MODIS-VIIRS Snow Cover Extent Data Product Continuity

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ABSTRACT

NASA snow cover data products have been produced since 2000 from the satellite and instrument series of the Terra and Aqua Moderate-resolution Imaging Spectroradiometer (MODIS), Suomi-National Polar Program (SNPP) Visible Infrared Imaging Radiometer (VIIRS), Joint Polar Satellite Series (JPSS) from satellites JPSS-1 and JPSS-2. In 2000 there was a single daily NASA satellite snow cover extent (SCE) data product from MODIS and, in 2023, there are now five daily NASA satellite SCE data products. A 23-year record of SCE composed of observations from five similar instruments has great potential for study of snow cover climatology changes and trends. Though the satellites and instruments are similar there are differences in orbits and instrument characteristics that can affect the detection of snow cover in the automated algorithms that produce the products. An algorithm continuity approach, using the same algorithm for both sensors, was taken to maximize product continuity. We present evidence of daily continuity in the NASA SCE products, and continuity of seasonal changes of SCE trends among the products.

INTRODUCTION

For more than 20 years the Moderate-resolution Imaging Spectroradiometer (MODIS) instruments on the Terra and Aqua satellites have provided daily near global coverage of Earth. The Terra and Aqua missions have far surpassed their original designed five-year lifetime. NASA has initiated preparing end-of-life plans for the aging Terra and Aqua missions. Terra and Aqua are now in orbital drift but will continue to observe Earth until passivation of the satellites occurs probably in 2025. The snow cover extent (SCE) records from the MODIS instruments have been used extensively by the scientific community for research and applications. How will the 20+ year record of MODIS snow cover products be continued? The NASA VIIRS snow cover products will extend the SCE Earth Science Data Record (ESDR) that began with MODIS in 2000. A VIIRS instrument is onboard the Suomi-National Polar-orbiting Partnership (SNPP), the Joint Polar Satellite System series of satellites (JPSS) JPSS-1 (NOAA-20) and JPSS-2 (NOAA-21) satellites and is planned to fly on JPSS-3 and JPSS-4 satellites likely extending the SCE ESDR to about 2040.

Currently, five polar orbiting satellites acquiring daily observations of the Earth are used to generate daily snow cover products as shown in the timeline in Figure 1. The observation history and foreseeable future of the satellites is time scaled to show overlap of satellites.

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Continuity is the situation where a data product continues through a change in data source in this case MODIS ends and the snow cover data products continue with VIIRS. Data continuity is a prerequisite for long-term monitoring of change and identifying trends (Román et al., 2023). The objective of this analysis is to evaluate continuity among the MODIS and VIIRS snow cover data products to determine their suitability for providing an SCE data record suitable for research on snow cover climatology.

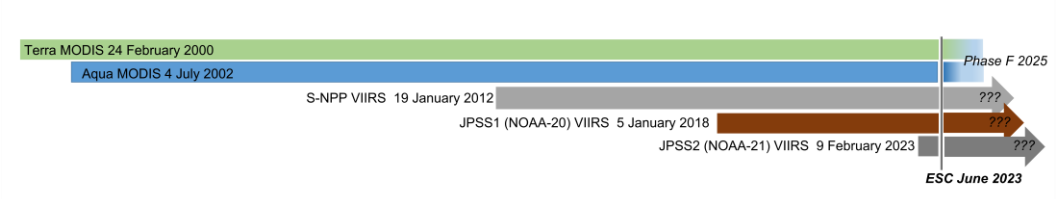

Figure 1. Timeline of Terra, Aqua, SNPP, JPSS-1, and JPSS-2 satellites. Time scaled to show overlap of satellites.

DATA PRODUCTS

Continuity among the MODIS Terra, Aqua, and VIIRS SNPP and JPSS-1 daily and daily cloud-gap-filled (CGF) products has been investigated. The data products are listed in Table 1. The MODIS and VIIRS CGF products provide a daily "cloud free" view of SCE. Data products are available from the National Snow and Ice Center (NSIDC) Distributed Active Archive Center (DAAC) which provides user support for the products, user guides and software tools. Details of the MODIS data products are described in the user guide (Riggs et al., 2019a) and the VIIRS data products are described in the user guides (Riggs et al., 2019b, and Riggs and Hall, 2021). The JPSS-2 data products (Table 1) are produced in the Land Science Investigator-led Processing System (LSIPS) and will be released to the community in the near future.

Table 1. Daily MODIS and VIIRS snow cover data products.

Instrument/ Satellite	ESDT Daily	ESDT Daily cloud-gap-filled	Resolution	Collection	Format
		MODIS			
Terra	MOD10A1	MOD10A1F	500 m	C61	HDF4EOS
Aqua	MYD10A1	MYD10A1F	500 m	C61	HDF4EOS
		VIIRS			
SNPP	VNP10A1	VNP10A1F	375 m	C2	HDF5EOS
JPSS-1 (NOAA-21)	VJ110A1	VJ110A1F	375 m	C2	HDF5EOS
JPSS-2 (NOAA-22)	VJ210A1	VJ210A1F	375 m	Not yet released	HDF5EOS

SNOW COVER EXTENT COMPARISONS

The MODIS and VIIRS data products contain several data layers, described in the user guides. We used the NDSI_Snow_Cover data layer from the daily products, and the NDSI_Snow_Cover_CGF data layer from the CGF products. Comparisons of the snow cover products were made for three regions with differing characteristics and different time periods to evaluate product continuity in different snow cover situations. The snow cover products were compared either by NDSI_Snow_Cover or NDSI_Snow_Cover_CGF data layer values or by binary SCE. SCE was determined by converting the NDSI_Snow_Cover or

NDSI_Snow_Cover_CGF data layers to binary snow cover by defining NDSI values of 10-100 as snow cover. NDSI values of 0-9 are defined as snow free land. Binary SCE is used for comparisons because convolved factors make it very difficult to compare NDSI_Snow_Cover values directly as discussed in Riggs and Hall (2020). Snow cover extent is the total area of snow cover observed on a day, calculated as the number of cells with snow cover then multiplied by cell area. The JPSS-2 products (Table 1) were not included in the analysis because they are not currently available to the community and not available for dates of some of the comparisons that have been done.

Pacific Northwest, USA Region

The Terra, Aqua, SNPP and JPSS-1 daily SCE and daily CGF products (Table 1) were compared to evaluate continuity among the four satellites. The objective of this comparison was to evaluate continuity among the products over a few consecutive days and evaluate whether the single day product that includes cloud cover or the "cloud free" CGF snow cover product provides the best product for monitoring snow cover. The SCE products for a single tile (tile h09v04) covering the Pacific Northwest region of the USA, from 1 – 11 March 2023 were compared.

The daily SCE maps (Table 1, *10A1) for 1–3 March 2023, which had the least cloud cover in the period are shown in Figure 2 to illustrate typical similarities and differences among the SCE maps. SCE is very similar among the MODIS and VIIRS products each day and is spatial consistent day-to-day (Figure 2). Cloud cover may or may not be the same among the products because of differences in times of acquisition, clouds may change in location, formation, and extent thus obscuring and changing the extent of snow observed (Figure 2). The acquisition time difference is greatest between Terra with a morning local crossing time and the afternoon local crossing times of Aqua, SNPP and JPSS-1. The Aqua, SNPP, and JPSS-1 crossing times are less than about 30 min apart. Also, the MODIS and VIIRS cloud mask algorithms are different in cloud detection tests applied because of spectral band differences between MODIS and VIIRS. So even if cloud cover is the same in two different products, for example, a result may be different if the cloud masking differs.

Cloud cover makes it difficult to compare SCE maps among the products because clouds obscure the surface and clouds can change between satellite acquisition times. In the daily product SCE maps (Figure 2) cloud cover in this period is consistent among the products however on 3 March the MYD10A1 has a greater cloud cover extent in the southwest sector of the tile than does the Terra MOD10A1. Perusal of Worldview (worldview.earthdata.nasa.gov) imagery of Terra and Aqua reveals that there was an increase in cloud cover in that region by the time of the Aqua acquisition. Clouds obscured some mountain cloud cover however that cloud cover changed in formation and location between the Aqua and SNPP acquisitions and some of the mountains snow cover that was obscured in Aqua was visible in the SNPP acquisition, thus explaining the SCE differences between Aqua and SNPP (Figure 2). That is an example of the level of investigation that sometimes needs to be done to evaluate daily differences in the daily SCE products that are caused by cloud cover.

The spatial extent of snow cover and clouds in the products for 1–11 March 2021 is plotted in Figure 3A. The extent of snow cover is similar among the products on most days but some days e.g., 2 March, the MYD10A1 (MODIS Aqua) SCE is notably less than the other products. On days 4–7 March MODIS SCE is similar but is notably less than SCE in the VIIRS products. Spatial extent of cloud cover tends to be more similar among the products than is SCE as shown in Figure 3B.

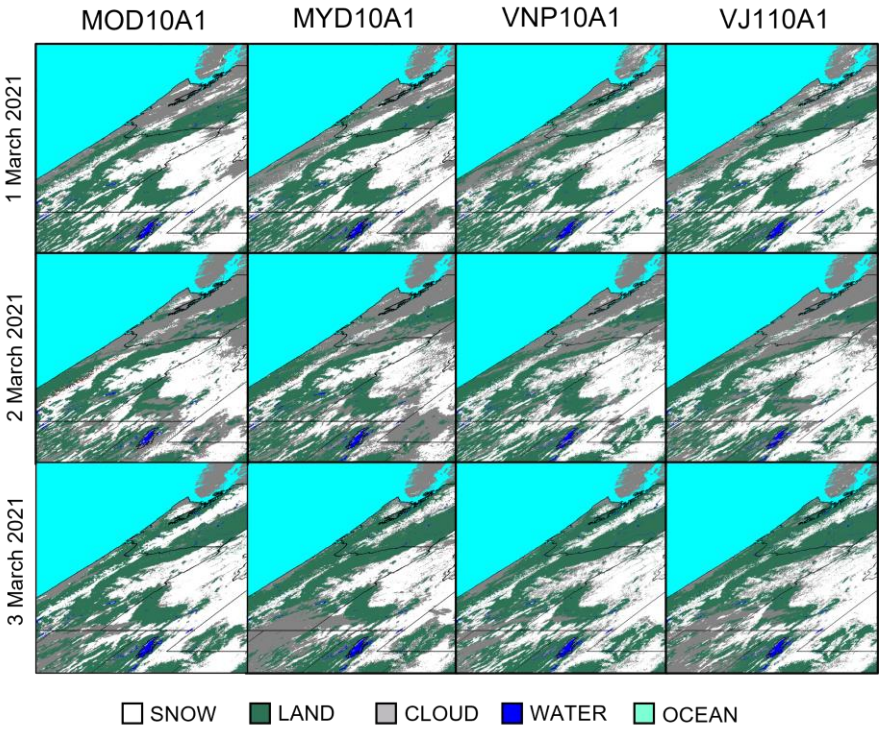

Figure 2. Daily MODIS and VIIRS SCE maps for tile h09v04, 1–3 March 2021. Binary SCE maps on sinusoidal projection.

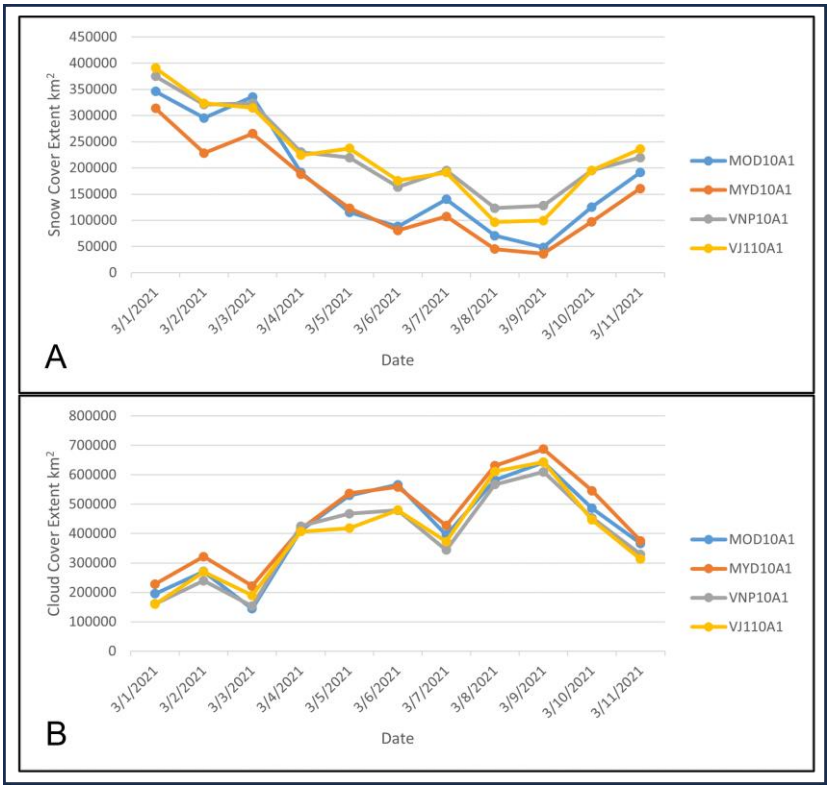

Figure 3. SCE and cloud cover extent of MODIS and VIIRS daily SCE products (*10A1) 1–11 March 2021. SCE is plotted in A, and cloud cover in B.

Comparing SCE in the daily product on a day and tracking SCE day-to-day is confounded by cloud cover. Day-to-day changes in SCE in the *10A1 products are confounded by changes in cloud cover. In this short time series (Figure 3) daily differences in SCE and day-to-day changes in SCE are related to daily and day-to-day changes in cloud over. A day-to-day decrease in SCE (Figure 3A) is associated with an increase in cloud cover e.g., 3–6 March SCE decreases in all SCE maps and cloud cover increases (Figure 3B). Then 9–11 March when SCE increases in all maps and cloud cover decreases (Figure 3A and 3B). The confounding cloud cover needs to be removed so that changes in SCE can be monitored. Similar recommendation to use the CGF products was made in Riggs et al. (2020).

The CGF products (*10A1F) provide a daily "cloud free" SCE to compare SCE maps and to monitor day-to-day changes in SCE. The MODIS and VIIRS CGF SCE products for 1–3 March 2021 are shown in Figure 4. The SCE is very similar spatially and temporally in the MODIS and VIIRS GCF SCE maps and unlike in the daily SCE maps (Figure 2) there is no cloud obscured snow cover. In the absence of cloud cover, SCE is very similar in all the MODIS and VIIRS SCE products every day (Figure 4). Daily comparisons of products and day-to-day changes in CGF SCE are not confounded by cloud cover (Figure 4). Daily SCE in the products on 1–11 March 2021 are plotted in Figure. 5. Over the period, 1–11 March 2021 the trend in SCE shows a slight decrease in all the MODIS and VIIRS maps (Figure 5) which is not apparent in the day-to-day changes in SCE in the daily products (Figure 3A). The SCE areas in CGF SCE (Figure 5) are different from areas for the daily SCE (Figure 3A) because the CGF SCE record began on 1 October 2020 which is the start of the water year and is continuous over the snow season whereas the daily SCE record in this comparison started and 1 March 2021 with cloud cover blocking snow cover that was present on previous days. Clearly, the CGF product is the daily product to utilize for evaluating continuity of SCE among the MODIS and VIIRS products, and for monitoring SCE over a season.

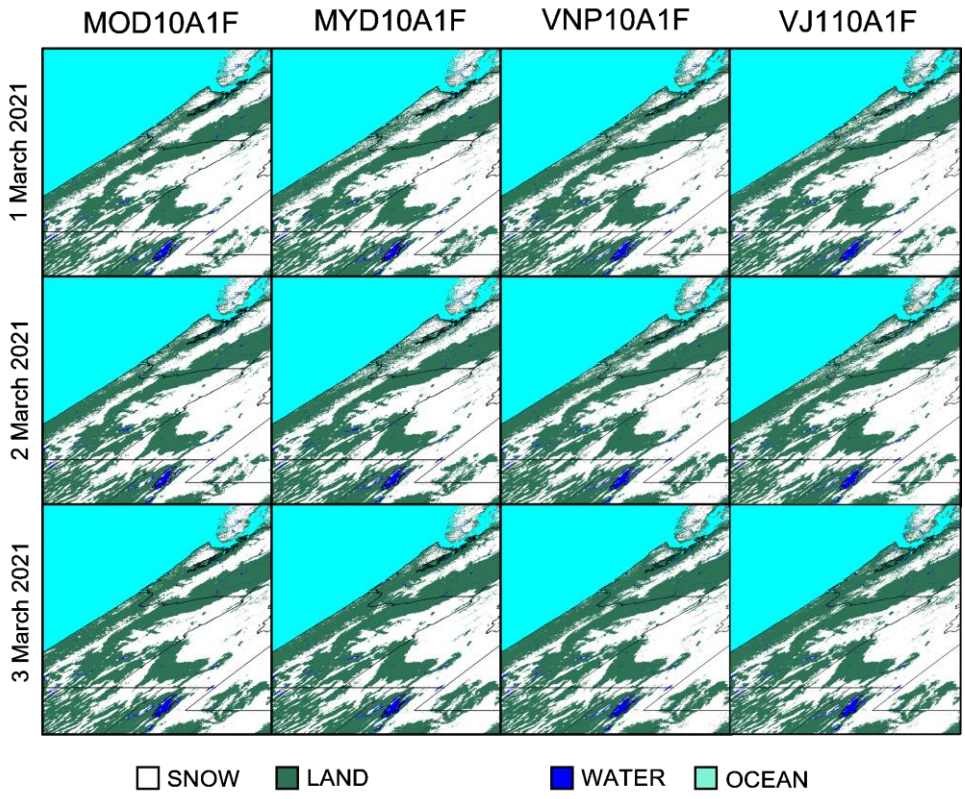

Figure 4. Daily MODIS and VIIRS GCF SCE maps, tile h09v04, 1–3 March 2021.

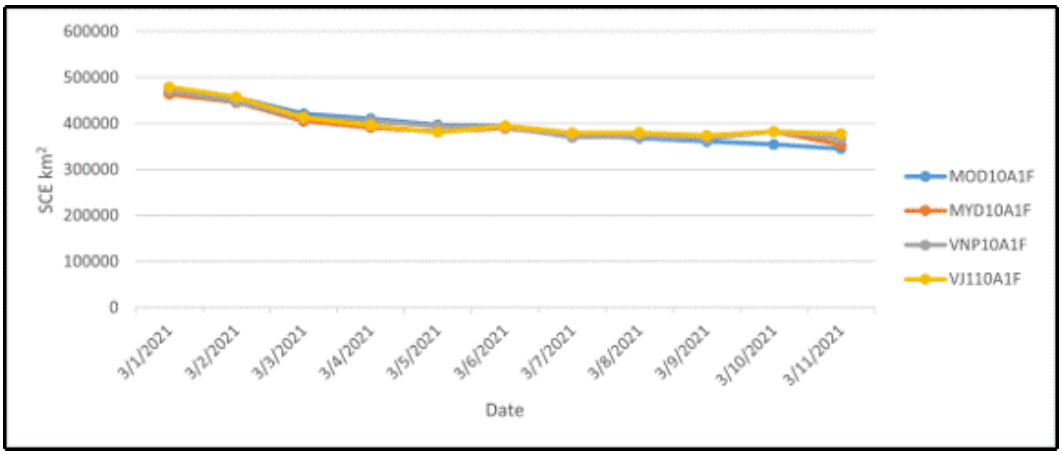

Figure 5. SCE of MODIS and VIIRS daily CGF SCE products (*10A1F) 1–11 March 2021.

Sierra Nevada Region

We investigated continuity of the Terra, Aqua, and SNPP CGF SCE products on the Sierra Nevada Mountain range region (Figure 6) for a winter period 1 December 2022 to 31 January 2023. During that winter period snow cover was continuously present and there were periods of consecutive days with clear views of the surface interspersed with days of cloud cover in the region. SCE extent is very similar in the MODIS and VIIRS daily CGF SCE products throughout this period (Figure 7). In the beginning of the time series, there was an overnight snow event on 1–2 December that deposited snow on the mountains and valleys. It is likely that the more conservative Aqua cloud mask erroneously mapped much of that snow as cloud thus snow was not mapped by Aqua and subsequent days of cloud cover over the region interfered with a return to close agreement in SCE among the three products. The Terra MODIS and SNPP VIIRS data products did not have that same problem with the cloud masking and thus correctly mapped snow from 1–4 December (Figure 7). We think that the cloud-gap filled SCE products are adequately representing the changing snow conditions in this Sierra Nevada region study area (Figure 7).

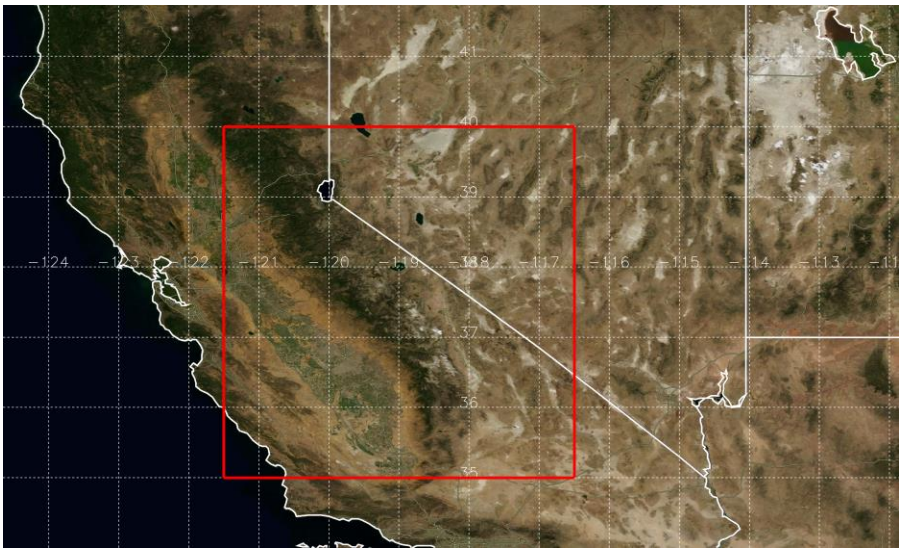

Figure 6. The Sierra Nevada study region is a 244,530 km^2 area that includes the Sierra Nevada Mountain range, and part of the intermountain region in the western United States. Geographic projection with 500 m grid cell resolution.

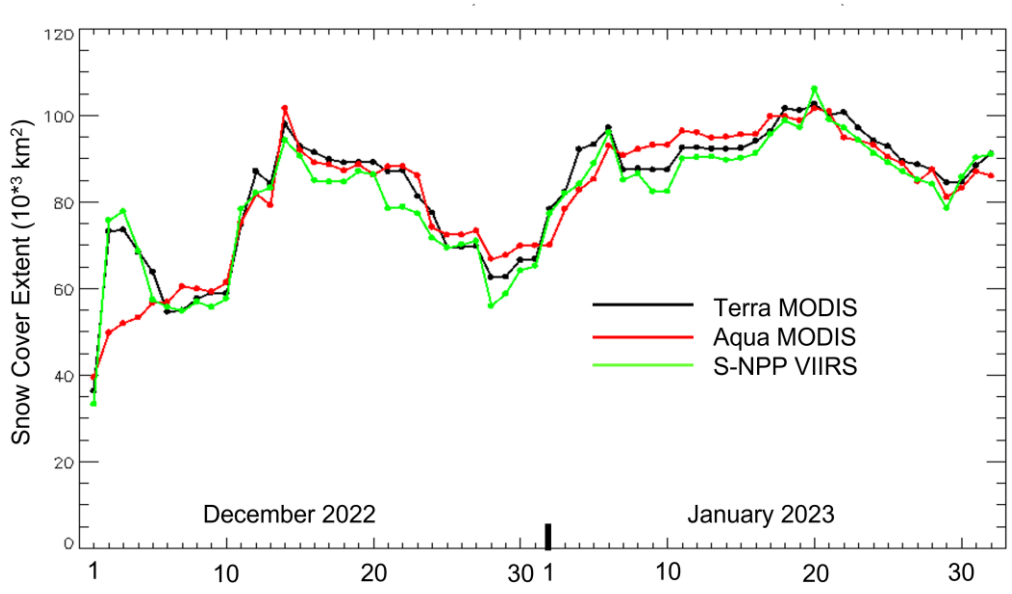

Figure 7. Comparison of daily SCE area among the Terra, Aqua, and SNPP CGF products from 1 December 2022–31 January 2023. Individual plots show results from the Terra MODIS cloud-gap filled (CGF) SCE product, MOD10A1F, the Aqua MODIS CGF SCE product, MYD10A1F, and the S-NPP VIIRS CGF SCE product, VNP10A1F.

Western New York, USA Region

We investigated continuity of the Terra, Aqua, and SNPP CGF SCE products in a region of western New York state region where lake effect snows occur frequently (Figure 8) for a winter period of 1 December 2022 to 31 January 2023. Lake effect snow events occur frequently in this region and cloud cover conditions can change between the morning and afternoon satellite overpasses as well as from day-to-day. Between 1 December 2022 and 31 January 2023, there were very few clear views of the surface. Additionally, a few lake effect snowstorms and ablation events occurred during this period. Timely observation of lake effect snow events, and ablation of snow cover was often not possible because of cloud cover thus, daily SCE is inconsistent among the Terra, Aqua and SNPP products (Figure 9) due to those factors. We do not expect the CGF SCE products can adequately capture the rapidly changing snow conditions in this area of western New York state at this time of year.

Figure 8. The Buffalo study region is a 13,306 km^2 study area in western New York, US. Geographic projection with 50 m grid cell resolution.

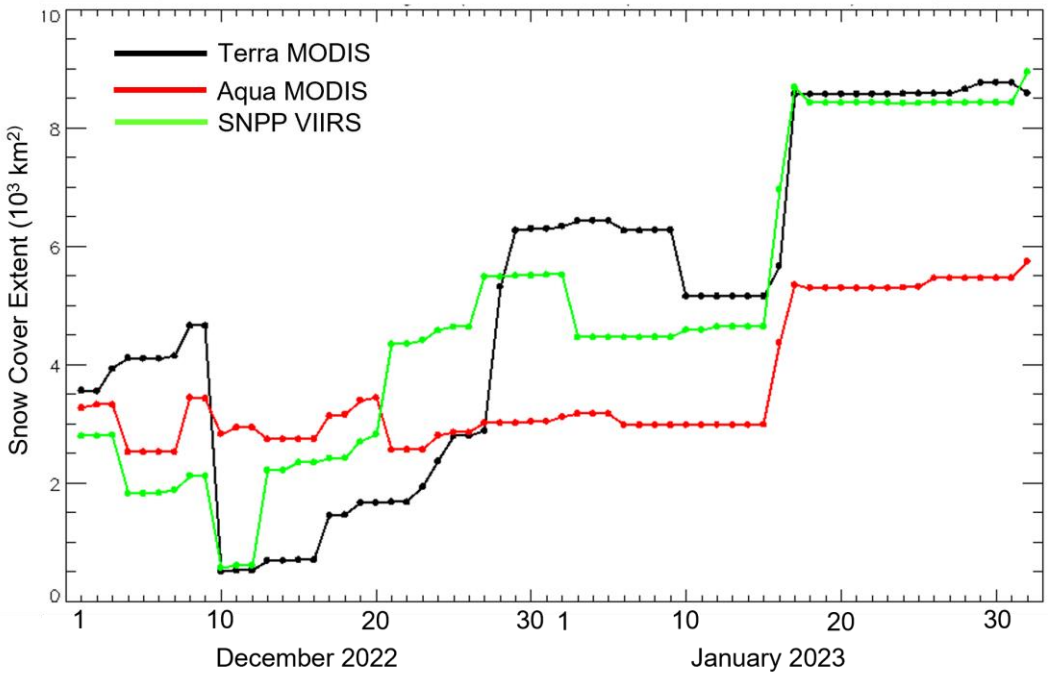

Figure 9. Comparison of SCE among the CGF Terra MODIS MOD10A1F, Aqua MODIS MYD10A1F, and SNPP VIIRS VNP10A1F from 1 December 2022–31 January 2023.

CONCLUSIONS

The daily CGF SCE products are preferable to utilize in investigations of SCE because they minimize the effect of cloud cover, especially for day-to-day monitoring of changes in SCE. SCE extent is very similar in both NASA MODIS and VIIRS SCE products, and trends in SCE are similar as demonstrated in the Pacific Northwest and Sierra Nevada comparisons. A similar result of excellent correspondence in SCE between MODIS and VIIRS SCE products was reported by Hall et al., (2019). VIIRS SCE products are an effective replacement for the MODIS SCE products. There is good continuity between the MODIS and VIIRS daily SCE products. However, there is a caveat, in regions with discontinuous snow cover over a season and frequent cloudy days, e.g., the western New York region the MODIS and VIIRS SCE products may be dissimilar in SCE on any day and large differences in SCE may be observed day-to-day. The MODIS and VIIRS SCE products can be used to build a long-term data record of SCE.

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