Brief Communication: Daily, gap-free snow cover information based on a combination of NPP VIIRS and MODIS data

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Abstract. Combining Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer
Suite (VIIRS) snow cover data and applying cloud- and data gap interpolation steps can be utilized to generate daily, gap-free
snow cover information. Provided by the German Aerospace Center (DLR) under the name "Global SnowPack", this product
has undergone several improvements, comprising the inclusion of VIIRS, a new threshold for the Normalized Difference Snow
index (NDSI), and considerable validation. The Global SnowPack offers unique opportunities for analyzing time series of
snow cover data since September 2000 and is freely available for visualization and download from DLRs GeoService.

1 Introduction

The German Remote Sensing Data Center (DFD) of DLR has released a globally available, cloud- and gap-free snow cover
product in 2015 (Dietz et al., 2015) based on the MODIS Snow Cover Daily L3 Global 500 m SIN Grid product (Hall and
Riggs, 2021). Named "Global SnowPack" and being made available on the DLR Geoservice[1], several combination and
interpolation steps are applied to the original snow cover product of the National Snow and Ice Data Center (NSIDC) to ensure
continuous information about the presence or absence of snow cover throughout the year. The motivation for this development
was the need for continuous, gap-free data for the detection of trends in snow cover duration for hydrological studies (Roessler
et al., 2021; Vydra et al., 2024) or analyses in the context of animal migration, long-term changes in animal behaviour
(Pokrovsky et al., 2024), or even the impact of snow cover change on genetical, evolutionary aspects (Mills et al., 2018;
Zimova et al., 2022). An estimate of the snow cover status below clouds is necessary for such studies, even though they come
at the price of slightly reduced accuracy when compared to clear-sky conditions (Gafurov and Bárdossy, 2009).

While the initial Global SnowPack product was derived from Aqua and Terra MODIS only, in this communication we present
an updated version of this approach, incorporating National Polar-orbiting Partnership (NPP) VIIRS data, resampling the
spatial resolution to 371 m, and applying an adjusted Normalized Difference Snow Index (NDSI) threshold for the
classification of the binary snow/no snow information that constitutes the output of the processing chain. An extensive accuracy
assessment has also been conducted.

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[1] https://geoservice.dlr.de/web/maps/eoc:gsp:daily

2 Data and Methodology

30 The snow cover products based on MODIS (MOD10A1/MYD10A1, (Hall and Riggs, 2021)) and NPP VIIRS (Riggs and Hall, 2020) constitute the basis for the daily snow cover information. These datasets come with pre-processed cloud masks, quality layers, and an NDSI layer. Landsat data was used to calibrate the NDSI threshold to classify binary snow/no snow information and validate the final product. A total of 381 Landsat scenes with snow cover are classified following the procedure described in (Koehler et al., 2022), which is modified based on the final deliverable of the Satellite Snow Product Intercomparison and

35 Evaluation Exercise (SnowPEx) (Ripper et al., 2019), has been prepared. Additionally, the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) digital elevation model (DEM) is used for the processing (Danielson and Gesch, 2011).
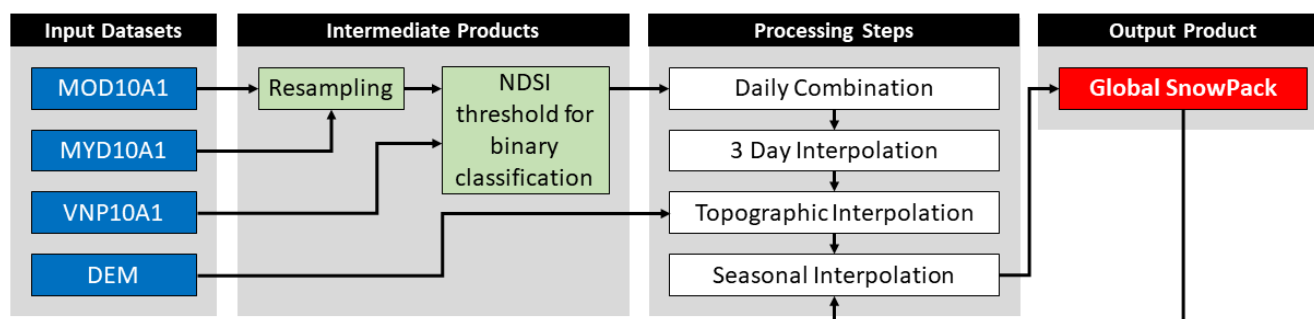
Figure 1: Workflow for the DLR Global SnowPack processing chain

As indicated in the introduction, a gapless, cloud-free, daily, binary snow cover product is desirable for numerous applications

40 and research, leading to the implementation of a workflow to completely remove all data gaps through a series of interpolation steps applied to the MODIS and VIIRS snow cover data. These interpolation steps (Figure 1) have been described by (Dietz et al., 2015; Gafurov and Bárdossy, 2009) and remain the same for the update presented here, with the addition of the daily VIIRS data since 2012 being an exception. Including an additional data source allows for three datasets going into the "Daily Combination" after 2012, increasing the amount of available data but not changing the general concept of the interpolation

45 chain. There are two additional changes to the processing, regarding the spatial resolution and binary snow cover classification.

2.1 Adjustment of the NDSI threshold to classify snow

The data sets from MODIS (Terra: MOD10A1; Aqua: MYD10A1) and VIIRS (VNP10A1) consist of the same layers, of which "NDSI_Snow_Cover" and "NDSI_Snow_Cover_Basic_QA" are being used. The latter indicates the quality of the values determined and serves as a first orientation for the composition of the daily snow cover extent based on the combination of all

50 available observations; if the quality values are the same, an empirically determined order of prioritization is used. Because a binary snow cover classification is desired for purposes such as the calculation of snow cover duration or trends, a threshold for the NDSI is required to separate snow-covered (≥ 50% Fractional Snow Cover; FSC) and snow-free (< 50% FSC) surfaces. The most suitable NDSI has been chosen through comparison with 381 classified Landsat reference scenes (distributed worldwide and covering all ecozones and seasons), by maximizing the F1 value. For MODIS the best NDSI threshold is an

55 average of 0.26 (MOD10A1 3000) and 0.23 (MYD10A1 3000) for Aqua and Terra, respectively. For VIIRS (VNP10A1) the best threshold is 0.23.

2.2 Resampling of the spatial resolution to 371 m

The higher spatial resolution of VIIRS with 12 arc seconds (371 m) compared to MODIS with 15 arc seconds (463 m) made a spatial adjustment of the MODIS scenes necessary. For this purpose, the data of the "NDSI_Snow_Cover" layer was divided
60 into a continuous and a discrete part. In the continuous part (less than or equal to 1.0) the new grid was interpolated linearly. For the discrete part (which includes classes such as water, clouds, etc.) the nearest neighbour method was used for interpolation. A comparison with the Landsat reference datasets showed that there was no significant loss of accuracy.

3 Results and Discussion

The processing chain illustrated in Figure 1, which includes the adjustments described in sections 2.1 and 2.2, leads to a binary,
65 daily snow cover information for the whole globe since September 1st 2000 with a spatial resolution of 371 m. All data gaps have been interpolated using either alternative sensor data, temporal interpolation, or snow line elevation information. Although the accuracy of these steps has been assessed in earlier studies (Dietz et al., 2015; Gafurov and Bárdossy, 2009), the quality has been re-evaluated using the data from 381 Landsat classifications and 50160 globally distributed snow stations from the Global Historical Climatology Network (Menne et al., 2012). This resulted in almost 73 Mio. single measurements
70 (with 33.4 Mio. from interpolated pixels).
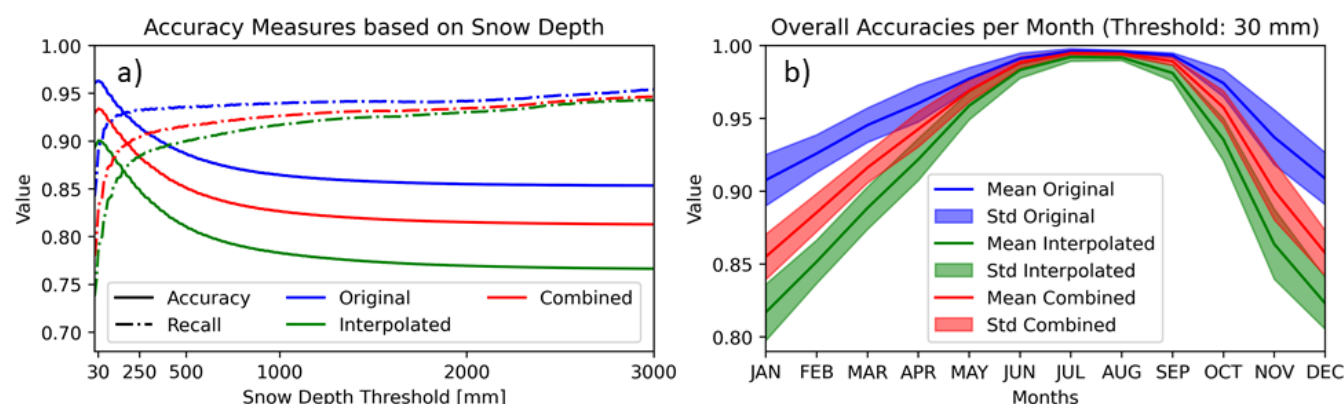
Figure 2: Original MOD10/VIIRS pixels (original), the interpolated pixels (interpolated), and the combined Global SnowPack product (combined) compared to different snow depths (a); Overall accuracy of the original, interpolated, and combined pixels throughout the year, based on station data with 30 mm snow depth threshold (b).

75 The challenge for the Landsat comparison is that only those pixels flagged as data gap in MODIS/VIIRS, but cloud-free in Landsat, can be compared to assess the accuracy of the interpolated pixels. The more precise cloud mask as well as the different observation time of Landsat compared to MODIS/VIIRS however allowed for a thorough assessment of almost 1 Mio. Km². The comparison with Landsat resulted in an F1 score of 0.94. The comparison with the station data is visualized in Figure 2:

The overall accuracy for the interpolated pixels reaches 90% at 30 mm snow depth, and the combined Global SnowPack
80 product reaches values of around 93% (Figure 2a). This accuracy varies throughout the year, with values ranging from 85% to
99% for the dataset combined from the interpolated and original MOD10/VIIRS data (at 30 mm snow depth, Figure 2b).

The improvement of adding VIIRS to the processing chain is illustrated in Figure 3: a considerable amount of cloud-free pixels
was incorporated into the combination of daily datasets with up to an additional 10.0% (MIN 2.1%, MEAN 5.6%, MAX
10.0%) of land pixels during summer and 8.7% (MIN 0.0%, MEAN 3.3%, MAX 8.7%) of snow pixels during spring.

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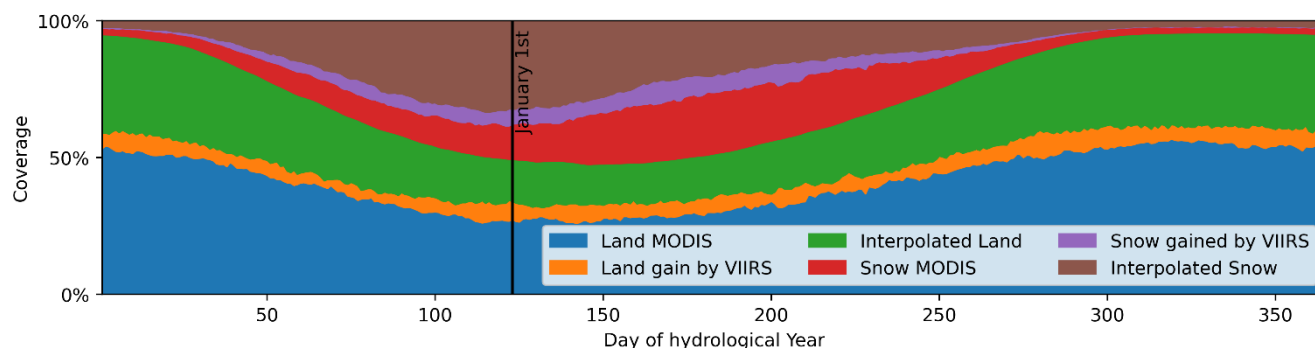
**Figure 3: Overview of the effect of the added VIIRS data: cloud-free land in MODIS (light green) and VIIRS (dark green),
interpolated land (olive green), cloud-free snow in MODIS (light blue) and VIIRS (sky blue), interpolated snow (dark blue).
Hydrological year runs from September 1st through August 31st.**

The initial data sources (MODIS and VIIRS snow cover products) have been assessed multiple times throughout the last
90 decades (e.g. in (Baker and Kilcoyne, 2011; Brubaker et al., 2005; Hall et al., 2002; Hall and Riggs, 2021)), which is why the
accuracy of those pixels not flagged as cloud/polar darkness or data gap were only validated with the snow depth station data
(Figure 2 a) and b), referred to as "original data").

4 Conclusions

The updated version of the Global Snowpack is processed from three individual daily snow cover datasets (Terra and Aqua
95 MODIS as well as NPP VIIRS) and provides a binary information about the presence or absence of snow for the whole globe.
The assessment relying on Landsat data showed that resampling the MODIS 500 m data to 371 m to match VIIRS does not
significantly reduce the accuracy, while the interpolation of cloud and polar darkness gaps introduces uncertainties based on
the duration of the data gaps. These uncertainties can easily be estimated and included in an uncertainty layer accompanying
the GSP product. The accuracy assessment relying on station and Landsat data revealed an F1 score of 0.94, and an overall
100 accuracy between 85% to 99% (mean 94%). The Global SnowPack product is publicly available on the GeoService of the
Earth Observation Center[2].

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[2] https://geoservice.dlr.de/web/maps/eoc:gsp:daily

Author contributions. Conceptualization: AD SR. Data curation: AD SR. Formal analysis: SR. Investigation: AD SR. Writing: AD SR

105 *Competing interests.* I declare that I have no competing interests

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