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Meeting Abstracts

Runoff Processes in Alpine Catchments: Challenges and Opportunities

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Runoff hydrology has a rich history of research on the mechanisms and pathways of how water is transferred from the catchment to the stream network. This work is primarily derived from observations in humid temperate mid-latitude watersheds with moderately sloping terrain and well-developed soil profiles. Runoff generation processes such as variable source area, transmissivity feedback, and fill-and-spill now dominate the literature and guide our model development. Unfortunately, runoff processes investigations in alpine catchments, particularly those dominated by glaciers, snow and frozen ground, are particularly scarce and it is unclear how concepts from more temperate latitudes apply. In this presentation, I will review the current paradigms of streamflow generation in alpine regions, highlighting the importance of surface-groundwater interactions, frozen soils, permafrost and other distinct alpine features. Data from several alpine watersheds will demonstrate the importance of the coupled energy and water cycles, and emphasise the how our understanding is advanced through multiple methodological approaches approaches (e.g. hydrometric, hydrochemical, geophysical, modelling) to refine our understanding of the timing, rates and pathways of runoff in this logistically challenging environment. Future opportunities and research directions will also be highlighted.

The 2010 Chile Mega-drought and its impacts on snow and glacier hydrology.

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Since 2010, a series of below-average hydrometeorological conditions in south-western south America has come to be labeled the “Chilean Mega-drought”. Although none of the individual years has been drier than the driest year on record, the extent and duration of the drought make it unprecedented in modern times. Snow and glacier regimes in the semiarid Andes of central Chile and Argentina have been affected, and this presentation attempts to summarize these effects by providing an overview of meteorological precursors, observations and modeling results. We show how Atmospheric Rivers have a significant role in explaining interannual snow accumulation variability, present observations from experimental catchments in the region, and discuss modeling results that attempt to predict the impact of drying conditions on snow dynamics and glacier mass balance.

Sagehen Creek Watershed, Sierra Nevada, USA: A long-term dataset for investigating groundwater-mediated streamflow response to variable maritime snowmelt and rainfall

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Sagehen Creek watershed is a forested research watershed in the Sierra Nevada Mountains about 30 km north of the town of Truckee, California. It was established by University of California (UC) Berkeley to focus on fish spawning and mortality and remains a UC Reserve with long-term monitoring over a large elevation gradient (1962-2541m). Annual precipitation is ~800 mm, with most falling as snow in the winter and upper parts of the basin receiving 2-3 times more precipitation than lower elevations. The watershed is underlain by volcanic bedrock with high groundwater storage, resulting in numerous wet meadows and high summer baseflow. Sagehen contains streamflow records beginning in 1953 collected by the U.S. Geological Survey (USGS), three Snow Telemetry (SNOTEL) stations beginning in 1980 but with snow courses back to 1932, COOP meteorological station with temperature and precipitation data since 1953 (1934m); and three towers (1934, 2114, and 2350 m) have measured temperature, humidity, wind, and radiation since 2009. Sagehen also has substantial remote sensing records, including numerous snow-on and snow-off lidar overfights. A recent resurgence of activity by Drs. Adrian Harpold (University of Nevada, Reno) and Jim Kirchner (ETH-Zurich) has resulted in more distributed snow and soil moisture measurements, as well as sap flow and eddy covariance systems. Current research foci are towards runoff generation processes, spatiotemporal variability in evapotranspiration and energy, tree water use, snow-forest interactions, snow energetics and rain on snow processes, and development of models and remote sensing validation.

Current status of meteorological and snow observations and reanalysis available in the French Alps.

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CNRM/CEN maintains two main experimental snow observatories in the French Alps : Col de Porte and du Lac Blanc (along with IRSTEA). Col de Porte is a mid-latitude mountain site (1325 m a.s.l.) located in Chartreuse massif (French Alps). For Col de Porte, a large database of observations, including weekly snow profiles but also meteorological and snow variables on a daily (1960-2017) to hourly basis (1993-2017) is available. Col du lac Blanc is a high altitude experimental site, located in Grandes Rouses massif (French Alps), initially designed for the study of snow-wind interactions. The dataset of meteorological and snow variables extends from 2010 to 2017. In the frame of INARCH network, snow and meteorological data from both sites have been made available for the scientific community. This presentation details the dataset from both sites.
In addition, this work describes the latest reanalysis release of snow-related simulations now covering 60 years over the French Alps. These simulations comprise: SAFRAN meterological reanalysis, Crocus

snowpack simulations and MEPRA avalanche risk analysis. This system is named S2M, the acronym of SAFRAN, SURFEX (land surface model comprising Crocus model) and MEPRA.
These in situ and simulations products are complemented by a wide database of remote sensing products from optical (Sentinel-2, SPOT6-7 and Pléaides) and radar (ALOS2 and Sentinel-1) sensors that are gathered on the kalideos project web site (www.kalideos.cnes.fr), also described in this work.

The key role of terrestrial imagery in semiarid mountainous areas: The snow monitoring system in Sierra Nevada (Spain)

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Snow resources play a key role in the hydrological regime in mountain areas in Mediterranean regions. However, the high variability of snow over these areas (i.e. the several accumulation-melting cycles throughout the year, with very different duration; the wide range of snow depth states, close to the order of magnitude of the surrounding micro-relief (1-1000m); and the particular patched snow distribution, ranging from one to hundreds of square meters) makes necessary accurate monitoring system that cover all these particularities. On one hand, the correct representation of precipitation, partially solved with the installation of more dense precipitation network at high elevation, but still with problems related with the discrimination between rain and snowfall. On the other hand, the need of high resolution snow cover maps, highly improved with a recent increasing number of high resolution satellite missions launched and the development of fusion algorithm that combines them with traditional ones, but without standardized ground-truth datasets to verify that algorithms and validate the new products

This work presents terrestrial imagery as part of the snow monitoring network in Sierra Nevada (Spain) highlighting its value as complementary measurements of the traditional monitoring instrumentation and as ground-truth data source for the retrieving and validation of snow maps algorithms. Selected locations were chosen for the installation of several time-lapse cameras on different spatial scales above 1200 m a.s.l. with different purposes. On the point scale, as complementary sensor installed in some of the meteorological stations (Refugio Porqueira, Cortijuela), they allow discriminating possible errors in precipitation observations (i.e. undercatch and rain on snow events). On the detail scale (Refugio Poqueira), they facilitate the generation 30x30m sub daily times series of snow cover area and snow depth are derived for the modelling of the snow processes on the subgrid scale (i.e. the definition of adapted depletion curves for semiarid environment). On the slope scale, (El Caballo hillslope) they provided a 2x2 km reference maps to validate fractional snow cover maps from different algorithms/satellite sensors sources; and replicates of these scales on different points throughout the study area (i.e. the direct validation of NDSI and spectral mixture models for retrieving of snow maps from Landsat).

Thus, snow variable times series derived from terrestrial photography constitute a validated reference data set to test the accuracy of snow products algorithms in complex environments. Besides its use as raw observation datasets to calibrate and validate models' results, terrestrial photography constitutes valuable information to complement weather stations observations.

How interactions between climate and vegetation impact hydrological processes in mountain headwater basins

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Source water from headwater basins along the North American Cordillera, provides a large proportion of the water for downstream hydroelectric operation, agriculture, industry, and municipal water supplies, and may be vulnerable to climate and accompanying vegetation changes. To investigate the sensitivity and response of headwater hydrologic response to climate and vegetation changes, physically-based, semi-distributed, hydrological models, using the Cold Regions Hydrological Modelling platform were driven with climate model-based perturbations of observations from instrumented research basins. Three research basins representative of high, mid and lower latitude cold regions basins in the Cordillera; Wolf Creek in Yukon Territory, Marmot Creek in the Canadian Rockies, and Reynolds Mountain East in Idaho, provided the observations. Simulations show that the effects of warming on peak snowpack and annual runoff can be offset by an increase in precipitation; however, the amount of offset varies with latitude. At lower and mid-elevations of these basins, vegetation change and climate change both act to decrease peak snowpack, snow transport, and sublimation. At high elevations, however, the effects of climate change on snowpack and runoff are partially offset by those of vegetation change. In simulations, vegetation changes counteract climate change effects on runoff volume, which has important consequences for future mountain basin water balance.

The hydrological role of glaciers in the Atacama Desert

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Water is a critical resource in the northern and central regions of Chile, as the area supports more than 40% of the country’s population, and the regional economy depends on agricultural production and mining, which are two industries that rely heavily on a consistent water supply. Due to relatively low rates of rainfall, meltwater from snow and ice bodies provides most of the annual water supply in these areas. Consequently, accurate estimates of runoff from the cryosphere are crucial for predicting current supply rates and future projections. While snow is generally a larger contributor of freshwater, during periods of drought ice bodies provide a significant source. In this talk, I will describe the results of ongoing field and modelling studies which aim to determine melt and sublimation rates of snow and ice bodies, as well as quantify the contribution of glaciers and rock glaciers to streamflow in the semiarid Andes. I will outline our advances as well as methodological considerations guiding our current and future research plans, focusing predominantly on glaciers and rock glaciers.

The first National Glacier Inventory of Argentina

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Glaciers are strategic water reserves and crucial components of the hydrological cycle in many sectors of the southern Andes. However, despite their socio-economic, scientific, cultural and environmental relevance, the current state and recent variations of glaciers in Argentina was poorly known. The National Law 26639 entitled "Minimum Standards for the Preservation of Glaciers and the Periglacial Environment" was promulgated in 2010, and included as one key objective the development of a National Glacier Inventory (NGI). The NGI was organized in three levels of increasing complexity and decreasing spatial coverage, with Level 1 consisting in the identification, mapping and characterization of all clean ice glaciers, debris-covered glaciers, snowfields and rock glaciers using satellite images. This level also included field campaigns to validate the glacier mapping in selected areas throughout the Andes. The first NGI (Level 1) was recently concluded and presented by IANIGLA-CONICET and the National Secretary of the Environment and Sustainable Development. The results indicate a total of 16078 ice masses covering a surface area of 5769 km2 in the Argentinean Andes between ca. 21° and 55°S. In this talk we will briefly discuss additional details about this first NGI and potential applications in glaciological, hydrological and climatological studies.

Ensemble Empirical Mode Decomposition for streamflow data analysis of snow-fed rivers along Central Andes of Argentina

Juan Rivera, Argentine Institute for Snow Research

Temporal variations in streamflow have crucial influences on the regional water resources in arid regions such the Central Andes of Argentina, where snowmelt is the main water source of the major rivers of the region. In order to identify non-stationary oscillations and long-term trends, we applied the Ensemble Empirical Mode Decomposition (EEMD) to centennial streamflow time series along the Central Andes of Argentina. This adaptive method allowed the identification of interannual and interdecadal modes of variability, which were linked to El Niño/La Niña occurrences and the Pacific Decadal Oscillation. Moreover, a declining long-term trend was found along the study area, which overlaps with the marked increase in demand of water for agriculture, energy production, industry and human consumption.

Snow depth distribution and storm events of high mountain Central Chile: A new experimental setup

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The quantity of water storage in the Chilean Andes is highly important for industry, agriculture and water supply to the region (approximately 40% of Chile's population live in Santiago), though remains poorly understood. Lack of high elevation in situ observations, combined with the complex topography of the Andes range, make predictions about the spatial and temporal variability of snow water equivalent difficult.

A particular uncertainty is associated with the preferential deposition and re-distribution of snow during storm events, which may be amplified by dry conditions of the region. Here we present the details of a newly established experimental catchment with the purpose of understanding local effects of wind on spatial snow depth distribution. Our setup combines multiple in situ observations between a 14 wirelessly networked automatic weather stations (recording air temperature, relative humidity, sonic snow depth and sonic wind speed and direction) and repeat high resolution scans of a VZ6000 terrestrial LiDAR (Light Ranging and Detection) system. We explore potential applications of our dataset at high elevation (~3500-3800 m a.s.l.) and provide a brief comparison of distinct scan periods.

A golden era for alpine catchments: the convergence of high-resolution atmospheric modeling, remote sensing, and hydrology

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Hydrology is often a data starved science. The amount of information required to fully characterize the hydrologic response of a basin is vastly greater than the number of observations available, even in heavily instrumented research basins. Key data gaps range from the precipitation and wind fields required for input to hydrologic models, to the vegetation and soil properties required to parameterize a hydrologic model, to the hydrologic states such as groundwater levels, soil moisture content, and snow water equivalent required to characterize the hydrologic processes and assess how well our hypotheses – often in the form of numerical models – match reality.

The nature of this problem is now changing such that hydrologists are often overwhelmed by data, though not always the data they would like. Estimates of precipitation and near surface wind speeds can be greatly improved through integrating recent advances in high-resolution atmospheric modeling, with satellite and surface precipitation radars adding additional information about both precipitation and even wind fields. In addition, novel remote sensing measurements from airborne lidar to high-frequency cube-sat imagery to hyperspectral imaging spectrometry provide enormous volumes of data for assessing the response of snow and vegetation. Finally, a long history of surface thermal measurements from satellites provides an untapped reservoir of information about the land surface. The challenge facing hydrologists now is how best to integrate and make use of these disparate data sources to better understand the hydrologic response of alpine catchments.

Decoupling of mountain snowpacks from hydrology due to climate warming

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Storage of winter snowfall in the seasonal snowpack and its subsequent release in spring as meltwater is key to understand runoff generation and its seasonality in many mountain basins. It is widely accepted that a warmer climate will reduce duration and magnitude of snowpack, will reduce spring runoff and probably will also affect the annual water balance. It is often assumed that the magnitude of these processes will be proportional to the intensity of the warming. This paper uses bias-corrected reanalysis data and the Cold Regions Hydrological Model to simulate snowpack and streamflow regimes of idealized catchments in 44 mountain regions of the world. The simulations are used to illustrate the existence of complex behaviour and substantial deviation from the hypotheses mentioned above, with very strong regional differences in the sensitivity of snow accumulation and duration to climate warming. As temperature increases, the river regimes tend to synchronize to the precipitation regimes, and the contribution of snowmelt to annual runoff is reduced. But, annual runoff is not strongly affected by changes in the seasonal snowpack. Overall the result show increased decoupling of snow regimes, snow hydrology and basin hydrology with increased warming, but with substantial regional variations in how this occurs. There are substantial regional variations in the magnitude of these changes in the hydrograph which are not always well related with the observed sensitivity of snowpack. Identifying the drivers of the variable response of snowpack and snow hydrology can help explain the desynchronization of snowpack and streamflow regimes with warming. This permits identification of the most vulnerable mountain areas to projected climate change.

Snow albedo and its physical controls from the NASA Surface Biology and Geology (SBG) imaging spectrometer mission: Global distribution of cal/val from INARCH

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Decades of satellite, airborne, and ground observations clearly show increased melting of glaciers and ice sheets, declines in sea ice, and decreasing spring snow cover. This increased melting of cryosphere cover makes Earth more absorptive of sunlight and moves enormous volumes of stored water from frozen state to liquid, raising sea level and changing water availability to large populations. However, the distribution of forcings controlling this accelerated melting is poorly known.

Atmospheric warming from greenhouse gases is contributing to this acceleration but its magnitude is uncertain due to our uncertainties in the controls on the dominant contributor to annual melt, absorbed sunlight, itself controlled by albedo. Despite this crucial role of albedo and solar radiation in snow and ice melt, sparse measurements have kept us from understanding the global distribution of controls on albedo, grain size (GS) and impurities, and from accurately modeling melt processes worldwide. Such an understanding is crucial to determining cryosphere melt and projecting its future behavior. To understand the current distribution of these powerful snow process forcings and their relative importance, the 2017 Earth Science Decadal Survey adopted the *Surface Biology and Geology* VSWIR imaging spectrometer concept as a Designated Measurement.

Here we describe the spectroscopic retrievals of snow grain size, radiative forcing by dust and black carbon, spectral albedo, and broadband albedo as used with the NASA Airborne Visible/Infrared Imaging Spectrometer (Classic and Next Generation) and the NASA Airborne Snow Observatory. We present the uncertainties in global to mesoscale climate modeling of snow melt from current uncertainties in grain size and radiative forcing. We present the mission requirements for such retrievals and the associated science in the context of the *SBG* concept.

Most germane to INARCH is a proposal described here to supplement the INARCH network's measurements with in situ VSWIR spectrometers to provide calibration and validation of snow spectral hemispherical-directional reflectance factors, snow albedo, snow grain size, and radiative forcing by light absorbing particles. INARCH's growth globally and the measurements of SBG will be synergistic in providing cryosphere and water cycle process understanding to ultimately constrain physically-based models.

Can MODIS reflectance assimilation improve snowpack simulations in alpine terrain?

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Uncertainties of meteorological forcing and shortcomings in the modelling of snow physical processes, when accumulated on time along a snow season, could produce large deviations in the simulations from real snowpack state. Ensemble snowpack simulations generated from an ensemble of meteorological forcings and snowpack model configurations have recently demonstrated a good capability on representing snowpack evolution. However, such ensemble simulations need to be combined with assimilation techniques in order to reduce the spread of the ensemble.

This work presents the first results of assimilating snow surface reflectance and snow covered areas in a ensemble of Crocus snowpack simulations with a particle filter technique. The study site where the evaluation is performed is the Col du Lautaret study area (French Alps). The evaluation compares the impact on the ensemble simulations of assimilation either "synthetic observations" (one member of the ensemble selected as an observations) or "real observations" from MODIS satellite imagery. Despite the results are prefatory, they show a good potential improving snowpack forecasting capabilities, reducing the spread of the ensemble. However, for particular dates, important differences between MODIS and simulated reflectances for particular bands, only allowed the assimilation of "synthetic observations" what shows the necessity of understanding the origin of this disagreement and improving assimilation techniques.

Simulating hydrological processes at two mountainous sites underlined by continuous permafrost in northern Yukon, Canada

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High latitude mountainous regions are typically underlined by sporadic, discontinuous or continuous permafrost, which plays a key role in the energy and mass fluxes exchange between the atmosphere, surface and sub-surface. However, a robust and reliable representation of the active layer thickness remains a great challenge in this remote and poorly understood environment. This study presents observations and simulations of permafrost thaw and snow accumulation and melt at two research sites in the mountains of northern Yukon, Canada. The stations are operative since 2014 and measure standard meteorological variable, liquid and solid precipitation, and soil temperature and water content profile. Point-scale models were set up at both sites using the Cold Regions Hydrological Model (CRHM) platform, including new modules to simulate permafrost. The model was set up using observed physical characteristics and parameters taken from previous studies under similar hydrological conditions. The model showed to properly simulate daily ground surface temperature with small bias (≤±0.5°C) and high correlation (r^2>0.85), and the active layer depth with a mean bias of -1.6 and -11 cm at the northern and southern site, respectively. Observed snow water equivalent from snow survey is underestimated by the model (mean bias ≤41 mm), likely due to snow undercatch. A sensitivity analysis of the key soil thermal properties and porosity to the active later simulations was performed using reference values from the literature. This study demonstrates the capabilities of the new modules included in CRHM that can be used to inform other studies in cold region environments.

Impact of meteorological forcing data on snowpack and streamflow simulations in the Canadian Rockies

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This study evaluates hydrological simulations of streamflow and snowpack regimes in the Canadian Rockies using various sources of meteorological forcing data. Hydrological models were created using the Cold Regions Hydrological Modelling platform (CRHM) for two mountain forest headwater basins: Marmot Creek Research Basin (~9.4 km^2) and Fortress Mountain Basin (~5.9 km^2). These models were parameterized from local field research findings to represent the relevant streamflow generation processes: wind redistribution of alpine snow, snow avalanching on steep alpine slopes, snow interception, sublimation, drip and unloading from forest canopies, infiltration to frozen and unfrozen soils, overland and detention flow, hillslope sub-surface water redistribution, and evapotranspiration from forests, clearings and alpine tundra. In-situ hourly observations from 14 high altitude weather stations, near-surface output from Environment and Climate Change Canada's 2.5-km Global Environmental Multiscale (GEM) atmospheric model in forecast mode (no bias correction), and bias corrected near-surface outputs from the 4-km Weather Research and Forecasting (WRF) model were

used to drive the hydrological models. Air temperature, relative humidity, wind speed, incoming shortwave radiation, and precipitation were extracted from stations and atmospheric models over each basin, and then interpolated by elevation to hydrological response units within each basin to drive the hydrological models over November 2014 to August 2017. Simulations of snowpack and streamflow using station data were acceptably good without calibration of model parameters. The snowpack simulations using GEM showed errors as modelled wind fields did not reflect the high wind speeds measured over ridges and GEM misrepresented winter precipitation dynamics. Streamflow simulation using GEM output for Marmot Creek was impacted by overestimation of late-lying snowcovers in the alpine due to overestimation of precipitation, while underestimation of precipitation from GEM output caused poor streamflow simulation for Fortress Mountain Basin. GEM-driven models therefore missed both the timing and magnitude of seasonal streamflow. WRF outputs were bias corrected using the quantile delta mapping (QDM) method with respect to station data during October 2005-September 2013 at Marmot Creek. Snowpack and streamflow simulations using the bias-corrected WRF outputs were much better than these using uncorrected outputs and achieved comparable predictability to simulations driven by station data.

Mapping high elevation spatial snow depths using tri-stereo optical satellite imagery

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Within the semi-arid Andes of Central Chile (33 - 36°S), the mountain snowpack represents a significant socio-economic importance and a sharp contrast to the limited, seasonally-dependent precipitation occurring at low elevations. Recent 'mega-drought' years have heightened the importance of water storage in the Central Andes, though there remains much uncertainty as to the quantity and spatial distribution of the high altitude snowpack. Despite a sound knowledge of snow processes, highly complex terrain and data scarcity generate difficulties for numerical modelling attempts, which may rely upon simple assumptions. These assumptions regularly fail to capture the heterogeneity of spatial snow depths that can be dictated by interaction of topographical and meteorological factors, which then translates into uncertainty of the simulated seasonal hydrograph response.

Measurement strategies for deriving spatial snow depth are numerous but can be limited by accessibility (Probe measurements), cost, range (airborne Light Detection and Ranging (LiDAR)), ground control (Airborne Structure from Motion), topographic shadowing (terrestrial LiDAR) or spatial resolution (gridded satellite products). Accordingly, we explore a recently developed methodology for deriving spatial snow depth from optical stereo image triplets of the French (CNES) Pléiades 1A and 1B satellites, following the approach of Marti et al. (2016). The method shows merit and here we highlight the advantages and drawbacks compared with alternative measurements/estimations.