WHERE IS THE SNOW: VALIDATING A FRACTIONAL-SNOW COVERED AREA PARAMETERIZATION FOR SNOW MELT FORECASTING WITH SATELLITE MEASUREMENTS

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ABSTRACT: The snow cover exhibits tremendous spatial and temporal variability, especially in complex topography. Fractional snow-covered area (*fSCA*) is a parameter used to describe how much ground is covered by snow. As such, *fSCA* is a relevant parameter in large-scale model applications, for instance to compute the surface radiation balance or for scaling snow melt runoff. Many studies therefore focused on formulating parameterizations for *fSCA,* requiring mean snow depth estimates and knowledge about the underlying topography. With the emergence of high-resolution satellite products, remotely-sensed *fSCA* estimates are becoming more readily available, opening new avenues to assimilate *fSCA* in models. Nevertheless, parameterizations are still required to fill the gap when satellite data are unavailable (e.g. between satellite revisits, when clouds obscure the ground and for forecasting). We therefore evaluated *fSCA* estimates from a recently proposed *fSCA* parameterization developed for peak of winter snow data with satellite *fSCA* from Sentinel-2 images generated by Theia over an entire winter season for Switzerland. Modelled *fSCA* maps were obtained from a 1 km gridded operational hydrological model that assimilated several hundred snow depth measurements and ran with data from the numerical weather forecast model COSMO. Furthermore, snow depth maxima were tracked over the season. While both *fSCA* estimates correlated significantly, intra-season differences were present. We therefore investigated *fSCA* maps derived from parameterized mean snow depth using flat field snow depth measurements whilst similarly tracking snow depth maxima. Overall, our results show that complementing satellite snow maps with a *fSCA* parameterization has great potential for large-scale models.

KEYWORDS: spatial snow distribution, subgrid parameterization, satellite data, snow melt, avalanche forecasting

1. INTRODUCTION

Since single flat field point snow depth observations are rarely representative of spatial averages in complex topography (Grünewald and Lehning (2015), Helbig et al. (2015)), ongoing research is still devoted to how spatial snow depth variability can be described in larger scale model grid cells, which do not explicitly model fine-scale processes. In these larger scale models the spatial distribution of snow depth is typically described by fractional snow-covered area (*fSCA*), which accounts for the mismatch between a spatial mean snow depth and the actual snow coverage. Capturing the temporal evolution of *fSCA* is a vital modeling component as well; as accumulation and melt season *fSCA* can differ substantially while mean snow depths remain similar (Niu and Yang (2007)).

Until recently, *fSCA* was often derived from mean snow depth scaled heuristically with terrain parameters (e.g. Roesch et al. (2001), Yang et al. (2007)). By linking coarse-scale satellite snow products to gridded-snow products new *fSCA* parameterizations differentiating between accumulation and melt season were developed (e.g. Swenson and Lawrence (2012)). Recently, a *fSCA* parameterization was derived based on high-resolution snow depth measurements in complex topography at peak of winter (Helbig et al. (2015)).

While the emergence of satellite snow products has increased the availability of observational, high-resolution, snow-covered area products, there remains a distinct need for computationally derived *fSCA* products. The availability of satellite-derived *fSCA* remains inconsistent due to time gaps between satellite revisits and cases when clouds obscure the ground. Additionally, satellite-derived *fSCA* is never available for forecasts. In all these instances, computationally derived *fSCA* estimates are required.

Our goal here was to compare *fSCA* products for coarse-scale model applications which require *fSCA* for scaling e.g. for snow melt output, surface albedos etc. Products ranged from parameterized *fSCA* based on snow depth maps extrapolated from station observations as well as from an energy balance snow model that assimilated station and precipitation data to satellite-derived *fSCA.*

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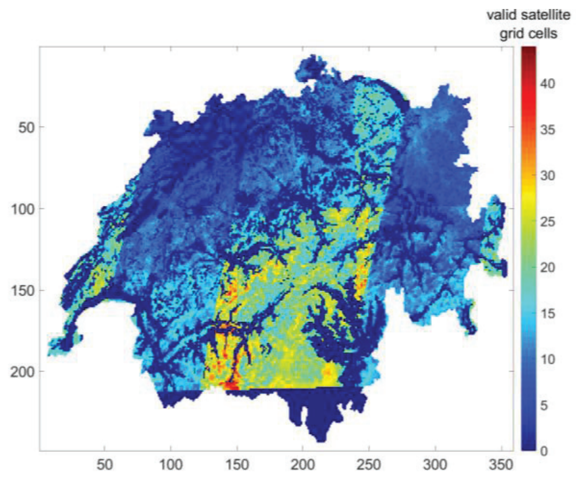

Figure 1: Number of useable 1 km satellite derived *fSCA* revisits per grid cell during the winter season starting from 2017/11/23 until 2018/07/02.

2. DATA AND METHODS

2.1 Satellite fSCA maps

Daily satellite derived *fSCA* maps were created for Switzerland from Sentinel-2 L2A and L2B images using the snow product generated by Theia (2018) over an entire winter season starting from 23 November 2017 until 02 July 2018. Envisaged temporal resolution of the Theia snow product is every fifth day if there are no clouds. The horizontal resolution of the snow product on the ground is 20 m. The Theia snow product is free (theia.cnes.fr). *fSCA* maps were derived in 1 km horizontal resolution from the fine-scale snow product by resampling after removing forested grid cells (Arealstatistik 1992/97, BFS GEOSTAT) and grid cells obscured by clouds. Forest was masked out since the satellite snow product is not reliable in densely forested areas. For the analyzed winter season 2017/2018, which consisted of 222 days, this resulted in a range of 0-44 and on average 9 useable satellite derived *fSCA* retrievals per grid cell (Figure 1).

2.2 Station parameterized fSCA maps

Flat field snow depth measurements from several hundred automatic weather stations (AWS) as well as manual observations distributed throughout Switzerland were used. AWS data are part of the Intercantonal Measurement and Information System (IMIS) operated by the WSL Institute of Snow and Avalanche Research SLF and of SwissMetNet operated by MeteoSwiss.

Flat field snow depths measurements were distributed to a 1 km grid spanning all Switzerland. Virtual stations were used. The corresponding virtual measurements were allocated by searching within a 20 km radius and a 100 m elevation difference. Both distance and elevation difference increased stepwise if no station was found but were limited to a maximum of 60 km distance and 200 m elevation difference.

Gridded flat field snow depth measurements were corrected by a subgrid parameterization for snow depth over mountainous terrain (Helbig and van Herwijnen (2017)). The parameterization combines a power law elevation trend scaled by the subgrid parameterized sky view factor (Helbig and Löwe (2014)) of the associated grid cell. Actual spatial mean snow depths are computed using station and grid cell elevations as well as sky view factors.

The *fSCA* parameterization of Helbig et al. (2015) was applied which is based on the subgrid parameterized standard deviation of snow depth over mountainous terrain at peak of winter and current spatial mean snow depth. Topographic scaling factors, a slope related parameter and a correlation length of topographic features were derived from a scale dependent analysis on high-resolution spatial snow depth measurements in Eastern Switzerland and the Spanish Pyrenees at peak of winter.

Daily station parameterized *fSCA* maps were generated using parameterized subgrid standard deviation of snow depth in each grid cell σ_{HS0} (Helbig et al. (2015)). Instead of peak of winter we used the current maximum gridded snow depth HS_0 in each grid cell which we corrected for subgrid topography as outlined above to compute σ_{HS0}.

2.3 Modelled fSCA maps

Daily modelled fSCA maps in 1 km resolution were obtained from a multilayer energy balance snow model provided in a multimodel framework (JIM, JULES investigation model) (Essery et al. (2013)). The mass and energy balance is solved for at maximum of three snow layers. The model framework JIM was set up to perform operational snow melt forecasting for Switzerland. Details on model choices with regards to the internal snowpack processes can be found in Magnusson et al. (2015, 2017).

We ran JIM for Switzerland in 1 km horizontal resolution with hourly numerical weather prediction (NWP) data from the COSMO-1 model (operated by MeteoSwiss). Spatial analysis of daily measured precipitation data (RhiresD) from MeteoSwiss are used as well as reanalysis COSMO-1 data. Daily flat field snow depth measurements from AWS and from manual ob

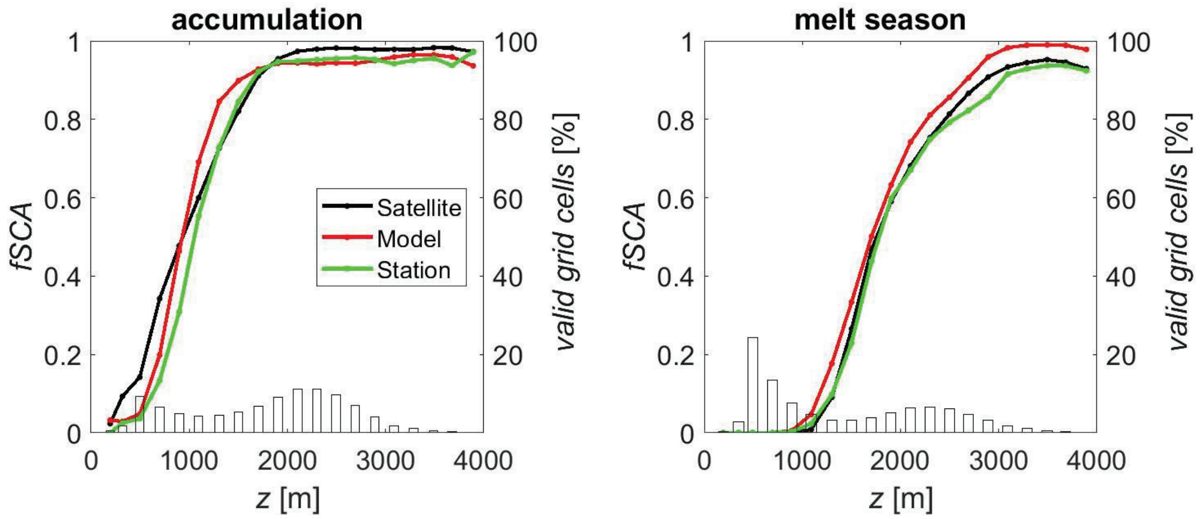

Figure 2. Fractional snow-covered area *fSCA* is shown as a function of mean elevation *z*. Colors indicate if *fSCA* was derived from the satellite snow product, modeled or parameterized from measurements only. Bars give the percentage of useable 1 km satellite derived *fSCA* grid cells (cloud and forest removed) within the corresponding elevation band. Left: Accumulation period; Right: Melt period.

servations in Switzerland are assimilated using optimal interpolation (Magnusson et al. (2014)).

Daily modeled *fSCA* maps are computed in JIM during the melt period with the parameterization of Helbig et al. (2015) and during accumulation with the standard deviation replaced by one of Egli and Jonas (2009). *fSCA* is implemented by tracking seasonal minimum and maximum modeled snow depth as well as the snow depth over the last 14 days.

3. RESULTS AND DISCUSSION

We separated the winter season into the two characteristic periods, namely accumulation and melt spatially consistent in mid-April. For the winter season 2017/2018 this resulted in 74 days with satellite data for the accumulation and 42 days for the melt period.

In general, all modeled and station parameterized *fSCA* maps compare well with satellite derived *fSCA*. Performance measures were overall better during melt than during accumulation. Overall, modelled *fSCA* maps compare slightly better with satellite derived *fSCA* maps.

During accumulation, the normalized root mean square error (NRMSE) for modeled *fSCA* maps was 22%, which was slightly lower than the station parameterized *fSCA* NRMSE of 26%. The Pearson correlation coefficient was also slightly higher for the modeled *fSCA* maps (r=0.83) than for station parameterized *fSCA* (r=0.78).

Similarly during melt the NRMSE for modeled *fSCA* maps (12%) was lower than for station parameterized *fSCA* (16%). The Pearson *r* was also higher for modeled *fSCA* maps (r=0.97) than for station parameterized *fSCA* (r=0.94).

When aggregated into 200 m elevation bands differences between all three *fSCA* maps get small (Figure 2). Largest differences of 21% occur during accumulation between station parameterized and satellite derived *fSCA* maps for elevations below 1000 m. NRMSE differences between the two parameterized *fSCA* products vanished during accumulation for modeled and station parameterized *fSCA* maps when averaged in elevation bands: 6% versus 7%. Pearson *r* were identical for the two products (r=0.99). During melt the NRMSE was now slightly better for station parameterized *fSCA* (2%) than for modeled *fSCA* maps (5%). Pearson *r* was 1 for both.

During accumulation satellite derived *fSCA* below 1000 m is larger than both modeled and station parameterized *fSCA* (Figure 2). One explanation could relate to a caveat Theia gives for their snow products. It says that some cold, low elevation, clouds can be wrongly classified as "snow".

Note that the percentage of useable 1 km satellite derived *fSCA* grid cells in each elevation band was generally lower than 20%.

While the differences between all three *fSCA* maps seem small (Figure 2), we illustrate the influence of *fSCA* differences on snow melt runoff. Modeled snow melt runoff is scaled with the corresponding *fSCA* to compute the updated snow

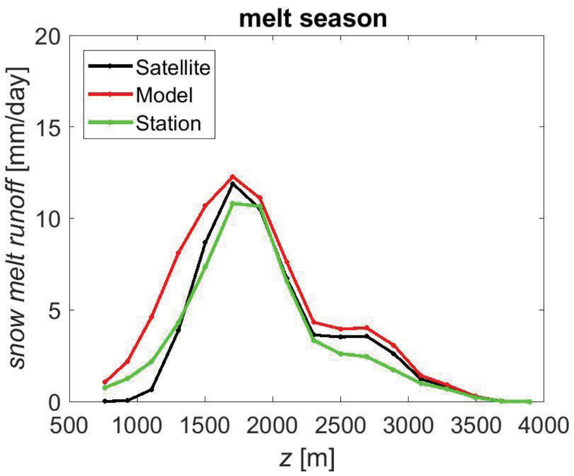

Figure 3: Modeled snow melt runoff is shown as a function of mean elevation *z*. Colors indicate if snow melt runoff was scaled with *fSCA* maps from the satellite snow product, modeled or parameterized from measurements only.

melt from a grid cell. The largest snow melt runoff differences, when averaged in 200 m elevation bands occur between model parameterized and satellite derived *fSCA* maps. Differences lie primarily between 1000 m and 1500 m and range up to 4 mm/day (Figure 3).

4. CONCLUSIONS

High-resolution Sentinel snow products were compared to parameterized *fSCA* maps for a winter season in Switzerland. An overall better agreement was achieved during melt than during accumulation for the 1 km *fSCA* maps. Nevertheless, an overall good agreement was obtained between both implementations of the *fSCA* parameterization and the satellite snow product. We therefore conclude that complementing satellite snow maps with a *fSCA* parameterization has great potential for large-scale models.

The performance of *fSCA* maps generated using measured flat field snow depth as input was only slightly worse during accumulation compared to the *fSCA* maps generated with the multilayer energy balance snow model. To shed light on the differences we need to further analyze the *fSCA* parameterization during the accumulation period preferably with high-resolution spatial snow depth data.

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