GHP Working Group (Project) Reports for the 33rd GEWEX SSG Meeting 2021

Working Group (Project) Name : The International Network for Alpine Catchment Hydrology (INARCH)
Reporting Period : 01 January – 31 December 2020
Starting Date : 2015
End Date (where appropriate) : 2020 (but seeking to extend)
URL : http://www.usask.ca/inarch/index.php

Membership

Contact(s) : John Pomeroy, University of Saskatchewan, Canada (Chair)
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For complete membership, see:
https://www.usask.ca/inarch/participants.php

Working Group Objectives, Goals & Accomplishments during Reporting Period

Overall Working Group Objective(s)

To better understand alpine cold regions hydrological processes, improve their prediction, diagnose their sensitivities to global change, and find consistent measurement strategies.

List of Working Group Goals

Adjust yearly

- To achieve this objective it is necessary to develop transferable and validated model schemes of different complexity that can support research in data sparse mountain areas. This leads to the following research questions relating to alpine hydrology and related snow and glacier studies and hydrometeorology:
- i. How different are the measurement standards and the standards for field sampling and do we expect distinctive differences in model results and hydrological predictability because of the sampling schemes, data quality and data quantity?
- ii. How do the predictability, uncertainty and sensitivity of catchment energy and water exchange vary with changing atmospheric dynamics in various high mountain regions of the Earth?
- iii. What improvements to high mountain energy and water exchange predictability are possible through improved physics in land surface hydrological models, improved downscaling of atmospheric models in complex terrain, and improved approaches to data collection and assimilation of both in-situ and remotely sensed data?
- iv. Do the existent model routines have a global validity, are they transferable and are they meaningful in different mountain environments?
- v. How do transient changes in perennial snowpacks, glaciers, ground frost, soil stability, and vegetation impact models of water and energy cycling in high mountain catchments?

List of 2 to 3 Major Key Results

Adjust yearly with respect to goals

- INARCH has led a special issue of the journal, Earth System Sciences Data, titled: "Hydrometeorological data from mountain and alpine research catchments" (https://essd.copernicus.org/articles/special_issue871.html). This represents an important collection of datasets from alpine research catchments around the world. So far the issue includes 23 data papers, with more continuing to be submitted.
- Organized and chaired the WMO High Mountain Summit - see below for details.
- An important study was conducted under the framework of INARCH (López-Moreno et al., 2020a, https://doi.org/10.1088/1748-9326/abb55f). In this study, snow hydrology predictions were made using a physical process snow hydrology model for 44 mountains areas worldwide. This enabled analysis of how snow and hydrological regimes will respond and interact under climate warming. The results show a generalized decoupling of mountain river hydrology from headwater snowpack regimes.

Other Science Highlights

Not part of the 2-3 major key results

- The annual report of ITP/CAS in INARCH; Yaoming Ma, Institute of Tibetan Plateau Research,Chinese Academy of Sciences
- The Institute of Tibetan Plateau Research,Chinese Academy of Sciences has been active in installing new hydro-meteorological observing stations and upgrading existing stations across the Tibetan Plateau. Nine new land-atmosphere interaction measureing systems are being installed, and eight land-atmosphere interaction systems have been updated with new sensors. A planetary boundary layer tower has been installed at the terminus of the Kuoqionggangri Glacier near Lhasa, which collects 5-layer profile measurements of atmospheric variables. Other hydrometric and meteorological observations, as well as detail glacier observations, are carried out here as well.
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- ANNUAL REPORT FROM HIEHE REMOTE SENSING EXPERIMENT RESEARCH SITE (2020)
- At the Heihe River Basin (HRB) in China, a suite of datasets was produced, consisting of long-term hydrometeorological, snow cover and frozen-ground data for investigating watershed science and functions from an integrated, distributed and multiscale observation network in the upper reaches of the basin. Meteorological and hydrological data were monitored from an observation network connecting a group of automatic meteorological stations (AMSs). In addition, to capture snow accumulation and ablation processes, snow cover properties were collected from a snow observation superstation using state-of-the-art techniques and instruments. High-resolution soil physics datasets were also obtained to capture the freeze–thaw processes from a frozen-ground observation superstation. The updated datasets were released to scientists with multidisciplinary backgrounds (i.e., cryospheric science, hydrology and meteorology), and they are expected to serve as a testing platform to provide accurate forcing data and validate and evaluate remote-sensing products and hydrological models for a broader community. The datasets are available from the National Tibetan Plateau Third Pole Environment Data Center at Beijing (http://www.tpdc.ac.cn/en/) [Che et. al., 2019].
- Based on the integrated dataset from HRB, some interesting progresses on the land surface model, precipitation calibration and monitoring river ice was made. A new integrated scheme was suggested that couples a radiative transfer model with a land surface model to simulate high spectral resolution snow surface reflectance information specifically targeting multisource satellite remote sensing observations. The integrated model extends the range of snow spectral reflectance simulation to the whole shortwave band and can predict snow spectral reflectance changes in the solar spectrum region based on meteorological element data [Shao et.al., 2020].

- Partially based on the precipitation observation in the HRB dataset, a method was presented for the production of gridded precipitation on the Tibetan Plateau (TP) to reduce the statistical distribution error by correcting for wind-induced undercatch and optimizing the interpolation method. The results show that undercatch correction can reduce the distributional error by 30% at most. The method effectively inhibits the smoothing effect in gridded precipitation and, compared to previous products, results in a higher mean value, larger 98th percentile and greater temporal variance. This study can help to improve the quality of gridded precipitation over the TP [Ma et.al., 2020].
- To ascertain the distribution and variation of high-altitude river ice at the basin scale, researchers at the HRB presented a method based on the normalized difference snow index (NDSI) algorithm to monitor river ice. Utilizing 450 Landsat images of river ice during the period from 1999 to 2018, they monitored the river ice in a long time series at the basin scale. This study provides a reference for research on the distribution and formation of river ice on the Tibetan Plateau [Li et. al., 2020].
- Wet alpine meadows generally act as a significant carbon sink, since their low rate of soil decomposition determines a much smaller ecosystem respiration (Re) than photosynthesis. However, it remains unclear whether the low soil decomposition rate is determined by low temperatures or by nearly-saturated soil moisture. Researchers at HRB explored this issue by using five years of measurements from two eddy-covariance sites with low temperature and significantly different soil water conditions. The results showed that both sites were carbon sinks. However, despite a smaller annual gross primary productivity, the wet site with a shallow groundwater showed a much higher carbon use efficiency and larger carbon sink than the dry site (which had a deeper water table) due to its much lower Re. Thier analyses showed that Re of the wet site was significantly decreased under the nearly-saturated soil condition during the unfrozen seasons. This effect of nearly-saturated soil water on Re increased with soil depths. In contrast, at the dry site the high soil water content favored Re. The corresponding soil temperature at both sites expectedly showed large and positive effects on Re. These results demonstrated that the high carbon sink of the wet alpine meadow was mainly caused by the inhibiting effects of the nearly-saturated soil condition on soil respiration rather than by the low temperatures. Therefore, they argue that a warming-induced shrinking cryosphere may affect the carbon dynamics of wet and cold ecosystems through changes in soil hydrology and its impact on soil respiration. In addition, their study highlights the different responses of soil respiration to warming across soil depths. The thawing of frozen soil may cause larger CO_2 emission in the top soil, while it may also partially contribute to slowing down soil carbon decomposition in the deep soil through decreasing metabolic activity of aerobic organisms [Sun et. al., 2020].
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- A group of researchers at the US National Center for Atmospheric Research (NCAR) have published a paper discussing how a variety of observations in mountain catchments can be used to better estimate precipitation in the mountains, and noted that in many ways, the best atmospheric model simulations may be better than simple interpolation of observations for estimating orographic precipitation (Lundquist et al., 2019).
- The NCAR group have worked to further develop physically based downscaling methods for mountain environments. In particular, they have developed a new lagrangian convection model to simulate convection in the Intermediate Complexity Atmospheric Research model (ICAR), and they have further refined the Ensemble Generalized Analog Regression Downscaling (En-GARD) to reduce biases in arid mountain ranges. They have also further evaluated ICAR to better understand numerical artifacts introduced in the top boundary (Horak et al., 2020), and added a spatially variable vertical coordinate system to minimize such issues in ICAR in the future (Reynolds et al 2020). They have used ICAR with a data assimilation scheme to estimate snow water equivalent in mountains with few in situ observations (Alonso-Gonzalez et al., 2020).

- The NCAR group have improved understanding of the spatial complexity of mountain snowpack. This work has included evaluation of new observing systems (Deschamps-Berger et al., 2020). They have shown the impacts of mountain snowpack heterogeneity on streamflow forecasting and climate change in work presented at the American Meteorological Society's annual meeting and Mountain Meteorology conference (Gutmann et al 2020a,b). They have further evaluated the impact of snow pack heterogeneity on elevation dependent warming in results to be presented at the American Geophysical Union (Gutmann et al 2020c,d). Finally, they have assessed the spread in model predictions of snow over continental domains (Kim et al 2020), and evaluated different modeling approaches to simulate forest canopy interception in mountain catchments (Lundquist et al 2020) and new observing methods for forest canopy interception (Raleigh et al 2020).
- Current work at NCAR also adds climate downscaling over the Himalayas using ICAR and GARD, the evaluation of climate changes in the Colorado River Basin, assessing variability and non-stationarity in extreme precipitation events in the Columbia River Basin, the implications of cloud microphysical assumptions for projecting changes in precipitation over the Sierra Nevada mountains, the efficient parallelization of a snow transport model for continental domain snow drift resolving simulations, and configuring ICAR for rain on snow flood simulations in both climate and weather forecasting contexts.
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- Use of INARCH data in ESM-SnowMIP
- Richard Essery, Cecile Menard, Xing Fang and John Pomeroy
- The Earth System Model – Snow Model Intercomparison (ESM-SnowMIP) aims at evaluating snow schemes in global coupled land-ocean-atmosphere Earth System Models, global land-only simulations driven with meteorological reanalysis and local simulations driven with in situ meteorological observations at well-instrumented reference sites. The INARCH sites Col de Porte, Reynolds Mountain East and Weissfluhjoch are among the ten reference sites used in the first set of ESM-SnowMIP experiments and have been used in four related publications to date (Essery et al. 2020, Krinner et al. 2018, Menard et al. 2019 and 2020).
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- Overview of CEN activities contributing to GEWEX INARCH (2019-2020)
- Many activities carried out at the Snow Research Center (part of CNRM, Météo-France – CNRS) in Grenoble contribute to INARCH. Of high relevance for the assessment of snow and meteorological conditions in the French mountain areas, is the meteorological and snow cover reanalysis, S2M, that thanks to recent work now extends from 1958 to present, and is published as an open-access dataset (Vernay et al ., 2019 ; https://doi.org/10.25326/37). This reanalysis is performed by the SAFRAN system, which adjusts a guess from a Numerical Weather Prediction model (ERA-40 reanalysis from 1958 to 2002, ARPEGE from 2002 to 2018) with the best possible set of available in-situ meteorological observations. SAFRAN outputs are used to force the Crocus detailed snowpack model within the land surface scheme SURFEX/ISBA. This provides the evolution of the snowpack and the associated avalanche hazard accounting for the main physical processes involved in a multilayer snowpack. This reanalysis is provided at massif-scale with discrimination of conditions according to altitude, elevation and slope within each massif. This data supports in particular studies of the interannual variability and trends in snow cover in French mountain regions (e.g. for the Pyrenees Lopez-Monero et al, 2020).
- A new, regional-scale, deep-learning based glacier model was developped and set up at the scale of the French Alps (Bolibar et al 2020a, collaboration with IGE and INRAE), permitting a reconstruction of recent past mass balances for all glaciers in the region as an open dataset (Bolibar et al., 2020b), and projections according to different climate scenarios. Both will support regional studies on the evolution of water resources in the context of shrinking alpine glaciers.

- Acquisition of snow and meteorological data in mid and high-altitude environment was pursued during the last year, at stations identified in the GCW cryonet network. The unique Col de Porte (1325 m a.s.l.) data series now covers over 60 years and is used as indicator of climate change in mid-altitude mountains in France (available on the national climate change observatory website ONERC : https://www.ecologie.gouv.fr/impacts-du-changement-climatique-montagne-et-glaciers#e3). The Col du Lac Blanc high-altitude observations (2720 a.s.l.) were complemented in the last years with new radiation and precipitation measurements, with a view of acquiring observations for most of the near-surface variables involved in the surface energy balance, in support of snowpack simulations and evaluation of NWP models.
- Highly relevant to the observation of snow cover trends in the European Alps for the past decades is a study, coordinated by EURAC, using more than 2’000 snow depth station data (Matiu et al., in review).
- Within the SNOw Under Forest project (SNOUF, collaboration IGE, INRAE, SLF-Davos and Univ of Edimbourgh), observations at Col de Porte were complemented with snow accumulation and ablation measurements below the forest, a detailed caracterization of the canopy, 2-year campain of sub-canopy radiation measurements and inovative and unique measures of canopy interception and discharge of solid precipitation events during 2 snow seasons (Sicart et al., in prep). These data support notably the evaluation of surface and snow models in sub-canopy conditions.
- Regarding mountain meteorology, the combination of partial information from precipitation radar data, with reflectivity profiles simulated by numerical weather prediction models, helped to develop an hybrid precipitation product over mountain regions overcoming limitations of precipitation radar in complex terrain (Le Bastard et al., in prep). The incoming solar and longwave radiation products derived from the Meteosat Second Generation satellite were also evaluated and used to create a new radiation product over the French mountain regions. Its use as a forcing of the Crocus snow cover model highlighted potential error compensations within the model (Quéno et al., 2020).
- The development of the detailed snow model Crocus was continued : one of the main focuses was the development of an assimilation system of snow reflectances acquired from satellites in the visible and the near-infrared spectra as well as snow depth data, that operates in the semi-distributed massifs geometry (Cluzet et al., 2020). The model also contributed to the ESM-SnowMIP simulations and publications.
- Techniques were developped and improved to retrieve snow wetness from satellite data (Sentinel 1), with potential for assimilation of these data within snow models (Karbou et al. 2020, in revision).
- CEN has contributed to several key products and services for the ski tourism sector, notably the provision of a pan-European data set for mountain meteorological and snow cover indicators as part of the Copernicus Climate Change service (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-tourism-snow-indicators?tab=overview). This includes reanalysis data 1960-2015 and multiple climate projections from 1950 to 2100, based on EURO-CORDEX. It addresses not only natural snow but also managed snow (accounting for grooming and snowmaking), co-designed with ski tourism industry stakeholders. The dataset is of potential use to a much wider range of users including research. Also, the PROSNOW project, coordinated by Météo-France and bringing together many INARCH stakeholders, has ended in 2020. The PROSNOW project, funded by Horizon 2020 from 2017 to 2020, has built synergies between weather and seasonal forecasting, in-situ and Copernicus Sentinel-2 satellite observations, and snow cover modeling, through standardized data exchange mechanisms to deliver real-time optimization of grooming and snowmaking in ski resorts. Bringing together academic and industrial partners in Austria, France, Germany and Switzerland, and co-designed and tested by 9 pilot ski resorts across the European Alps during the winter 2019-2020, this service is being implemented commercially starting for the winter 2020-2021. It supports ski resorts operations under increasingly challenging operating conditions due to climate change, while reducing

the related use of water and energy. It contributes to raising awareness on climate change impacts and societal transitions in mountain areas. (see https://prosnow.org/ and Morin, 2020).

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- Recent Cariboo Alpine Mesonet Developments in the Nechako and Quesnel watersheds, British Columbia, Canada
- Stephen J. Déry, Marco A. Hernández-Henríquez, and Jeremy E. Morris
- In the Nechako and Quesnel watersheds of the Cariboo Mountains, British Columbia, Canada, there have been major alpine mesonet developments. In recent years, the Cariboo Alpine Mesonet (CAMnet) has expanded to the 47,234 km2 Nechako and 12,191 km2 Quesnel watersheds, in northern British Columbia (BC), Canada, to form a network of 15 active weather stations and nine precipitation gauges as of October 2020. The stations are deployed in valley and mountain settings at elevations ranging from 70 m to 2105 m a.s.l. along a longitudinal transect from the Coast Mountains, onto the Interior Plateau, then into the Cariboo Mountains. CAMnet spans a vast area across north central BC's region in complex terrain comprising glaciers, lakes, rivers, reservoirs, and a multitude of landcover and vegetation types. The parameters typically measured at CAMnet weather stations include air temperature and relative humidity, wind speed and direction, atmospheric pressure, snow depth, precipitation, and soil temperature at 15 minute intervals.
- Quesnel Watershed Development
- To monitor more closely the atmospheric conditions of Quesnel Lake (North America's deepest freshwater fjord lake) and the surrounding area, three weather stations were deployed in summer 2018 at Dock Point, Goose Point, and Raft Creek (Fig. 1). All three weather stations are controlled by Onset HOBO data loggers. HOBO instruments are used to measure air temperature and relative humidity, wind speed and direction, and atmospheric pressure. These stations help fill the observational data gap that exists surrounding the shores of Quesnel Lake and complement the data collected from the Plato Point and Long Creek weather stations that were deployed in response to the 2014 Mount Polley Mine tailings pond breach.
- Nechako Watershed Development
- On 28 July 2020 a comprehensive 6 m tall weather station was deployed at Mount Sweeney at an elevation of 1702 m a.s.l. to better monitor storms such as "Pineapple Expresses" known to cause heavy precipitation events (e.g., flooding) impacting the upper Nechako Watershed and surrounding area. Mount Sweeney is located ~133 km southwest of Houston in the Tahtsa Ranges of BC's Coast Mountains, overlooking Tahtsa Lake and the Nechako Reservoir (Figs. 1, 2). The station is equipped with sensors that measure air temperature and relative humidity, wind speed and direction, snow depth, incoming solar radiation, and atmospheric pressure. In addition, the station has one near-surface and one subsurface temperature probe and an all-weather Pluvio2 weighing precipitation gauge mounted at a height of 3 m within an Alter shield. During summer 2020 an array of nine HOBO tipping bucket rain gauges was also deployed in BC's upper Nechako Watershed (Fig. 1). The tipping bucket rain gauges were installed along a longitudinal transect from the Tahtsa Ranges onto the Interior Plateau. The precipitation data collected from the Mount Sweeney weather station and the tipping bucket precipitation gauges deployed throughout the Nechako Watershed contribute to the ongoing efforts to produce more accurate regional precipitation fields and to improve understanding of atmospheric river events.
- Publication - In Preparation
- A paper is in preparation that reports on the recent CAMnet developments in the Nechako and Quesnel watersheds from 2017 to 2020 and provides an update from our previous effort describing CAMnet from 2006 to 2017 (Hernández-Henríquez et al., 2018). Since 2017 extreme conditions have plagued our study areas, from two record wildfire seasons (2017/2018) to major floods in 2020. Thus

one of the objectives of this paper is to share our data to the broader community in light of these events, and contribute to the ongoing research efforts on Quesnel Lake following the Mount Polley incident.

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- University of Innsbruck: Research team Human-environment systems research / Alpine Hydroclimatology (Prof. Ulrich Strasser, Dr. Michael Warscher). Update on our research in the Rofental over the past year
- Research projects (ongoing/just finished):
- \- FuSE-AT: Future snow cover evolution in Austria (ACRP).
- \- PROSNOW: Provision of a prediction system allowing for management and optimization of snow in Alpine ski resorts (H2020 IA).
- \- ESM-SnowMIP: Assessing snow models and quantifying snow-related climate feedbacks.
- Hardware/Sensors:
- Since the meteorological station instrumentation in the Rofental has been documented in the overview paper (Strasser et al. 2018) the following extensions have been installed:
- 1. Bella Vista station (2805 m a.s.l.): a new snow scale with ultrasonic snow depth sensor that allows - together with the snow pillow/ultrasonic arrangement at the main station upslope - to track lateral snow redistribution events, like the one on Dec 28 2019 that caused a deathly avalanche in the adjacent skiing area slope (see press news). Both the upper and the lower installation are approximately 25 m apart from each other; one is frequently registering snow erosion, the other its deposition. Both sites are now equipped with the same snow temperature profile sensor. In addition, the setup is complemented by an acoustic snow drift sensor. At Bella Vista, we are running a webcam with the entire installation in its viewfield (https://www.schoeneaussicht.it/de/corporate/webcams).
- 2. Latschbloder station (2919 m a.s.l.): this autonomous site representative for the typical areas getting ice-free is now also equipped with the same snow temperature profile sensor as the other sites.
- 3. Proviantdepot station (2737 m a.s.l.): this entirely new autonomous site has been brought into operation in fall 2019. It comprises sensors for temperature, humidity, wind speed and direction, air pressure, precipitation, radiative fluxes (short- and longwave, up and down), surface temperature, snow depth, snow water equivalent, layered density and liquid water content (snow pack analyzer).
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- Progress from Mountain Water Futures project (http://www.mountainwaterfutures.ca/) of the Global Water Futures program, Canada. - John Pomeroy, Sean Carey, and others.
- The effects on hydrology of concomitant changes in climate, vegetation and soils have seldom been considered in snow dominated mountain basins. The response of mountain hydrology to vegetation/soil changes in the present and a future climate was modelled in three snowmelt dominated mountain basins in the North American Cordillera. Cold regions hydrological models developed for each basin using current and expected changes to vegetation and soil parameters were driven with recent and perturbed high-altitude meteorological observations. Monthly perturbations were calculated using the differences in outputs between the present and a future climate scenario from 11 regional climate models. In the three basins, future climate change alone decreased the modelled peak snow water equivalent (SWE) by 11-47% and increased the modelled evapotranspiration by 14-20%. However, including future changes in vegetation and soil for each basin changed or reversed these climate change outcomes. In Wolf Creek, YT a statistically insignificant increase in SWE due to vegetation increase in the alpine zone was found to offset the statistically significant decrease in SWE due to climate change. In Marmot Creek, AB, the increase in annual runoff due to the combined effect of soil and climate change was statistically significant while

their individual effects were not. In the relatively warmer Reynolds Mountain, ID, vegetation change alone decreases annual runoff volume by 8%, but changes in soil, climate, or both do not affect runoff. At high elevations in Wolf and Marmot creeks, the model results indicate that vegetation/soil changes moderated the impact of climate change on peak SWE, the timing of peak SWE, evapotranspiration, and annual runoff volume. However, at medium elevations, these changes intensified the impact of climate change, further decreasing peak SWE and sublimation. The hydrological impacts of changes in climate, vegetation, and soil in mountain environments were similar in magnitude but not consistent in direction for all biomes; in some combinations, this resulted in enhanced impacts at lower elevations and latitudes and moderated impacts at higher elevations and latitudes.

- The spatial distribution of snow water equivalent (SWE) and melt are important to estimating areal melt rates and snow cover depletion dynamics in high mountains. High resolution observations were made using large numbers of sequential aerial photographs taken from an Unmanned Aerial Vehicle on an alpine ridge in the Fortress Mountain Snow Laboratory in the Canadian Rocky Mountains from May to July. With Structure-from-Motion and thresholding techniques, spatial maps of snow depth, snow cover and differences in snow depth (dHS) during ablation were generated in very high resolution as proxies for spatial SWE, spatial ablation rates, and snow cover depletion (SCD). The results indicate that the initial distribution of snow depth was highly variable due to overwinter snow redistribution and the subsequent distribution of dHS was also variable due to albedo, slope/aspect and other unaccountable differences. However, the initial distribution of snow depth was five times more variable than that of subsequent dHS values which varied by a factor of two between north and south aspects. dHS patterns were somewhat spatially persistent over time but had an insubstantial impact on SCD curves, which were overwhelmingly governed by the initial distribution of snow depth. The reasons for this are that only a weak spatial correlation developed between initial snow depth and dHS. These findings suggest that hydrological and atmospheric models need to incorporate realistic distributions of SWE, melt energy and cold content and so must account for realistic correlations (i.e. not too large or too small) between SWE and melt in order to accurately model snow cover depletion.
- Unmanned Aerial Vehicles (UAV) were applied to the sub-canopy snow depth challenge. The effectiveness of UAV-lidar and UAV-SfM in mapping snow depth in both open and forested terrain was tested in a 2019 field campaign in the Canadian Rockies Hydrological Observatory, AB. Only UAV-lidar could successfully measure the sub-canopy snow surface with reliable sub-canopy point coverage, and consistent error metrics (RMSE <0.17m and bias -0.03m to -0.13m). Relative to UAV-lidar, UAV-SfM did not consistently sense the sub-canopy snow surface, the interpolation needed to account for point cloud gaps introduced interpolation artefacts, and error metrics demonstrate relatively large variability (RMSE <0.33m and bias 0.08 m to -0.14m).
- Snow mass budgets in forested mountain basins depend on structure of the forest canopy as well as properties of the snow intercepted by and accumulated under the canopy. UAV-borne LiDAR has the potential to improve measurements with finer spatial resolutions of forest canopy characteristics and snow depth than other airborne LiDAR systems. Six UAV LiDAR surveys along with surface snow and topographic surveys were conducted at a variable-density needleleaf forest in Marmot Creek Research Basin between February and May 2019. Differential snow depths were calculated over a range of resolutions and compared with ground observations for validation. Common canopy metrics such as LAI, canopy closure and distance to tree trunk were calculated from point cloud densities collected at different elevations and compared with ground observations. The results showed a bias in ground point cloud density towards canopy gaps. To prevent overestimation of area snow depth, the point clouds were bias-corrected by distance to trunk. The bias-corrected results show, for the

first time in a dense evergreen forest, detailed patterns of snow accumulation, snow interception losses and snow ablation in relation to the spatial distributions of canopy characteristics.

- Atmospheric boundary layer (ABL) dynamics over glaciers mediate the response of glacier mass balance to large scale climate forcing. Despite this, very few ABL observations are available over mountain glaciers in regions of complex terrain. The results of an intensive field campaign were conducted over 12 days in June 2015 at Athabasca Glacier, an outlet of Columbia Icefield in the Canadian Rocky Mountains have been analyzed. The vertical structure of the above-glacier ABL differed from that expected for ‘glacier winds’; strong daytime down-glacier winds extended through lowest 200 m of glacier ABL with no evidence of up-valley return flow aloft. A wind speed maximum close to the glacier surface, characteristic of a ‘glacier wind’ was only observed during early morning hours and one afternoon. Lapse rates along the glacier flowline exhibited a characteristic reversal of the environmental lapse rate punctuated by periodic disruption and warming. Down-glacier cooling was weaker during periods displaying external forcing, while during ‘glacier wind’ periods stronger down-glacier cooling led to larger warming during disruptions. These results raise several outstanding questions that can be assessed using these data as a test-bed for modelling spatio-temporal variations in ABL/SBL climate and surface energetics in complex glaciated terrain.
- In recent years, record wildfires in and beyond the Canadian Rockies resulted in heavy smoke drifting over the mountain range, obscuring sunlight and darkening the ice surface as ashes deposit on the ice. These two processes affect key components of the surface energy and mass balance of the glacier in different and partially compensating ways. As mountain glaciers in the Canadian Rockies can provide an important contribution to downstream water resources in late summer and the frequency and intensity of forest fire activity are expected to shift due to climate change, understanding the impact of forest fires on glacier melt processes is important. The possibly compensatory impacts of forest fire smoke and soot deposition on the energy and mass balance of mountain glaciers were investigated on the instrumented Athabasca glacier in the Canadian Rockies for the 2014-2019 melt seasons using intensive field observations and the process-based cold regions glacier hydrological model CRHM-Glacier. Data analysis and melt modelling results indicate that the fire-related process with the greatest impact on surface melt depends on the timescale. At daily timescales during fire activity, the presence of smoke in the atmospheric layer above the glacier can strongly reduce the hourly melt rate by reducing shortwave irradiance. However, at the seasonal scale, the presence of smoke is partially compensated by the lower surface albedo linked with soot deposition. At the inter-annual timescales, an emerging feedback loop continues to affect surface melt even after the smoke is gone: soot deposited on the ice surface feeds microbial growth, further decreasing the albedo and increasing melt. This study provides valuable insights on the impacts of wildfire activity on glacier melt patterns, which subsequently affects downstream hydrology.
- The impacts of forest disturbances on streamflow in Bow River Basin above Calgary were diagnosed using the Cold Regions Hydrological Modelling platform (CRHM). Hydrological models were created in CRHM for two forested basins: Upper Bow River Basin (~7823.6 km2) and Elbow River Basin (~1191.9 km2) above Calgary. These models were parameterized from local research results from soils studies in recent forest patch-cuts above Barrier Lake, evapotranspiration studies at Fortress Mountain and hydrology and soils studies from Marmot Creek Research Basin. The models represented the relevant streamflow generation processes: wind redistribution of snow, gravitational snow transport on steep mountain slopes, glacier accumulation and melt, intercepted snow from forest canopies, infiltration to frozen and unfrozen soils, hillslope sub-surface water redistribution, and evapotranspiration from forests, grassland, clearings and alpine tundra. The models were driven by the bias corrected near-surface outputs from the Weather Research and Forecasting (WRF) model during October 2000-September 2015. First, air temperature, vapour pressure, wind speed, incoming shortwave radiation, and precipitation outputs from the 4-km WRF were bias-corrected using the

same outputs from 10-km Global Environmental Multiscale and Canadian Precipitation Analysis (GEM-CaPA), generating an initial 10-km bias corrected WRF. Then, additional precipitation bias correction was performed by a double-mass curve analysis of streamflow from the model runs using the initial 10-km bias corrected WRF and Water Survey of Canada (WSC) streamflow observations from natural flow gauges in Upper Bow River and Elbow River above Calgary. With these two-step bias corrected WRF, the streamflow simulations showed reasonable predictions compared to the observed streamflow, with Nash-Sutcliffe efficiency ranging from 0.25 for Elbow River at Sarcee Bridge, Calgary to 0.72 for Bow River at Banff, and model bias ranging from -0.16 for Bow River at Lake Louise to 0.22 for Elbow River at Sarcee Bridge, Calgary. Then, simulations of forest disturbances were conducted for three types of disturbance scenarios: wildfire, lodgepole pine (Pinus contorta var. latifolia) salvage harvesting, and mountain pine beetle (Dendroctonus ponderosae Hopkins) infestation. Forest canopy parameters and soil parameters for infiltration were adjusted for three wildfire severity scenarios, ranging from 20% reduction in forest canopy for low wildfire severity to a 80% reduction in forest canopy with development of hydrophobic soil for high wildfire severity. Two lodgepole pine forest harvesting scenarios were created: half-maximum harvest area (25% pine area) and maximum harvest area (50% pine area) by adjusted lodgpole pine forest area, forest canopy and soil storage parameters from soil compaction during harvesting. Two scenarios of final stage of mountain pine beetle infestation were set up, and both are 100% lodgepine area affected, with one allowing salvage logging and the other keeping infested lodgepole pine trees standing. For the Bow River and Elbow rivers at Calgary, high wildfire severity and secondarily mountain pine beetle infestation with salvage logging resulted in an increase in streamflow volume. High wildfire severity followed by mountain pine beetle with salvage logging and maximum harvest area scenarios increased the volume and daily discharge of the June 2013 flood. Other forest disturbance scenarios had minimal impacts on streamflow.

- In high mountain basins, empirical relations between melt and temperature have often been preferred over physical energy budget calculations for snow and glacier melt. Major reasons for this are cited as the lack of high-elevation observations of shortwave irradiance and uncertainty in estimating irradiance from other variables. Empirical methods for the estimation of shortwave irradiance are based primarily on air temperature and have been developed at lower elevations for snowmelt energy budget, soil thaw or evapotranspiration calculations. Empirical methods and two reanalysis products were evaluated for estimating atmospheric transmittance. Observations from thirty snow-dominated and/or glacierized sites in North America, Europe, South America and the Himalayas were used to develop an atmospheric shortwave radiation transmittance model based on air temperature and humidity, which, when coupled with existing extraterrestrial shortwave radiation models, permits a more accurate estimation of shortwave irradiance than was previously possible. The globally available reanalysis products provided good estimates of shortwave irradiance for a site at lower elevation (<3000 m a.s.l.) but did not provide robust results at higher elevations.
- The Cold Region Hydrological Modelling platform (CRHM), now including a glacier hydrology module, providing a capacity to: 1) diagnose the sensitivity of glacierized catchment hydrology and mass balance to glacier and climate change, 2) gain understanding of emerging processes, such as the impact of forest-fire smoke on glacier melt, and 3) catchment-scale predictions of future alpine hydrology from currently glacierized catchments. Additionally, CRHM-glacier shows robust results across multiple mountain climates, from the Canadian Rockies, Yukon, the Himalayas and Andes. CRHM-glacier is a useful diagnostic and predictive tool for advancing the understanding of glacierized hydrological catchments.
- To examine the hydrological sensitivity of mountain headwater basins to climate change, a sensitivity method is introduced in which the current climate is perturbed based on a range of temperature increases and precipitation changes. These perturbations are applied to high-resolution hourly

observations as forcings in modelling experiments assessing the effect of temperature and/or precipitation forcing change on elevation-dependent hydrological responses in three mountain basins from the North American Cordillera; Wolf Creek, YT, Marmot Creek, AB and Reynolds Mountain East, ID. Simulations using multiple elevation bands show that both peak snowpack and annual runoff respond to both warming and precipitation changes and these responses vary with latitude. The timing and magnitude of peak snow water equivalence (SWE) are both sensitive to changes in temperature and precipitation in all three basins, but the effects of temperature dominate the timing. Total annual runoff is less sensitive. Under the maximum precipitation increases expected from N/ARCCAP RCM-GCM simulations, the impacts of warming on total annual runoff in these basins can be offset by precipitation increases, but not the impacts on peak snowpack. To offset the impact of 2°C warming on total annual runoff, precipitation would need to increase by 4% in Wolf Creek, by 1% in Marmot Creek and 5% in Reynolds Mountain. To offset the impact of 2°C warming on peak snowpack, precipitation would need to increase by 12% in Wolf Creek and by 18% in Marmot Creek but cannot be offset in Reynolds Mountain based upon any expected future maximum precipitation increases.

Working Group Activities during Reporting Period

List of Working Group Activities and Main Result

- INARCH co-Chair, Igancio López Moreno, participated as a contributing author in this IPCC special report: IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (eds.)]. 1170 pps. López-Moreno, J.I. contributing authors of Chapter 2 (High mountain areas). https://report.ipcc.ch/srocc/pdf/SROCC_FinalDraft_Chapter2.pdf
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- As a contribution to the Future Earth Sustainable Water Futures Programme (SWFP), INARCH has formed a working group on Climate Impacts on Global Mountain Water Security, http://water-future.org/working_groups/climate-impacts-on-global-mountain-water-security/. The activities and objectives, and membership, of this working group parallel the broader goals of INARCH, thus providing a mechanism for expanding the influence and exposure of this work through the SWFP. The Grand Challenge that this working group addresses is: how to develop a global scientific approach to better understand, predict and manage alpine water resources in the face of dramatically increasing risks?
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- INARCH contributed to the WMO High Mountain Summit in Geneva, October 2019 (https://highmountainsummit.wmo.int/en), with Professor Pomeroy as co-chair of the Summit. The aim was 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. A summary of the Call for Action is below.
- Avoiding the Impending Crisis in High Mountain Weather, Climate, Snow, Ice and Water: Pathways to a Sustainable Global Future
- Call for Action:
- The high mountain regions are the home of the cryosphere, and source of global freshwater that are transmitted by rivers to much of the world. Preservation of ecosystem function and services from

these regions is essential to global water, food and energy security. Climate change and development are creating an unprecedented crisis in our high mountain earth system that threatens the sustainability of the planet. There is great urgency to take global action now to build capacity, invest in infrastructure and make mountain and downstream communities safer and more sustainable. This action must be informed by science, local knowledge and based on transdisciplinary approaches to integrated observations and predictions.

- We, the participants at the WMO High Mountain Summit 2019, hereby commit to the goal that people who live in mountains and downstream should have open access to hydrological, cryospheric, meteorological, and climate information services to help them adapt to and manage the threats imposed by escalating climate change. To meet this goal we commit to an Integrated High Mountain Observation and Prediction Initiative, organized as collective, intensive campaigns of analysis and forecasting demonstration projects in key high mountains and headwaters around the world. The Initiative will co-design solutions, build capacity and suggest investments with information users, providers and producers to address the front lines of climate, cryospheric, and hydrological change in support of natural hazard risk management and adaptation in mountain regions and downstream. We urge the relevant organisations to collaborate and specifically organize as a matter of urgency, intense observation and prediction campaigns in a WMO Year of Mountain Prediction. The Initiative will contribute to the desired International Year of Mountains, and Year of Snow and Ice and will be co-produced and supported by a consortium of national institutions, international initiatives, user groups, researchers and science networks from policy, operations, practice and scientific research under the convening leadership of WMO.
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- INARCH Chair, John Pomeroy, was invited by WMO to attend the United Nations Climate Change Conference, COP25, as an Observer and to make two presentations on climate change and water in relation to the Sustainable Development Goals and to the Changing Cryosphere in Madrid, Spain in December 2019. (See press release: https://news.usask.ca/media-release-pages/2019/the-world-is-losing-its-cool-with-the-loss-of-snowpacks-and-glaciers,-posing-threats-to-water-security.php)

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

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

- We might wish to lead the write up of a synthesis scientific article over the next year.
- As alpine research catchments, several INARCH sites have hydrometeorological stations spanning a wide range of elevations within a small area. We are now designing an additional ESM-SnowMIP experiment using data from the Marmot Creek Research Basin, which has stations spanning a 900 m elevation range in a 9.4 km2 area. This experiment will evaluate the degradation in model performance when in situ driving data is replaced with simple elevation-adjusted data, as often used in climate impacts studies. Difficulties for 1D models in representing exposed high-mountain snow conditions will also be investigated.

Science Issues and Collaboration during Reporting Period

Contributions to Developing GEWEX Science and the GEWEX Imperatives.

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

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- Also:
- Che, T., Li, X., Liu, S., Li, H., Xu, Z., Tan, J., Zhang, Y., Ren, Z., Xiao, L., Deng, J., Jin, R., Ma, M., Wang, J., and Yang, X.: Integrated hydrometeorological, snow and frozen-ground observations in the alpine region of the Heihe River Basin, China, Earth Syst. Sci. Data, 11, 1483–1499, https://doi.org/10.5194/essd-11-1483-2019, 2019.
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- Hernández-Henríquez, M. A., Sharma, A. R., Taylor, M., Thompson, H. D. and Déry, S. J.: The Cariboo Alpine Mesonet: Sub-hourly hydrometeorological observations of British Columbia's Cariboo Mountains and surrounding area since 2006, Earth Syst. Sci. Data, 10, 1655-1672, doi: 10.5194/essd-10-1655-2018, 2018.
- Ma, Y., Hu, Z., Xie, Z., Ma, W., Wang, B., Chen, X., Li, M., Zhong, L., Sun, F., Gu, L., Han, C., Zhang, L., Liu, X., Ding, Z., Sun, G., Wang, S., Wang, Y., and Wang, Z.: A long-term (2005–2016) dataset of integrated land–atmosphere interaction observations on the Tibetan Plateau, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2020-85, in review, 2020.

- Ménard, C. B., Essery, R., Barr, A., Bartlett, P., Derry, J., Dumont, M., Fierz, C., Kim, H., Kontu, A., Lejeune, Y., Marks, D., Niwano, M., Raleigh, M., Wang, L., and Wever, N.: Meteorological and evaluation datasets for snow modelling at 10 reference sites: description of in situ and bias-corrected reanalysis data, Earth Syst. Sci. Data, 11, 865–880, https://doi.org/10.5194/essd-11-865-2019, 2019.
  - Nieberding, F., Wille, C., Fratini, G., Asmussen, M. O., Wang, Y., Ma, Y., and Sachs, T.: A Long Term (2005–2019) Eddy Covariance Data Set of CO_2 and H_2O Fluxes from the Tibetan Alpine Steppe, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2020-63, in review, 2020.
  - Peng, S., Ding, Y., Liu, W., and Li, Z.: 1 km monthly temperature and precipitation dataset for China from 1901 to 2017, Earth Syst. Sci. Data, 11, 1931–1946, https://doi.org/10.5194/essd-11-1931-2019, 2019.
  - Strasser, U., Marke, T., Braun, L., Escher-Vetter, H., Juen, I., Kuhn, M., Maussion, F., Mayer, C., Nicholson, L., Niedertscheider, K., Sailer, R., Stötter, J., Weber, M. and Kaser, G. (2018): The Rofental: a high Alpine research basin (1890 m – 3770 m a.s.l.) in the Ötztal Alps (Austria) with over 150 years of glaciological and hydro-meteorological observations, Earth Syst. Sci. Data, 10, 151-171, https://doi.org/10.5194/essd-10-151-2018.
  - Vernay, M., Lafaysse, M., Hagenmuller , P., Nheili , R., Verfaillie , D., & Morin , S. (2019). The S2M meteorological and snow cover reanalysis in the French mountainous areas (1958 - present)[Data set]. AERIS. https://doi.org/10.25326/37
- 150 years of glaciological and hydrometeorological data for the Rofental are documented in Strasser et al. (2018), available at https://doi.org/10.5194/essd-10-151-2018. All new data since 2017 is made available in 10 min timesteps at https://www.pangaea.de/?q=%40ref104365. For the documentation of the new station at Proviantdepot, and the new sensors at all three locations, including all data, an ESSD paper follow-up is in preparation (Warscher et al. 2020). Like the first ESSD paper, this publication will again also include the contributions by the Department of Atmospheric and Cryospheric Sciences of the University of Innsbruck, Geodesy and Glaciology of the Bavarian Academy of Sciences and Humanities, and the Hydrographic Service of Tyrol.
- Selected measurements of the Bella Vista and Latschbloder sites are operationally visualized by the European Avalanche Warning Services EAWS at https://avalanche.report/weather/measurements and https://www.lawis.at/station/.

- The death of Hochjochferner is documented at https://blogs.egu.eu/divisions/cr/2020/01/17/education-in-glaciology-witnessing-the-death-of-a-glacier.
- Warscher, M., Prinz, R., Mayer, C., Niedertscheider, K., Nicholson, L. and Strasser, U. (2020): The high Alpine research basin Rofental (1890-3770 m a.s.l.) in the Ötztal Alps (Austria): Snow reference stations and extending 150 years hydrometeorological and glaciological datasets, Earth Syst. Sci. Data (in preparation).

b. Analysis
  - see above

c. Processes
  - see above

d. Modeling
  - see above

e. Application
- https://github.com/NCAR/icar
- https://github.com/NCAR/gard

f. Technology Transfer
  - see above

g. Capacity Building
  - see above

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

a. Observations and Predictions of Precipitation
  - This is a fundamental aspect of INARCH with respect to mountain precipitation

b. Global Water Resource Systems
  - This is a focus for river that have mountain headwaters - these are about 50% of human water supplies around the world.

c. Changes in Extremes
  - Extreme flood events in mountains are covered as are GLOFS, glacier lake outburst floods.

d. Water and Energy Cycles
  - The coupled water and energy cycle is intrinsic to cold regions hydrology that is the core of INARCH.

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

- TBD

Contributions to WCRP including Current Grand Challenges

Briefly list any specific areas of your panel's activities in particular to the grand challenges "Extremes" and "Water for the Food Baskets" which is not covered under 2.

- TBD

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

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

- Collaboration with UNESCO IHP and information collaboration with SPICE and Global Cryosphere Watch (CliC).

- Contribution to developing the WMO High Mountain Summit
- 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 2020

Meeting title, dates and location.

- Presentations at conferences:
- Gutmann, ED, L Bearup, TH Painter, K Andreadis, 2020a: Spatial Heterogeneity of Snow Affects Remote Sensing, Modeling, and Data Assimilation Interpretation. 100th American Meteorological Society Annual Meeting
- Gutmann, ED, Thomas H Painter, Lindsay Bearup, Konstantinos Andreadis, Carrie Vuyovich, Glen E Liston, Dylan Reynolds, Jessica D Lundquist 2020b: Heterogeneity of Mountain Snow: Measurement, Modeling, and Implications. 19th Conference on Mountain Meteorology
- Gutmann, ED; K Ikeda, J Hamman, JR Arnold, R Rasmussen 2020c: Understanding Heterogeneity to Improve Snow-albedo Feedbacks in a Simplified Regional Climate Model (invited). AGU Fall Meeting 2020
- Gutmann ED, Kristi R Arsenault, Carrie Vuyovich, Glen E Liston, Adele Reinking, Alessandro Fanfarillo, Andrew James Newman, Jessica D Lundquist, Barton A Forman, Shugong Wang, Melissa Wrzesien, and Jeffrey Richard Arnold 2020d: Multi-scale Snow-Atmosphere Interactions Over Mountain Snowpack for Climate Applications (invited). AGU Fall Meeting 2020
- Lundquist, JD; SE Dickerson-Lange, ED Gutmann, T Jonas, D Reynolds 2020: Which Family Trees of Snow Interception Modeling History have the Essentials for Success? AGU Fall Meeting 2020
- Raleigh MS, Ethan D Gutmann, and John T Van Stan II, 2020: Quantifying canopy-intercepted snow mass from tree sway observations: a demonstration over six winters in a subalpine coniferous forest. AGU Fall Meeting 2020.
- Reynolds, Dylan; Bert Kruyt, Ethan D Gutmann, Tobias Jonas, Michael Lehning and Rebecca Mott 2020: Improvements to an intermediate complexity atmospheric model for high-resolution downscaling in very complex terrain. AGU Fall Meeting 2020.

List of Workshops and Meetings Planned in 2021 and 2022

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

- The 5th Annual INARCH Workshop, originally planned for March 31 – April 1, 2020, has been cancelled due to COVID-19. We will look to hold another in-person meeting when the circumstances allow. In the interim, we are exploring options for a virtual gathering.

Other Meetings Attended On Behalf of GEWEX or Panel in 2020

- COP25, Madrid 2019
- WMO High Mountain Summit, Geneva, Oct 2019
- WMO/Arctic Council Earth System Modelling Workshop, Nov 2019 Iceland

Publications during Reporting Period

List of Key Publications

- Abegg, B., Morin, S., Demiroglu, C., François, H., Rothleitner, M. and Strasser, U. (2020): Overloaded! Critical revision and a new conceptual approach for snow indicators in ski tourism, Int. J. Biomet., https://doi.org/10.1007/s00484-020-01867-3.

- Aksamit, N. O., and Pomeroy, J. W.: Scale Interactions in Turbulence for Mountain Blowing Snow, J. Hydrometeor., 19, 305–320, https://doi.org/10.1175/JHM-D-17-0179.1, 2018.
- Aksamit, N. O. and Pomeroy, J. W.: Warm-air entrainment and advection during alpine blowing snow events, The Cryosphere, 14, 2795–2807, https://doi.org/10.5194/tc-14-2795-2020, 2020.
- Alonso-González, E., López-Moreno, J. I., Navarro-Serrano, F., Sanmiguel-Vallelado, A., Aznárez-Balta, M., Revuelto, J., & Ceballos, A. (2020). Snowpack sensitivity to temperature, precipitation, and solar radiation variability over an elevational gradient in the Iberian mountains. Atmospheric Research, 104973, https://doi.org/10.1016/j.atmosres.2020.104973.
- Alonso-González, E., Gutmann, E., Aalstad, K., Fayad, A., and Gascoin, S. 2020: Snowpack dynamics in the Lebanese mountains from quasi-dynamically downscaled ERA5 reanalysis updated by assimilating remotely-sensed fractional snow-covered area, Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2020-335, in review.
- Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L.M., Coppola, E., Eckert, N., Fantini, A., Giacona, F., Hauck, C., Huss, M., Huwald, H., Lehning, M., López-Moreno, J.-I., Magnusson, J., Marty, C., Morán-Tejéda, E., Morin, S., Naaim, M., Provenzale, A., Rabatel, A., Six, D., Stötter, J., Strasser, U., Terzago, S. and Vincent, C. (2018): The European mountain cryosphere: a review of its current state, trends, and future challenges, The Cryosphere, 12, 759-794, https://dx.doi.org/10.5194/tc-12-759-2018.
- Blöschl, G. and many others (e.g., Strasser, U.) (2019): Twenty-three Unsolved Problems in Hydrology (UPH) – a community perspective, Hydrol. Sci. J., https://doi.org/10.1080/02626667.2019.1620507.
- Bolibar, J., Rabatel, A., Gouttevin, I., Galiez, C., Condom, T., and Sauquet, E. (2020a) Deep learning applied to glacier evolution modelling, The Cryosphere, 14, 565–584, https://doi.org/10.5194/tc-14-565-2020, 2020.
- Bolibar, J., Rabatel, A., Gouttevin, I., and Galiez, C. (2020b) A deep learning reconstruction of mass balance series for all glaciers in the French Alps: 1967–2015, Earth Syst. Sci. Data, 12, 1973–1983, https://doi.org/10.5194/essd-12-1973-2020, 2020.
- Cluzet, B., J. Revuelto, M. Lafaysse, F. Tuzet, E. Cosme, G. Picard, L. Arnaud and M. Dumont (2020) Towards the assimilation of satellite reflectance into semi-distributed ensemble snowpack simulations, Cold Regions Science and Technology, 170, https://doi.org/10.1016/j.coldregions.2019.102918
- DeBeer, C. M., Wheater, H. S., Pomeroy, J. W., Barr, A. G., Baltzer, J. L., Johnstone, J. F., Turetsky, M. R., Stewart, R. E., Hayashi, M., van der Kamp, G., Marshall, S., Campbell, E., Marsh, P., Carey, S. K., Quinton, W. L., Li, Y., Razavi, S., Berg, A., McDonnell, J. J., Spence, C., Helgason, W. D., Ireson, A. M., Black, T. A., Davison, B., Howard, A., Thériault, J. M., Shook, K., and Pietroniro, A.: Summary and synthesis of Changing Cold Regions Network (CCRN) research in the interior of western Canada – Part 2: Future change in cryosphere, vegetation, and hydrology, Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2020-491, in review, 2020.
- DeBeer, C. M., Sharp, M., and Schuster-Wallace, C.: Glaciers and Ice Sheets, In: Goldstein, M.I., and DellaSala, D.A. (Eds.), Encyclopedia of the World's Biomes, 4, Elsevier, 182–194, https://doi.org/10.1016/B978-0-12-409548-9.12441-8, 2020.
- De Gregorio, L., Günther, D., Callegari, M., Strasser, U., Zebisch, M., Bruzzone, L. and Notarnicola, C. (2019): Improving SWE Estimation by Fusion of Snow Models with Topographic and Remotely Sensed Data, Remote Sensing, 11, 2033, https://doi.org/10.3390/rs11172033.
- De Gregorio, L., Callegari, M., Marin, C., Zebisch, M., Bruzzone, L., Demir, B., Strasser, U., Marke, T., Günther, D., Nadalet, R. and Notarnicola, C. (2019): A novel data fusion technique for snow cover retrieval, Journal of Selected Topics in Applied Earth Observations and Remote Sensing JSTARS, Vol. 12, No. 8, https://doi.org/10.1109/JSTARS.2019.2920676.
- Deschamps-Berger, C., Gascoin, S., Berthier, E., Deems, J., Gutmann, E., Dehecq, A., Shean, D., and Dumont, M.: Snow depth mapping from stereo satellite imagery in mountainous terrain: evaluation using airborne laser-scanning data, The Cryosphere, 14, 2925–2940, https://doi.org/10.5194/tc-14-2925-2020, 2020.
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Lafaysse, M., Lejeune, Y., Marke, T., Marks, D., Marty, C., Menard, C. B., Nasonova, O., Nitta, T., Pomeroy, J., Schaedler, G., Semenov, V., Smirnova, T., Swenson, S., Turkov, D., Wever, N., and Yuan, H.: Snow cover duration trends observed at sites and predicted by multiple models, The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-182, in review, 2020.

- Fang, X. and Pomeroy, J. W.: Diagnosis of future changes in hydrology for a Canadian Rockies headwater basin, Hydrol. Earth Syst. Sci., 24, 2731–2754, https://doi.org/10.5194/hess-24-2731-2020, 2020.
- Förster, K., Garvelmann, J., Meißl, G. and Strasser, U. (2018): Modelling forest snow processes with a new version of WaSiM, Hydrol. Sci. J., https://dx.doi.org/10.1080/02626667.2018.1518626.
- Förster, K., Hanzer, F., Stoll, E., Scaife, A. A., MacLachlan, C., Schöber, J., Huttenlau, M., Achleitner, S. and Strasser, U. (2018): Retrospective forecasts of the upcoming winter season snow accumulation in the Inn headwaters (European Alps), Hydrol. Earth Syst. Sci., 22, 1157-1173, https://dx.doi.org/10.5194/hess-22-1157-2018.
- Gascoin, S., Barrou Dumont, Z., Deschamps-Berger, C., Marti, F., Salgues, G., López-Moreno, J.I., Revuelto, J., Michon, T., Schattan, P. and Hagolle, O., 2020. Estimating fractional snow cover in open terrain from Sentinel-2 using the normalized difference snow index. Remote Sensing, 12(18), p.2904, https://doi.org/10.3390/rs12182904.
- Günther, D., Hanzer, F., Warscher, M., Essery, R. and Strasser, U. (2020): Including parameter uncertainty in an intercomparison of physically-based snow models, Frontiers in Earth Sciences (accepted).
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- Hanzer, F., Förster, K., Nemec, J. and Strasser, U. (2018): Projected hydrological and cryospheric impacts of 21st century climate change in the Ötztal Alps (Austria) simulated using a physically based approach, Hydrol. Earth Syst. Sci., 22, 1593-1614, https://dx.doi.org/10.5194/hess-22-1593-2018.
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