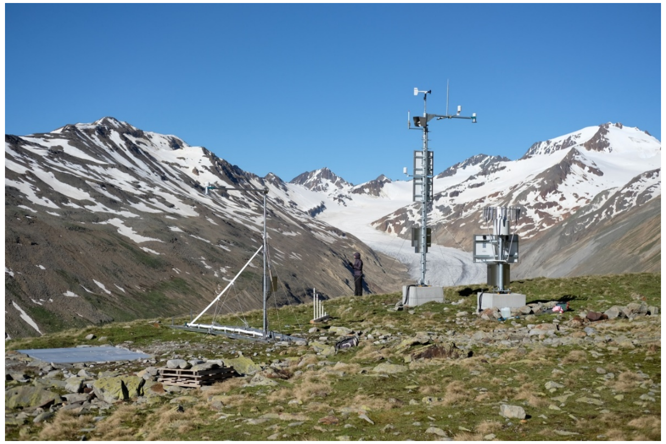
- Improve mountain hydrometeorological and related observations, understanding and predictions to help adapt to rapid climate change.
- Implement recommendations from the WMO High Mountain Summit—integrated observation and prediction systems. *How can we build up integrated alpine catchment prediction systems and apply them to the larger earth systems that derive from mountains*?
- 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 human-water and ecological interactions to develop solutions to help achieve water sustainability in high mountain river basins and downstream?*

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

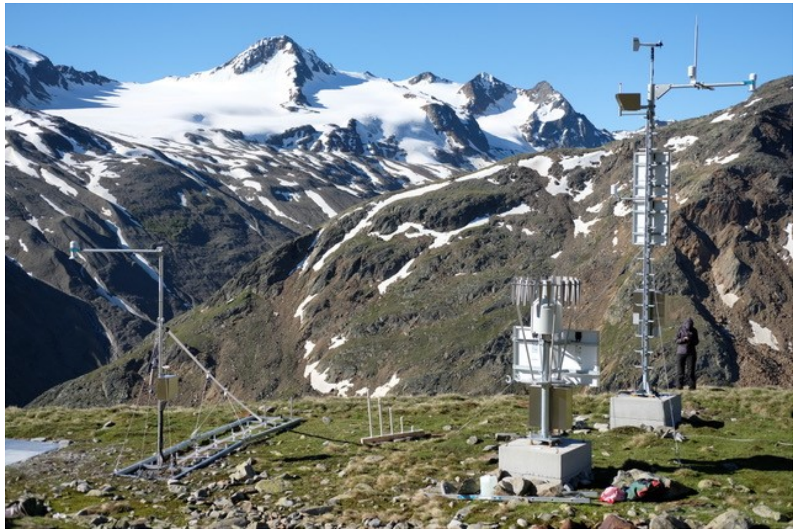
1. How different are the observation and measurement approaches amongst INARCH basins and do we expect distinctive differences in our understanding of basin response and hydrological predictability because of the sampling schemes, and data quality and quantity?
2. How do the predictability, uncertainty 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?

Common Observing Period Experiment (COPE)

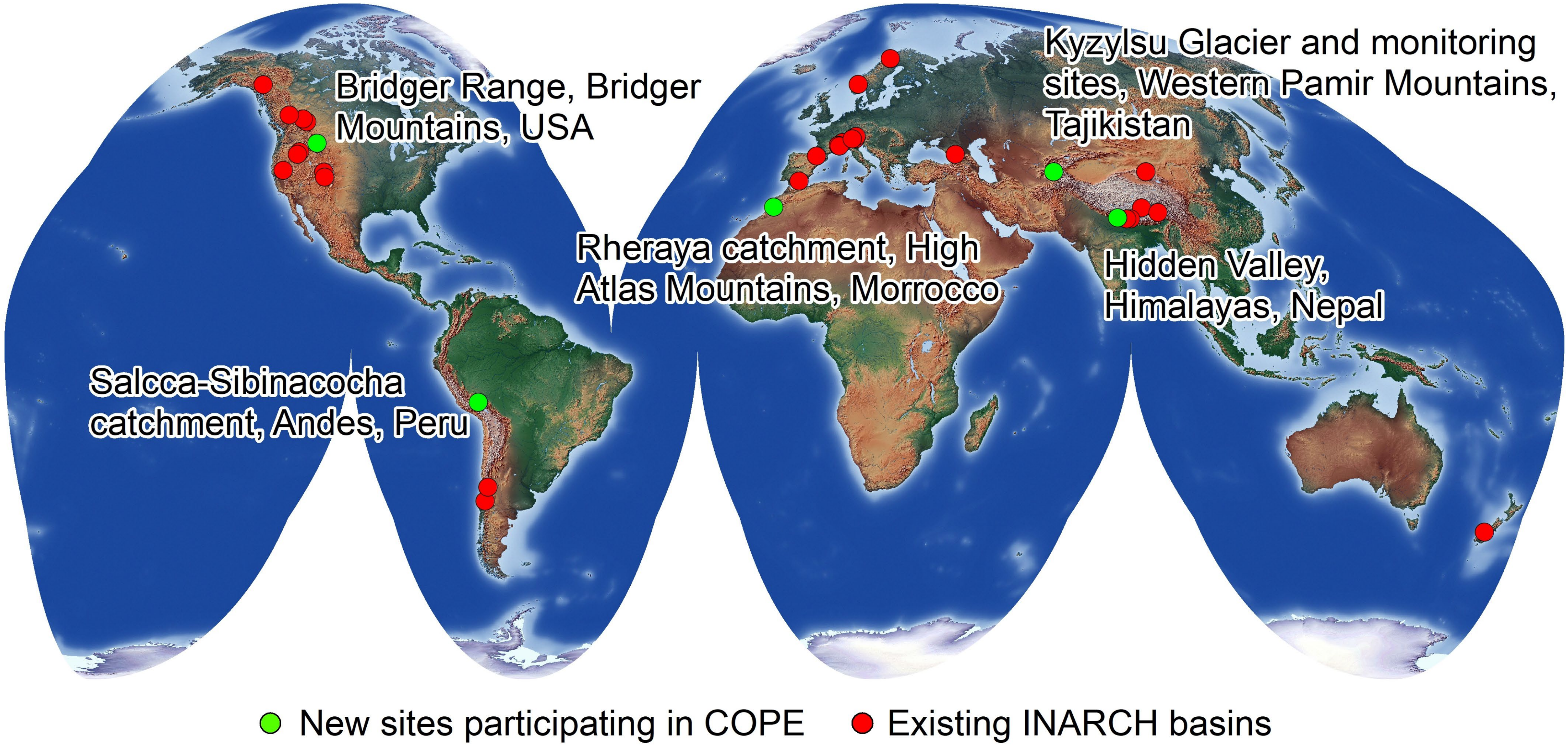
2022–2024

- focusing on obtaining high-quality measurements,
- ensure all sensors are working,
- enhance observations at our mountain research basins,
- fly supplementary UAV acquisitions,
- run high resolution models and
- work together for comparison of processes, data sharing, and model testing in challenging environments
- https://inarch.usask.ca/science-basins/cope.php



Common Observing Period Experiment (COPE)

2022–2024



Common Observing Period Experiment (COPE)

2022–2024

Current status and activities of COPE

- Collecting meta-data gathering and developing data management system
- Developing and deploying sensors and systems to be used across a number of sites
- Exploring models for application across sites

COPE Steering Committee

- John Pomeroy
- Ignacio Lopez Moreno
- Ekaterina Rets
- Eric Sproles
- Ulrich Strasser
- Lindsey Nicholson
- Rainer Prinz
- James McPhee
- Franziska Koch
- Vincent Vionnet
- Wouter Buytaert
- Ethan Gutmann
- Dhiraj Pradhananga

Coordination and support

- Stephen O'Hearn
- Chris DeBeer

A	E	
Catchment	**Rofental**	**M**
Country	Austria	Ch
Mountain range	Eastern European Alps	Th
Primary contact	Ulrich Strasser	Ya
Latitude	46.8333 N	
Longitude	10.8254 E	
Min elev	1891 m a.s.l.	
Max elev	3772 m a.s.l.	
Area	98 km2	
Main land cover(s)	alpine	de
Lithology	Gneiss	
Mean DJFM Temp	-9.2°C (3026 m.a.s.l.)	"4
Mean DJFM Precip	321 mm (3026 m.a.s.l.)	"15
Snow characteristics	deep, cold	Co
Glaciarized area (%)	ca. 25%	
Forcing Data	10 min. resolution available	
T	various	Va
RH	various	Va
Kin	Kipp&Zonen	Kip
Kout	Kipp&Zonen	Kip
Lin	Kipp&Zonen	Kip
Lout	Kipp&Zonen	Kip
Net radiometer	Kipp&Zonen	
Wind speed	Kroneis and other	Yo
Wind direction	Kroneis and other	Yo
Precipitation	Ott Pluvio and other (+ Pr	On
Pressure	Yes	Va
Additional comments	ca. 9 automatic weather/s	2 n
Data for validation		
Hydrological Instrume		
Water level	Yes	
Discharge (metering, etc)/M	Yes	ye
Water temperature	Yes (Vent)	
Isotopes	Sampler available at the gaug	
Isotopes type (O18, D, T)		
Isotope sampling Temporal		
Water conductivity/Tempor	Sampler available at the gaug	
Turbidity/Temporal resoluti		
Sediment load (gravels)/Te	Only suspended load	
Water sampling hydrogeoch		
groundwater level		
Soil moisture		ye
Other		
Hydromet/Cryosphere		
Terrestrial Laser Scanner	Yes, for Hintereisferner	
UAV - sensor		
Snow surveys	For COPE	sa
Time lapse photos/Tempor	Yes	Ye
SWE instruments, pillows/T	1 pillow, 2 scales, 1 Snow F	bl
Snow depth/Temporal reso	Sommer USH-8 / USH-9,	Fl
Temp soil	Sommer, Campbell 107	Ca
Surface temp	Sommer, Kipp&Zonen C	Ca
Eddy Cov.	Not permanent, but avail	ye
Ice elevation	Hintereisferner	
debris covered ice elevatio	Hintereisferner	
glacier mass balance	Hintereisferner, Vernagtferne	
glacier ice thickness	yes (1997)	
Additional data for hy		
Vegetation map	Corine land cover	sa
Map of soils	European soil database	no
Information on soil depth		ye
DEM/Spatial resolution	Yes, super high resolution av	

Observe, Predict, Protect