Soil State Monitoring during Fall 2022 and Winter 2023 at an Experimental Site in Ontario, Canada to Support L- and Ku-band SAR Observations of Snow from the CryoSAR Airborne System

ZEINAB AKHAVAN[1], RICHARD KELLY[1], AARON THOMPSON[1], AND PETER TOOSE[2]

ABSTRACT

During the 2022-2023 winter season, field measurements were taken to monitor the variations in the soil moisture and freeze-thaw state of the near-surface soil under both snow-free and snow-covered conditions. Measurements of soil moisture and temperature parameters were conducted across six stations to track the soil freeze-thaw oscillations over these field sites. Each station was equipped with two Steven's Hydra Probe soil sensors (installed vertically), capable of measuring the soil moisture, temperature, permittivity, and electrical conductivity parameters from the top 0-5.7 cm of soil. The Hydra Probe uses the potential of the radio wave (50 MHz) reflected back from the soil to calculate soil's dielectric permittivity. The magnitude of the complex dielectric permittivity is subject to fluctuations of moisture and salt present in the soil. Additional multiple i-button temperature loggers were installed to measure the temperature at different depths. Airborne CryoSAR observations of the field site were conducted using a multi-frequency fully polarimetric Synthetic Aperture Radar (SAR) system operating at Ku- (13.5 GHz) and L-band (1.3 GHz) with the aim of characterizing the freeze-thaw state of the underlying soil more comprehensively for research into snow mass estimation. This paper describes the variations in soil moisture status at the six soil stations during the winter (in solid and liquid format) and the response from the Ku- and L-band SAR observations. This work is being conducted to support the Terrestrial Snow Mass Mission in planning at Environment and Climate Change Canada and the Canadian Space Agency.

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Verification and Analysis of the NOAA/NWS Baltimore/Washington Weather Forecast Office Winter Storm Threat Experimental Product

CONNOR BELAK[1] AND BRIAN LASORSA[1]

ABSTRACT

Information about winter storms occurring in the medium range (days 3-7) is in high demand by emergency managers, transportation planners, the general public, and broadcast/print media. The NOAA/National Weather Service Baltimore/Washington Weather Forecast Office (WFO LWX) developed and implemented an experimental product in 2016 that assesses and depicts both forecaster confidence and potential impact for winter storms in the medium forecast range. This publicly available experimental product is called the Days 3-7 Winter Storm Threat (WST). The WFO LWX Days 3-7 WST experimental product is designed for easy interpretation by general users, while also displaying uncertainty information for decision makers.

The WST product integrates data from the National Blend of Models (NBM), the National Centers for Environmental Prediction (NCEP)/Weather Prediction Center (WPC), and local expertise from WFO LWX staff. This local expertise is derived from forecaster experience working with core customers, combined with knowledge of local winter climatology and meteorology, to determine the level of winter storm threat. The product integrates locally-known impacts and forecaster confidence to develop the winter storm threat to a region, and is used by forecasters as a decision-making aid during impact-based decision support briefings.

This presentation will provide verification results of the WFO Days 3-7 WST from the winters of 2020-2021 through 2022-2023, analyze performance, and highlight several impactful events. Emphasis on this presentation will be the performance of the WST during Winter 2022-2023, when the algorithms were changed to become based on the NBM. The results of this research will guide future improvements to the Winter Storm Threat experimental product.

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Forest Snow Depth Mapping using Novel Sub-Canopy Unpiloted Aerial Vehicle (UAV) Flight Planning

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ABSTRACT

The spatiotemporal variability of snow depth is significantly higher within forested regions as compared to open/flat terrain. Contrasts in canopy density and tree type results in snow accumulation/ablation differences over small spatial scales (<10 cm). It is difficult to accurately capture this using modern UAV sensors (lidar/photogrammetry) and conventional overhead lawn-mower style flight plans due to the obstructed view of the snow surface beneath dense tree canopies.

Here we present a novel, multi-step approach to enable modern day low-cost UAVs to navigate sub-canopy and to measure UAV snow depth within forest regions. First, above canopy lidar observations are normalized via real-time speed control to accurately map the location of all obstacles (trees). Second, lidar observations are used to identify free space within decreasing elevation bands. Finally, the path planning algorithm A* is applied to find optimal sub-canopy flight corridors.

These sub-canopy UAV surveys capture considerably more detail in the snow surface than conventional overhead flights. Notably, the distribution of snow accumulation surrounding tree trunks are better represented in the below canopy UAV snow depth products than conventional above canopy approaches.

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Modelling and Analysis of Cross-Polarized Radar Backscatter at C, X and Ku Bands for SWE Retrieval Algorithm

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ABSTRACT

There have been many studies of radar backscatter response to snow which include satellite (Sentinel-1), airborne (NASA SnowEx) and tower-based radar measurement (NoSREx) at C, X and Ku bands and even planned future satellite missions. These studies have been vital in developing and advancing the X and Ku dual frequency retrieval algorithm for SWE (snow water equivalent). Although the primary focus of the algorithm is the co-polarized radar backscatter, the cross-polarized signal can give important details can give important details about the snowpack as well. As such, studying and modelling cross-pol radar backscatter from snow correctly and accurately is important.

The cross-pol is predicted by modelling snow as a bi-continuous media of air and ice, controlled by grain size parameter k_c and aggregation parameter b and then solved using the DMRT (dense media radiative transfer). Parameter b is kept small ($b = 0.4$) to have clusters of ice particles which increases the cross-pol. The DMRT equations are solved iteratively, and it can be shown that cross-pol majorly contributes to the higher order terms. Including the backscattering enhancement results in 2.5-3 dB enhancement for co-pol and cross-pol backscatter, which increases the cross-pol to co-pol ratio as predicted by Sentinel-1. The cross-pol radar data is also used to reduce the need for a prior information when doing the SWE retrieval using the X and Ku dual frequency algorithm. The cross-pol radar measurements are used to do the classification of the co-pol radar data and this classification is used to drive the algorithm to find the correct solution for SWE. This method is validated using both airborne and tower radar data.

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Refining & Automating DAV Snow Melt Algorithms using Passive Microwave Calibrated Enhanced-Resolution Brightness Temperature (CETB) Data in Alaska Watersheds

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ABSTRACT

Snowmelt is vital in snow-covered regions as it provides water for groundwater recharge, agriculture, industry, and domestic use. Understanding timing and magnitude of snowmelt is essential for water cycle, seasonal distribution of runoff, and disaster management (wildfire and flooding). For years, passive microwave (PMW) brightness temperatures (Tb) have been used to identify melt-freeze dynamics in snowpack. Liquid water in snow causes an increase in emissivity, drastically increasing Tb, which can be detected through PMW remote sensing. The research employs the newly available Calibrated, Enhanced-Resolution Brightness Temperature (CETB) dataset to estimate the timing of snowmelt at higher spatial resolution (~3-6 km). Melt detection algorithms will be refined using the diurnal amplitude variation (DAV) approach established by Ramage *et al*. We will determine and automate the range and optimum Tb and DAV thresholds (legacy thresholds of 246K / ±10K for Special Sensor Microwave Imager or SSM/I) in Alaska watersheds using existing and supplemental observational and reanalysis datasets as well as different mathematical analysis, such as histogram and time series analysis, and derivatives. We expect improved melt timing and a range of thresholds sensitive to different terrain and environments. We will compare algorithm results with ground-based measurements compiled from multiple sources, such as air and snow temperatures, snow water equivalent (SWE), snow depth and stream discharge. This study offers an understanding of how the use of higher-resolution CETB data and automatic approaches can enhance snowmelt analysis, granting hydrologists the ability to examine timing and patterns of snowmelt across different regions and snow types.

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SWE Impact Index: Toward Identifying Critical Regions with SWE Observational Needs

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ABSTRACT

Seasonal snow is a vital part of the water cycle, supplying life-giving fresh water to billions of people across the United States and the world. At the same time, large snowpack with sudden melt events including rain-on-snow events leads to catastrophic extreme flood events, causing large societal and economic consequences. Even though we recognize that human societies in snow-dominant regions are somehow affected by snowpack, an open question still exists: In which regions are more accurate and timely snowpack information critically needed than other regions? Here, we propose a new "SWE Impact index" map showing regions where SWE information is relatively important across the continental U.S. The SWE Impact index is a societal index based on the historical amounts of maximum SWE, rapid snow accumulation and snowmelt, and population. Including population in the index provides a measure of the socio-economic susceptibility for the given areas. In this presentation, we will provide an overview of how we develop the SWE Impact index using a gridded SWE data and preliminary results of the index map. This work will help us identify "critical regions" where reliable SWE observations are particularly needed in terms of societal impacts.

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Assimilation of Airborne Gamma-Ray Observations Provides Utility for SWE Estimation in Forested Environments of the Northeastern United States

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ABSTRACT

An accurate estimation of snow water equivalent (SWE) has been a critical issue for water supply predictions and snowmelt-driven flood management. Data assimilation (DA) is a promising approach to improve modeled SWE estimations at a large spatial scale by merging remote sensing measurements into model predictions. In forested regions, however, most remote sensing techniques for estimating snowpack (e.g., passive microwave, photogrammetry, & lidar) is hampered by the effects of the forest canopy, resulting in large uncertainties in the SWE estimations. A well-established, but little-known airborne gamma radiation technique has provided a strong potential to estimate snowpack conditions in forested environments because the gamma-ray technique uses a difference in gamma-ray particles between snow-off and snow-on conditions by limiting canopy effects. In this study, we assimilated airborne gamma-based SWE retrievals into the Noah land surface model with multiparameterization options (Noah-MP) in the Northeastern U.S. via the NASA Land Information System framework. Our results show that assimilation of the airborne gamma-ray SWE observations improved the modeled SWE despite the limited number of gamma SWE observations (up to only four observations during the winter period) even in densely forested regions.

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Eastern Snow Conference 2020-2022: The Virtual Years

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ABSTRACT

Like all organizations, the Eastern Snow Conference (ESC) was directly impacted by the COVID-19 pandemic. And like all other organizations, the ESC adjusted and adapted to the range of real and threatened restrictions imposed by federal, regional, and local governments. Thus, the uninterrupted streak of annual ESC meetings over seven decade (1950's – 2010's) was broken, resulting in no meeting in 2020 and virtual meetings in 2021 and 2022. This new format came with a new set of benefits and challenges, many of which played out behind the scenes and were not publicly announced. This presentation will discuss what was lost and gained during these three unusual years for the ESC. Attention will be paid towards the lessons learned in hosting virtual meetings, participating in a large joint conference with other organizations, and the financial impacts on the non-profit organization of the ESC. The results suggest that the cryosphere sciences community is resilient, persistent, and supportive throughout such challenges, emphasizing the importance of organizations like the Eastern Snow Conference as a leading forum for the community.

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Post Processing Techniques for Better Surface Density Estimates for Use in Wildlife Tracking Applications

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ABSTRACT

Surface layer snow density has a direct impact on the mobility of wildlife in the winter season. There is a density threshold that determines whether or not a snowpack can support the weight of an animal. Thus, the pathing of wildlife throughout the winter is directly impacted by the spatial distribution of snow density in their habitats. We present two methods to better estimate surface density at scale. First, using a known model to determine bulk density from snow depth, we tune the model parameters with least squares adjustment using depth and surface density data from the ABoVE field campaign. Second, we developed a non-linear state model that steps through the modeling time period and incorporates satellite derived Land Surface Temperature (LST) measurements to better simulate snowpack densification resulting from melt-freeze of the snowpack surface on warm days. For the goal of wide scale wildlife tracking across Washington State, we use the NoahMP snow model within the Land Interface System Framework (LISF) to produce initial estimates of snow characteristics (multilayer density, SWE, depth). The appropriate snow characteristics are used as the inputs to both methods and we present a comparison of results and the implications for wildlife tracking purposes in Washington State.

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Comparing Active and Passive Observations of Snowmelt Refreeze in the Sierra Nevada

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ABSTRACT

The diurnal snowmelt refreeze cycle is the earliest detectable signal of melting snowpack, and therefore a valuable forecast tool for freshwater resources. There are two methods for detecting snowmelt refreeze cycles from space. Synthetic aperture radar (SAR) from the sentinel 1A and 1B satellites can provide occasional diurnal observations in certain regions of the planet. 37V GHz Brightness temperature measurements from satellites such as the Special Sensor Microwave Imager / Sounder (SSMIS) fleet can be used to retrieve snowmelt refreeze signals with broader coverage and higher repeat frequency, but at a lower resolution. We have proposed a way to increase the resolution of near-daily brightness temperature snowmelt refreeze cycle observations by combining the two satellite methods when there are simultaneous observations. Towards this end, we provide the first direct comparison of SAR and brightness temperature snowmelt refreeze in the Sierra Nevada and the Yosemite area.

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Characteristics of Extreme Daily Snowfall Events near Arctic Coastal Regions

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ABSTRACT

Climate change is causing the Arctic to warm, which has implications for conditions across North America and Eurasia. Changes in the Arctic affect seasonal snowpack conditions, sea ice, and soil characteristics, which might imply a changing susceptibility of large regions to disasters, such as wildfire or flooding, as warming continues. We have completed preliminary work looking at seasonal snowpack formation and trends by focusing on heavy snowfall events occurring early in the season. These were diagnosed and examined using reanalysis meteorological data and snow datasets generated by the recently updated Brown Temperature Index Model. Extreme events cause significant changes to the snow cover and snow depth on daily time scales. Across several Arctic regions, we identified important controls on these events, including a promising link between open (ice-free) ocean conditions and increased coastal snowfall in Eurasia. The results we present are robust across all datasets studied.

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Using ICESat-2 Altimetry to Derive Snow Depth over the Boreal Forests and Tundra of Alaska in Support of the SnowEx 2022/2023 Campaign

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ABSTRACT

The SnowEx 2022/2023 campaign was conceived to address questions about snow water equivalent (SWE), snow depth, and albedo in boreal forest and tundra environments. A series of field and airborne missions were conducted to accomplish these objectives through snow pit measurements, synthetic aperture radar (SAR), and lidar, among other methods. There has also been an emerging interest in using surface elevation measurements from the Ice, Clouds, and Land Elevation Satellite-2 (ICESat-2) mission for snow depth estimates. In this work, we present preliminary snow depth retrievals as derived from a combination of ICESat-2 data and snow-off digital elevation models (DEMs). We compare the ICESat-2 results to snow depths gathered from airborne lidar in March and October 2022 over five field sites in Alaska (Bonanza Creek, Caribou Creek, Creamer's Field, Toolik Station, and the Arctic Coastal Plain). Our results show general agreement between ICESat-2 and lidar-derived snow depths, particularly when the terrain is flat and vegetation is accounted for. The mean bias in ICESat-2 snow depth relative to airborne lidar is -0.08 m We will expand upon these results in future work, using comparisons with field data, SAR, and stereographic imagery.

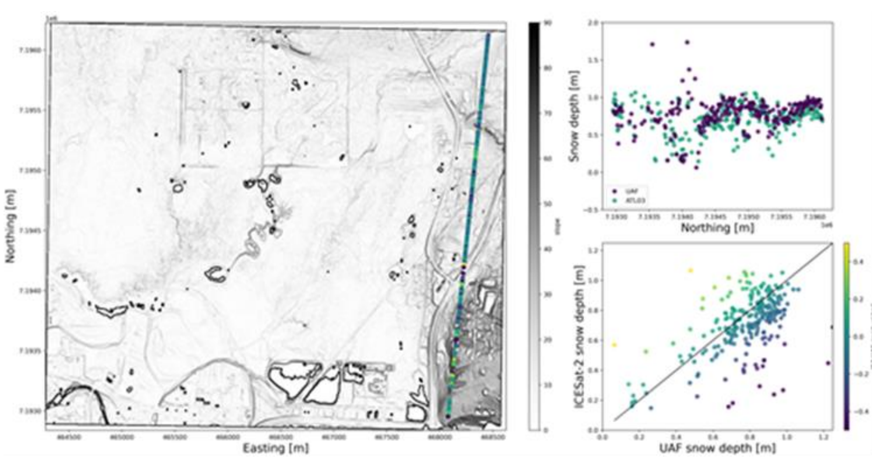

Figure 1. (Left) A slope map of Creamer's Field in Fairbanks, AK derived using airborne lidar. The line is an ICESat-2 track that passed the field site on 21 March, 2022, with the colors representing snow depth residuals between ICESat-2 and airborne lidar. (Top right) Along-track snow depth estimates for the ICESat-2 ATL03 product (green) and the UAF airborne lidar (purple). (Bottom right) Scatter plot of snow depths, with points colored by the snow depth residuals.

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Monitoring Lake Ice Thickness Changes Using Interferometric SAR

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ABSTRACT

Freshwater lake ice thickness is an important observable, both broadly relevant to human activities and a key driver of physical, chemical, and ecological processes in cold regions. In northern regions, where lakes contribute up to 40% of surface area, lake ice data is an especially important input into climatological and meteorological models. The remote nature and sheer number of Canadian lakes – over 900,000 greater than 10 hectares – makes satellite-based observation the only practical comprehensive monitoring method for many systems. Active microwave-band instruments are particularly appealing due to their ability to selectively penetrate cloud and snow cover by modulating the wavelength used; Differential Interferometric Synthetic Aperture Radar (DInSAR) has been proposed as a tool for monitoring ice thickness for some time, but research has been stymied by difficulty in acquiring quality image pairs and temporal coherence loss between pairs.

RADARSAT Constellation Mission (RCM) offers substantially improved revisit times (4-day); we evaluate its potential to overcome these limitations and extract lake ice thickness interferometrically. Interferograms are derived from a set of 5-m resolution compact-polarization images of Kluane Lake and Aishihik Lake, Canada. Topographic phase contributions are simulated using ArcticDEM and removed: resulting ice thickness growth measurements are then compared to thermodynamically simulated values (CLIMo using ERA5 reanalysis as input) and *in situ* measurements from the Kluane Lake Research Station where possible. Mean DInSAR-derived thickness growth shows generally good agreement with these datasets. Phase unwrapping can be complicated by the formation of long, thin zones of low coherence associated with ridging or cracking. These results support the potential use of DInSAR as a tool for high-resolution lake ice thickness monitoring.

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Ruminations on Machine Learning and Snow Mass

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ABSTRACT

Machine learning applications, with particular relevance to terrestrial snow, have received a lot of attention in recent years. Despite all the efforts to harness machine learning in the prediction of snow depth (or SWE), many challenges remain. This presentation highlights commonly used machine learning techniques and will discuss the many perils and pitfalls.

A suite of commonly-used algorithms – support vector machine regression (SVM), Gaussian process regression (GP), ensemble learners (EL), long short-term memory networks (LSTM), and gated recurrent networks (GRU) – focused on time series regression will be presented. The machine learning predictions presented here rely on a mixture of satellite-based measurements of passive microwave radiometry from AMSR-E and AMSR2 or advanced land surface model output from the NASA Land Information System (LIS) as the inputs. All algorithms discussed here employ supervised learning using either ground-based observations from SNOTEL (geophysical space) or passive microwave brightness temperature (observation space) serving as the training targets.

Examples of what does work, and more importantly, what does ***not*** work, will be presented. This presentation will show that machine learning is not, despite all the marketing, magic. Machine learning is merely applied math. Furthermore, it will be argued that machine learning is not a panacea. However, as more and more snow researchers find machine learning increasingly useful in their research, the trend of machine learning adoption will continue to increase as "big data" grows ever bigger. The goal of this research is to help share ideas and enhance community understanding of machine learning algorithms as applied to terrestrial snow in pursuit of a solution to an ill-posed, underdetermined problem that has vexed the snow community for decades.

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The Feasibility of GNSS Reflectometry for Remote Sensing of Lake Ice Physical Properties: On-Ice Snow Depth

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ABSTRACT

In this study, we conducted an experiment to examine the use of Ground-based Global Navigation Satellite System Interferometric Reflectometry (GNSS-IR) for estimating and monitoring on-ice snow depth at a mid-latitude lake site on the southwestern shore of the MacDonald Lake, in the Haliburton Forest and Wild Life Reserve Ltd near the town of Haliburton, Ontario, Canada (78.56° W, 45.24° N). The primary instrument for this study was a GNSS antenna-receiver unit installed on a 5-m tower on the shore of MacDonald Lake. The first evidence supporting the consistency of the "top layer" trend with snow accumulation is the in-site snow-depth measurements made during 11 field visits. The Least-Squares Harmonic Estimation (LS-HE) method was applied to retrieve modulated dominant frequencies of the signal-to-noise ratio (SNR) periodic pattern to estimate the depths of the overlaying snowpack. Assessment of results against in situ and modeled on-ice snow measurements show the capability of GNSS-IR to retrieve on-ice snow depth (root-mean-square error (RMSE): 4 cm; Spearman's correlation: 0.77). The GNSS-IR snow-depth retrievals are also well-supported by the variation of on-land snow depth values obtained from the MacDonald weather station. In Figure 1, looking at on-land snow variation, specifically from Dec 1 to Dec 9, and from Jan 26 to Mar 6, one can see a tendency in the top layer trend to follow the on-land snow pattern.

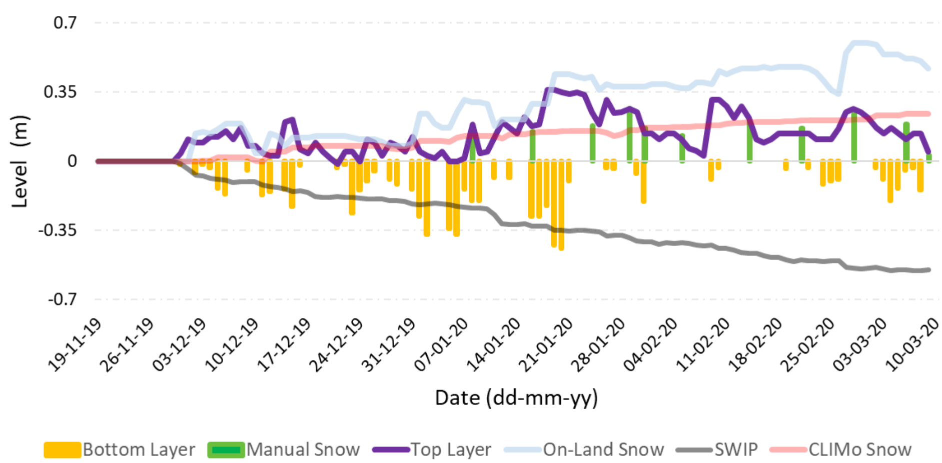

Figure 1. Comparison between Antenna heights obtained from two main contributing layers using GNSS-IR and supplementary data.

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Characterization of the Vermont Snowpack

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JAMES SHANLEY[3], AND ANDREW SCHROTH[2]

ABSTRACT

Across the northeastern United States, snowfall and the local to regional snowpack are critical components of the hydrologic cycle, yet their effect on the surrounding environmental system are relatively understudied. The most recent region-wide analyses of snow and winter-season climate in the northeast extend to the early 2000s, with low spatial coverage. Yet the northeastern snowpack plays a first principle role in delaying water availability to the terrestrial system by storing water until periods of intermittent and continuous snowmelt. Further, the amount of water in the snowpack and the timing of snowmelt are expected to strongly influence downstream runoff (timing and volume), spring nutrient fluxes, flooding, and drought. Both snow water equivalent (SWE) and snowpack water storage representation have largely been overlooked in the northeast, in part due to scarce observations. In response, a cold-weather environmental observation network has been established to span the summit- to-shore continuum in Vermont for advanced environmental analysis and planning and operational decision-making capability. The 22 monitoring stations span from near Lake Champlain in Burlington, VT, to a high-elevation station near the summit of Mount Mansfield and extends to the Sleepers River research Watershed in Danville, VT to incorporate and build upon existing longer-term records of snow observations. Using distributed ground-based sensors combined with unmanned aircraft system (UAS)-based sensing and hydrologic modeling, this effort provides an improved understanding and characterization of snowpack spatial and temporal variability across aspects, elevations, and canopy coverage regimes.

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Detecting Snow in Western New York using Sentinel-1a, -1b, MODIS, VIIRS and IMS: A Case Study

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ABSTRACT

Knowledge of the amount of snow and timing of snowmelt allows managers to optimize use of water resources and to improve predictions of water availability. With spaceborne visible/near-infrared (VIS/NIR) and synthetic aperture radar (SAR) data, it is possible to map snow cover and to delineate areas of wet snow. For a study area in western New York State when cloud cover was prevalent (December 2022 through January 2023), we created a daily time series of snow-cover extent (SCE) maps derived from VIS/NIR data products from the Moderate-resolution Imaging Spectroradiometer, Visible Infrared Imaging Radiometer Suite and Interactive Multisensor Snow and Ice Mapping System; we also used data from the European Space Agency's Sentinel-1b Multi-Spectral Imager and Sentinel-1a C-band synthetic aperture radar (SAR), when available, because SAR data are largely unaffected by cloud cover. Using SAR data alone, it can be difficult to distinguish dry or wet snow cover from snow-free land, especially if the snow-free land is wet. The combined use of C-band SAR data, VIS/NIR snow maps and meteorological station data provides more confidence in snow-cover detection than when C-band SAR data are used alone. Occasional views the surface during this cloudy period may be captured using the VIS/NIR data. Thus, detection of snow using C-band SAR data is facilitated when a VIS/NIR snow mask and meteorological station data are employed to delineate snow-covered areas.

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Retrieval of Snowpack Density and Ice Grain Radius from Time-Domain Diffuse Optical Measurements

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ABSTRACT

Lidar is widely used to map the geometry of the top surface of snowpacks. However, because snow is a collection of highly transparent and forward scattering ice grains, most photons in an incident laser pulse scatter many times beneath the surface before returning to the receiver. In this work we show that the measurable time delay caused by subsurface scattering events can be exploited to estimate volumetric properties of the snowpack - namely, snowpack density, ice grain radius, and impurity concentration.

We model the propagation of laser light within the snowpack using a photon diffusion model that was originally developed by the medical imaging community to model light transport in human tissue. We show that, for clean snow, the parameters of this model - the absorption coefficient, effective scattering coefficient, and mean speed of light - can be written solely as functions of grain radius and snowpack density if grains can be approximated as spherical.

We illuminate the snowpack surface at a single point using a pulsed laser source, and use a photon-counting SPAD detector to measure the time-dependent intensity of light that exits the snowpack a small distance (5-10 cm) from the laser spot. We fit a curve to these measurements that has the same form as the appropriate solution to the time-dependent photon diffusion equation, and then choose the grain size and density that can best reproduce the parameters of the fitted curve. We validate our method using measurements collected for a variety of snow types.

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Bias Correction of an Ensemble Mean Reanalysis-Based Permafrost Soil Temperature Product Using Snow Cover and Vegetation

TYLER C. HERRINGTON[1], ANDRE R. ERLER[2], AND CHRISTOPHER G. FLETCHER[1]:

ABSTRACT

Reanalysis products provide spatially homogeneous coverage for a variety of climate variables in regions where observational data are limited. However, soil temperature estimates in many reanalysis products are biased cold by 2-7 K across the Arctic, particularly in the cold season. In previous work we showed that a soil temperature product based on the ensemble mean of all available reanalysis products generally outperformed the individual soil temperature estimates of any individual product. Biases over permafrost regions, however, remained relatively large. Here we utilize mean bias subtraction, multiple linear regression, and a random forest regression technique to bias-correct an ensemble mean permafrost soil temperature product. In addition to the thermodynamic state of the land surface in the reanalysis, the random forest regressor also uses information relating to remotely sensed snow cover and vegetation. As part of this process, we develop a vegetation classification scheme that reflects the functional impacts of vegetation on snow cover and soil temperature, in order to compare the vegetation cover assumed in the reanalysis products to European Space Agency Climate Change Initiative (ESA-CCI) vegetation cover. We train our models primarily on soil temperature data from Eurasia, as data from North America is sparse. The performance of the correction algorithm will be evaluated in different regions, with specific attention to data-poor regions in North America. The importance of different predictors, and in particular the role of snow biases and vegetation cover will be discussed.

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Passive Microwave Remote Sensing of Snowmelt and Freeze/Thaw in the Kuparuk Basin, Alaska, using Calibrated Enhanced-Resolution Brightness Temperature (CETB) from SSMI/S and SMAP

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ABSTRACT

The relationship between snow and permafrost on Arctic terrain has significant implications for water storage, flooding hazards, and infrastructure vulnerability. Studies show that earlier snowmelt and high runoff cause increased permafrost thaw and earlier freeze/thaw cycles, which can be especially problematic for communities in Arctic regions facing disproportionate warming from climate change. To analyze permafrost vulnerability due to snow dynamics, we compared snowmelt and soil moisture in the Kuparuk River Basin in Northern Alaska from 2010-2019. We used Calibrated, Enhanced-resolution Brightness Temperatures (CETB) from two passive microwave sensors, Special Sensor Microwave Imager/Sounder (SSMIS: F18) 37 GHz vertically polarized channel and Soil Moisture Active Passive (SMAP) at 1.41 GHz vertically and horizontally polarized channels. Snowmelt onset timing and duration are derived from SSMI/S brightness temperature (Tb) and diurnal amplitude variations (DAV) threshold exceedance which is sensitive to changing levels of liquid water content. Additional pixel level standard deviation statistics were used to understand dynamics and finer spatial differences. Soil thaw and refreeze dynamics are captured using the Normalized Polarization Ratio successfully utilized with SMAP data3, along with SMAP Level-3 L-band radiometer soil products. The end of high DAV corresponds with snow saturation and snow depletion. It appears that soil thaw is closely aligned in time with high DAV and continues to fluctuate above seasonal freeze thresholds until snow accumulation. We investigate the spatial patterns of multiple factors to test whether early snow melt, longer melt refreeze, early snow saturation and disappearance increase permafrost vulnerability at different elevations and environments.

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Implementation and Field Validation of a Passive Radioisotope SWE sensor in the Catskill Mountains, NY

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ABSTRACT

Snow water equivalent (SWE) is an important environmental variable in studies of the hydrologic cycle, water availability and climate change. Conventional methods of SWE measurement are labor intensive and can produce errors during freeze/thaw cycles. Automated non-contact samplers can reduce or eliminate these issues. We tested a Campbell Scientific CS725[2] at one site in the upper Neversink River Basin for possible inclusion in the USGS Next Generation Water Observing System. The instrument determines SWE by passively monitoring the attenuation in the snowpack of radiation emitted by potassium and thallium in the soil. To maximize the number of comparable datasets, the instrument was co-located at the long-term Frost Valley YMCA National Atmospheric Deposition Program monitoring site in the Catskill Mountains at Claryville, NY. Data were collected in 6-hour intervals for three seasons. To verify the accuracy of the CS725, conventional measurements of SWE were collected whenever substantial changes in snowpack occurred. Measurements were made at four locations along a 30-meter snow course running through the experimental site. At each location SWE was measured using a Snowmetrics[2] 12-inch tube sampler and a 250cc wedge sampler. The mean SWE was calculated from the conventional measurements and compared to the CS725. The difference between the methods ranged from -16.9 mm to +11.2 mm. In general, the CS725 measurement was 5-20% higher than the conventional method, with a median of 11%, which falls within the 5-35% range found in similar studies of the CS725.

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Ku and L-band SAR Observations of Terrestrial Seasonal Snow and Lake Ice in Ontario during Winter 2023 using the CryoSAR Airborne System

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ABSTRACT

The Cryosphere-Observing SAR (CryoSAR) system is a Ku- and L-band synthetic aperture radar (SAR) system designed to conduct observations of snow and ice on land and water bodies, and soil moisture status. The CryoSAR system is a fully polarimetric SAR with the capability to conduct single or repeat pass observations for interferometric SAR (InSAR) applications. There is significant interest in the Ku (13.5 GHz) polarimetric response and L-band (1.3 GHz) InSAR measurements of snow on land and water to estimate snow water equivalent, a key variable in water resource management applications and in climate change studies. The CryoSAR radars can be operated independently or together. They can also be deployed on a relatively small aircraft, such as a Cessna 208, which is widely available across North America, Europe and beyond, making the system relatively agile in its deployment. An adjustable mounting system has been designed to enable the instrument to be installed from inside and aircraft and at specified look angles. In fall 2022 and winter 2023, a season-long deployment of the system was conducted in Ontario as part of a Canadian Space Agency-funded project and in support of the Terrestrial Snow Mass Mission. Flights were conducted over selected sites in Ontario including the Haliburton Highlands and Powassan. Field campaigns were also conducted on the ground to provide correlative ground reference data. A combination of traditional field observations of snow properties, and detailed state-of-the-art measurements of microstructure properties were made to quantify the snowpack bulk and stratigraphic characteristics of the snow at the different field sites. This paper presents the initial observations made with the CryoSAR system at Ku- and L-band and correlative field measurements. Results focus on the polarimetric responses from snow on land and on lake ice and demonstrate its applicability for terrestrial snow monitoring.

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Interpreting Cosmic Ray Neutron-Based Snow Water Equivalent Estimates from Heterogenous Snow Distributions

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ABSTRACT

Conventional methods of snow water equivalent (SWE) methods are questionable in the spatially heterogenous snow of prairie environments. Despite low annual snowfall, snowpacks on North American prairies are extensively redistributed by wind, leading to scouring of open areas, and accumulation behind barriers (e.g., trees and fences) or topographically low areas. Cosmic ray neutron sensing (CRNS) techniques are capable of making SWE estimates that are more representative of the areal average than conventional methods due to their large areal footprint, approximately 200-300 meters radius. A CRNS instrument was deployed at the Central Agricultural Research Center in central Montana, USA as a part of the NASA SnowEx field campaign during winter 2020-2021. CRNS has shown to be sensitive to areal average SWE within its footprint in a prairie environment. However, the moderated neutron flux from varying spatial distributions of shallow snowpack within the sensor's footprint remains as a source of uncertainty in SWE estimates. To address this uncertainty, we use a Monte Carlo neutron transport model to simulate the CRNS response under varying spatial distribution patterns of snowpack. Preliminary results showed that bare field conditions near the CRNS can yield larger neutron counts, and thus depressed SWE estimates. Once the effects are known, we hope to be able to correct SWE measurements for changes in the snow distribution. These results aid in the interpretation of CRNS SWE estimates in the prairie and demonstrate the value of CRNS observations in highly variable shallow snow environments.

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SWE Retrieval Algorithm Advances Using X and Ku-band Radar

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ABSTRACT

Snow water equivalent (SWE) retrieval via radar volume scattering at X and Ku bands (10 and 17 GHz) has been the basis of snow satellite concepts such as the European CoReH2O concept. In the decade since then, significant advances have been made in our understanding of the physics of the radar signature. And, critically, the retrieval approach has been validated through multiple airborne and tower-based field campaigns in several countries. This X/Ku algorithm now forms the basis of a new NASA snow mission concept that has put the snow community within grasp of achieving the long-desired goal of global SWE at high resolution for the first time.

At the core of the algorithm is a dense media radiative transfer (DMRT) model. A parameterization study demonstrated that the problem can be simplified to one of solving for just two unknowns—SWE and the microwave scattering albedo—removing the need for high-precision snowpack modeling. The retrieval solution is determined through a cost function minimization approach after accounting for surface scattering from the snow-soil interface, low vegetation, and the scattering albedo. We will show validation results using both tower and airborne data up to 750mm of SWE, and discuss the options for obtaining the necessary input parameters.

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Application of a Deep Learning Nested U-Net for Reflectivity Inpainting in Spaceborne Radar Blind-Zones

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ABSTRACT

CloudSat's Cloud Profiling Radar (CPR) is one of the few observation-based systems for remotely monitoring high-latitude snowfall. However, the CPR is unable to observe hydrometeor activity within the lowest 1.2 km of the atmosphere due to ground-clutter contamination. This radar "blind-zone" limits CloudSat's ability to detect and measure the intensity of shallow snowfall processes occurring near the Earth's surface, leading to increased uncertainty in CloudSat-derived snowfall estimates. Here, we develop a deep learning U-Net++-style convolutional neural network (i.e. blindpaint) for predicting reflectivity within a radar blind-zone. By relating latent information encoded in blind-zone-aloft clouds with additional context from collocated atmospheric climate variables, blindpaint learns to predict the presence and intensity of near surface reflectivities. Blindpaint demonstrates a higher proof of detection and lower false alarm rate to traditional inpainting methods, indicating an improved ability to predict the presence of near surface hydrometeors. The pixel-level accuracy of the inpainted blind-zone reflectivity values from blindpaint also demonstrate mean absolute error performance improvements that are an order of magnitude lower than traditional inpainting techniques. Additionally, by training blindpaint on a combination of CPR-calibrated KaZR surface radar datasets at multiple locations (along with collocated ERA-5 atmospheric data), and simulating the blind-zone, we are able to produce a generalized model which can then be applied to spaceborne observations from CloudSat. Machine learning inpainting techniques like those explored in this work demonstrate a compelling utility in enhancing current and future spaceborne remote sensing missions by revealing important connections between the blind-zone and the surrounding atmospheric state.

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How Representative are Low Resolution Sea Ice Concentration Products of Conditions at Coastal Sites along the Central Western Antarctic Peninsula?

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ABSTRACT

Macroalgal forests exist along the northern portion of the western Antarctic Peninsula (WAP). However, few studies have documented its distribution farther south in the central WAP. In 2019, macroalgal cover was determined at 14 coastal sites located along a latitudinal gradient (64°-69° S) through quantitative analysis of diver-collected video from replicated vertical transects collected at depths between 40 m and 5 m. A strong negative correlation was documented between total macroalgal cover and all the sea ice concentrations evaluated (National Ice Center Charts, AMSR-E and AMSR-2 and the National Snow and Ice Data Center Sea Ice Index). However, these remote-sensing derived sea ice concentrations are captured at large spatial scales relative to the scale of the sampling sites (~100 meters across). To investigate how representative these sea concentrations are of conditions at the studied shallow water coastal sites, sea ice concentrations from Landsat (30 m) and MODIS (1000 m) were computed for buffers ranging from 100 m 10,000 m around each site and then compared to concentrations from the larger footprint products. In general, the larger footprint sensors indicated lower sea ice concentrations than Landsat or MODIS. However, the observed differences at individual sites were typically consistent across buffer sizes. This indicates that while the sites had higher sea ice concentrations than retrieved from the lower resolution products, the higher concentrations appear to consistent across spatial scales from 100s to 1000s of meters.

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Multidisciplinary Observatory for Arctic Climate Change and Extreme Events Monitoring (MOACC)

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ABSTRACT

The Multidisciplinary Observatory for Arctic Climate Change and Extreme Events Monitoring (MOACC) proposal is submitted by the Université de Sherbrooke (lead institution-UdeS), University of Toronto (UofT), Western University (WU) and Université de Montréal (UM). The main objective of our project is to develop a permanent multidisciplinary scientific infrastructure that enables long-term observations of Arctic climate change, bringing together experts from a wide range of expertise and institutions. The project is led by Prof. Alexandre Langlois (UdeS) and Prof. Kimberley Strong (UofT) and responds to a consensus on the lack of temporal observations that are crucial to understand feedback processes and to promote model development in the Arctic. The innovative aspect of this proposal resides in its multidisciplinary approach while enabling long-term Arctic measurements spanning several disciplines. The proposed observatory will be located at the Canadian High Arctic Research Station (CHARS) in Cambridge Bay, Nunavut, while enhancing the reach of CHARS with linkages to the Environment and Climate Change Canada supersite in Iqaluit. Our ambition is to establish the site as one of the largest instrumented high Arctic observatories dedicated to the monitoring of key indicators that drive climate change. The site will generate and enhance partnerships, not only with Canadian research centers and organizations, but also with international research partners and networks.

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It's all About Timing: Exploring the Relationship between Snowmelt and Caribou (*Rangifer tarandus*) Migration in the Northwest Territories of Canada

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ABSTRACT

Recent studies suggest that snow characteristics may be primary drivers of migration, largely due to caribou's high level of mobility and their dependence on landscape conditions for locomotion. To investigate whether and how snow characteristics such as melt/refreeze status and the presence of ice are related to caribou movement, we used GPS (Global Positioning System) tracking collar data provided by the Government of the Northwest Territories' Department of Environment and Natural Resources to identify individual animal location and migration patterns, with a focus on female animals in the Bathurst herd. We analyzed 117 individual female caribou with more than 30,000 observations between 2007 and 2016 from the Bathurst herd in the Northwest Territories of Canada. We used a hierarchical model to estimate the beginning, duration, and end of spring migration and compared these statistics against snowpack characteristics (i.e., the timing of melt onset and melt/refreeze cycles) which we derived from 37 GHz vertically polarized (37V GHz) Calibrated, Enhanced Resolution Brightness Temperatures (CETB) at 3.125 km resolution. We found that the start and end of the female herd's spring migration closely followed melt onset and migration duration was longer when melt onset occurred earlier, suggesting that melt onset events provide triggers for migration or favorable conditions that increase mobility. We did not find any significant relationships when we tested them at the individual level, however. A causal relationship between snowmelt timing and caribou migration would allow for anticipation of the herd's migratory behavior and potential shifts in herd ranges.

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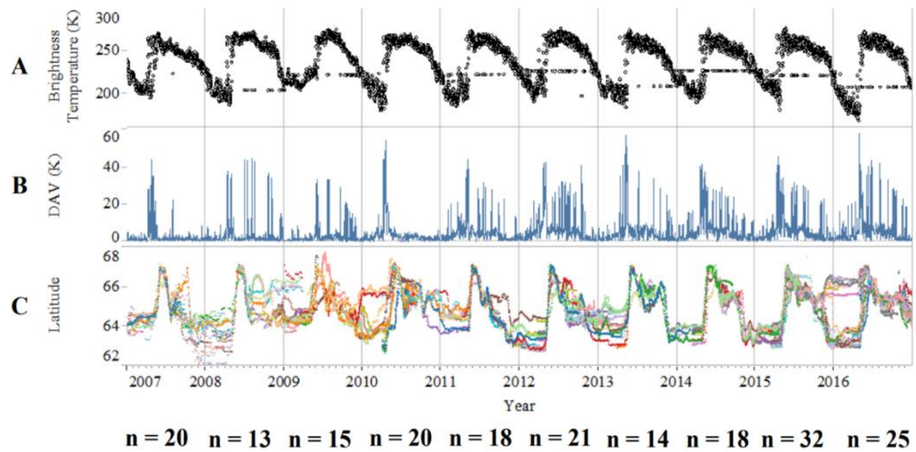

Figure 1. Time series of 3.125 km EASE-Grid pixels and female caribou latitudinal movement (northward migration) caribou departure locations between 2007 and 2016. The top two graphs are of brightness temperature (A) and diurnal amplitude variation (DAV) (B). The graph includes individual tracks of female caribou latitudinal movement through time (C). Individual female caribou are colored by unique collar ID. Collar ID legend has been omitted, as there are >100 unique IDs within this time span. Number of individuals per year is noted below each year's panel, where n = number of individuals.

Examination of Microwave Backscatter of Freshwater Lake Ice Using Polarimetric Decomposition

CONNOR MCRAE-PHARO[1] AND GRANT GUNN[1]

ABSTRACT

Polarimetric decomposition is an invaluable technique for analyzing microwave signals reflected off freshwater ice features. In this study, we utilize Radarsat 2 quad-pol captures to investigate backscatter from two lakes: Old Crow Lake in the Yukon and Noel Lake in the Northwest Territories, each representing a contrast in morphometries (shallow and deep, respectively). The contrast in depth is designed to present two unique ice compositions, accounting for the presence and absence of tubular bubbles at the ice-water interface. Polarimetric decomposition allow for the identification of the dominant scattering mechanisms that occur for ice with and without tubular bubbles. Results showed that the ice was characterized by dominant single-bounce scatter, regardless of morphometry, followed by orders of magnitude weaker volume-scattering signal and a slight to nonexistent double-bounce signal. These findings have important implications for remote sensing applications, such as opening the prospect of freshwater ice thickness retrieval as interferometry performs with higher confidence with single bounce interactions. Overall, the application of polarimetric decomposition of freshwater ice backscatter shows promise as a valuable tool for understanding the relative contribution of the physical properties of the ice to radiative transfer and can be used to improve our current methods of ice and climate monitoring in the cryosphere.

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Retrieving Snow Density from Ground-Based Radar and Airborne Lidar Observations and Spatial Prediction for Distributed Snow Water Equivalent in Sub-Alpine Mountain Environments

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ABSTRACT

Constraining snow depth from repeated airborne lidar acquisitions enables the retreival of snow density from radar travel-time along transects at 1-m resolution. These inferred observations of bulk snow density illustrate spatial patterns and features that are not captured by sparse manual measurements. We combine ground-penetrating radar (GPR) surveys and airborne lidar acquisitions in subalpine environments, covering a range of terrain and ecological parameters such as elevation, slope, aspect, forest canopy, and burned forest area, which capturing variability in snow density due to differences in surface energy balance and wind exposure. These terrain and vegetation parameters can be derived from airborne lidar acquisitions and serve as the basis of features within a supervised learning framework to extrapolate snow density estimates across the study regions. Several machine learning models of snow density are compared, but the choice of a best model is difficult to quantitatively assess, as outputs have similar statistical representations but differing spatial patterns. Estimates of the snow water equivalent (SWE) are calculated, using the density map and lidar snow depths, at a scale of tens of square kilometers. The total SWE estimated by any choice of density model is similar in bulk value. This work implores a deepened focus on the meteorological, terrain, and ecological variables controlling the densification of snow in subalpine mountain watersheds with the intent of studying predictor importance and model applicability. An improved observational comprehension of the influences of snow densification will enable snow scientists to better assess and improve physically modeled snow density.

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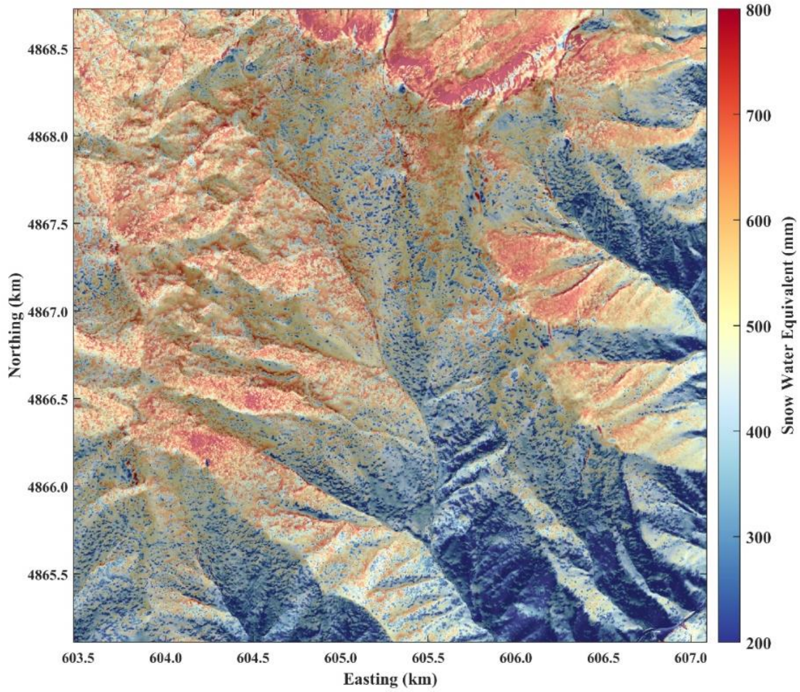

Figure 1. Snow water equivalent of Mores Creek Summit, Idaho was estimated from helicopter-borne lidar acquisitions and density spatially distributed via artificial neural networks.

Altimetric Ku-band Radar Observations of Snow on Sea Ice Simulated with SMRT

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ABSTRACT

Sea ice thickness is essential for climate studies and numerical weather prediction. Radar altimetry has provided sea ice thickness measurement since the launch of ERS-1 and currently through CryoSat-2, but uncertainty in the scattering horizon used to retrieve sea ice thickness arises from interactions between the emitted signal and snow cover on the ice surface. Therefore, modelling the scattering of the electromagnetic waves with the snowpack and ice is necessary to retrieve the sea ice thickness accurately. The Snow Microwave Radiative Transfer (SMRT) model was used to simulate the altimeter waveform echo from the snow-covered sea ice. A new field campaign was conducted in the Deese Strait near Cambridge Bay, Nunavut, Canada in April 2022. Measurements included microstructure from x-ray tomography and roughness measurements from structure from motion. These data and datasets from ground campaigns linked to CryoVex 2017 near Alert, Canada, and Operation Ice Bridge 2016 in Eureka Sound, Canada, were used to parameterise SMRT. Evaluation of SMRT in altimeter mode was performed against CryoSat-2 waveform data in pseudo-Low Resolution Mode. Simulated and observed waveforms showed good agreement, although it was necessary to retrieve ice surface roughness. Retrieved ice surface roughness in Cambridge Bay was 1.7 mm, which was close to the observed value of 1.4 mm for flat ice. A pseudo low resolution mode correction factor was required in the radar equation to capture the pulse peakiness in Cambridge Bay. Simulation of Ku-band and Ka-band backscatter in preparation for the ESA CRISTAL mission demonstrated the dominance of scattering from the snow-sea ice interface at Ku-band, with some surface scattering particularly for first year ice. At Ka-band, however, while the scattering from the snow surface dominates, the snow-sea ice return is non-negligible for first year ice, and volume scattering is more prevalent for multiyear ice. This is the first study to consider scattering within the snow and demonstrate the origin of CryoSat-2 signals. SMRT can be used to develop a physical retracker algorithm to retrieve snow depth and sea ice thickness for radar altimeter missions.

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Canadian Snow Radar Satellite Mission Science Readiness Advancements

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ABSTRACT

Environment and Climate Change Canada (ECCC) and the Canadian Space Agency (CSA) continue to advance a new satellite Ku-band radar mission focused on providing moderate resolution (500 m) information on seasonal snow mass. Like many regions of the northern hemisphere, estimates of the amount of water stored as seasonal snow are highly uncertain across Canada. To address this gap, a technical concept capable of providing dual-polarization (VV/VH), moderate resolution (500 m), wide swath (~250 km), and high duty cycle (~25% SAR-on time) Ku-band radar measurements at two frequencies (13.5; 17.25 GHz) is under development. In this presentation, results from the Trail Valley Creek experiment (TVCEx) conducted in winter of 2018-19 will be presented. Data collected during the CryoSAR 2022-23 campaign in Powassan, Ontario, Canada will also be shown in the context of how the proposed snow radar mission can improve SWE retrievals in agricultural lands.

Using the UMASS airborne Ku-band radar instrument and satellite observations from RADARSAT-2 and TerraSAR-X, we show that it is possible to retrieve background soil properties allowing to separate the background from the snowpack contribution of the Ku-band signal and isolate the snow volume scattering to facilitate radar-based SWE retrievals. We also show that the ground-based snow sampling strategy deployed during the TVCEx, providing statistical distributions of snow microstructure and density, is crucial to properly estimate the radar signal from forward modelling.

Ground-based snow properties, soil and weather station information, drone LiDAR/optical data and radar observations collected for the CryoSAR campaign will also be presented.

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Validation of Snow Water Equivalent Products: Dialed in for Non-Mountain Regions but Challenges Remain in Complex Terrain

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ABSTRACT

We advance the evaluation of gridded snow water equivalent (SWE) products by using reference data from both snow courses and airborne gamma-derived SWE estimates to evaluate fourteen datasets over North America. These products cover a broad range of snow analysis from those based on Earth-observation data (JAXA-AMSR2, Snow CCI SWE v1 and v2), coupled land-atmosphere reanalysis (ERA5, ERA5-Land, ERA5-Snow, GLDASv2.2, MERRA2, JRA-55), snow models of varying complexity driven by reanalysis data (Crocus driven by ERA-Interim and ERA5, Brown Temperature Index Model (TIM) driven by ERA5 and JRA-55), and data assimilation schemes (U. Arizona). We assess product performance across both non-mountainous and mountainous regions and analyze the sensitivity of this performance to the choice of reference data set. In non-mountain areas, product performance is insensitive to the choice of reference dataset and there is strong agreement of reference SWE up to spatial scales of at least 25 km, comparable to the grid spacing of most coarse resolution products. In mountain areas, there is poor agreement between the reference datasets even at short distances (<5 km) and the choice of reference dataset strongly influences the sign and magnitude of the product errors (bias and RMSE) due to systematic elevation differences among the reference data locations and the product grid cell centroids. Minimizing these systematic elevation-driven biases is essential to a fair evaluation of the product performance and improves the median RMSE of the model-based products by one third and almost 50% using gamma and snow courses, respectively. Our full analysis demonstrates that we can robustly validate product SWE estimates in non-mountain regions and are able to provide relative rankings of product performance in mountain regions.

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Snow Depth Mapping on Canada's Sub-Arctic Lakes

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ABSTRACT

Snow accumulation on lake ice influences ice growth and the timing of ice melt due to snow's highly insulative and reflective properties. Therefore, the lake ice thickness is expected to vary spatially over the lake due to heterogeneous snow accumulation from wind redistribution and snowpack metamorphism. Although lake ice models perform well in simulating ice thickness, they are very sensitive to the value of snow depth and density. However, mapping snow depth spatially over the entire lake has presented challenges partially due to poorly known lake ice surface elevation and snow variability. Current snow depth and ice surface elevation observations are sparse and mostly restricted to point measurements. This study used a multi-sensor approach utilizing Ground Penetrating Radar (GPR) and Remotely Piloted Aircraft System (RPAS) acquisitions collected over Canadian sub-Arctic lakes to map the distributed snow depth during the 2021 to 2022 winter season. The resulting one-meter spatial resolution snow depth maps were compared to *in situ* observations, showing a relative error of 33% in December 2021 (RMSE = 4.15 cm, Bias = -1.52 cm), and 14% in March 2022 (RMSE = 5.87 cm, Bias = 4.64 cm). Using this multi-sensor approach, we have developed a framework for mapping the snow depth distributed on lakes. Simultaneously collecting ice thickness observations furthers understanding of the spatial relation between snow depth, ice thickness, and ice surface elevation. The findings of this research can lead to an improved understanding of snow and lake ice interactions, which is essential for northern communities' safety and well-being.

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Comparing Passive Microwave Snowmelt Detection Methods Using Ground-Based Snowmelt Observations

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ABSTRACT

Melting snow is an integral factor in understanding both the hydrologic cycle and energy budget of many regions. Monitoring wet or melting snowpacks is vital for river flood predictions, water resource management, monitoring climatic trends and changes, and avalanche risk forecasting. It is also important for researchers and government agencies monitoring snow depth and snow cover using passive microwave satellites, as liquid water in snow can cause high brightness temperatures due to differences in dielectric properties between wet and dry snow. Sites that collect continuous ground measurements of snow liquid water content are rare, while satellite observations are easily accessible and have the potential for snowmelt monitoring on a global scale. The goal of this study is to compare and evaluate the information provided by different snowmelt detection methods that use passive microwave satellite observations. Certain algorithms may be more sensitive to certain types of melt events, such as midwinter melt/refreeze events or spring melt onset/duration. For example, previous work has shown that the DAV (diurnal amplitude variation) method is best at showing mid-winter and melt onset events, while it is less useful for detecting late-stage spring melting. This study extends that research by applying similar analysis methods to different snowmelt detection algorithms. Snowmelt events detected using various algorithms applied to AMSR2 passive microwave brightness temperature data are compared to ground-based snowmelt observations, including continuous liquid water content measured by a Snow Pack Analyzer-2 located within the Sleeper's River Research Watershed in Vermont.

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MODIS and VIIRS Snow Cover Extent Continuity

GEORGE A. RIGGS[1] AND DOROTHY K. HALL[2]

ABSTRACT

NASA snow cover data products have been produced since 2000 from the satellite and instrument series of the Terra and Aqua Moderate-resolution Imaging Spectroradiometer (MODIS), Suomi-National Polar Program (SNPP) Visible Infrared Imaging Radiometer (VIIRS), Joint Polar Satellite Series (JPSS) from satellites JPSS1 and JPSS2. In 2000 there was a single daily satellite snow cover extent (SCE) data product from MODIS, in 2023 there are five daily satellite SCE data products. A 23-year record of SCE composed of observations from five similar instruments has great potential for study of snow cover climatology changes and trends. Though the satellites and instrument are similar there are differences in orbits and instrument characteristics that may affect the detection of snow cover in the automated algorithms that produce the products. An algorithm continuity approach, using the same algorithm for both sensors, was taken to ensure continuity of products. We present evidence of daily continuity in the SCE products, and continuity of seasonal changes of SCE trends among the products.

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Comparative Analysis of NOAA and NASA Snow Cover Extent Products

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ABSTRACT

Key satellite-derived snow cover extent (SCE) Earth Science Data Records (ESDR) from NOAA and NASA are invaluable in monitoring SCE variability and change. However, questions remain regarding specific SCE values, including confidence limits for these climate ESDRs. Here, we report on a new effort to achieve a better understanding of each product's strengths and weaknesses to ensure the best SCE ESDR at meso-to-macro scale levels is available to the climate community and others in need of such valuable information. Analyses are underway utilizing NOAA/IMS and NASA MODIS and VIIRS products on regional and seasonal levels over the past two decades. In addition to cases studies for individual regions and dates, project analyses include longitudinal evaluations over a wide range of landscapes. Preliminary results for selected regions in all seasons are providing encouraging spatial correlations between products, though fall extents are found to differ between the NOAA and NASA products more than winter and spring extents. This is likely due to a combination of more extensive cloud cover and lower solar illumination during fall. Ultimately, study results will direct users to a particular map product depending upon their needs with regard to spatial resolution or temporal continuity.

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Evolution of Global Snow Cover – Analysis of 23 Years of DLR's Global SnowPack and Latest Processor Developments

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ABSTRACT

As an essential climate variable, the area covered by snow should be recorded daily and with a sufficient spatial resolution. This is currently only achieved with medium-resolution optical remote sensing sensors. The Global SnowPack processor developed at DLR enables the daily derivation of a gap-free (without data gaps due to clouds or polar night) global snow cover in near real time by combining temporal and topographical interpolation methods. So far, the daily snow product from MODIS on Terra and Aqua has been processed, but now also the daily snow product from Suomi NPP VIIRS is included (Sentinel-3 OLCI will also be included in the near future). As a result, we now have a 23-year data set of global uninterrupted snow cover, which can be used both for trend analysis and for forecasting extreme hydrological events. For the determination of long-term trends, the accuracy and the duration of the time series are decisive, for the hydrological application rather the timeliness.

Our pixel-based trend analysis showed most significant developments in the full snow cover season throughout the full hydrological year (Figure 1; meteorological autumn to summer), where more than 30% of the area showed a significant trend of snow cover duration (two-thirds show a decrease). In addition, analyzes at catchment area level were also made. We will present these results and application examples.

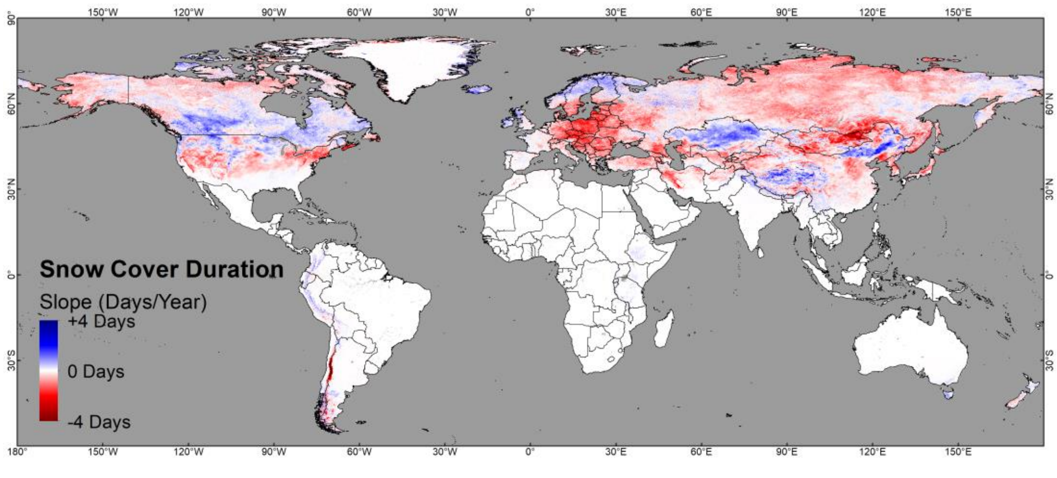

Figure 1. Global trend of full snow cover duration (whole hydrological year).

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The Application of Disdrometers and Present Weather Detectors to Improve the Automated Measurement of Solid Precipitation

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ABSTRACT

There are many advantages for automating precipitation measurement including remote operation, cost efficiencies, and increased measurement frequency that may not be realized with manual observation practices. However, the unsupervised observation of precipitation often increases the level of uncertainty in regards to quality assurance. In addition, key precipitation parameters, such as precipitation type, are unobserved. Popular automated all-weather weighing gauges used in cold regions generally depend on user-defined signal processing or require the user to trust on-board proprietary filtering algorithms to determine interval precipitation amount from bucket weight differential. Either of these techniques can benefit from ancillary information derived from disdrometers or present weather detectors. Two disdrometers (one optical and one radar based) were installed at two Canadian precipitation supersites (the Bratt's Lake and Caribou Creek Solid Precipitation Inter-Comparison Experiment sites) as a proof of concept for Environment and Climate Change Canada's (ECCC) operational networks and to support ongoing instrument intercomparison efforts. Although no practical automated reference exists at these sites to assess the accuracies of the two disdrometers, an ensemble approach incorporating the Double Fence Automated Reference (DFAR) for solid precipitation measurement is used to show their capabilities for improving precipitation detection, removing false precipitation reports, and deducing precipitation type for calculating rain:snow ratios and applying wind-bias transfer function adjustments.

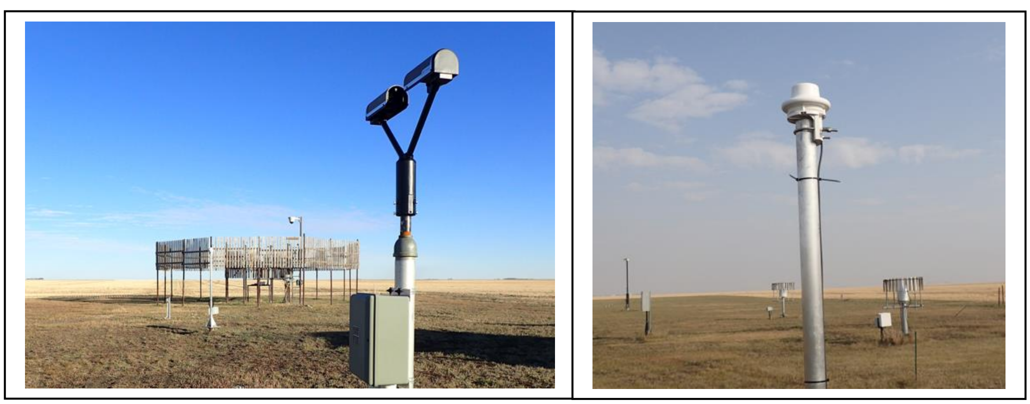

Figure 1. Two disdrometers installed at the ECCC Bratt's Lake precipitation intercomparison supersite in Southern Saskatchewan Canada. Left: OTT Parsivel[2] optical disdrometer with the DFAR in the background. Right: Lufft WS100 Doppler radar disdrometer

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Snow Water Equivalence and Stratigraphy Records from White Glacier, Axel Heiberg Island, Nunavut: 1959-2023

LAURA THOMSON[1] AND MILES ECCLESTONE[2]

ABSTRACT

White Glacier on Axel Heiberg Island, Nunavut, is one of seven Canadian reference glaciers to the World Glacier Monitoring Service, with near-continuous mass balance observations spanning 1959-2023. While an important indicator of climate-driven changes in this region of the Arctic, these data also comprise a valuable record of snow accumulation and distribution patterns thus presenting an opportunity to investigate temporal trends and spatial patterns in regional snowfall over the last 60+ years.

The winter snowpack on White Glacier is measured annually in April/May at approximately 15 locations and includes measurements of snow water equivalence (SWE) and stratigraphy (Figure 1). From 1959 to 2022, we calculate an average annual winter snowpack SWE of 205 ± 114 mm w.e. from snow pits above 800 m a.s.l. (n=748). While accumulation increases weakly with elevation (approx. 54.5 mm w.e./km), SWE observations at the highest sites are found to be notably lower than the average accumulation rate of 371 mm w.e. a^{-1} measured in a snow/firn shaft spanning the years 1929-1962 on nearby Müller Ice Cap. No statistically significant trend in snowfall has been detected from these *winter* (September-May) snowpacks to support a hypothesized "warmer, wetter Arctic" at this location. However, mass balance stake measurements and snow depth sounder data suggest *summer* accumulation should no longer be considered negligible, as was once thought, in the calculation of glacier mass balance.

Figure 1. Snow pit analysis at White Glacier in 2012, expertly demonstrated by Miles Ecclestone.

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Improving our Understanding of ICESat-2 Ice Thickness Estimates in the Canadian Arctic Archipelago using *in situ* and Drone Measurements

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ABSTRACT

The Canadian Arctic Archipelago (CAA) is a unique sea ice region located across northern Canada, adjacent to the Arctic Ocean. To date, monitoring of sea ice within the CAA has lacked volumetric / ice thickness information. NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2), was launched in 2018 and included a key objective to estimate sea ice thickness. The Advanced Topographic Laser Altimeter System (ATLAS) aboard ICESat-2 measures surface elevation at high resolution with a footprint diameter of approximately 11 m. ATLAS was designed to obtain accurate and routine estimates of sea ice surface height and freeboard (ice plus snow thickness) relative to the height of the adjacent ocean. However, open water within the CAA is scarce due to high concentrations of *in situ* formed landfast ice with few open water leads, and snow thickness is generally unknown. To better understand these uncertainties, researchers from Environment and Climate Change Canada conducted surveys on the sea ice between April 10th to 28th, 2022, documenting sea ice surface heights, snow depth, freeboard and ice thickness using a combination of manual, global navigation satellite system (GNSS) surveys and drone measurements. Surveys were conducted along 5 ICESat-2 satellite overpasses, at 57 sites, and along 86 km of continuous transects with coincident snow depth and EM-31 electromagnetic induction sensed sea ice thickness observations. Comparisons of our *in situ* measurements with the ICESat-2 satellite products for sea ice elevation (ATL07), and sea ice freeboard (ATL10) will be presented.

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Using Lakes as Snow Pillows: Monitoring Snowfall from Lake Water Pressure in the Adirondack Mountains, NY

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ABSTRACT

Snowfall is a fundamental winter weather observation that is used for benchmarking weather models, forcing snowpack models, and tracking climate change. However, accurate measurement of snowfall is challenging, due to precipitation gauge undercatch, wind redistribution, and other local effects. A recently published method (Pritchard et al., 2021, J. Hydrometeorology) used water pressure measured in lakes during the winter to estimate the mass of snow falling onto the lake surface. The rationale behind this method is simple: if snow falls on to the lake surface, the water pressure in the lake will increase, either by additional weight on top of the ice or by adding water to lake. This method has the potential to increase the footprint over which snow is measured by multiple orders of magnitude, because the entire lake surface acts as a giant snow pillow, reducing measurement errors that can arise in conventional, point-scale snowfall measurements. However, the lake snowfall method has not been broadly tested, and only at high latitude and high altitude. We evaluate the viability of the method in a location with more variability in winter weather, including midwinter melt events, to determine whether it can be applied in regions with temperate climates. Specifically, we test the method in Arbutus Lake, located within a long-term ecological monitoring site in the Adirondack Mountains of New York, in winter 2022-2023. Lake-estimated snowfall is compared to nearby snow and meteorological observations, and we supplement the method with streamflow measured at the lake inlet and outlet.

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Estimating Snow Density using Optical & Mechanical Properties Instrumented on Lightweight Probe

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ABSTRACT

Snow microstructure research at present aims to characterize snow properties such as density, grain size equivalent, and specific surface area (SSA) using mechanical and optical properties. There are various techniques used to estimate these properties, although each come with speed, accuracy and cost tradeoffs. Although some methods, such as x-ray tomography, are extremely accurate, the method is time intensive, requires field precision, and expensive. Our research aims to use lower-cost probes with active near-infrared and force penetration measurements to estimate density. Although this does not seek to replace the accuracy of x-ray tomography or snowmicropenetrometer (SMP), it may be able to fill the gap for a more durable, convenient and cost-effective technique for density estimations over dry snow. The sensors of the probe are oriented vertically along the probe and pushed into the snow, depth being calculated using an internal barometer. A non-linear regression model is then used to calculate density using these two measurements, and coefficients are derived using in-situ density measurements over various snowpacks.

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NASA SnowEx 2023 Tundra and Boreal Forest Field Campaign in Alaska, U.S.

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ABSTRACT

NASA's SnowEx was initiated by the Terrestrial Hydrology Program in 2017 to study snow remote sensing challenges in different environments in preparation for a future snow mission opportunity. The specific focus of SnowEx is on testing and maturing technology for satellite remote sensing of global snow water equivalent (SWE) and albedo. Over the 2022-2023 winter, SnowEx an airborne and ground-based snow campaign was conducted in Alaska to address SWE, snow depth and albedo measurement questions unique to taiga and tundra snowpacks. Four sites were selected in Interior Alaska, a boreal forest environment with discontinuous permafrost and seasonal taiga snowpack. Two sites were located on the North Slope of Alaska, a region dominated by low-stature land cover, tundra snowpack, and continuous permafrost. A suite of airborne and ground-based validation activities in fall 2022 and spring 2023 were conducted to quantify and compare the capabilities of radar, altimetry and multispectral sensors to measure SWE and snow depth during the winter season and albedo during the spring melt period. The SnowEx field campaign will provide snow datasets in support of testing and advancement of remote sensing, modeling, and measurements techniques needed for the development of global SWE products. This presentation will provide an overview of this winter's field and airborne activities in Alaska and a summary of the data collected.

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Fig. 1. Snow measurements being made at the Upper Kuparuk-Toolik tundra site during the March SnowEx 2023 campaign, Photo credit: Svetlana Stuefer.

Remote Sensing and Cloud Computing: Determining Lake Ice Phenology Using Google Earth Engine and Sentinel-1 SAR Imagery

BRENDAN WARK[1] AND GRANT GUNN[1]

ABSTRACT

Monitoring lake ice phenology is crucial for climate modelling and managing the logistics of daily life in remote northern communities. Determining lake ice phenology using *in situ* measurements is costly and time-consuming, and standard remote sensing techniques have substantial processing and storage requirements. This project blends remote sensing and cloud computing to make large-scale lake ice phenology monitoring fast and accessible with minor hardware requirements.

The project runs a dynamic threshold variability method (DVTM) algorithm on the Google Earth Engine (GEE) processing environment. The DVTM requires a single shapefile of up to 10,000 lakes as input, then collects all Sentinel-1 C-band synthetic aperture radar (SAR) acquisitions covering the lakes a given winter season. It then creates a range of thresholds based on how much the backscatter values within the lakes change between Sentinel-1 acquisitions. Whenever the range of thresholds is crossed, the algorithm flags that date as melt or freeze onset for that specific lake.

Algorithm validation has been conducted on three study areas with 400 lakes each and has been focused on the melt onset portion of the algorithm. All three study areas are within the Alaska North Slope. Based on results from the Canadian Lake Ice Model (CLIMo), temperature records from weather stations, ERA5 reanalysis data, and qualitative analysis of Sentinel-1 SAR imagery, the algorithm can accurately determine the melt onset date of 80% of lakes.

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Bulk Snow Density Retrievals from Passive Microwave Remote Sensing and Automatic Weather Stations in a Tundra Environment

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ABSTRACT

Available methods to monitor snow density are limited spatially and temporally. *In situ* methods require substantial labour and are relatively costly. This research proposes a novel technique to retrieve bulk snow density estimates from passive microwave (PM) remote sensing. A traditional style PM snow water equivalent (SWE) model is rearranged so snow density is the variable of interest instead of snow depth. Daily automatic weather station (AWS) observations are used to parameterize the snowpack in the scene with snow depth and air temperature observations. The Environment and Climate Change Canada AWS in Eureka, Nunavut is chosen to train and validate the algorithm. Snow density records are available for the Eureka site through the Canadian Historical Snow Water Equivalent dataset. Two snowpack models are investigated for this algorithm – a one-layer model (typically used in PM SWE retrievals) and a two-layer model (a slab layer with underlying depth hoar layer). In the two-layer model, 3D gradient descent is used to produce density estimates for each layer, which are then aggregated for a bulk snow density estimate. Climatological analysis of the site provides some prior knowledge of the conditions of the scene, to further control the behaviour of the machine learning (ML) algorithm. These controls are included as components of the ML's cost function (with the PM signal component of standard ML) to introduce temporality, inertia, and logic into the algorithm. Ultimately, this approach could be expanded to retrieve snow density estimates from PM observations over the Northern Hemisphere.

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Influence of Snow Capture by Forest Canopy for a Seasonal Snowpack in the Adirondack Mountains, NY

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ABSTRACT

During the winters in Upstate New York, seasonal snow is often captured by tree canopies that delay snow from depositing on the surface and affect the rate at which the snow melts in the snowpack. Tree canopies often shade the snowpack slowing sublimation and melting rates if most of the snowpack is covered by trees. Differential melting of the snowpack occurs if the snowpack receives uneven amounts of sunlight from forested areas that have a mix of open and closed canopies. Quantifying the effect of canopy interception of snow is difficult because many snow study sites are focused on open areas and/or fields where instruments, satellites, and manual measurements are more accessible. We focus on the Arbutus Lake watershed, located within the Huntington Wildlife Forest (HWF) in the central Adirondack Mountains of New York, USA. The Arbutus Lake watershed is heavily forested with a mix of conifer and deciduous trees. For our study, we use traditional snow depth/SWE transect methods collected on a biweekly timeframe to quantify how snow depth (SD) and snow water equivalent (SWE) vary between three canopy types: heavily coniferous, heavily deciduous, and an entire open canopy field. We examine the spatiotemporal dynamics of the snowpack under different energy budgets and relate it to midwinter melt events. Preliminary results show a distinct change in SD and SWE values in our snowpack depending on whether it is beneath a closed or open canopy type. Additional results show that SD and SWE values differ depending on whether there has been a recent snowstorm or after a long period of melt.

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Daily continental scale snow water equivalent data for North America

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ABSTRACT

Existing continental scale snow water equivalent (SWE) datasets are inadequate to meet many of the societal and scientific needs, such as understanding the impact of warming climate on cold region water cycle. Here, we present the preliminary result of our efforts to model the continental scale daily SWE over North America using a methodology called Blender. Blender is similar in theory to SWE reconstruction and is formulated as a mass-and-energy constrained optimization problem. The general methodology merges remote sensing observation of snow cover fraction with model outputs from land simulation models. Blender utilizes the MODIS cloud gap filled snow covered area (MODIS-CGF) to constrain the optimal estimate of snowfall, SWE, air-temperature, and ground-heat flux generated by Noah-MP simulations. The compute routine is implemented in Julia using Julia for Mathematical Optimization and interior point line-search algorithms. In the current setup we use results from Snow Ensemble Uncertainty Project (SEUP) which used the NASA Land Interface Systems Framework (LISF) running Noah-MP model simulations forced by Modern Era Retrospective Analysis for Research and Applications (MERRA-2) data at a nominal spatial resolution of 0.05 degrees (~5km). The 0.5 km resolution MODIS-CGF snow cover dataset is resampled to 0.05 degrees SEUP resolution for the final Blender run to generate a daily SWE map of North America. Our future goal is the generate a higher resolution (~1km) daily SWE map of North America for a 20-year period, spanning water years 2002 and 2021.

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Spatiotemporal Prediction of Snow Accumulation with Recurrent Graph Convolutional Networks

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ABSTRACT

The accurate prediction and estimation of annual snow accumulation has grown in importance as we deal with the effects of climate change and the increase of global atmospheric temperatures. Airborne radar sensors, such as the Snow Radar, are able to measure accumulation rate patterns at a large-scale and monitor the effects of ongoing climate change on Greenland's precipitation and run-off. Tracking and forecasting these internal ice sheet layers is important for calculating snow mass balance, extrapolating ice age from direct measurements of the subsurface, and inferring otherwise difficult to observe ice dynamic processes. Precise understanding of the spatiotemporal variability of snow accumulation in the Greenland ice sheet is important to reducing the uncertainties in current climate model predictions and future sea level rise. Given the amount of snow accumulation in previous years using the radar data, in this paper, we propose a machine learning model based on recurrent graph convolutional networks to predict the snow accumulation in recent consecutive years at a certain location. In this work, we proposed a temporal, geometric, multi-target machine learning model based on GCN-LSTM that predicts the annual snow accumulation of Greenland from 2007 to 2011 given the annual snow accumulation from 1997 to 2006. Our proposed model was shown to perform better and with more consistency than equivalent non-geometric and non-temporal models. While our model succeeds at predicting shallow layer thicknesses with reasonable accuracy, there are opportunities for improvement and generalization.

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