Snow Depth Retrieval and Downscaling using Satellite Laser Altimetry, Machine Learning, and Climate Reanalysis

A Case Study in Mainland Norway

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Summary

Seasonal snow plays a crucial role as water reservoirs and energy balance component, but accurately estimating the depth of the snowpack remains a challenge, particularly in remote areas. ICESat-2 laser altimetry has the potential to provide precise snow depth measurements by comparing satellite-based snow surface elevation profiles with high-quality Digital Elevation Model (DEM) of the snow-free ground. However, the satellite's acquisition pattern is sparse both in time and space, raising the need for additional steps to produce a spatially complete snow-depth map.

This study generated downscaled snow depth maps by employing a machine-learning regressor to combine snow depths derived from ICESat-2 ATL08 product (2018-2022) with ERA-5 Land data. The methodology involves careful co-registering the data, applying bias correction on DEMs using ICESat-2 surface elevations from snow-free conditions as a reference. Subsequently, snow depth maps are generated by statistically downscaling ERA-5 time-series data on snow depth with the derived snow depth, using terrain, vegetation, and wind parameters. Our results are able to reproduce snow depth patterns at the hill-slope scale, achieving an R-Squared value of 0.68 and a Spearman correlation coefficient of 0.81 when compared to lidar-based snow depth acquired in Hardangervidda, Norway. This approach is applicable globally in any location where accurate snow-free DEMs are available.

Additionally, this study contributes a Gradient Descent Co-registration algorithm, which offers possibilities for handling large-scale datasets at a fine resolution. And, a bias correction workflow is utilized to address uncertainties of DEM and ICESat-2, which refines the conventional elevation differencing workflow of producing snow depth.

The thesis is structured as follows: *Chapter 1* provides an introduction to the role of snow cover, observations techniques and thesis objectives. *Chapter 2* reviews the key concepts of the methodologies, including snow depth variability, satellite laser altimetry, DEM uncertainties, co-registration, machine learning, climate reanalysis, downscaling techniques. *Chapter 3* presents a workflow for snow depth retrieval, including gradient descent co-registration, evaluating DEM against ICESat-2 ATL08, applying bias correction, and downscaling of ERA-5 using ICESat-2 derived snow depth. *Chapter 4* presents the methodology's application in mainland Norway, including snow depth validations. *Chapter 5* discusses the uncertainties and limitations. Finally, *Chapter 6* concludes remarks.

Keywords: Snow depth, ICESat-2, Co-registration, Machine learning, Bias correction, Statistical downscaling

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