Advancements in Snow Depth Retrieval Using Satellite Altimetry and Machine Learning: A Case Study in Mainland Norway

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 satellite altimetry has the potential to provide precise snow depth measurements by comparing satellite-based snow surface elevation profiles with a 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 data to produce a spatially complete snow-depth map. This study generated snow depth maps for mainland Norway by employing machine-learning methods to combine snow depths derived from the ICESat-2 ATL08 product (2018-2022) with ERA-5 Land data. The methodology involves careful data co-registration, benchmarking of DEM uncertainties using ICESat-2 surface elevations from snow-free conditions as a reference, and applying a machine learning-based bias correction on the derived snow depths. Subsequently, snow depth maps are generated in an XGBoost regressor by statistically downscaling ERA-5 snow depth timeseries with the derived snow depth, using terrain, vegetation, and wind parameters. **Our results suggest that while ERA-5 alone overestimates snow depth on a national scale, our approach removes this bias and is able to reproduce snow depth patterns at hillslope scale when compared to lidar-based snow depth maps acquired in the field.** The approach is applicable globally wherever accurate snow-free DEMs are available.

The thesis is structured as follows: Chapter 1 provides an introduction to the role of snow cover, its variability, and observations of snow cover. Chapter 2 reviews the key concepts of snow depth remote sensing, including satellite altimetry, DEM uncertainties, related studies, and machine learning-based regression. Chapter 3 presents a workflow for snow depth retrieval, including evaluating ICESat-2 ATL08 against DEM, processing DEM and ICESat-2 using the co-registration algorithm, accounting for error distribution using geostatistics, and applying machine learning for error classification and prediction, cross-validation, and calibration and downscaling of ERA-5 using ICESat-2 snow depth products. Chapter 4 presents the methodology's application in a snow depth case study in mainland Norway, including snow depth validation in local areas. Chapter 5 discusses the results, the main uncertainties of snow retrieval, and the snow depth distribution. Finally, Chapter 6 provides a future outlook and concluding remarks.

Keywords: Snow Depth, ICESat-2, DEM, Co-registration, Machine Learning, XGBoost, Bias Correction, Statistical Downscalling.