Comparison of VIIRS and NOAA/Rutgers IMS Snow-Cover Frequency Maps of North America

DOROTHY HALL[1], GEORGE RIGGS[2], NICOLO DIGIROLAMO[2], THOMAS W. ESTILOW[3], AND DAVID ROBINSON[3]

ABSTRACT

Though the mean winter maximum snow-cover extent (SCE) can cover up to ~50 million km^2 over Northern Hemisphere land areas, there is a large amount of variability in the month-to-month and interannual SCE in the Northern Hemisphere where ~98 percent of Earth's seasonal snow is located. We use the Suomi National Polar-orbiting Partnership (S-NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) daily cloud-gap filled 375-m resolution Normalized-Difference Snow Index (NDSI) maps derived from the VNP10A1F NASA standard data snow-cover product to develop a time series of SCE in North America. To assess the data-product quality, we compare VIIRS snow-mapping results with a climate data record-quality SCE product generated at the Rutgers University Global Snow Lab from the NOAA/U.S. National Ice Center 24-km Interactive Multisensor Snow and Ice Mapping System (IMS) (the NOAA/Rutgers IMS product). To compare with the NOAA/Rutgers IMS snow maps, we developed monthly VIIRS maps showing percent of days in a month that were snow covered for the first six months of 2019, degrading the resolution of the VIIRS maps to 24 km so that the VIIRS and NOAA/Rutgers IMS maps could be compared directly on the same grid. Results show good correspondence between the VIIRS and NOAA/Rutgers IMS monthly SCE snow-frequency maps for North America, with 88.2 – 99.8 percent agreement for total snow cover. The correspondence between the two independent datasets increases our confidence in satellite-derived SCE from both products.

INTRODUCTION

About 98 percent of Earth's seasonal snow-cover extent (SCE) is found in the Northern Hemisphere, with a mean winter maximum SCE over land areas that can cover ~50 million km^2 (Sturm, 2020). Seasonal snow cover is a critical component of Earth's energy balance, in part, because it reflects much of the incoming solar radiation back to space. It is also an excellent insulator of the ground beneath. Continental snowmelt contributes to spring and summer streamflow and is an important water resource for billions of people worldwide as well as being a hazard that can cause flooding and other environmental problems. In forested areas, snowmelt recharges aquifers which can be important sources of municipal water supply (Malle *et al*., 2019; Swistock, 2020). Changes in seasonal snow cover have a profound effect on Earth's energy balance and have substantial societal consequences, some of which might be positive, but most of which are problematic. The only way to monitor continental-scale SCE on a daily or sub-daily basis is via satellite remote sensing.

[1] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA
[2] SSAI / NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3] Department of Geography, Rutgers University, Piscataway, NJ, USA

To evaluate the monthly extent and variability of SCE in North America, we provide comparisons of the Suomi National Polar-orbiting Partnership (S-NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) daily cloud-gap filled standard 375-m resolution snow-cover maps, VNP10A1F (Riggs and Hall, 2020; Riggs and Hall, 2021) with the monthly SCE maps developed by the Rutgers University Global Snow Lab (RUGSL) from the NOAA/US National Ice Center 24-km Interactive Multisensor Snow and Ice Mapping System (IMS) (the NOAA/Rutgers IMS product). The NOAA/Rutgers IMS maps are quality-controlled for consistency, with aggregation to monthly maps and SCE area calculations performed according to the Rutgers routine (Robinson *et al*., 1993; Estilow *et al*., 2015). NASA VIIRS SCE data products will extend the MODerate-resolution Imaging Spectroradiometer (MODIS) snow cover Environmental Science Data Record that began in 2000 and may end in 2023 when plans call for the MODIS instruments to be decommissioned [*https://www.earthdata. nasa.gov/learn/articles/from-terra-to-terra-firma*]. The VIIRS SCE maps permit detailed studies of snow cover at the watershed scale, as well as multi-year trends in SCE at continental and basin scales to be calculated when combined with the longer MODIS record (Hall *et al*., 2019). VIIRS SCE products will likely be available through the 2030s on the Joint Polar Satellite System (JPSS) (Justice *et al*., 2013) and will thus be available to extend the MODIS SCE record and potentially contribute to a moderate-resolution SCE climate data record when 30 years of MODIS and VIIRS data are available.

Absolute validation of the VIIRS SCE maps is not possible because there is no 'gold-standard,' validated hemispheric or global snow-cover dataset available. Thus, in this work, we begin to compare the VIIRS SCE with the independently-developed NOAA/Rutgers IMS SCE time series.

BACKGROUND

On 28 October 2011 the first in a series of VIIRS instruments was launched on the S-NPP satellite. VIIRS permits the generation of daily SCE maps at 375-m resolution (Figure 1) which is an improvement on, but compatible with, the 500-m spatial resolution of the MODIS snow-cover maps (Riggs *et al*., 2017; Riggs and Hall, 2020) and permits detailed studies of snow cover at the watershed scale globally. A complete record of daily, global VIIRS snow-cover products (VNP10A1F) from 19 January 2012 to the present is available from the NASA DAAC at the National Snow and Ice Data Center (NSIDC). VNP10A1F is a cloud-gap-filled (CGF) snow map product developed from the VNP10A1 SCE standard NASA product (Riggs and Hall, 2021). The fully automated algorithm to produce the VIIRS CGF products is modeled after, and compatible with the MODIS CGF algorithm (Hall *et al*., 2019; Riggs *et al*., 2019; Riggs *et al*., 2020; Riggs and Hall, 2021). Numerous authors have used MODIS snow-cover products to show interannual change in continental- and basin-scale SCE worldwide (for example, see: Parajka and Blöschl, 2008; Wang *et al*., 2017; Aguirre *et al*., 2018; Hammond *et al*., 2018; Saavedra *et al*., 2018; Choudhury *et al*., 2021; Hall *et al*., 2021).

VNP10A1F uses a Normalized Difference Snow Index (NDSI) data layer, providing snow cover for each pixel or cell, in increments ranging from NDSI = 0 to 100 (Figure 1). Lower NDSI values are associated with lower snow-cover fractions and NDSI = 100 is associated with a pixel or cell that is completely snow covered (Riggs *et al*., 2021). The resulting maps provide global, daily, cloud-free SCE for each pixel or cell. There are uncertainties in the VIIRS CGF snow-cover products due to the: 1) original VNP10A1 products, and 2) CGF algorithm. These uncertainties are discussed in the literature (e.g., see Hall *et al*., 2019) and in the MODIS and VIIRS user guides (Riggs *et al*., 2018; Riggs and Hall, 2021) and need not be repeated here.

The NOAA/Rutgers IMS SCE maps are derived from daily analyses of mostly-visible imagery from a constellation of geostationary and polar-orbiting satellites and sensors, and ground station data in addition to VIIRS band data. The maps are generated by trained meteorologists, thus are not fully automated (Helfrich *et al*., 2018). At Rutgers, data are subject to quality control procedures established over decades of working with IMS products and their predecessors, that includes establishing consistent land masks, grid-cell areas, and approaches to generating a variety of daily,

weekly, seasonal, and annual products (Robinson *et al.*, 1993; Estilow and Robinson, 2015). Daily IMS SCE data consist of binary (snow/no snow) values for each 24-km grid-cell, which are used to calculate monthly SCE frequency.

RESULTS: COMPARISON WITH THE 24-KM RUGSL IMS SNOW-COVER EXTENT SNOW-FREQUENCY MAPS

Though there is no "gold standard" global snow-cover map with which to compare the VIIRS time series of SCE, valuable information can be gained from comparing independently-derived SCE maps. Here we compare VIIRS and NOAA/Rutgers IMS snow-frequency maps for North America.

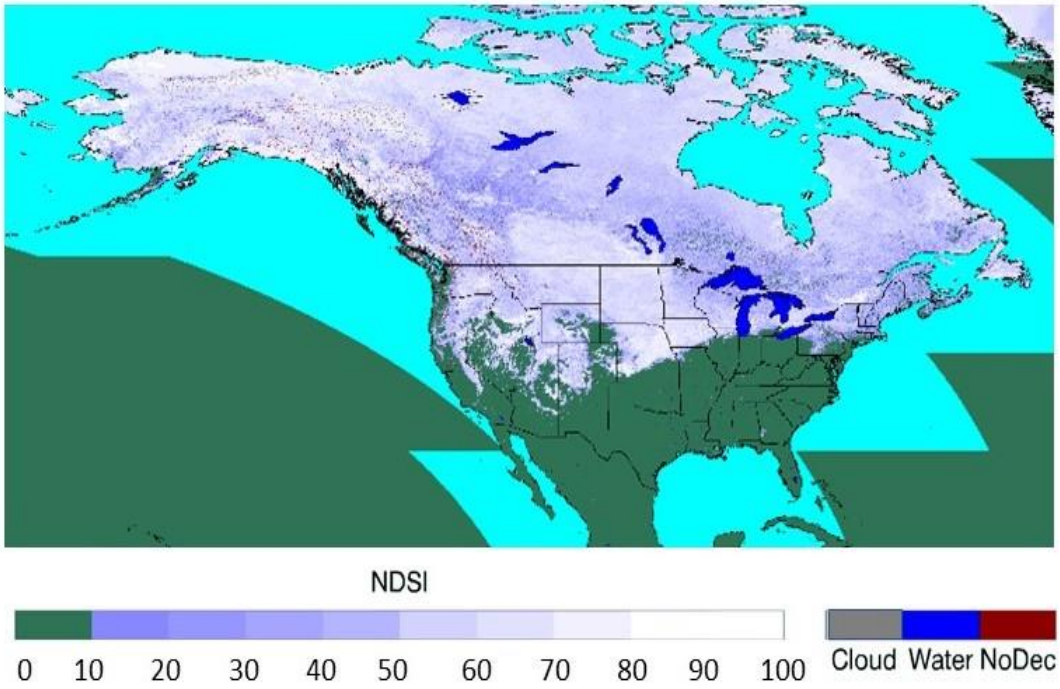

Figure 1. VNP10A1F VIIRS normalized-difference snow index (NDSI) snow-cover extent (SCE) map of North America, 1 March 2019.

To enable the comparison, the VIIRS and NOAA/Rutgers IMS maps were projected to a common grid with a spatial resolution of 24 km^2. A binary map was produced from the VNP10A1F map product using a value of NDSI = 10 or greater to indicate snow in a cell, to compare with the binary NOAA/Rutgers IMS map. For each month, the daily VNP10A1F tiles were used to produce tiles indicating the percent of days with snow cover for each 375-m cell. The North America tiles were digitally stitched together to produce a 375-m map of North America, from which the SCE was determined.

We compared monthly VIIRS and NOAA/Rutgers IMS SCE snow-frequency maps for the first six months of 2019 (Table 1). Results show excellent agreement overall, but also some differences that we attribute to differences in methodologies used to develop the maps, sensor differences, differences in spatial resolution and the handling of cloud-cover.

Table 1. Comparison of total SCE mapped using the NOAA/Rutgers IMS and VIIRS SCE maps for the first six months of 2019, in km^2.

Month in Year 2019	NOAA/Rutgers (km^2)	VIIRS (km^2)	Percent agreement
January	15,860,500	15,749,400	99.7
February	16,242,000	16,281,600	99.8
March	15,105,800	15,246,900	99.1
April	11,485,600	11,715,400	98.0
May	7,861,700	7,971,700	98.6
June	3,832,500	4,315,100	88.2

Figure 2, below, shows a comparison of March 2019 snow maps of North America. The total amount of snow cover in the NOAA/Rutgers IMS map (left) was 15,105,800 km^2 *vs.* 15,246,900 km^2, for the VIIRS map (right).

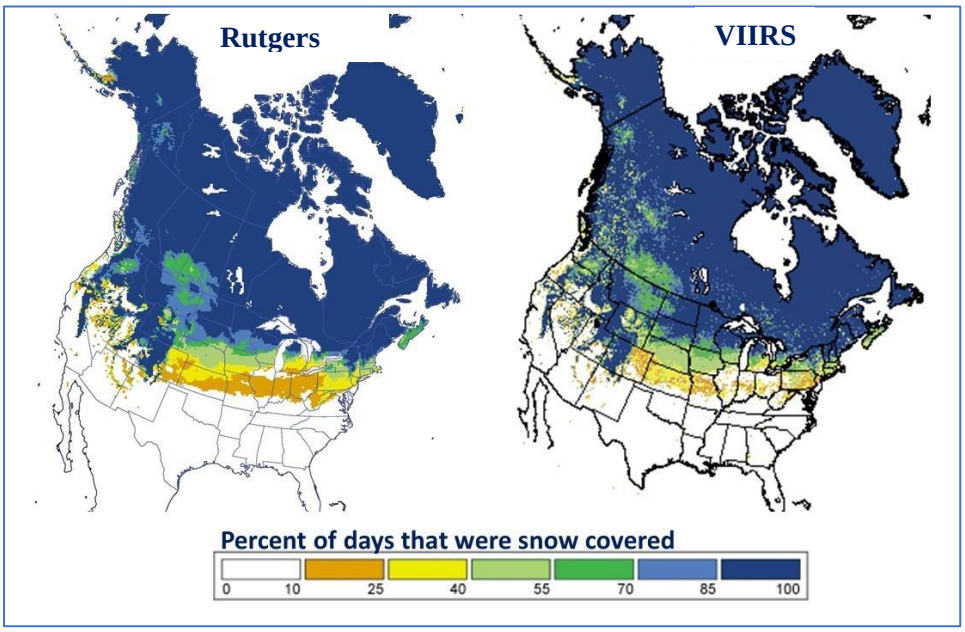

Figure 2 (a & b). Comparison of the NOAA/Rutgers IMS monthly SCE map (Left) from March 2019 with a VIIRS monthly SCE map (Right) from March 2019, both produced to provide percent of days that were snow covered.

The algorithms and methodologies to produce these maps are entirely different. As discussed previously, the NASA VIIRS maps are derived using only VIIRS band data and the VIIRS cloud mask product to produce a fully automated SCE map product. The NOAA/Rutgers IMS SCE maps are generated using multiple satellites with primarily visible sensors, and ground station data in addition to VIIRS band data and is not fully automated. Though there are many similarities in the maps, hemispheric-scale SCE maps developed using different input data and at different spatial resolutions are expected to provide some differences in SCE. For one thing, the maps may be derived from imagery and ground station data acquired at different times of the same day which can lead to some differences especially in areas having shallow or ephemeral snow. Additionally, differences in cloud screening methodologies between the VIIRS and NOAA/Rutgers IMS SCE mapping techniques influence the amount of snow that is mapped.

DISCUSSION AND CONCLUSION

There are important differences between the NOAA/Rutgers IMS and NASA VIIRS SCE maps, yet when monthly maps of percent of days that are snow covered are gridded identically, there is excellent overall agreement between the maps regarding the total amount of SCE. The NOAA/Rutgers IMS maps have the advantage of human intervention in their production and both satellite and *in situ* measurements are used to produce the maps. Thus, the use of a cloud mask is not needed. On the other hand, the VNP10A1F map product is derived from the VNP10A1 product that includes cloud cover, then the cloud cover is masked using the VIIRS cloud mask product. The VIIRS maps used in this comparative study are developed from the cloud-gap filled NASA VIIRS standard product, VNP10A1F. The VNP10A1F algorithm looks back on previous cloud-free days to map snow when the current day is cloudy. Full-resolution VIIRS SCE maps at 375-m spatial resolution provide detail that is not possible in the IMS 24-km resolution SCE maps. Despite the differences, the agreement achieved when mapping snow in North America, at least for the first six months of 2019, is encouraging.

In future work, we will study a longer time period and focus on areas of disagreement between the two SCE products. We will evaluate specific differences between them in concert with other information such as MODIS and VIIRS single-band data and Landsat-8 and -9 higher resolution (30 m) data. This will assist in determining the strengths and weaknesses of both the VIIRS and NOAA/Rutgers IMS SCE data records.

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