Comparison of NASA MODIS / VIIRS Cloud-Gap-Filled with other Satellite-Derived Snow-Cover Maps

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INTRODUCTION

Seasonal snow cover regulates the surface energy balance, in large part due to its high albedo and low thermal conductivity, influencing earth-surface processes and availability of water resources. Since 2000 NASA standard snow-cover maps have been available from the MODerate-resolution Imaging Spectroradiometer (MODIS) on the Terra satellite and, since 2002, on the Aqua satellite at a spatial resolution up to 500 m, and since 2012 from the Suomi-National Polar Program (S-NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) at 375-m resolution. These daily, global snow-cover products are used extensively in studies of seasonal snow-cover dynamics at regional and hemispheric scales. A limitation of these products is that they cannot map snow through cloud cover. To mitigate this limitation, NASA cloud-gap-filled (CGF) standard snow-cover map products were developed from the Terra/Aqua MODIS and the S-NPP VIIRS sensors and are named MOD/MYD10A1F and VNP10A1F, respectively.

The purpose of this work is to evaluate the accuracy of the NASA CGF snow-cover maps through comparisons with existing satellite-derived snow-cover maps. *First*, we look at time series data to assess continuity between the NASA CGF snow products. We then compare VNP10A1F with NOAA's Interactive Multisensor Snow and Ice Mapping System (IMS) 1- and 4-km snow maps (Helfrich *et al*., 2007; Woods and Helfrich, 2019) for a 2,487,610 km^2 study area in the western U.S. and southern Canada (Figure 1). *Next,* we compare VNP10A1F snow maps with snow maps derived from 30-m resolution USGS Landsat-8 Operational Land Imager (OLI) data using the USGS fSCA (Selkowitz and Forster, 2016) and the Landsat CFMask-derived snow map. The CFMask is the USGS operational cloud and cloud shadow detection algorithm that is applicable with data from Landsat and Sentinel-2 (Zhu and Woodcock, 2012; Foga *et al*., 2017). For the comparisons using fSCA, which provides fractional snow cover, we used a cutoff to create binary snow maps where snow-cover fraction ≥15% in a pixel is mapped as "snow," and everything else is mapped as "other."

RESULTS

Comparison of NASA CGF snow products

Previous results show excellent correspondence between the Terra MODIS CGF snow maps (MOD10A1F) and the S-NPP CGF snow maps (VNP10A1F), with small differences in snow-cover extent (SCE) attributed to differences in spectral bands, native resolution, sun angle and time of day of image acquisition (Riggs and Hall, 2020). A high degree of continuity is expected because the VNP10A1F algorithm was developed specifically to match the MOD/MYD10A1F algorithm to

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enable the creation of a climate data record (Hall *et al*., 2019; Riggs *et al*., 2019). Figure 2 shows an example of the excellent agreement (R = 0.099, mean bias -0.0001 million km^2) between SCE measured using the MOD10A1F and VNP10A1F for the Upper Klamath Lake basin which is within the study area shown in Figure 1.

Figure 1. Study area (2,487,610 km^2) covering all or parts of 11 states in the western U.S. and part of southern Canada.

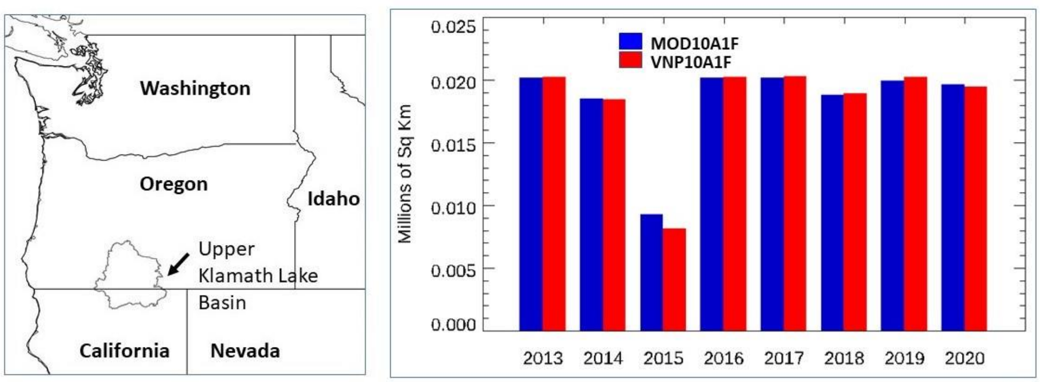

Figure 2. Location map is on the left. Graph shows winter (DJF) snow extent in millions on km^2 in the UKL Basin as measured using the MOD10A1F and VNP10A1F NASA cloud-gap-filled snow-cover products.

Comparison of NASA CGF snow products with other satellite-derived snow products

To assess the agreement of the NASA CGF daily snow maps with other established SCE maps, we plotted the SCE in km^2 from the VNP10A1F and IMS 1-km and 4-km resolution SCE maps for water years (WY) 2016, 2017 and 2018. Results from WY 2018 are shown in Figure 3. In all three years, the IMS 1- and 4-km results are virtually identical (R^2 = 99), with a mean bias of -0.002 km^2 (for 2016) and -0.004 (for 2017 and 2018) (Table 1).

The coefficient of determination, R^2, between the VIIRS CGF and IMS snow products is high in all three years and, for example, in the 2018 WY, only 4 percent of the days on which data were available between the first of October and the end of May show large ($\geq$15 percent) differences between the VNP10A1F and IMS 1-km SCE (Table 1). However, there are many days in different areas within the study area (see Figure 1) where there are large differences in the SCE mapped using VIIRS and IMS, for example in early November of 2017 and at the end of January/early February of 2018 (Figure 3). There are two main causes for these differences. 1) The IMS often tends to “fill in” and thus map too much snow, probably due to analysts’ decisions to fill in partially snow-covered areas, and because of the IMS coarser resolution compared to the NASA CGF snow maps.

2) The VIIRS CGF maps cannot "see" new snow if it falls while the area is cloudy, or "see" existing snow that has melted while clouds are present.

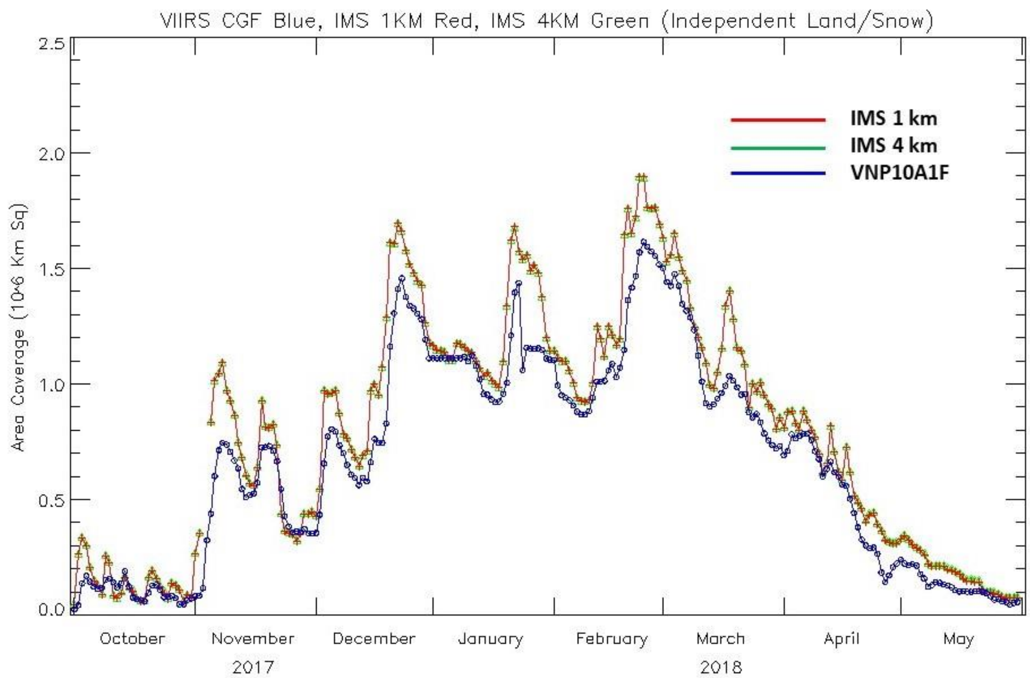

Figure 3. IMS 1- and 4-km and VNP10A1F SCE in km2 in the western U.S./southern Canada study area for WY 2018.

Table 1. Comparison of time series snow maps (VNP10A1F minus IMS 1 km) for three partial water years in the northwestern U.S./southern Canada study area shown in Figure 1.

Water Year	RMSE*	R^2	Mean Bias*	Percent of days for which the difference exceeds 15%
2016	0.166	0.962	0.102	5
2017	0.143	0.970	0.080	3
2018	0.160	0.963	0.119	4

* unit is = 1,000,000 km^2

Comparison of NASA CGF snow products with higher-resolution Landsat-derived snow products

To illustrate the first point indicating that the IMS maps tend to "fill in" and thus sometimes map too much snow, we compare VIIRS and IMS snow maps with higher-resolution (30 m) Landsat OLI data for a 29 November 2015 Landsat scene (path/row 039/026) located at the U.S./Canada border in northcentral Montana and southeastern Alberta/southwestern Saskatchewan (Figure 4). The VIIRS map provides greater detail than does IMS. In the VIIRS map, Figure 4c, the various shades of purple and white represent different values of the normalized-difference snow index (NDSI) that can be used to estimate fractional snow cover within a pixel, with the white pixels indicating nearly 100 percent snow coverage and the darkest purple pixels indicating ~10 percent.

In Figure 5 we show difference maps using VNP10A1F vs the USGS fSCA snow map, and IMS 1-km *vs* fSCA for the same general area in northern Montana / southern Canada on 29 November 2015 as shown in Figure 4. To develop these snow maps, two Landsat-8 OLI scenes were stitched together. Both the VNP10A1F VIIRS and IMS maps agree well with the Landsat fSCA map, with the VNP10A1F *vs* fSCA agreement being somewhat higher, at 90 percent, than the IMS 1-km *vs* fSCA agreement at 88 percent.

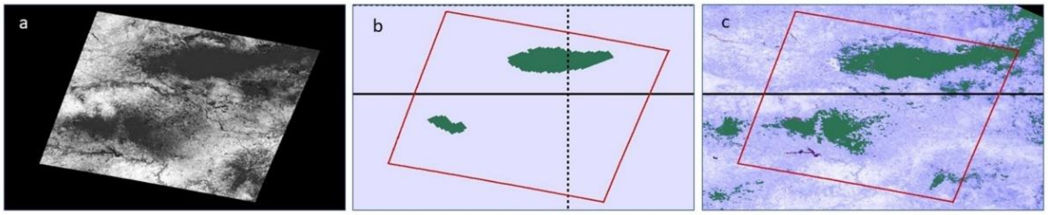

Figure 4. The study area spans the U.S./Canada border in northcentral Montana and southern Canada, 29 November 2015; all are mapped to a common lat/long grid at 500-m resolution. a) Landsat-8 OLI bands 4, 3, 2 in which snow is white and non-snow features are black (i.d. #LC08_L2SP_039026_20151129_20200908_02_T1); b) IMS snow map in which snow is light purple and non-snow features are green; c) VIIRS VNP10A1F snow map in which the various shades of purple and white represent different NDSI values; white is nearly 100 percent snow cover and dark purple is ~10 percent snow cover.

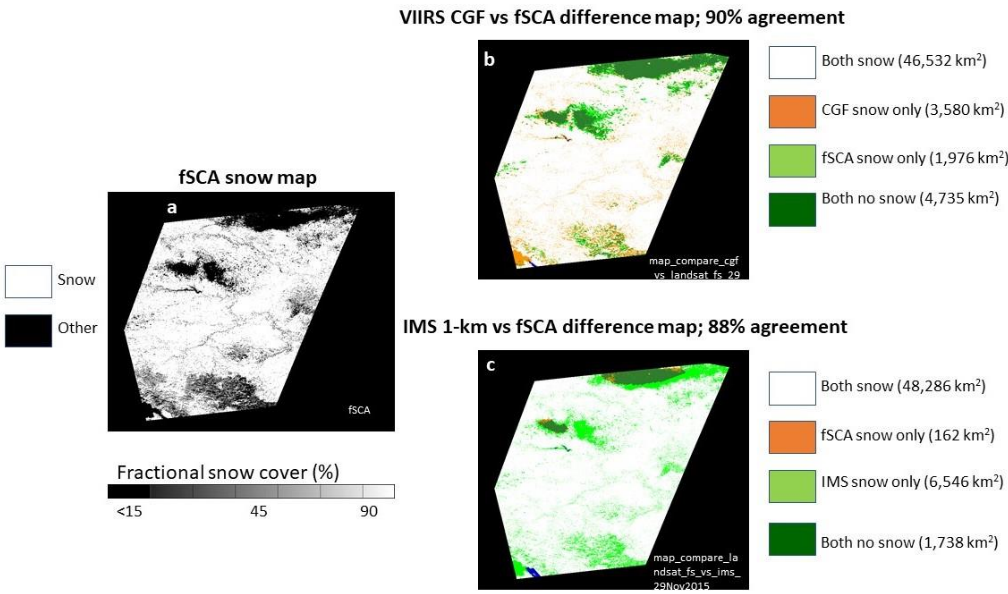

Figure 5. 29 November 2015 maps of an area in northern Montana/southern Canada mapped to a common lat/long grid at 500-m resolution. a) Landsat-8 OLI USGS fSCA snow map; b) VNP10A1F *vs* fSCA snow map shows 90 percent agreement; c) IMS 1-km snow map *vs* fSCA snow map shows 88 percent agreement. The following Landsat-8 OLI scenes were used to develop the snow maps in these figures: LC08_L2SP_039026_20151129_20200908_02_T1 and LC08_L2SP_039027_20151129_20200908_02_T1.

We also looked at 12 March 2021 Landsat-8 OLI scenes from the study area in southern Oregon/northern California that includes the UKL basin. We compared the Landsat fSCA snow map with the CFMask snow map, finding 90 percent agreement; we also compared VNP10A1F *vs* CFMask and found 87 percent agreement. Then we compared VNP10A1F *vs* fSCA for the same area, finding 91 percent agreement (Figure 6).

Uncertainties in cloud-gap-filling

The NASA fully-automated standard MODIS/VIIRS CGF maps can miss snow during cloudy conditions because a snow-cover decision cannot be updated until the clouds clear, thus the snow-map result from MOD10A1 from the most recent previous clear day, is retained in the MOD10A1F (CGF) algorithm. (MOD10A1 is the NASA standard daily snow map that includes clouds and is input to the MOD10A1F algorithm.) However, the IMS map production is not fully automated and thus key information such as from meteorological station data and local observations is used in the production of their daily maps, so the IMS products can be advantageous during extended periods of cloud cover. In Figure 7 the IMS map (lower panel) correctly captures some snow cover beneath clouds that is missed by the MOD10A1 algorithm (upper panel). The reason was investigated, and it was determined that there was an error in the MOD35 cloud mask used as input to the MOD10A1 snow-mapping algorithm. The shape of the 'cloud' feature on this 25 March 2012 MOD10A1F snow map shown in the red rectangular area is similar to a snow feature in the NOAA IMS 4-km snow map from the same day (lower panel). When the cloud mask was removed from the MOD10A1 daily snow map, a feature that appears to be snow is revealed (not shown). The determination that this really is a snow feature was confirmed by visual interpretation of other satellite data and NOAA station data.

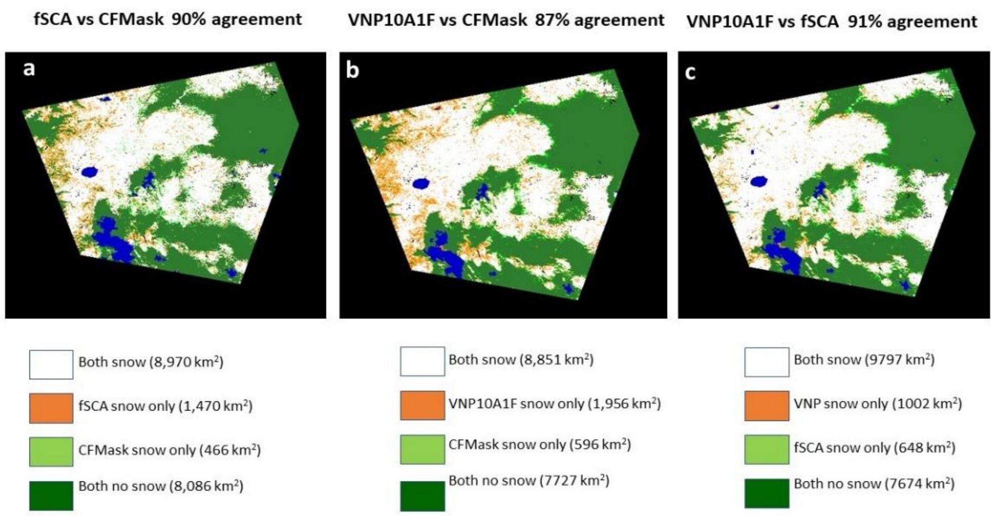

Figure 6. Comparison of Landsat-derived and VNP10A1F snow maps for an area in southern Oregon and northern California that includes the UKL basin, 12 Marsh 2021, mapped to a common lat/long grid at 500-m resolution. a) Landsat-8 OLI USGS fSCA snow map *vs* CFMask snow map; b) VNP10A1F snow map vs Landsat CFMask snow map; c) VNP10A1F snow map *vs* Landsat OLI fSCA snow map.

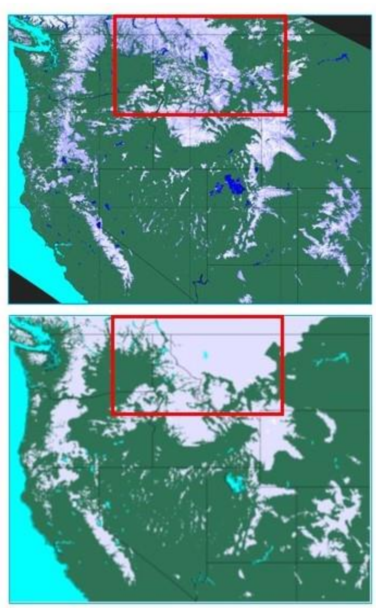

Figure 7. Due to cloud obscuration in the MOD10A1F product which is input to MOD10A1F, the MODIS CGF map (upper panel) does not show as much snow in Montana (within the red rectangle) as was mapped by IMS (lower panel) and was visible on other satellite imagery and meteorological station data on these 25 March 2012 snow maps.

DISCUSSION AND CONCLUSION

Under clear-sky conditions, differences in native resolution, sun angle and time of day account for most of the differences between the NASA and NOAA snow maps (Riggs and Hall, 2020). However, time series show that the IMS snow maps often tend to map more snow compared to the MODIS and VIIRS. When there are several days of cloud cover in a row, the NASA CGF maps may underperform the IMS maps on a given day in an area where a snowstorm produces a large snowfall while the area is cloudy or snow may melt (and thus cannot be updated by the CGF algorithms). Within the MOD10A1F algorithm there is a cloud persistence data layer that informs the user of the number of days since the last clear day when an observation was made.

The NASA CGF (in this case VNP10A1F) and IMS snow maps show 90 and 88 percent agreement, respectively, with the fSCA map for an area in northern Montana/southern Canada on 29 November 2015 (Figure 5). For an area in southern Oregon/northern California, the agreement is similar on 12 March 2021 (Figure 6). Many additional comparisons with Landsat-derived maps under both clear and partly-cloudy conditions are needed to gain quantitative insights into this analysis of NASA CGF uncertainties. This preliminary study provides examples of some ways that the NASA CGF uncertainties can be evaluated.

The NASA standard MODIS (MOD/MYD1A1) and VIIRS (VNP10A1) snow-cover maps have uncertainties that are consistent and have been well described in the peer-reviewed literature. Though there is no current snow product that is the 'gold standard,' and thus the community-accepted 'ground truth' for snow mapping, when the NASA CGF snow-map products (that use MOD/MYD10A1 and VNP10A1 as input) were compared with IMS 1- and 4-km snow maps and 30-m resolution Landsat-derived snow maps (fSCA and CFMask) for this small study, the NASA CGF standard SCE maps, MOD/MYD10A1F and VNP10A1F, consistently show good results.

Data availability

The NASA standard Terra and Aqua MODIS cloud-gap-filled snow-cover products may be found at: *https://nsidc.org/data/MOD10A1F/versions/61/print* and *https://nsidc.org/data/MYD10A1F/versions/61*, respectively. The NOAA IMS 1- and 4-km resolution snow maps are available at: *https://nsidc.org/data/g02156*. Landsat Operational Land Scanner (OLI) data are available from the EarthExplorer site at *https://earthexplorer.usgs.gov/*.

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