INARCH:
International Network for Alpine Research Catchment Hydrology

John Pomeroy, and INARCH colleagues

Centre for Hydrology & Global Institute for Water Security,
University of Saskatchewan, Canada

www.usask.ca/inarch

GHP Annual Meeting, Santiago, Chile, 24 October, 2018

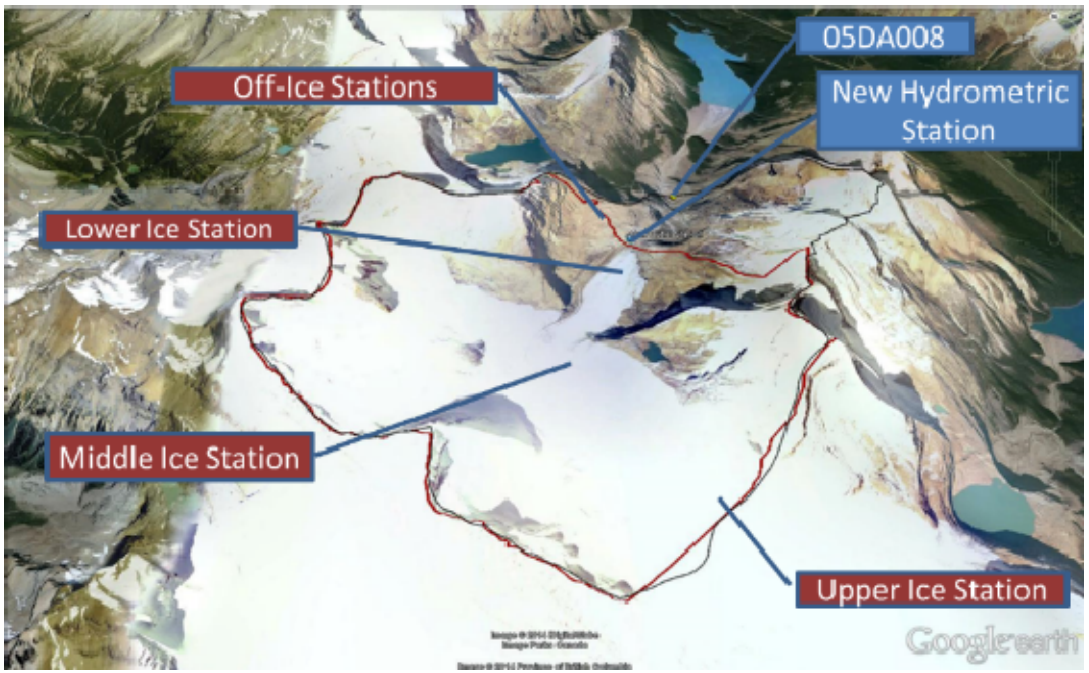
INARCH Objectives

To better

- understand alpine cold regions hydrological processes,
- improve their prediction,
- diagnose their sensitivities to global change

and

To find consistent measurement strategies.



INARCH 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 **a global validity**?
5. How do **transient changes** in perennial snowpacks, glaciers, ground frost, soil stability, and vegetation **impact alpine water and energy models**?

INARCH Research Basins

Austria: 1. Open Air Laboratory (OpAL);
Canada: Canadian Rockies Hydrological Observatory - 2. Marmot Creek Research Basin; 3. Peyto Glacier; 4. Quesnel River Research Basin; 5. Wolf Creek Research Basin;
Chile: 6. Upper Diguillín River Basin; 7. Upper Maipo River Basin;
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. Zugspitze Basin and Schneefernerhaus Research Station;
Nepal: 16. Langtang Catchment;
Norway: 17. Finse Alpine Research Centre;
Spain: 18. Izas Research Basin;
Sweden: 19. Tarfala Research Catchment;
Switzerland: 20. Dischma Research Catchment; 21. Weissfluhjoch Snow Study Site;
USA: 22. Dry Creek Experimental Watershed; 23. Grand Mesa Study Site; 24. Reynolds Creek Experimental Watershed; 25. Senator Beck Basin Study Area; 26. Sagehen Creek, Sierra Nevada.

Data Requirements

Surface based data requirements for this project 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

Data Requirements

The ideal is for sites to be Integrated Alpine Observing and Predicting Systems (IAOPS). A provisional classification scheme for IAOPS 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

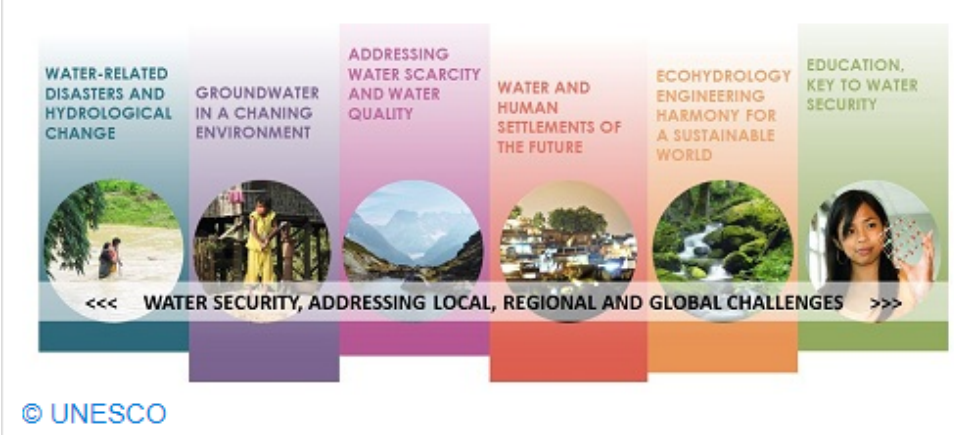
CLASS C: gauged catchments that contain Class B sites and detailed vegetation coverage, soils, topography, snowcovered area, glacier mass balance or permafrost information

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.

Linkages

- GEWEX GHP Projects
  - Cold/Shoulder Season Precipitation Near 0ºC project
  - Changing Cold Regions Network and Global Water Futures
  - Western US RHP & Water for Foodbaskets
- Global Cryosphere Watch
- WMO-SPICE and WMO High Mountain Summit
- TPE (Third Pole Environment)
- Future Earth, Sustainable Water Futures Programme (SWFP)
- International Commission for Snow and Ice Hydrology (IUGG)
- UNESCO-International Hydrological Programme efforts on climate change impacts on snow, glacier and water resources within the framework of IHP-VIII (2014-2021) ***'Water Security: Responses to Local Regional and Global Challenges'.***



Workshops held

- **The 3rd INARCH Workshop** was held at the Schneefernerhaus Environmental Research Station, Zugspitze, Germany, 8–9, February, 2018
- Local organizers: Matthias Bernhardt and Karsten Schulz (University of Natural Resources and Life Sciences, Vienna, Austria)
- Others in the organizing committee included Georg Kaser (University of Innsbruck, Austria), John Pomeroy and Chris DeBeer (University of Saskatchewan, Saskatoon, Canada).

Participants at the 3rd INARCH Workshop, 2018 (photo: Markus Weber)

3rd INARCH Workshop

- Issues:
  - Snow and Glacier Hydrology;

>More climate sensitivity and vulnerability studies are needed in INARCH – we need to focus on a concerted effort using a selection of models driven by perturbed or downscaled climate on this using INARCH basins and data.
>INARCH will continue to encourage scientifically appropriate, physically realistic approaches to snow and ice hydrology.

  - Observations Including Remote Sensing;

>INARCH research basin observational datasets will be proposed to GCW for inclusion in their global data portal. INARCH will provide input to GCW to inform their development of observational guidelines using current science.
>INARCH will continue to publish datasets and metadata in the ESSD special issue.
>INARCH basins will contribute to future coupled surface and remote sensing observational studies including multispectral missions.

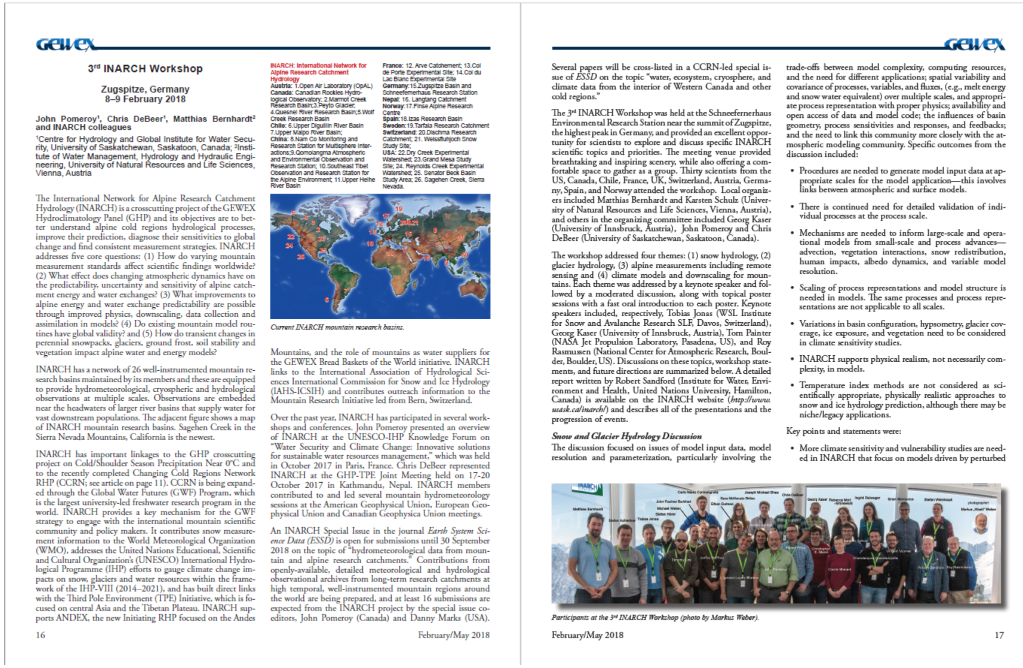
  - Climate Models and Downscaling

>Dynamical downscaling is needed to create INARCH mountain policy runs for future climate at scales appropriate for snow and glacier hydrology models

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.
- 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.
- 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.

3rd INARCH Workshop



GEWEX

3rd INARCH Workshop

Zugspitze, Germany
8–9 February 2018

John Pomeroy[1], Chris DeBeer[1], Matthias Bernhardt[2] and INARCH colleagues

[1]Centre for Hydrology and Global Institute for Water Security, University of Saskatchewan, Saskatoon, Canada; [2]Institute of Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Life Sciences, Vienna, Austria

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 addresses five core questions: (1) How do varying mountain measurement standards affect scientific findings worldwide? (2) What effect 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 has a network of 26 well-instrumented mountain research basins maintained by its members and these are equipped to provide hydrometeorological, cryospheric and hydrological observations at multiple scales. Observations are embedded near the headwaters of larger river basins that supply water for vast downstream populations. The adjacent figure shows a map of INARCH mountain research basins. Sagehen Creek in the Sierra Nevada Mountains, California is the newest.

INARCH has important linkages to the GHP crosscutting project on Cold/Shoulder Season Precipitation Near 0°C and to the recently completed Changing Cold Regions Network RHP (CCRN; see article on page 11). CCRN is being expanded through the Global Water Futures (GWF) Program, which is the largest university-led freshwater research program in the world. INARCH provides a key mechanism for the GWF strategy to engage with the international mountain scientific community and policy makers. It contributes snow measurement information to the World Meteorological Organization (WMO), addresses the United Nations Educational, Scientific and Cultural Organization's (UNESCO) International Hydrological Programme (IHP) efforts to gauge climate change impacts on snow, glaciers and water resources within the framework of the IHP-VIII (2014–2021), and has built direct links with the Third Pole Environment (TPE) Initiative, which is focused on central Asia and the Tibetan Plateau. INARCH supports ANDEX, the new Initiating RHP focused on the Andes

INARCH: International Network for Alpine Research Catchment Hydrology
Austria: 1.Open Air Laboratory (OpAL)
Canada: Canadian Rockies Hydrological Observatory; 2.Marmot Creek Research Basin;3.Peyto Glacier; 4.Quesnel River Research Basin;5.Wolf Creek Research Basin
Chile: 6.Upper Diguillin River Basin 7.Upper Maipo River Basin;
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.Zugspitze Basin and Schneefernerhaus Research Station
Nepal: 16. Langtang Catchment
Norway: 17.Finse Alpine Research Centre
Spain: 18.Izas Research Basin
Sweden: 19.Tarfala Research Catchment
Switzerland: 20.Dischma Research Catchment; 21. Weissfluhjoch Snow Study Site;
USA: 22.Dry Creek Experimental Watershed; 23.Grand Mesa Study Site; 24. Reynolds Creek Experimental Watershed; 25. Senator Beck Basin Study Area; 26. Sagehen Creek, Sierra Nevada.

Current INARCH mountain research basins.

Mountains, and the role of mountains as water suppliers for the GEWEX Bread Baskets of the World initiative. INARCH links to the International Association of Hydrological Sciences International Commission for Snow and Ice Hydrology (IAHS-ICSIH) and contributes outreach information to the Mountain Research Initiative led from Bern, Switzerland.

Over the past year, INARCH has participated in several workshops and conferences. John Pomeroy presented an overview of INARCH at the UNESCO-IHP Knowledge Forum on "Water Security and Climate Change: Innovative solutions for sustainable water resources management," which was held in October 2017 in Paris, France. Chris DeBeer represented INARCH at the GHP-TPE Joint Meeting held on 17-20 October 2017 in Kathmandu, Nepal. INARCH members contributed to and led several mountain hydrometeorology sessions at the American Geophysical Union, European Geophysical Union and Canadian Geophysica Union meetings.

An INARCH Special Issue in the journal *Earth System Science Data (ESSD)* is open for submissions until 30 September 2018 on the topic of "hydrometeorological data from mountain and alpine research catchments." Contributions from openly-available, detailed meteorological and hydrological observational archives from long-term research catchments at high temporal, well-instrumented mountain regions around the world are being prepared, and at least 16 submissions are expected from the INARCH project by the special issue co-editors, John Pomeroy (Canada) and Danny Marks (USA).

Several papers will be cross-listed in a CCRN-led special issue of *ESSD* on the topic "water, ecosystem, cryosphere, and climate data from the interior of Western Canada and other cold regions."

The 3rd INARCH Workshop was held at the Schneefernerhaus Environmental Research Station near the summit of Zugspitze, the highest peak in Germany, and provided an excellent opportunity for scientists to explore and discuss specific INARCH scientific topics and priorities. The meeting venue provided breathtaking and inspiring scenery, while also offering a comfortable space to gather as a group. Thirty scientists from the US, Canada, Chile, France, UK, Switzerland, Austria, Germany, Spain, and Norway attended the workshop. Local organizers included Matthias Bernhardt and Karsten Schulz (University of Natural Resources and Life Sciences, Vienna, Austria), and others in the organizing committee included Georg Kaser (University of Innsbruck, Austria), John Pomeroy and Chris DeBeer (University of Saskatchewan, Saskatoon, Canada).

The workshop addressed four themes: (1) snow hydrology, (2) glacier hydrology, (3) alpine measurements including remote sensing and (4) climate models and downscaling for mountains. Each theme was addressed by a keynote speaker and followed by a moderated discussion, along with topical poster sessions with a fast oral introduction to each poster. Keynote speakers included, respectively, Tobias Jonas (WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland), Georg Kaser (University of Innsbruck, Austria), Tom Painter (NASA Jet Propulsion Laboratory, Pasadena, US), and Roy Rasmussen (National Center for Atmospheric Research, Boulder, US). Discussions on these topics, workshop statements, and future directions are summarized below. A detailed report written by Robert Sandford (Institute for Water, Environment and Health, United Nations University, Hamilton, Canada) is available on the INARCH website (*http://www.usask.ca/inarch/*) and describes all of the presentations and the progression of events.

Snow and Glacier Hydrology Discussion
The discussion focused on issues of model input data, model resolution and parameterization, particularly involving the trade-offs between model complexity, computing resources, and the need for different applications; spatial variability and covariance of processes, variables, and fluxes, (e.g., melt energy and snow water equivalent) over multiple scales, and appropriate process representation with proper physics; availability and open access of data and model code; the influences of basin geometry, process sensitivities and responses, and feedbacks; and the need to link this community more closely with the atmospheric modeling community. Specific outcomes from the discussion included:

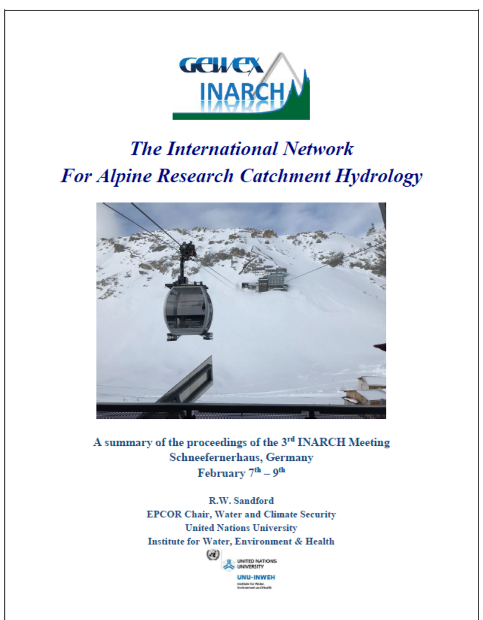
- Procedures are needed to generate model input data at appropriate scales for the model application—this involves links between atmospheric and surface models.
- There is continued need for detailed validation of individual processes at the process scale.
- Mechanisms are needed to inform large-scale and operational models from small-scale and process advances—advection, vegetation interactions, snow redistribution, human impacts, albedo dynamics, and variable model resolution.
- Scaling of process representations and model structure is needed in models. The same processes and process representations are not applicable to all scales.
- Variations in basin configuration, hypsometry, glacier coverage, ice exposure, and vegetation need to be considered in climate sensitivity studies.
- INARCH supports physical realism, not necessarily complexity, in models.
- Temperature index methods are not considered as scientifically appropriate, physically realistic approaches to snow and ice hydrology prediction, although there may be niche/legacy applications.

Key points and statements were:

- More climate sensitivity and vulnerability studies are needed in INARCH that focus on models driven by perturbed

Participants at the 3rd INARCH Workshop (photo by Markus Weber).

Feb–May 2018 issue of GEWEX News on pages 16–18:
https://www.gewex.org/gewex-content/uploads/2018/08/Feb-May2018.pdf.



GEWEX INARCH

The International Network
For Alpine Research Catchment Hydrology

A summary of the proceedings of the 3rd INARCH Meeting
Schneefernerhaus, Germany
February 7th – 9th

R.W. Sandford
EPCOR Chair, Water and Climate Security
United Nations University
Institute for Water, Environment & Health

UNITED NATIONS UNIVERSITY
UNU-INWEH

Detailed summary written by Bob Sandford available at:
http://www.usask.ca/inarch/wkshp3_report.php
.

The Schneefernerhaus Research Station, Zugspitze, and surrounding views from the meeting space (photos: Chris DeBeer).

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. Pomeroy, D. Marks

- 18 data papers contributed / issue closed 30 Sept, 2018

"*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. …The guest editors invite contributions of 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 well-instrumented mountain regions around the world*."

GEWEX
INARCH

Science Highlights

IOP Publishing Environ. Res. Lett. 12 (2017) 074006 https://doi.org/10.1088/1748-9326/aa70cb

Environmental Research Letters

LETTER

Different sensitivities of snowpacks to warming in Mediterranean climate mountain areas

J I López-Moreno[1,13], S Gascoin[2], J Herrero[3], E A Sproles[4], M Pons[5], E Alonso-González[1], L Hanich[6], A Boudhar[7], K N Musselman[8], N P Molotch[9,10], J Sickman[11] and J Pomeroy[12]

[1] Pyrenean Institute of Ecology, CSIC, Zaragoza, Spain
[2] Centre d'Etudes Spatiales de la Biosphère, CNRS/CNES/IRD/UPS, Toulouse, France
[3] Fluvial Dynamics and Hydrology Research Group, Andalusian Institute for Earth System Research, University of Córdoba, Granada, Spain
[4] Center for Advanced Arid Zone Studies, CEAZA, Chile
[5] Observatory of Sustainability, Andorra
[6] Cadi Ayyad University, Marrakech, Morocco
[7] Sultan Moulay Slimane University, Béni-Mellal, Morocco
[8] National Center for Atmospheric Research—NCAR, Boulder, CO, United States of America
[9] Institute of Arctic and Alpine Research and Dept. of Geography, University of Colorado, Boulder, CO, United States of America
[10] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States of America
[11] Environmental Sciences, University of California, Riverside, CA, United States of America
[12] Centre for Hydrology, University of Saskatchewan, Saskatoon, Canada
[13] Author to whom any correspondence should be addressed.

E-mail: nlopez@ipe.csic.es

Keywords: snow, Mediterranean mountains, climate warming, snow simulations

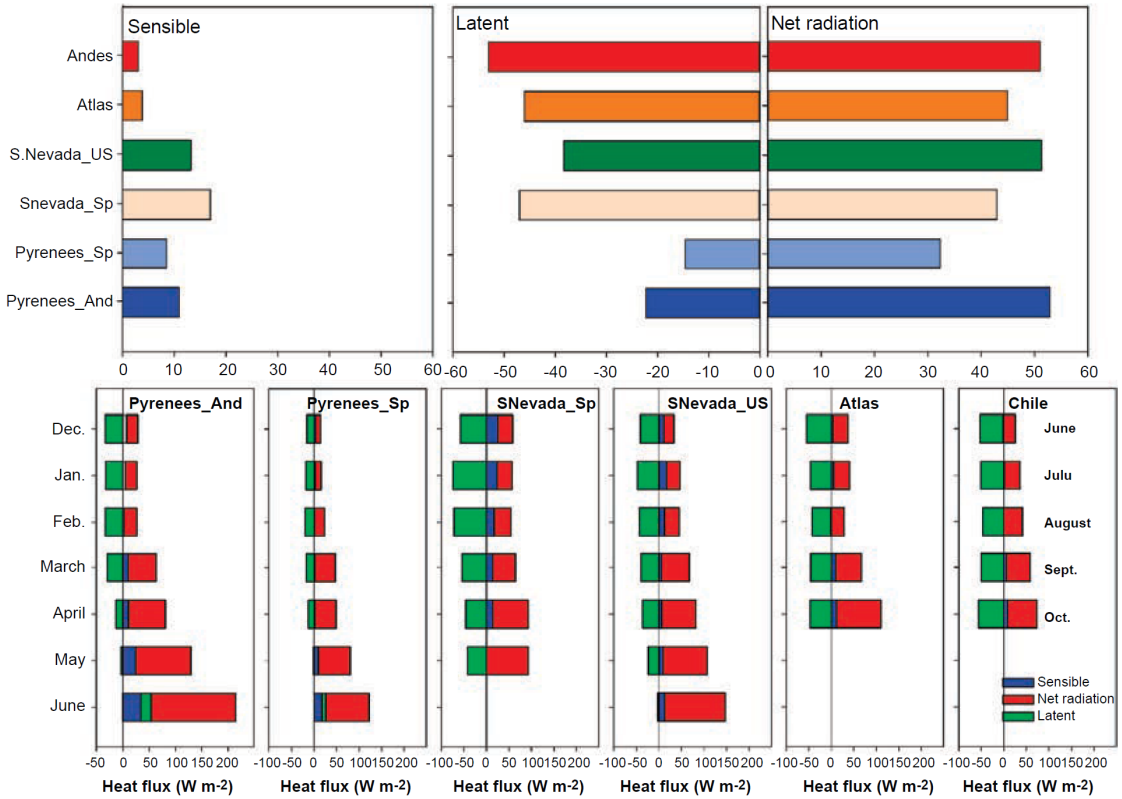
Supplementary material for this article is available online

OPEN ACCESS

RECEIVED 17 November 2016
REVISED 20 April 2017
ACCEPTED FOR PUBLICATION 3 May 2017
PUBLISHED 30 June 2017

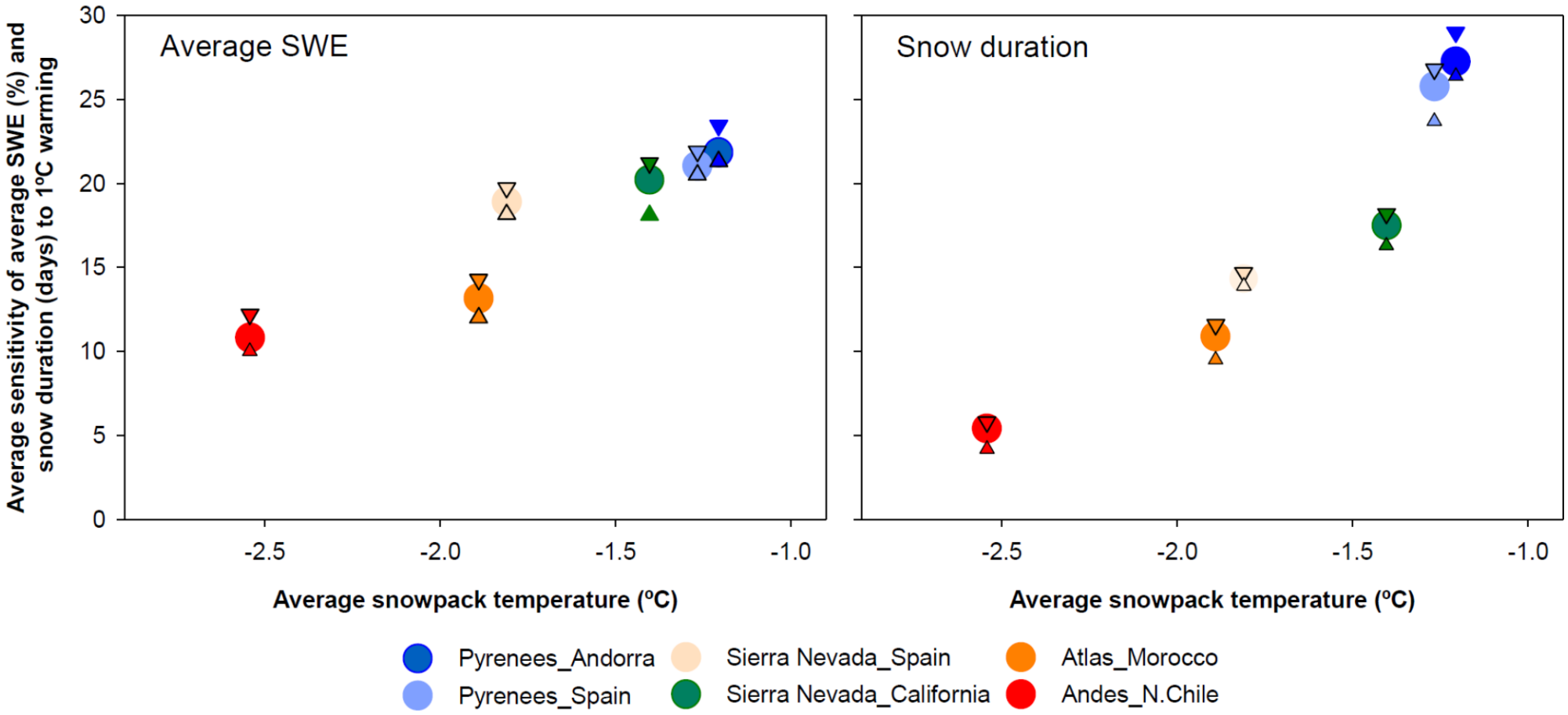
Abstract

In this study we quantified the sensitivity of snow to climate warming in selected mountain sites having a Mediterranean climate, including the Pyrenees in Spain and Andorra, the Sierra Nevada in Spain and California (USA), the Atlas in Morocco, and the Andes in Chile. Meteorological observations from high elevations were used to simulate the snow energy and mass balance (SEMB) and calculate its sensitivity to climate. Very different climate sensitivities were evident amongst the various sites. For example, reductions of 9%–19% and 6–28 days in the mean snow water equivalent (SWE) and snow duration, respectively, were found per °C increase. Simulated changes in precipitation (±20%) did not affect the sensitivities. The Andes and Atlas Mountains have a shallow and cold snowpack, and net radiation dominates the SEMB; and explains their relatively low sensitivity to climate warming. The Pyrenees and USA Sierra Nevada have a deeper and warmer snowpack, and sensible heat flux is more important in the SEMB; this explains the much greater sensitivities of these regions. Differences in sensitivity help explain why, in regions where climate models project relatively greater temperature increases and drier conditions by 2050 (such as the Spanish Sierra Nevada and the Moroccan Atlas Mountains), the decline in snow accumulation and duration is similar to other sites (such as the Pyrenees and the USA Sierra Nevada), where models project stable precipitation and more attenuated warming. The snowpack in the Andes (Chile) exhibited the lowest sensitivity to warming, and is expected to undergo only moderate change (a decrease of <12% in mean SWE, and a reduction of <7 days in snow duration under RCP 4.5). Snow accumulation and duration in the other regions are projected to decrease substantially (a minimum of 40% in mean SWE and 15 days in snow duration) by 2050.



- Mediterranean mountain water and energy fluxes to snow
- Expanded analysis using *Cold Regions Hydrological Model* (CRHM) to examine snow sensitivity to warming in 44 mountain basins worldwide.

WCRP Grand Challenges:
Melting Ice and Global Consequences



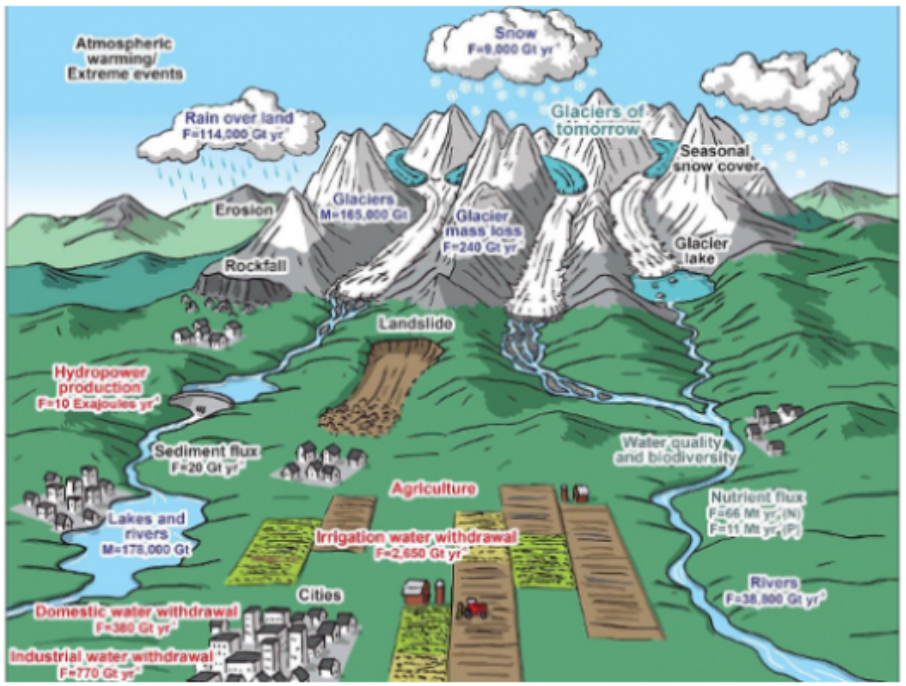
Lopez Moreno et al., Environ. Res. Letters, 2017

INARCH and WMO

High Mountain Summit

25–27 February, 2019, Geneva

HOME | ABOUT | PARTNERS | PRE-REGISTRATION | PROGRAMME | OUTCOMES



High Mountain Summit

Will take place on 25-27 February 2019 in Geneva, Switzerland

The organizers are encouraging the participation of relevant stakeholders, practitioners, research communities, and decision-makers from national, regional, and international institutions, representing all regions of the world affected by changes in the high mountain climate and ecosystems, in recognition of the regional diversity of impacts, and the need for specific solutions.

To express your interest in attending this global event, please complete the **Expression of Interest (pre-registration) Form**.

https://highmountainsummit.wmo.int/en

INARCH and Future Earth

Sustainable Water Futures Programme

Working Group on ***Climate Impacts on Global Mountain Water Security***

Activities and Outputs:

- Assembling climate change scenarios and hydrological model forcing data;
- Setup, testing, calibration/validation, and scenario generation for atmospheric and hydrological models over various high mountain regions globally, including climate model downscaling and bias correction;
- Running climate scenarios/sensitivity analyses, and linking these to hydrological models to examine impacts on water availability (e.g. timing, magnitude, and duration of flows) and better understand and predict water management concerns.
- Relating these results to water security of mountain communities, impact on mountain cultures and ecosystem services and to downstream water use for communities, energy and food.

http://water-future.org/working_groups/climate-impacts-on-global-mountain-water-security/

4th INARCH Workshop

Where: Hotel Portillo, Chile.
32.8ºS, 70.1ºW
2,880 m a.s.l.

When: Oct 24-26, 2018

Next Steps

- Mountain downscaling toolbox portal completion and posting to INARCH website
- LSS-H Model comparison and development – ongoing project linked to GEWEX-GLASS
- Pre-assessment synthesis article from INARCH for IPCC AR6 WG1 (Physical Science Basis) and AR6 WG2 (Impacts, Vulnerability and Adaptation, including Cross Chapter Paper on Mountains).
- WMO High Mountain Summit
- GEWEX RHPs – US Water for Foodbaskets, Canada - GWF, ANDEX