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Machine Learning–Based Gap-Filling of Satellite Snow Products Using Time-Lapse Photography and Meteorological Data

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Reliable information on snow cover dynamics is essential for water resource management, climate impact assessments, and ecological studies. In mountainous regions, where spatial variability is high and long-term observations are limited, satellite-based snow products often present the primary source of information. However, their performance is constrained in complex terrain by cloud cover, coarse spatial resolution, and data gaps. Therefore, the validation of satellite-derived snow cover data is crucial for reducing uncertainty. In this study, we employed a low-cost, ground-based time-lapse camera to monitor snow cover (SC) and to support the validation, gap-filling, and improved reliability of satellite-derived snow cover products.

Time-lapse photography was obtained using a camera trap installed at the Skalnaté Pleso Observatory in the High Tatra Mountains (Slovakia). The camera captured daily images of a south-eastern slope during four snow seasons (2021/22–2024/25). An automated image-processing workflow was applied to derive snow cover percentage from the photographs, including horizon-based image alignment, masking of non-relevant areas, and automatic snow classification based on blue-band intensity thresholds. The resulting camera-derived SC was compared with satellite-based fractional snow cover (FSC) from Sentinel-2 products (Fractional Snow Cover and Gap-filled Fractional Snow Cover marked as S_FSC and S_GFSC) and MODIS products (MOD10 and MYD10 marked as M_TERRA_FSC and M_AQUA_FSC) within the camera's field of view.

The analysis revealed substantial differences in data availability between ground-based and satellite observations, with time-lapse photography providing more continuous records during periods of frequent cloud cover. Camera-derived SC captured short-term snow accumulation and melt dynamics that were often missed or temporally smoothed in satellite products. Relative to camera observations, Sentinel products overestimated SC by 11.3 % (S_GFSC) and 9.1 % (S_FSC), whereas MODIS products underestimated SC by -9.5 % (M_AQUA_FSC) and -7.7 % (M_TERRA_FSC).

Data gaps in satellite products were addressed using a Random Forest machine-learning approach trained on SC derived from terrestrial time-lapse photography. To avoid sensor-mixing biases, separate models were trained for each Sentinel-2 and MODIS product. By integrating local meteorological variables such as daily air temperature, precipitation, snow depth, and global radiation, the models were able to capture the non-linear nature of snow dynamics. Our study

demonstrates that combining time-lapse photography with satellite products and in situ meteorological measurements enables more accurate reconstruction of snow cover dynamics, particularly in periods of rapid snow accumulation and melt in alpine environments.

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