Dear Dr. Blöschl:

Thank you for your comments. We had previously revised the paper but we were unable to upload it when we uploaded the original response to the referees' comments. However, we have made further changes, described below, and have now been able to upload the revised manuscript.

We look forward to hearing from you regarding the revised manuscript.

Sincerely,
Dorothy Hall

Please note that the blue bold font represents today's response, and the black bold font is copied and pasted from our earlier responses. Referees' comments are in non-bold black font.

We have softened and toned down the following statement: "We conclude that the MODIS Terra CGF is the more accurate MODIS snow-cover product." In the revised paper that we've uploaded, we have restated that as follows in the Abstract: According to our preliminary validation of the Terra and Aqua MODIS CGF SCE products in the western U.S. study area, we found higher accuracy of the Terra product as compared to the Aqua product. The MODIS CGF snow-cover time series may be used to extend the SCE data record from 2000, into the VIIRS era through the early 2030s and perhaps beyond.

In our response to the referees' comments that we had previously uploaded, we responded to comments #5 and #6 of Referee #1, and also the question about validation of snow depth posed by Referee #2. Our original responses are provided below in black font. Additional comments in response to your queries are shown in blue font.

From Reviewer #1's review:

5) Why only temporal filter is considered for gap-filling method? During snowmelt, snow-line approach or some kind of spatial filter can be more efficient.

Authors: There are many other useful methods of gap filling, but the method described in our paper is the method that is used to develop the new product that will be available starting this summer or fall. We are beyond the point where different methods can be considered since the new algorithm uses the CGF method, all of the programming has been completed by the MODIS Project and the products will be available soon. It is too late to change the algorithm for Collection 6.1.

There is no doubt that other methods of gap filling are useful and perhaps even more accurate or efficient than the method used in the NASA standard MODIS CGF product. However the method selected, as described in Hall et al. (2010) and Riggs et al. (2017b), cannot be changed because the CGF product is "in production."

Therefore we do not understand why Referee #1 wants us to compare gap-filling methods beyond saying that there are some very good methods out there that differ from the method that we've selected. Several years ago we selected one method based on the fact that we must produce the product very quickly after data acquisition. For example, we don't have the luxury of waiting until the clouds clear after the day in question and then looking back to fill in gaps caused by clouds. We needed an algorithm that produces a snow map within a few hours after data acquisition and we settled on the CGF algorithm described in this paper. That was decided and approved by the MODIS Project several years ago. We cannot change it now.

6) The results show only few examples which does not allow to see clearly if the results are robust and general. More thorough analysis (longer time periods, seasonal evaluation, larger/different regions) will allow to draw much more robust findings.

Authors: We agree with this comment, but we are unable to do a thorough and global analysis because the product is not yet being produced by the MODIS and VIIRS Projects. When processing starts, the product will be downloadable through the National Snow and Ice Data Center starting in the fall of 2019.

In order to develop a time series in this pre-production phase, we need to do a considerable amount of programming. We've done this by developing a Terra MODIS CGF SCE time series for the western U.S. data set for 2012. For this revised version of the paper, and in response to this and other comments, we ran a 3-month time series using VIIRS SCE maps (see Figure 9). Running a CGF time series is computationally burdensome, and therefore a comprehensive, global analysis cannot be accomplished until after the official MODIS processing begins. Even after production begins it will take many months until the complete MODIS and VIIRS time series (from 2000 to present for MODIS and from 2011 to present for VIIRS) can be processed. Complete processing is likely to occur sometime in the year 2020 for both the MODIS C6.1 and VIIRS C2 CGF SCE products.

Recently we found out that MODIS data processing of Collection 6.1, that includes producing the CGF snow product, will begin by early October 2019. It may take up to one year to process all of the data, globally, from 2000 – present. Until processing has been completed near the end of the year 2020, we cannot do comprehensive global validation.

In short, processing will not be complete in a time frame that is reasonable for providing the revisions to this paper. And it is important that this paper be published so that users of the new products will have the information contained in this paper when the products first become downloadable from NSIDC in the fall of 2019. After processing has been completed, global validation will be possible by users globally. Comprehensive global validation is not something that is possible for one person or one small group to complete.

Additionally, VIIRS data processing is not likely to start until later this fall. Therefore it won't be possible to even begin validating the VIIRS CGF snow products probably until early 2020. Again, many months will be required for the NASA VIIRS Project to fully process the VIIRS time series (2011 – present).

Comment from the editor that Reviewer #2's comment about global validation was not addressed adequately:

I agree that validation of the satellite data is only possible by comparison with measurements. The manuscript presents validation against the NOAA snow depth data provided by the dense network of meteorological stations. Such networks are not available in other countries. Can we trust that the CGF maps are valid also in those parts of the world where the network density does not allow detailed validation?

Our original response is shown below. Additional comments are shown in blue.

Authors: Evaluation of the CGF maps in other countries will have to wait until the products are released and available to download through NSIDC (beginning in the fall of 2019). In areas of the world where the network of meteorological stations is not dense enough to allow validation, there are other methods to evaluate the uncertainties. These methods, discussed in the paper, include comparison with other snow maps, comparison with higher-resolution satellite data (such as with Landsat or Sentinel data), and comparison with surface reflectance maps such as from MODIS and VIIRS.

The MODIS SCE products have been validated and evaluated in many regions of the world; there are numerous peer reviewed articles published on this topic. However, the VIIRS SCE daily tiled product has not yet been released; only the swath product is available, so evaluation research has not yet appeared in the literature because users tend to be more comfortable using a tiled product than a swath product. In our comparisons between MODIS and VIIRS CGF products we have found very good agreement between MODIS and VIIRS SCE and CGF products thus there is the expectation that the VIIRS products will have similar accuracy to that reported for MODIS. We acknowledge, however, that the comparisons are necessarily limited because product production has not yet begun.

It is incumbent on the user to validate the product in his/her study area. While we, the product developers, can do preliminary validation, we cannot perform global validation. For one thing we are not as knowledgeable about snow-covered areas on different continents and in different countries as are the researchers who live there.

Evaluation of MODIS and VIIRS Cloud-Gap Filled Snow-Cover Products for production of an Earth Science Data Record~~: Advantage and Uncertainties~~

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Abstract. MODerate resolution Imaging Spectroradiometer (MODIS) cryosphere products that have been available since the launch of the Terra MODIS in 2000 and the Aqua MODIS in 2002 include global snow-cover extent (SCE) (swath, daily and eight-day composites) at 500 m and ~5 km spatial resolution ~~and daily snow albedo~~. These products are used extensively in hydrological modeling and climate studies~~, of local and regional climate, and are increasingly being used to study augment studies of regional hydrological and climatological changes over time~~. Reprocessing of the complete snow-cover data record, from Collection 5 (C5) to Collection 6 (C6) and Collection 6.1 (C6.1), has ~~led to~~provided improvements in the MODIS product suite. Suomi National Polar-orbiting Partnership (S-NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Collection 1 (C1)~~-~~ snow-cover products at 375 m spatial resolution have been available since 2011~~,~~ and are currently being reprocessed for Collection 2 (C2). Both the MODIS C6.1 and the VIIRS C2 products will be available to download through the National Snow and Ice Data Center beginning in the fall of 2019, with the complete time series available in 2020. To address the need for a cloud-reduced or cloud-free daily ~~snow~~ SCE product for both MODIS and VIIRS, a ~~new~~ daily cloud-gap filled (CGF) snow-cover ~~product~~ algorithm was developed for MODIS C6.1 and VIIRS C2 processing. MOD10A1F (Terra) and MYD10A1F (Aqua) are daily, 500-m resolution ~~cloud-gap filled (~~ CGF~~)~~ ~~snow-cover~~ SCE map products from MODIS. VNP10A1F is the daily, 375-m resolution CGF ~~snow-cover~~SCE map product from VIIRS. These CGF ~~maps~~ products ~~provide daily cloud-free snow maps, along with~~include quality-assurance data such as~~including~~ cloud-persistence ~~maps~~ statistics showing the age of the ~~snow or non-snow~~ observation in each pixel. The objective of this paper is to introduce the new MODIS and VIIRS standard CGF daily SCE products and to provide preliminary evaluation of uncertainties in the gap-filling methodology so the products can be used as the basis for a moderate-resolution Earth Science Data Record (ESDR) of SCE. ~~The objective of this paper is to introduce the new MODIS and VIIRS standard CGF daily SCE products and to provide preliminary evaluation of uncertainties in the products so the products can be used as the basis for a moderate-resolution Earth Science Data Record (ESDR) of SCE. SCEprovide preliminaryion of from the CGF products, moderate-resolutionSCE. Work is ongoing to evaluate and document uncertainties in the MODIS and VIIRS standard daily CGF snow-cover products. In this work~~T~~, we~~

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developed MODIS and VIIRS time series of the MODIS and VIIRS CGF products and have been developed and evaluated those time series in selected study sites in the United StatesU.S. and southern Canada. Analysis of the MOD/MYD10A1F product accuracys for study areas in the western United States shows excellent results in terms of accuracy of snow-cover mapping. When there are frequent clear-sky episodes, MODIS is the satellite instruments are able to capture enough clear views of the surface to produce accurate useful snow-cover information and snow maps. Even in the extensively-cloud-covered northeastern United States during winter months, snow maps from MODIS CGF products are useful, though the snow maps are likely to miss some snow, particularly during the spring snowmelt period when snow may fall and melt within a day or two, before the clouds clear from the storm that deposited the snow. A time-series comparison of three months of Terra MODIS and S-NPP VIIRS CGF snow-cover maps, xx – xx, 2012, reveals xxx. Comparisons between the Terra and Aqua CGF snow-cover maps TheObserved differences, though small, have revealed differences that are related toare largely attributed to differences in cloud masking in the two algorithms and also differences in time of day of image acquisition. AHowever, a nearly three-month time-series comparison of Terra MODIS and S-NPP VIIRS CGF snow-cover maps for a large study area covering all or parts of 11 states in the western United States and part of southwestern Canada reveals excellent correspondence between the Terra MODIS and S-NPP VIIRS products, with a mean difference of 11,070 km^2 for a large (~2,487,610 km^2)which is ~<0.45 percent of the study area in the western U.S. that includes all or parts of 11 states and part of southwestern Canada. We conclud According to our preliminary validation of the Terra and Aqua MODIS CGF SCE products in the western U.S. study area, wWe also eAdditionally, we found that t that thehigher accuracy of the Terra productMODIS CGF is the more accurate thanas compared to -the Aqua MODIS snow-cover product,product. The MODIS CGF snow-cover time series and should therefore form be the basis of an Environmental Science Data RecordESDR that willmay be used to extend the CGF SCE data record from the Terra MODIS beginning in 2000, through into the VIIRS era, at least through the early 2030s and perhaps beyond.

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1 Introduction

Regular snow-cover mapping of the Northern Hemisphere from space began in 1966 when the National Oceanic and Atmospheric Administration (NOAA) began started producing weekly snow maps to improve weather forecasting (Matson and Wiesnet, 1981). A 53-year climate-data record (CDR) of Northern Hemisphere snow-cover extent (SCE), based on NOAA's snow maps is now available at the Rutgers University Global Snow Lab (Robinson et al., 1993; Estilow et al., 2015) at a resolution of 25 km^2. Since the 1960s, snow-cover mapping from space has become increasingly sophisticated. Not only has the temporal resolution of the NOAA snow maps increased from weekly to twice-daily, but the spatial resolution has also improved over time. Furthermore, dData from multiple satellite platforms and instruments with visible/near-infrared (VNIR) and short-wave infrared (SWIR) bands are now available to support improved snow mapping and snow/cloud discrimination as compared to the earliest satellite snow-cover maps when sparse satellite data were available.

Using t~~T~~h~~Due to increasing global temperatures, especially in more-northerly areas in the Northern Hemisphere, th~~e Rutgers CDR, ~~has been used by~~ researchers ~~for decades, and in recent years to show~~have shown that SCE has been declining and melt has been occurring earlier in the Northern Hemisphere (e.g., Déry and Brown, 2007). This shortening of the snow season has many implications such as, for example, in the western United States (Mote et al., 2005; Stewart, 2009; Hall et al., 2015), with earlier snowmelt contributing to a longer fire season (Westerling et al., 2006; O'Leary et al., 2018) and other environmental and societal problems. However, the coarse resolution of the Rutgers CDR is not suitable for regional and basin-scale studies.

Meltwater from mountain snowpacks provides hydropower and water resources ~~to drought-prone areas such as the western United States~~. Accurate snow measurement is needed as input to hydrological models that predict the quantity and timing of snowmelt during spring runoff. SCE can be input to models to estimate snow-water equivalent (SWE) which is the quantity of most interest to hydrologists and water management agencies. A~~Increasingly~~ accurate predictions save money and water because reservoir management improves withas ~~measurement accuracy~~knowledge of SWE ~~improve~~ncreases.

M~~oderate~~edium-resolution SCE maps are produced daily from multiple satellite sensors such as from~~are on~~ the MODerate-resolution Imaging Spectroradiometer (MODIS) on both the Terra ~~, launched in 1~~(1999 launch), and Aqua (~~, launched in~~ 2002 launch)~~,~~ ~~and~~ satellites~~,~~ and from the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi - National Polar Partnership (S-NPP) and the Joint Polar Satellite System – 1 (JPSS-1) satellites, launched in 2011 and 2017, respectively. S~~These s~~now maps from MODIS, in particular, are used extensively by modelers and hydrologists to study regional and basin-scale~~local~~ SCE and to develop snow-cover depletion curves for ~~multiple~~ hydrological ~~and climatological~~ applications. Algorithms utilizing data from the VIIRS and MODIS~~se~~ sensors provide global ~~swath-based~~ snow-cover maps with ~~at~~ spatial resolutions ranging from 375 m to 500 ~~1 k~~m under clear skies. Instruments on the Landsat series of satellites for which the record began in 1972, and other higher-resolution sensors, such as from the more-recent Sentinel series, provide still-higher spatial resolution data from which snow maps can be developed, though lower temporal resolution.

Cloud cover is the single most-important factor affecting the ability to map SCE accurately using visible and near infrared (V~~V~~NIR) and short-wave infrared (SWIR) sensors. Clouds ~~often~~ frequently create ~~daily~~ gaps in snow-cover~~SCE~~ maps that are generated using data ~~only~~ from VNIR and SWIR sensors. Cloud-gap filling can be used to mitigate the cloud issue using VNIR and SWIR sensors. Additionally, m~~M~~~~Though useful, m~~ethods to combine passive-microwave snow-cover maps with VNIR maps to eliminate clouds have been developed ~~are only partially successful~~ (e.g., see Foster et al., 2011) but there are substantial limitations to the resulting products even though the passive-microwave sensors can provide images through cloud cover. ~~COne way to mitigate the cloud issue is through cloud-gap filling can be used to mitigate the cloud issue using VNIR and SWIR sensors (CGF).~~

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~~In this paper, we describe the~~ Terra and Aqua MODIS and ~~the~~ S-NPP VIIRS cloud-gap filled (CGF)~~CGF algorithm~~SCE map products have been developed to address the ~~cloud-gap~~ issues caused by gaps in data from cloud cover when using VNIR and SWIR sensors~~., data products and uncertainties~~. These~~are~~ new products ~~that~~ have not previously been available. ~~. Also discussed are advantages and uncertainties of the CGF SCE products from MODIS and VIIRS. In addition to the inherent uncertainties in the MODIS snow maps, discussed elsewhere (e.g., Hall and Riggs, 2007, and in many numerous other papers), there are additional uncertainties related to gap filling that are addressed herein. We also discuss the development of a moderate-resolution Environmental Science Data Record (ESDR) of SCE and using MODIS and VIIRS standard snow-cover maps. JPSS launches containing VIIRS sensors are planned through at least 2031, continuing the SCE record at moderate spatial resolution.~~

The objective of this paper is to introduce the new MODIS and VIIRS standard CGF daily SCE products and to provide preliminary evaluation of uncertainties in the gap-filling methodology so ~~that SCE from the CGF~~the products can be used as the basis for a moderate-resolution Earth Science Data Record (ESDR) of SCE. ~~se~~A thorough analysis of the uncertainties of these ~~new~~ products globally will ~~not~~ be possible ~~until~~only after the entire time series ~~have~~of both MODIS and VIIRS have been processed and archived which is likely to occur sometime in 2020. ~~The objective of this paper is to introduce readers to the new MODIS and VIIRS standard CGF daily snow-cover products and to identify methods to evaluate and document uncertainties in the products. A thorough analysis of the uncertainties is not possible until all of the product time series has been processed and archived which is likely to occur sometime in 2020.~~

2 Background

2.1 Terra and Aqua MODIS

The MODIS instruments have been providing daily snow maps at a variety of temporal and spatial resolutions beginning on 24 February 2000 following the 18 December 1999 launch of the Terra spacecraft using a subset of the 36 channels ~~available on the MODIS sensors~~. A second MODIS was launched on 4 May 2002 on the Aqua spacecraft and the data record began on 4 July ~~n xx xxxx~~ 2002. The MODIS sensors ~~provide~~ allowed the development of a large suite of land, atmosphere, and ocean products [https://modis.gsfc.nasa.gov], including ~~daily~~ maps of global snow cover ~~and sea ice~~. The prefix, MOD, refers to a Terra MODIS algorithm or product and MYD refers to an Aqua MODIS algorithm or product. When the discussion in this paper refers to both the Terra and Aqua products ~~it will be designated as such using~~we will use the M*D nomenclature. Information on the full MODIS standard cryosphere product suite is available elsewhere [https://modis-snow-ice.gsfc.nasa.gov/].

Since the launches of the Terra and Aqua spacecraft, there have been several reprocessings of the entire suite of MODIS Land Data Products [https://modis-land.gsfc.nasa.gov/]. ~~Specifically~~In recent years, reprocessing from Collection 5 (C5) to Collection 6 (C6) and ~~in the near future,~~ Collection 6.1 (C6.1)~~,~~ has ~~led to~~been accomplished to

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provide improvements in the MODIS snow-cover standard data products to the user community (Riggs et al., 2017a and 2018).

A great deal of validation has been conducted on the MODIS snow-cover products through the C5 era (e.g., Klein and Barnett, 2003; Parajka and Blöschl, 2006; Hall and Riggs, 2007; Frei and Lee, 2010; Arsenault et al., ~~2012 and~~ 2014; Parajka et al., 2012; Chelamallu et al., 2013; Dietz et al., 2013), including validation with higher-resolution snow maps derived from satellite imagery, such as from Landsat Thematic Mapper, Enhanced Thematic Mapper Plus and Operational Land Imager (TM/ETM+ and OLI) (e.g., see Huang et al., 2011; Crawford, 2015; Coll and Li, 2018). ~~Crawford (2015) found strong spatial and temporal agreement between Terra MODIS snow-cover fraction and Landsat TM/ETM+ derived snow cover, noting that some high-altitude cirrus cloud contamination was observed and transient snow was sometimes difficult for the MODIS algorithm to detect.~~ Though use of higher-resolution data is valuable for comparison and validation purposes, ~~however,~~ use of meteorological-station data ~~for validation~~ (e.g., Brubaker et al., 2005) is the only true validation of ~~the~~ snow-cover products when adequate station data are available. Comparing extent of snow cover derived from MODIS with snow cover from other satellite products, though extremely useful, is not true validation because all derived snow-cover products have uncertainties.

A new feature of the MODIS C6 and C6.1 product suites provides the snow decision on each map as a normalized-difference snow index (NDSI) value instead of fractional-snow cover (FSC) (Riggs et al., 2017a and 2018). This has the important advantage of allowing a user to more-accurately determine FSC in their particular study area by applying an algorithm ~~to derive FSC from the NDSI that is tuned~~~~they can tune to a specific study area~~to derive FSC from the NDSI. The C5 FSC algorithms (Salomonson and Appel, 2004 &~~and~~ 2006) ~~is still useful for estimating FSC globally for Terra MODIS data products, but is of more-limited utility for specific ,and especially well-characterized study areas. That algorithm~~ remain~~s~~ useful ~~globally~~ and can easily be applied to the MODIS C6 and C6.1 and VIIRS ~~C1 and~~ C2 NDSI data to derive an estimate of FSC globally.

2.2 S-NPP VIIRS

There are 22 channels on the S-NPP VIIRS instrument. Though the ~~the~~ key VIIRS snow-mapping channels, I1 (0.600 – 0.680 μm) and I3 (1.580 - 1.640 μm), are ~~-~~ also available on ~~both VIIRS and~~ MODIS (with slight differences in the wavelength range), some of bands that are used in cloud mapping that are available on the MODIS sensors, are not available on the VIIRS. As a result there are differences in the MODIS and VIIRS cloud masks that affect the SCE standard products. Additionally, the Terra MODIS and the S-NPP VIIRS data are acquired at different times of the day allowing for movement of clouds and for some snow-cover changes. Furthermore, the spatial resolution of the MODIS SCE products is 500 m while the resolution of the VIIRS SCE products is 375 m.

S-NPP VIIRS C2~~1~~ SCE products [https://doi.org/10.5067/VIIRS/VNP10.001] are designed to correspond to the MODIS C6.1 SCE products (Riggs et al., 2017a and b). There were many revisions made in the MODIS C6 and

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C6.1 algorithms that improved snow-cover detection accuracy and ~~information content~~QA ~~of~~in the data products. Though there are important differences between the MODIS and VIIRS instruments ~~(e.g., the VIIRS 375 m native resolution compared to MODIS 500 m)~~, some of which are described in the previous paragraph, the snow-detection algorithms ~~and data products are~~were designed to be as similar as possible so that the 19+ year MODIS ESDR of global SCE can be extended into the future with the S-NPP and Joint Polar Satellite System (JPSS)-1 VIIRS snow products and with products from future JPSS platforms.

2.~~3~~~~1~~ Methods to reduce or eliminate cloud cover in MODIS-derived snow-cover maps

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The objective of the NASA standard MODIS and VIIRS CGF snow-cover algorithms is to generate snow maps daily in the normal operational processing stream of MODIS and VIIRS snow products. As part of the early MODIS snow-product suite, eight-day maximum snow-cover maps (M*D10A2) were designed to provide greatly-reduced cloud cover. However these maps are available only once every eight days, the maps frequently retain some cloud cover, and it is difficult to determine on which days during the eight-day period snow was or was not observed; furthermore, only maximum observed snow cover is provided for any given eight-day period. In spite of the limitations, the eight-day maximum snow maps have been useful in many studies (e.g., O'Leary et al., 2018; Hammond et al., 2018). ~~However, t~~The ~~current~~cloud-gap filling cloud-clearing method that uses current day and/or previous day(s) of MODIS daily snow-cover products to fill gaps created by cloud cover ~~and~~ is far superior to the eight-day maximum method of cloud clearing.

Many effective methods have been developed to reduce or eliminate cloud cover in the MODIS standard snow-cover products as well as other satellite-derived snow-cover products. These methods~~,~~ includ~~e~~~~ing~~ temporal and spatial filtering, and use of data from two or more ~~than one~~ satellites. Fusion of ground and satellite measurements is another method to mitigate the influence of clouds. ~~Though we cannot provide an exhaustive review here, in the following paragraphs we refer to some of the methods~~In the following paragraphs we provide a brief overview of selected works that address the cloud-clearing issue using MODIS SCE products.~~provide examples of cloud-cover mitigation of snow-cover mapsstandard~~ ~~Our objective is to generate the CGF snow maps daily in the normal operational processing stream of MODIS and VIIRS snow products. The cloud-clearing method uses current day and/or recent previous day(s) of MODIS daily snow-cover products to fill gaps created by cloud cover. If timeliness were not a constraint then interpolation of snow cover over time, both on previous and future days, could be a part of a cloud-clearing algorithm, and would increase the accuracy of the snow cover map on any given day.~~

The presence of cloud cover prevents daily continuous SCE maps from being produced using VNIR and SWIR sensors. To reduce the effects of cloud cover in the MODIS snow-cover maps, researchers have employed a variety of different methods. As part of the early MODIS snow-product suite, eight-day maximum snow-cover maps (M*D10A2) were designed to provide greatly-reduced cloud cover. However these maps are available only once every eight days, the maps frequently retain some cloud cover, and it is difficult to determine on which days during the eight-day period snow was or was not observed. In spite of this, the eight-day maximum snow maps have been useful in many studies, e.g., M*D10A2 has been used successfully to develop snowmelt-timing maps (O'Leary et al., 2018) and to map snow zones (Hammond et al., 2018).

and spatial

Forward

Use of two or more days to map snow cover can be called temporal filtering. The presence of cloud cover prevents daily continuous SCE maps from being produced using VNIR and SWIR sensors. To reduce the effects of cloud cover in the MODIS snow-cover maps, many researchers have employed a variety of different methods. For example, as part of the early MODIS snow-product suite, eight-day maximum snow-cover maps (M*D10A2) were designed to provide greatly-reduced cloud cover. However these maps are available only once every eight days, the maps frequently retain some cloud cover, and it is difficult to determine on which days during the eight-day period snow was or was not observed. In spite of this, the eight-day maximum snow maps have been useful in numerous research studies, e.g., M*D10A2 has been used successfully to develop snowmelt-timing maps (O'Leary et al., 2018) and to map snow zones (Hammond et al., 2018), and are still available in C6.0 and 6.1.

Many other methods have also been developed to reduce or eliminate cloud cover in the MODIS snow-cover product suite. Parajka and Blöschl (2008) used a 7-day temporal filter causing a reduction of cloud coverage of >95%, maintaining an overall accuracy of >92% when SCE was compared with in-situ data. Other methods to reduce cloud cover have also been successful (e.g., see for example, Tong et al., 2009a & b; Coll and Li, 2018). Gafurov and Bárdossy (2009) developed a cloud-clearing method consisting of six sequential steps that begins with using Terra and Aqua snow cover maps, ground observations, spatial analysis and finally snow climatology to clear clouds and generate a cloud-free daily snow-cover map with high accuracy. Gafurov et al. (2016) developed an operational daily snow-cover monitoring tool using that same cloud-clearing method with enhancements, with a mean accuracy of 94% for a case study of the Karadarya River basin in Central Asia. To fill gaps caused by cloud cover, use of forward and backward gap-filling methods to eliminate cloud cover have been used successfully with the MODIS standard snow products and other satellite data. Use of forward (e.g., Parajka and Blöschl, 2008; Gafurov et al., 2016) and backward (e.g., Foppa and Seiz (2012)) and multi-temporal forward/backward interpolation gap-filling methods to reduce cloud cover have been used successfully by many researchers with the MODIS standard snow products and other satellite data (for example, see Parajka and Blöschl, 2008; Gafurov et al., 2016; Malnes et al., 2016).

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Foppa and Seiz (2012) developed a temporal forward and backward gap-fill method to create a "cloud-free" daily snow map from the daily global MOD10C1 data product. Additionally, a Malnes et al. (2016) used a multi-temporal forward/backward interpolation gap-filling technique was used to create a cloud-free daily snow map from MOD10A1 products that was then used to detect the first and last snow-free day in a season for northern Norway (Malnes et al., 2016).

2.3.2 Spatial filtering

A sA sSpatial-filtering method s that usess the relative position of a cloud-obscured pixel to the regional snow-line elevation (SNOWL) was developed by Parajka et al. (2010) using Terra MODIS data to create "cloud-free" snow maps which that produced robust snow-cover mapsping even in situations of extensive cloud cover. .

A combination of SNOWL and temporal forward and backward gap filling was used by Hüsler et al. (2014) to create "cloud free" satellite snow cover maps using data from the Advanced Very High Resolution Radiometer (AVHRR) of the European Alps. Malnes et al. (2016) used a multi-temporal forward/backward interpolation gap-filling technique to create a cloud-free daily snow map from MOD10A1 products that was then used to detect the first and last snow-free day in a season for northern Norway.Gafurov and Bárdossy (2009) developed a cloud-clearing method consisting of six sequential steps that begins with using Terra and Aqua snow cover maps, ground observations, spatial analysis and finally snow climatology to clear clouds and generate a cloud-free daily snow-cover map with high accuracy. **2Data-fusion methods of cloud clearing**

A cubic spline interpolation method has been used with good results by some researchers (Tang et al., 2013 & 2017; Xu et al., 2017) as a temporal CGF method using MODIS snow-cover products. Some researchers have developed CGF techniques that combined Terra and Aqua, time interpolation, spatial interpolation and probability estimation, e.g. López-Burgos et al. (2013) to create "cloud-free" SCA maps. Deng et al. (2015) combined MOD, MYD and SNOWL SCE and AMSR2 SWE data and temporal filtering to create a daily "cloud-free" snow cover maps of China. Combining different methods sequentially to remove clouds is also a way to create CGF products (Dariane et al., 2017). A cubic spline interpolation method has been used with good results by some researchers (Tang et al., 2013 & 2017; Xu et al., 2017) as a temporal CGF method using MODIS snow-cover products. Crowdsourcing by cross-country skiers combined with MODIS snow-cover products has also been used to create daily CGF products (Kadlec and Ames, 2017).

A common method to reduce cloud cover on a daily snow map is to combine or fuse results from the daily Terra (MOD10A1) and Aqua (MYD10A1) snow maps (see for example, Gao et al., 2010a & 2010b and 20111; Li et al., 2017; Paudel and Anderson, 2011; Thompson et al., 2015; Dong and Menzel, 2016; Yu et al., 2016; Xu et al., 2017). Dong and Menzel (2016) developed a multistep method including probability interpolation, to eliminate

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~~cloud cover using combined Terra-Aqua MODIS snow-cover products.~~ These methods~~is~~ take~~s~~ advantage of the fact that the Terra and Aqua satellite overpasses occur at different times of the day and, since clouds move, oftentimes more snow cover or non-snow-covered land cover can be imaged and mapped using data from both satellites, as compared to using the Terra or Aqua MODIS data alone. ~~However~~ Though this method of cloud clearing is useful, it is of limited utility for large areas because changes in cloud cover are typically small between Terra's 10:30 am local time equator crossing and Aqua's at 1:30 pm.

Additionally, r~~Percent r~~eductions in cloud cover that are achieved by combining Terra and Aqua daily snow-cover data are highly variable and dependent on many factors such as location, time of year, daily weather and cloud conditions, etc., and have been reported to vary. A factor that impacts the quality of both the Aqua MODIS snow-cover and the cloud-cover products, used to mask clouds, is that many of the detectors in the critical 1.6 µm band used in both algorithms is non-functional on the Aqua MODIS. As an example, for the western U.S. study area shown in Fig. 1, for 14 March 2012 and 19 March 2012, using a snow-cover map that combined Terra and Aqua snow cover products, the MOD10A1 snow product showed 71.7 percent clouds while the combined Terra and Aqua products showed 67.0 percent for 14 March 2012. ~~; for another date, 19 March 2012, MOD10 showed 71.8 percent clouds while the combined Terra/Aqua snow map showed 68.4 percent.~~ Combining the MOD and MYD snow maps definitely can reduce cloud cover but there are issues with the Aqua snow maps (see below) and reliance on the continued availability of two nearly-identical sensors is ~~problematic~~unrealistic for development of an ESDR because satellites do not last indefinitely.

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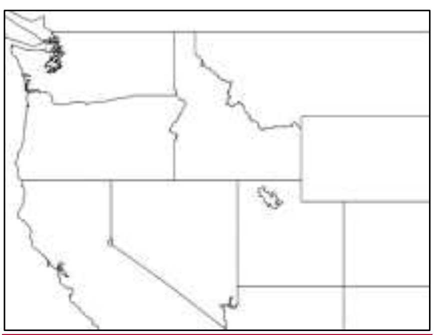

Figure 1: Study area covering all or parts of 11 states in the western United States and part of southern Canada. This study area is 2,487,610 km^2 in area.

~~**2.3.4 Fusion of ground and satellite measurements**~~

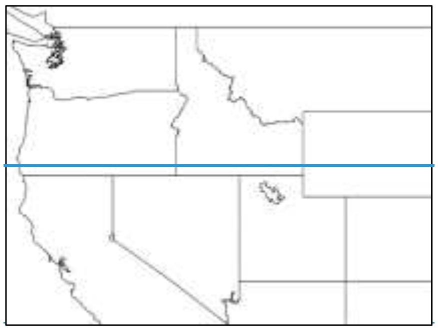

Figure 1: Study area covering all or parts of nine states in the western United States and part of southern Canada. The following MODIS tiles were used to develop the composite: h08v04, h09v04, h10v04, h08v05, h09v05, h10v05.

Fusion of ground- based and satellite- based snow observations is also an effective approach to map snow-cover"see beneath" clouds. This method of cloud clearing is used successfully by NOAA to develop the Interactive Multisensor Snow and Ice Mapping System (IMS) SCE products (see Helfrich et al., 2007 and 2012).

3Hybrid methods to reduce cloud cover are also effective. For example, Gafurov and Bárdossy (2009) developed a cloud-clearing method consisting of six sequential steps that begins with using Terra and Aqua snow cover maps, ground observations, spatial analysis and finally snow climatology to clear clouds and generate a cloud-free daily snow-cover map with high accuracy. Other researchers have developed CGF techniques that combined Terra and Aqua, time interpolation, spatial interpolation and probability estimation, e.g. López-Burgos et al. (2013) to create "cloud-free" SCEA maps. Deng et al. (2015) combined MOD, MYD and SNOWL SCE and AMSR2 SWE data and temporal filtering to create daily "cloud-free" snow cover maps of China. Combining different methods sequentially to remove clouds is also a way to create CGF products (Dariane et al., 2017). A cubic spline interpolation method has been used with good results by some researchers (Tang et al., 2013 & 2017; Xu et al., 2017) as a temporal CGF method using MODIS snow-cover products. Crowdsourcing by cross-country skiers combined with MODIS snow-cover products has also been used to create daily CGF products (Kadlec and Ames, 2017). Many other methods to reduce cloud cover have also been successful (e.g., see for example, Tong et al., 2009a & b; Tang et al., 2013 & 2017; Xu et al., 2017Dariane et al., 2017; Xu et al., 2017; Coll and Li, 2018).

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The CGF method of Hall et al. (2010) and Riggs et al. (2018) is the method that was selected for the NASA MODIS standard SCE products because of its ease-of-use, effectiveness and because it relies on data from only one sensor at a time to produce results.

2.4 Differences between Terra and Aqua MODIS snow-cover maps

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Beginning inSince the MODIS C6 re-processing, the Quantitative Image Restoration (QIR) algorithm (Gladkova et al., 2012) has been used in the Aqua MODIS snow algorithm to restore the lost data from the non-functional band 6 detectors so that the same snow-cover mapping algorithm can be used in both Terra and Aqua. Beginning with the launch of the Aqua MODIS, some detectors in Aqua MODIS band 6 have not functionedB since band 6 (with a center wavelength of ~1.6 µm) is, a key band for to snow-coverSCE mapping, experienced degradation issues even before the launch of the Aqua satellite in 2002 and many of its detectors are non-functioning there was a degredation in the Aqua MODIS SCE mapping algorithm as compared to the Terra MODIS algorithm8. Therefore, fFor C5 and earlier collections, Aqua MODIS band 7 (~2.1 µm) was used instead of band 6 in the snow-mapping algorithm (Riggs et al., 2006). Additionally,An additional complication is that ttThe cloud-masking algorithm for Terra uses MODIS band 6 but the cloud-masking algorithm forr the Aqua algorithm was adapted to use band 7 instead of band 6 because of the non-functioning detectors in Aqua band 6 for Collection 5 and earlier collections. This resulted in the Terra and Aqua algorithms often providing different snow-mapping results in many snow-covered areas due to the reduced accuracy of the Aqua algorithm. IHowever, even in C6 and C6.1 in which the QIR is employed to map snow in both the Terra and Aqua SCE algorithms, there are still more cloud/snow discrimination errors in the Aqua cloud-mask algorithm as compared to the Terra algorithm because the QIR is not used for cloud masking within the Aqua datacloud mask. This results in more snow commission errors in MYD10L2 (Aqua) snow maps as compared to MOD10L2 (Terra) snow maps. Because of the greater uncertainties inherent in snow mapping using MYD10 algorithms for reasons mentioned above, and because any combined method using both Terra and Aqua data is dependent on more than one sensor providing data, we do not recommend the Aqua MODIS SCE product to be part of a planned MODIS-VIIRS ESDR for SCE. Additionally, since both the Terra and Aqua MODIS sensors are well beyond their design lifetimes, it is not realistic to depend on both to provide data indefinitely into the future.

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Fusion of ground based and satellite based snow observations is also an effective approach to "see beneath" clouds. This method of cloud clearing is used by NOAA to develop the Interactive Multisensor Snow and Ice Mapping System (IMS) SCE products (see Helfrich et al., 2007 and 2012).

Our objective is to generate the CGF snow maps daily in the normal operational processing stream of MODIS and VIIRS snow products. The cloud-clearing method uses current day and/or recent previous day(s) of MODIS daily snow-cover products to fill gaps created by cloud cover. If timeliness were not a constraint then interpolation of snow cover over time, both on previous and future days, could be a part of a cloud-clearing algorithm, and would increase the accuracy of the snow cover map on any given day.

3 Methodology and Results

The new standard CGF products of Collection 6.1 and C2, respectively, M*D10A1F and VNP10A1F, enable researchers to download and use cloud-free MODIS and VIIRS daily snow SCE maps along with quality-assurance

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(QA) data information to assess uncertainties of the gap-filling algorithm. Reference Figure 1 here StudyHereFor the present work, we focus on a large (2,487,610 km^2) study area covering all or parts of 11 states in the western U.S. and part of southern Canada (Figure 1). Examples of the daily Terra MODIS standard and CGF and the daily S-NPP VIIRS standard and CGF cloud-free map products for thise western U.S. study area (Fig. 1) may beare seen in Fig. 2. Note someThere are some differences in cloud cover between the Terra MODIS (top left) and S-NPP VIIRS (top right) standard snow maps. The MOD10A1F scenesnow map is 65.8 percent (1,637,066 km^2) cloud-covered, vs 60.6 percent (1,506,924 km^2) in the VNP10A1F snow map. The difference in cloud coverage is largely due to the differences in the cloud masking of MODIS and VIIRS SCE maps, as described earlier. However, difference in the locations of clouds is also a contributing factor because the Terra MODIS and S-NPP VIIRS images were acquired at different times on the same day, and clouds move. There may also be changes in the location of snow cover within a day (due to melting of shallow snow, for example). Even given these small differences in the standard products that include clouds, the CGF snow maps shown in the bottom row of Fig. 2 are very similar, with 15.2 percent (378,634 km2) snow cover on the MOD10A1F snow map and 16.6 percent (413,794 km2) snow cover on the VNP10A1F snow map. Thus the VIIRS maps shows fewer clouds and more snow than does the Terra MODIS map in this example.

in area.Examples of the dThe daily Terra MODIS CGF S-NPP SCE product is similar to MOD10A1 product but is cloud-free for the western U.S. study area (Fig. 1), as seen in Fig. 2. There are some differences in cloud cover between the Terra MODIS (top left) and S-NPP VIIRS (top right) snow maps. The percentage of clouds in the MOD10A1F scene is 65.8 percent (1,637,066 km2), vs 60.6 percent (1,506,924 km2) in the VNP10A1F snow map. Th difference in cloud coverage isis is largely due to the differences in the cloud masking of MODIS and VIIRS, described earlier. It isHowever dare also a factor because the images were acquired at different times on the same day, and clouds moveTperhaps even some changes in snow cover. The CGF snow maps shown in the bottom row of Fig. 2 are very similar, with 15.2 percent (378,634 km2) snow cover on the MOD10A1F snow map and 16.6 percent (413,794 km2) snow cover on the VNP10A1F snow map, with VIIRS modis/viirsmapping more snow than MODIS.

the accuracy of the snow observation depends in part on the age of the observation, i.e., number of days since last cloud-free observation, thus information on cloud persistence is included with each product. The accuracy of the observation at the pixel level depends on the cloud masking of the swath product, M*D10_L2, for MODIS and VNP10_L2 for VIIRS. The MODIS and VIIRS snow-cover swath products are gridded and mapped into the daily tiled products that are input to M*D10A1F and VNP10A1F CGF algorithms.

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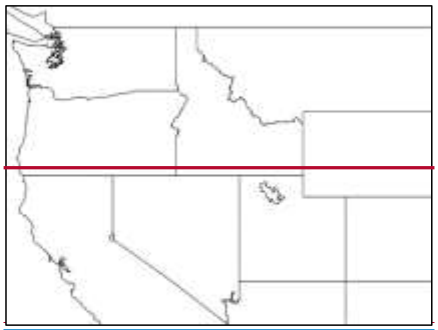
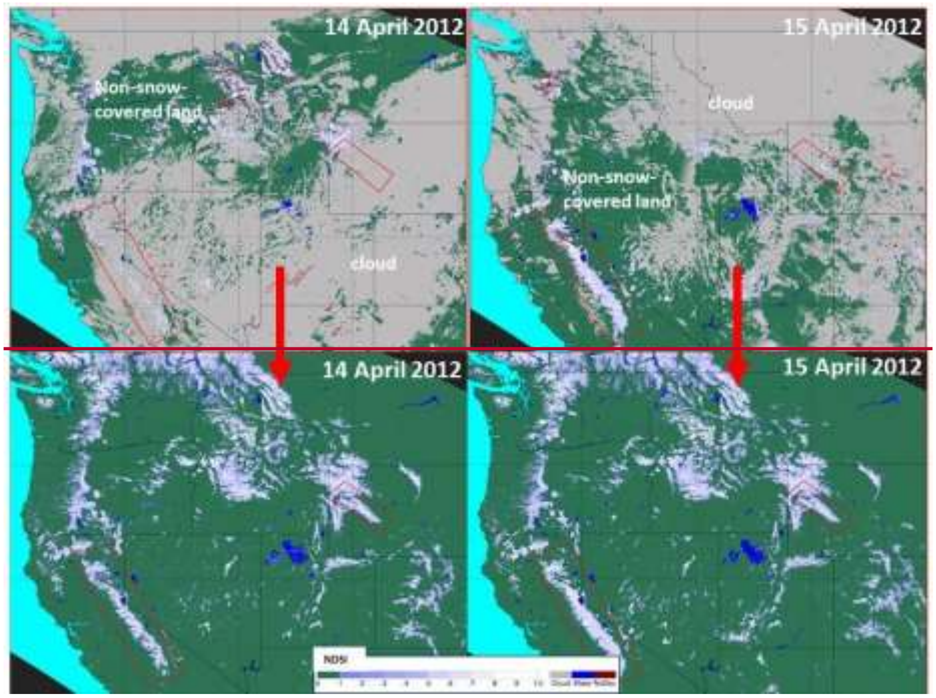


Figure 1: Study area covering all or parts of nine states in the western United States and part of southern Canada. The following MODIS tiles were used to develop the composite: h08v04, h09v04, h10v04, h08v05, h09v05, h10v05. The areal extent of this study area is 2,487,610 km^2.

431 
14 April 2012
15 April 2012
Non-snow-covered land
cloud
cloud
Non-snow-covered land
14 April 2012
15 April 2012
NDSI

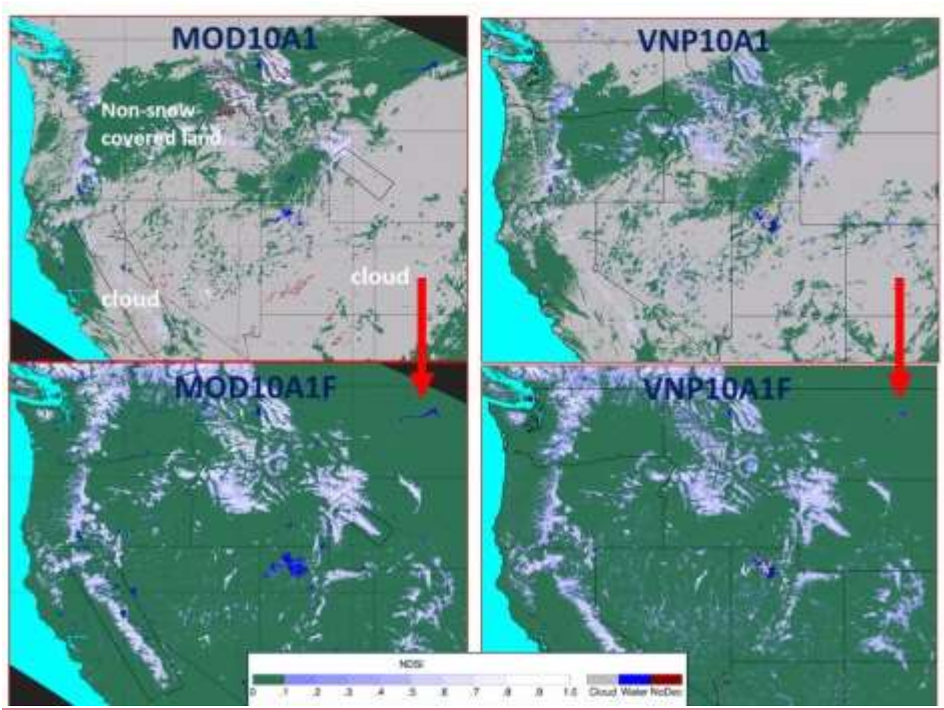


Figure 2: ~~**Top Row** –~~Examples of ~~the C6 MOD10A1 and the new Collection 6.1 MOD10A1F MODIS snow maps~~MODIS and VIIRS standard and cloud-gap filled (CGF) snow maps on 14 April 2012 for a study area in the western United States/southwestern Canada (see **Fig. 1**). **Top** ~~**row**~~ **left**: MODIS MOD10A1 C6.1 snow map~~s~~ showing extensive cloud cover on 14 ~~and 15~~ April 2012. **Top right**: VIIRS VNP~~PN~~10A1 C1 snow map also showing extensive cloud cover on 14 April 2012. **Bottom left**~~**row**~~: MOD10A1F C6.1 ~~cloud-gap filled (~~CGF~~)~~ map~~s~~ corresponding to the MOD10A1 snow map~~s~~ in the top row, also for 14 ~~and 15~~ April 2012. **Bottom right**: VNP10A1F CGF map corresponding to the VNP10A1 snow map in the top row, also for 14 April 2012. In all of the snow maps, ~~N~~non-snow-covered land is green. Regions of interest ~~(ROI)~~ containing the Sierra Nevada Mountains in California and Nevada (109,575 km^2), and the Wind River Range in Wyoming (22,171 km^2), are outlined in red on the MODIS snow maps. The following MODIS tiles were used to develop the MODIS composites: h08v04, h09v04, h10v04, h08v05, h09v05, h10v05. Each VIIRS swath that included coverage of this study area was composited to create a daily map, then the daily maps were used to create the VNP10A1F snow map for 14 April 2012.

~~**REVISE this FIGURE. Instead of showing the 15 April 2012 MODIS image pair, replace that with 14 April VIIRS snow maps.**~~

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Though cloud-gap filling provides a cloud-free snow map every day, the accuracy of the snow observation depends in part on the age of the observation, i.e., number of days since last cloud-free observation, thus information on cloud persistence is included with each product. The accuracy of the observation at the pixel level depends on the snow-cover algorithm that includes cloud masking of the swath product, M*D10_L2, for MODIS and VNP10_L2 for VIIRS. The MODIS and VIIRS snow-cover swath products are gridded and mapped into the daily tiled products which that are input to M*D10A1F and VNP10A1F CGF algorithms.

The accuracy of athe snow observation is dependent on many factors. In this work, we focus -on the uncertainties of the gap–filling method; we do not address the inherent accuracy of the snow maps because that has been documented elsewhere by many previous studies, at least for the MODIS SCE products. The accuracy ofUncertainties in the CGF maps that relate to the gap-filling methodology, shown in Fig. 2 depends in part on the age of the observation, i.e., number of days since last cloud-free observation. To address this, information on cloud persistence for each pixel is included with each product. The accuracy of the observation at the pixel level also depends on the Ccloud masking of the swath product, M*D10_L2, for MODIS and VNP100_L2 for VIIRS, represents an additional uncertainty in the both products and contributes to differences between the snow-mapping results. The MODIS and VIIRS snow-cover swath products are gridded and mapped into the daily tiled products that are input to M*D10A1F and VNP10A1F CGF algorithms (Riggs et al., 2017a).

IFor MODIS, inputs to the MODIS CGF algorithms are the current day M*D10A1 and the previous day M*D10A1F products. The CGF daily snow map is created by replacing cloud observations in the current day M*D10A1 with the most-recent previous cloud-free observation from the M*D10A1F (Hall et al., 2010; Riggs et al., 2018). The algorithm tracks the number of days since the last cloud-free observation by incrementing the count of consecutive days of cloud cover for a pixel. This is stored in the cloud-persistence count (CPC) data array. If the current day observation is 'cloud' then the cloud count is one and is added to the CPC count from the previous day's M*D10A1F and written to the current day's M*D10A1F algorithm. If the current day observation is 'not cloud,' then the CPC is reset to zero in the current day's M*D10A1F CPC. If the CPC is 0, that means that the snow-cover observation is from the current day. If the CPC for the current day is ≥1, that represents the count of days since the last 'non-cloud' observation. On the day that the CGF mapping algorithm is initialized for a time series,, for example, 1 xx February 2012, the CGF snow-cover map is identical to the MODIS daily snow-cover map (M*D10A1) and the cloud-persistence count (CPC) map will show zeros for non-cloud observations and ones for cloud observations (Riggs et al., 2018). As the time series progresses, a nearly-cloud-free snow map is produced on about Day 5 8 in theis example, shown in Fig. 3, on whichwhen the percent clouds cover is only 3.88.0 percent of the snow map (Fig. 3), though it takes 24 days to achieve a completely cloud-free map in this example (not shown). The same method is used to develop the VNP10A1F CGF snow-map products. For the same initialization of the time series, beginning on 4 February 2012, a nearly-cloud-free snow map is produced on Day 5x when the clouds cover is only xxx6.7 percent of the map, and it takes xxx days to achieve a completely cloud-free VNP10A1F CGF snow map (Fig. 3).

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61.23 36.52 25.18 19.19 15.94 11.20 10.16 8.03 5.74 4.16
PCT_CLOUD_VIIRS_CGF_ALL
50.78 23.28 14.21 10.20 6.71 4.70 4.48 3.18 2.17 2.02

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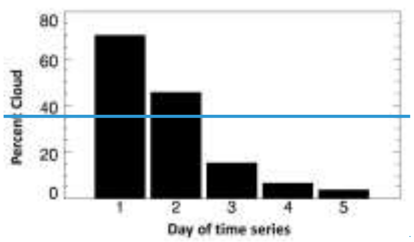

Figure 3: Percent cloud cover on a scene from the western United States (see location of the study area in Fig. 1). Note that the percentage of cloud cover decreases dramatically in the first few days following the beginninginitiation of the CGF time series on 1 February 2012, herein denoted as Day 1. The percent cloud cover drops from about 75 percent on Day 1 to 3.8

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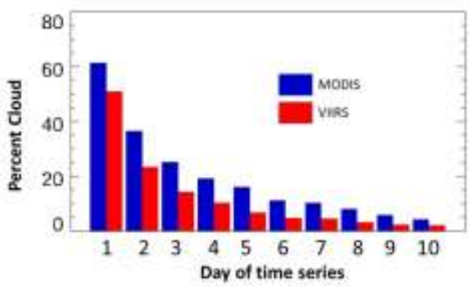

Figure 3: Percent cloud cover in a Terra MODIS (MOD10A1F) and an S-NPP VIIRS (VNP10A1F) time series of snow-cover maps for the western United States study area (see location in Fig. 1). Note that the percentage of cloud cover decreases dramatically in the first few days following the 4 February 2012 initiation of the CGF time series, denoted here as Day 1. In this example, the percent cloud cover drops from about xx percent on Day 1 to xx percent on Day 5 for the MOD10A1F time series and xx percent on Day 1 to xxx percent on Day x for the VNP10A1F time series..

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A CPC data arraymap is associated with each CGF snow map so that a user may determine the age of the snow observation of each pixel (Fig. 4). For each pixel, the uncertainty of the observation increases with time since the last clear view. To help a user assess the accuracy of an observation, the count of consecutive days of cloud cover is incremented and stored as QA in the CPC map that specifies how far back in time the observation was acquired. For example, for 19 March 2012, when a pixel has a CPC = 0, this means that the reported NDSI value for that pixel was acquired on 19 March 2012. When a pixel has a CPC=1 this means that the reported NDSI pixel value is one day old, hence it was acquired on 18 March, and so on (Fig. 4). A user can decide how far back in time they would like to use an observation, and can easily develop a unique CGF map, utilizing the CPC information that is most appropriate for their application.

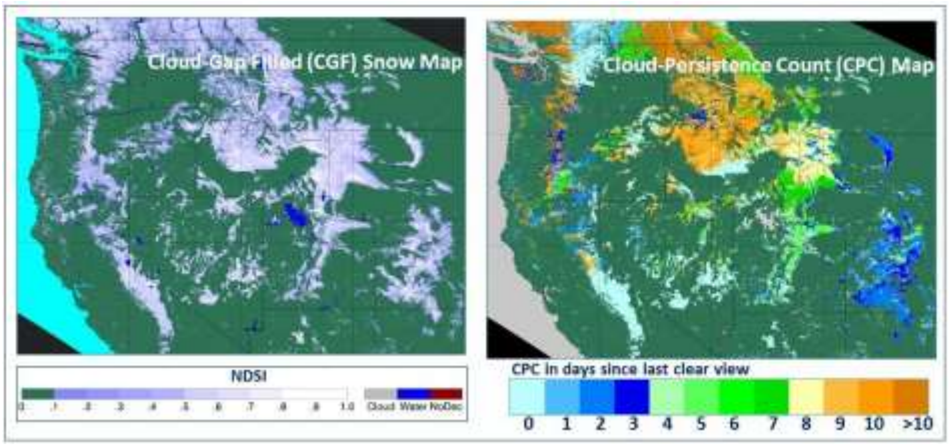

Figure 4: Left ~~-~~– Terra MODIS c~~C~~loud-gap filled (CGF) MOD10A1F snow map for 19 March 2012. Right – Cloud-persistence count (CPC) map from the quality assurance (QA) dataset for the ~~19 March~~ CGF snow map seen at left. For 19 March 2012, when a pixel has a CPC = 0, this means that the NDSI value for that pixel was acquired on 19 March 2012. When a pixel has a CPC=1 this means that the NDSI pixel value is one day old, hence it was acquired on 18 March, and so on.

For the snow-cover product suite, t~~T~~he time series are started with the first day of acquisition for each mission, then reset ~~when~~ on October 1st ~~is reached~~of each year. The first days of the gap-filling time series for the Terra and Aqua MODIS CGF production are 24 February 2000 and 24 June 2002, respectively. The first day of gap filling for the S-NPP VIIRS CGF production ~~is the first day of VIIRS data collection which~~ is 21 November 2011. With those exceptions, gap-filling sequences begin on the first day of each water year~~, October 1st~~.

The MODIS data-acquisition record is nearly continuous from the beginning of the missions however, there are brief periods -- minutes to hours -- when either the Terra [https://modaps.modaps.eosdis.nasa.gov/services/production/outages_terra.html] or Aqua [https://modaps.modaps.eosdis.nasa.gov/services/production/outages_aqua.html] MODIS data were not acquired or data were "lost." In general, those outages have minimal effect on the snow-cover data record. There have also been some VIIRS data outages which are also tracked [https://modaps.modaps.eosdis.nasa.gov/services/production/outages_npp.html]. However, in addition, there are ~~also~~ a few~~rare~~ extended data outages of one to five days that have occurred in the MODIS Terra record. Extended outages~~, and~~ may occur in the future. ~~George, do you know of gaps in the VIIRS~~

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data record? The gap-filling algorithms for both MODIS and VIIRS are designed to continue processing over daily or multi-day gaps in the data record. A missing day of MODIS or VIIRS NDSI snow-cover input is processed as if it were completely cloud obscured so the previous day's CGF result is retained and the CPC is incremented by one. Orbit gaps and missing swath or scan line data within a tile are processed as a cloud observation with the previous good observation retained and the CPC is incremented for the current day. This provides a continuous snow-cover data record for the CGF product. See Riggs et al. (2018) for further details.

4 Results: 3.1 Evaluation and Validation Analysis

In this section, we provide evaluation and validation for study areas in the western United States and a study area in the northeastern United States/southeastern Canada. We also look a regions of interest (ROIs) within the primary western United States study area shown in Figure 1. TAt the time of this writing, the MODIS and VIIRS CGF SCE products are not yetwill be available to download s. Sometime during the fall of 2019 the products will be downloadable through the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, USA. To enable some early evaluation of the products we produced CGF Terra and Aqua MODIS time series of selected areas in the western U.S. and in the northeastern U.S. and southeastern Canada. Here we provide evaluation and some validation for study areas in the western U.S./southwestern Canada and a study area in the northeastern U.S./southeastern Canada. We also look at regions of interest (ROI) within ourthe primary western U.S./southwestern Canada study area shown in Fig. 1. To begin to evaluate the products we produced Terra and Aqua MODIS time series of areas in the western U.S. and in the northeastern U.S. and southeastern Canada. We selected the year 2012 for the time series because both MODIS and VIIRS data were available in that year. Comprehensive global validation studies will not be possible to perform until the data sets are released through NSIDC and the entire MODIS and VIIRS records have been processed. This maywill take several months following initial release of the data; the full data records should be available in 2020..

There are many ways to evaluate the uncertainties in the CGF snow-cover maps but only one way to perform absolute validateeion of the maps. The CGF maps can be compared with other daily snow-cover map products (e.g., NOAA IMS 4-km snow maps Helfrich et al., 2007 and; 2012; Chen et al., 2012), with snow maps developed from higher-resolution maps such as from Landsat and Sentinel, and with reflectance images derived from satellite data. This allows us to evaluateevaluation of the products but does not constitute absolute validation.

In the U.S., the SCEThe only way to validate the products can be validated is using NOAA snow depth data https://gis.ncdc.noaa.gov/maps/ncei/summaries/daily as has been done for MOD10A1 (Collections 1 – 5) by many authors (e.g., Brubaker et al., 2005; Chen et al., 2012). However the density of meteorological stations is highly variable in the U.S. and the network of meteorological-station data over the globe is even more variable, especially in higher latitudes. Therefore the snow maps can only truly be validated where there is a dense network of

~~meteorological stations, though we can sometimes successfully interpolate between stations when stations are farther apart.~~

4.1 ~~Compare with~~Validation using NOAA snow depth data~~.~~

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Snow depths from NOAA ~~snow depth data~~ (~~e.g., see~~ Fig. 5) can be overlain on a MODIS CGF snow map as shown in the example in Fig.~~ure~~~~s.~~ 6 ~~and 7~~. Based on NOAA snow-depth data indicating the presence of snow cover, o~~O~~n 16 April 2012 the Terra MODIS CGF map appears to map the location of snow cover very well in an ROI in Utah that includes part of the Wasatch Range~~, based on NOAA snow-depth data indicating the presence of snow cover~~. A NASA WorldView true-color (corrected reflectance) Terra MODIS image is shown alongside a Terra MODIS CGF snow map with NOAA snow depths superimposed on an ROI in south-central Utah (Fig. 6a, b & c). There are no other NOAA stations that report snow cover except the ones shown in Fig. 6b. The dark blue and light blue circles indicate snow depths of~~ up to or~~ ≥~~>~~254.0 mm, and the white circle indicates a snow depth of 0.1 – 25.4 mm, revealing that the MOD10A1F snow map accurately ~~reflects~~shows the location of snow cover in this ROI.

Figure 5: Snow depth (mm) from 16 April 2012 for part of the continental United States. Source: NOAA National Climate Data Center https://gis.ncdc.noaa.gov/maps/ncei/summaries/daily.

~~On 16 April 2012 the MODIS CGF map appears to map the location of snow cover very well in an ROI in Utah that includes part of the Wasatch Range, based on NOAA snow-depth data indicating the presence of snow cover. A NASA WorldView true-color (corrected reflectance) Terra MODIS image is shown alongside a Terra MODIS CGF~~

snow map with NOAA snow depths superimposed on an ROI in south-central Utah (Fig. 6a, b & c). There are no other NOAA stations that report snow cover except the ones shown in Fig. 6b. The dark blue and light blue circles indicate snow depths of up to or >254.0 mm, and the white circle indicates a snow depth of 0.1 – 25.4 mm, revealing that the MOD10A1F snow map accurately reflects the location of snow cover in this ROI.

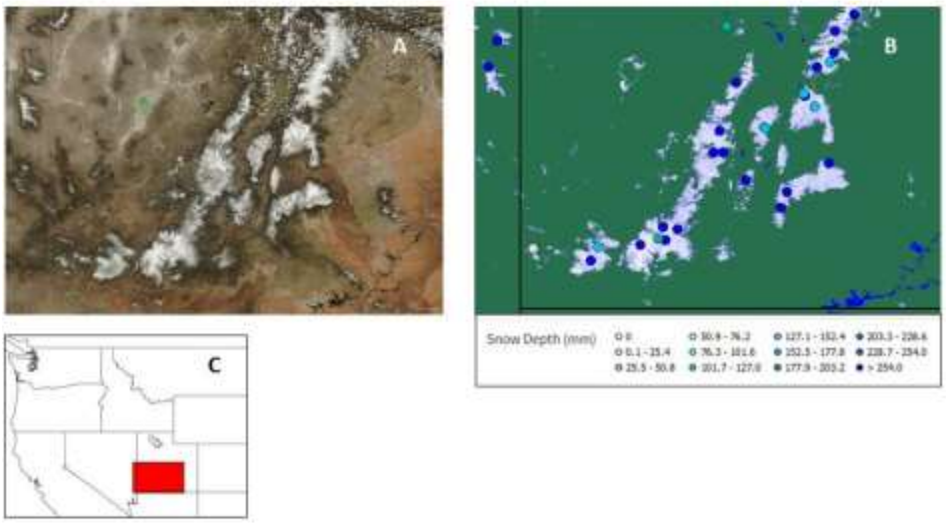

Figure 6a: NASA WorldView true-color (corrected reflectance) Terra MODIS image of a region on interest (ROI) in central Utah, USA.S.A., including the southern part of the Wasatch Range, acquired on 16 April 2012. Fig. 6b. Snow depths from NOAA are mapped onto the Terra MODIS CGF map, MOD10A1F, for 16 April 2012 for the same area shown in Fig. 6a. Open circles indicate stations that report snow depth, though none is visible in this snow map. Fig. 6c. Location map where the red rectangle delineates the ROI..

3.114.2 Compare with higher-resolution images and derived snow maps.

In the absence of meteorological-station data or in addition to it, aA good way to evaluate the accuracy of the MODIS CGF SCE maps is to compare them with snow maps derived from higher-resolution sensors such as from the Sentinel-2A (S-2A) Multispectral Instrument (MSI) 30-m resolution images derived from the Harmonized Landsat Sentinel-2 (HLS) dataset [https://hls.gsfc.nasa.gov/] (Claverie et al., 2018). As an example, we compare snow cover mapped in MODIS CGF snow-cover products with snow cover derived from Sentinel-2A Multispectral Instrument (MSI) 30-m resolution images from the Harmonized Landsat Sentinel-2 (HLS) dataset [https://hls.gsfc.nasa.gov/] (Claverie et al., 2018) as seen in for an ROI in Montana, in (Fig. 7a and, b & cshow a comparison of an S-2A image and a Terra MODIS CGF snow map from 2 December 2016).

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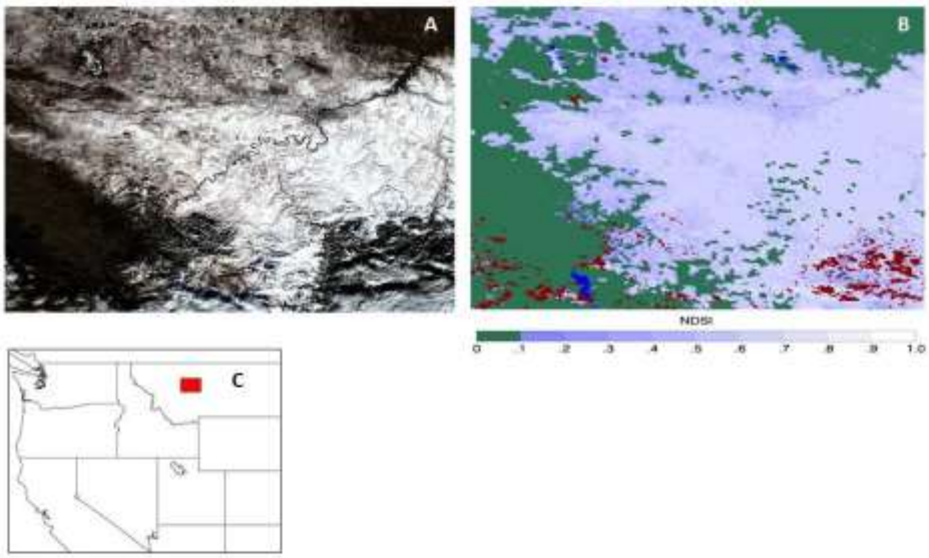

Figure 7a: Sentinel-2A 'true-color' image showing snow cover in shades of white and grey, acquired on 2 December 2016 for a region of interestn (ROI) in the state of Montana, U.S.A. Black indicates non-snow-covered ground. Fig. 7b. The MOD10A1F cloud-gap-filled (CGF) snow map of the same area and on the same date as is shown in Fig. 7a. In the CGF snow map in Fig. 7b, snow is depicted in various shades of white and purple, corresponding to Normalized Difference Snow Index (NDSI) values. Pixels shown in red represent 'no decision' by the NDSI algorithm. Fig. 7c. The red box corresponds to the location of the images in the ROI in Montana, shown in Fig. 7a and Fig. 7b.

Snow cover on 2 December 2016 may be seen on the Sentinel-2A (S-2A) image in shades of white and grey from this RGB composite image (bands 4, 3 and 2 (red (664.6 nm), green (559.8 nm) and blue (492.4 nm), respectively)) in Fig. 7a. Though the location of snow cover in the S-2AS2 image is visually very close to the snow cover depicted in shades of purple to white in the CGF snow map of Fig. 7b, there is not perfect correspondence. The point of this comparison is to demonstrate the utility of high-resolution imagery to evaluate the CGF maps, not to perform a detailed and quantitative comparison that would involve our selecting an algorithm to map snow cover in the S-2AS2 image, with its inherent uncertainties. Therefore this is an example of evaluation and comparison of snow maps, and not validation of the CGF map product.

4.3 3.12 Effect of cloud cover on the accuracy of the CGF snow-cover maps.

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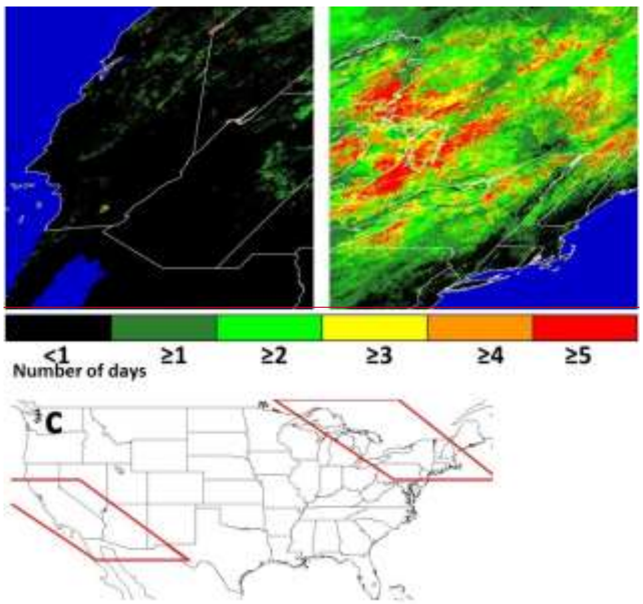
The accuracy of the CGF snow decision in each pixel is influenced by cloud persistence, or the number of days of continuous cloud cover. T~~his is because t~~he algorithm updates the snow map ~~under clear-sky conditions, or~~ when there are breaks in cloud cover, ~~according to~~as determined by the MODIS or VIIRS cloud mask. To demonstrate differences in cloud coverage and thus to illustrate ~~differences~~ sources of~~in~~ CGF uncertainty~~,~~ between two climatologically-different areas ~~in the United States~~~~continental U.S.~~, we show the mean number of days of ~~continuous~~ cloud cover for an ~~study~~ area in the western U.S./northern Mexico and in the northeastern U.S./southeastern Canada for the month of February 2012 (Fig. 8a, b & c). Greater accuracy in snow-cover decisions in ~~for~~ the CGF snow-cover product is ~~possible~~ achieved when there are more views of the surface as illustrated for ~~in~~ the month of February 2012; in the western U.S./northern Mexico ROI (Fig. 8a) are fewer days of clouds and more views of the surface ~~(that includes the Sierra Nevada Mountains ROI discussed earlier)~~ as compared to~~vs. in part of the~~ northeastern U.S./southeastern Canada (Fig. 8b~~a~~). ~~For example, for February 2012 the mean number of days of continuous cloud cover on a per-grid cell basis in the northeastern U.S./southeastern Canada (2.67 days) is greater than in the western U.S./northern Mexico (0.49 days) as seen in Fig. 8b. Figs. 8a and 8b demonstrate graphically that there were more views of the surface in the western study area as compared to the eastern study area for the month of February 2012. Thus the expectation is, that the accuracy of the CGF snow maps at this time of year is higher in western U.S. study areas as compared to cloudier northeastern U.S. study areas.~~



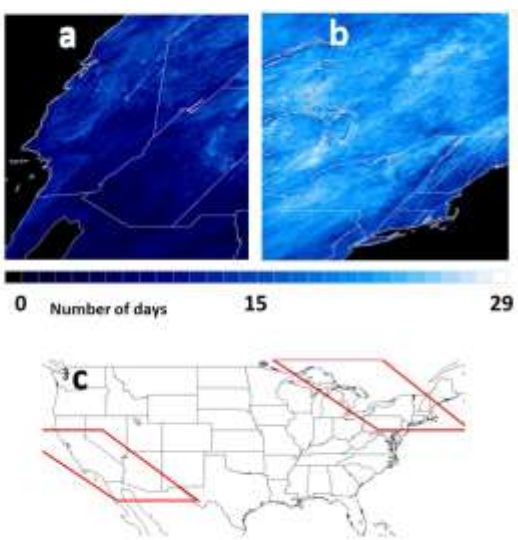


Figure 8a, b and c and 8b: Fig. 8a. Maps showing the mean number of days of continuous cloud cover (a measure of cloud persistence) for February 2012 derived from the MOD35 cloud mask used in the MOD10A1F snow-cover products. Fig. 8a. A study area: 8a) in the western U.S., extending into northern Mexico, and 8b) . Fig. 8b. A study area in the nNortheastern U.S./southeastern Canada. Fig. 8c. Location mMap showing outlines, in red, the locations of the study areas shown in Figs. 8a and 8b.

4.3 Comparison of a time series of MODIS and VIIRS cloud-gap filled SCE maps

~~For the study area in the western U.S. shown in Figure 1,~~ A ~~~~3-month (14~~1~~ February~~xx~~ – 30 April~~1 xx~~, 2012) time series of Terra MODIS and S-NPP VIIRS SCE map products (Fig. 9) wasere developed, processed and evaluated for the study area ~~in the western U.S.~~ shown in Fig. 1. ~~. Note in Figure 9 the~~The difference in SCE between the MODIS and VIIRS snow maps for each day of ~~the~~the ~~-~~time series is shown in the graph. Overall, the snow maps agree very well though t~~.~~ he ~~mean difference shows that In general, the~~ Terra MODIS snow maps show ~~more/~~less snow as compared to the VIIRS snow maps, with a mean daily difference of -11,070 ~~sq~~ km^2. ~~, which represents only 0.45 percent of the study area~~ which is only ~0.45 percent of the study area.~~.~~ ~~Overall, the snow maps agree very well.~~ Reasonss for disagreement between MODIS and VIIRS on a given day ~~daily basis~~ are that the Terra MODIS images are acquired at a different time of the day (10:30 A.M. equatorial crossing time) as compared to the S-NPP VIIRS images (1:30 P.M. equatorial crossing time); cloud-cover differences on the original snow maps (before gap filling) ~~can~~ also explain some of the difference in ~~amoun~~extent of snow mapped. This is largelys because of differences in cloud masking between the MODIS and VIIRS SCE products as described earlier, ~~in Section xx~~and as illustrated in the example shown in Fig. 2.~~.~~

~~Further analysis has confirmed that the differences in SCE between the two snow maps are largely due to differences in cloud masking.~~

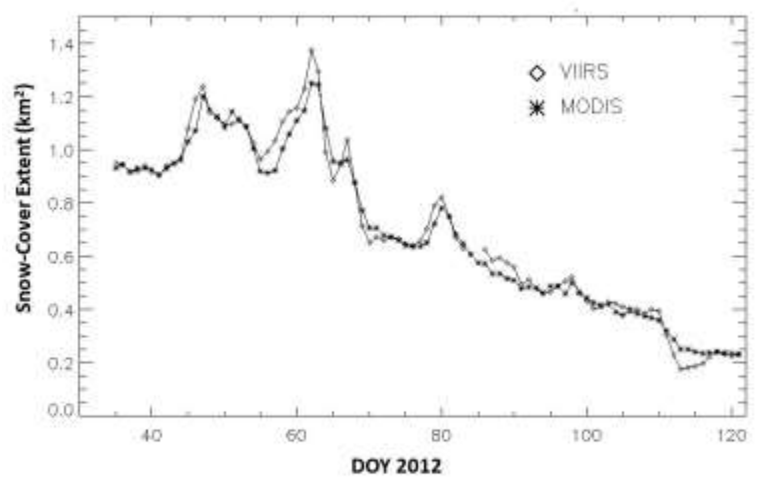


Figure 9: Time series showing differences in snow-cover extent (SCE) derived from Terra MODIS and S-NPP VIIRS cloud-gap filled (CGF) snow maps for a nearly 3-month period extending from 4 February – 30 April, 2012. Though the time series began

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on 1 February, snow-cover extent from 1 – 3 February snow cover is not shown because, in this example, ~~xxx~~the gap-filling algorithm was started on 1 February had not filled most of ~~in~~ the gaps from clouds until 4 February.

~~4.4 Development of Environmental Science Data Records using Cloud-Gap Filled Snow Maps~~

4.45~~3.13~~ Comparison of Terra and Aqua MODIS snow maps for inclusion in an Earth Science Data Record (ESDR)~~.~~

~~Because of the greater uncertainties inherent in snow mapping using MYD10 (Aqua) vs MOD10 (Terra) algorithms for reasons mentioned above that focus on Aqua band 6 issues, and because any combined method using both Terra and Aqua data is dependent on more than one sensor providing data, we do not recommend the Aqua MODIS SCE product to be part of a planned MODIS-VIIRS ESDR for SCE.~~ We analyzed Terra and Aqua CGF snow maps and time-series plots to determine which maps are better suited to being part of a moderate-resolution ~~the~~ SCE ESDR. First we compared snow maps ~~map data~~ from both Terra and Aqua from 1 February through 30 April 2012 for ROIs including the Wind River Range, Wyoming, and the Sierra Nevada Mountains in California and Nevada (see red rectangles in Fig. 2, left panels, for locations). In the first few days of each time series, the CGF algorithm is actively removing clouds from the daily maps, until both the Terra and Aqua daily maps are completely cloud-free by approximately DOY 20 of the Wind River Range ROI time series and Day 10 of the Sierra Nevada ROI time series ~~as seen in Fig. 9~~. Pixels for which the algorithm provided "no decision" were excluded from the analysis. The plots on the top row in Fig. 10~~9~~ show agreement of the Terra ~~MODIS~~ and Aqua CGF maps~~agreement~~ of percent snow cover as R=1.0, and Mean Bias=1.69 for the Wind River Range ROI time series and R=0.96 and Mean Bias=1.13 for the Sierra Nevada ROI time series. ~~Difference in percent clouds in each ROI (in which the difference = Terra minus Aqua) reveals that the Aqua snow maps generally have more clouds than do the Terra snow maps.~~

T~~Even when the "no-decision" pixels are excluded, t~~here are ~~still~~ differences in ~~Terra and Aqua~~ cloud masking that ~~preclude~~ prevent the Terra and Aqua time series from being identical. This is especially notable from ~DOY 35 – 70 of the Wind River Range time series (see top left graph in Fig. 10~~9~~). This corresponds to a period with significant cloud cover that is being mapped differently by the Terra and Aqua cloud masks (see bottom row in Fig. 10~~9~~). Difference in percent cloud cover by day for Terra ~~MODIS~~ minus Aqua CGF for the ROI including the Wind River Range and the ROI including the Sierra Nevada Mountains are shown in the bottom row of Fig. 10~~9~~. T~~Difference in percent clouds in each ROI reveals that t~~he Aqua snow maps generally have more clouds than do the Terra snow maps.~~The Aqua MODIS snow maps tends to have more cloud cover during the study period than does the Terra MODIS snow maps.~~

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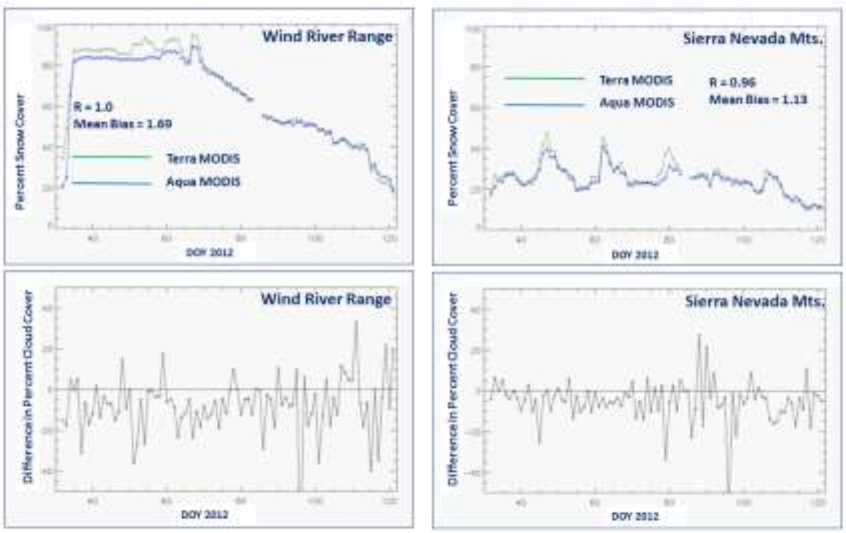

Figure 10~~9~~: Top Row. Time-series plots of percent snow cover in a 22,171 km^2 scene (see location of the ROI that includes the Wind River Range, Wyoming, in Fig. 2) and in a 109,575 km^2 scene (see ROI that includes the Sierra Nevada Mts., in Fig. 2) using M*D10A1F snow-cover maps for a time series extending from 1 February through 30 April (DOY 32 – 121) 2012. Bottom Row. Difference in percent cloud cover by day for Terra MODIS minus Aqua MODIS for the ROI including the Wind River Range and the ROI including the Sierra Nevada Mountains, corresponding to the top panels, showing that the Aqua MODIS ~~has~~ shows more cloud cover during the study period than does the Terra MODIS.

Though the percent snow cover on the Terra and Aqua snow maps is highly correlated in the ~~example~~ time series shown in Fig. 10~~9~~, there is also quite a bit of disagreement for example from about DOY 35 – 70 for the Wind River Range. Our analysis of both CGF snow maps for this western U.S. study area indicates that the Terra MODIS snow maps are ~~is~~ superior ~~for reasons that are~~~~as discussed~~for reasons described below. Further analysis, after the full dataset has been reprocessed, is required to confirm this.

The primary reason for disagreement between the Terra MODIS and Aqua MODIS snow maps in C5 and earlier collections is that the ~~-~~ 1.6 µm channel (b~~B~~and 6) on the Aqua MODIS sensor has some non-functioning detectors (MCST, 2014) as described earlier. Other reasons include low illumination and terrain shadowing. The reader is referred to the MODIS C5 Snow Products User Guide (Riggs et al., 20~~1~~06) for ~~more~~ details concerning the effect of the non-functioning detectors on the Aqua snow-cover maps in data collections prior to C6.

For C6, the MYD10A1 snow-mapping algorithm uses the ~~Quantitative Image Restoration (~~QIR~~)~~ ~~(of~~ Gladk~~c~~ova et al., ~~(~~2012) to correct the Aqua MODIS band 6 radiances for the non-functioning detectors, and thereby to enable use of the same algorithm as is used for the Terra MODIS. Differences in cloud cover, and in cloud masking account for differences in snow-mapping results between the C6 Terra and Aqua MODIS snow maps shown in Fig. 10~~9~~. The lower panels in Fig. 10~~9~~ illustrate differences in the cloud masking for Terra and Aqua for the 4~~1~~ February – ~~30~~ April 2012 time series.

An ~~specific~~ example to illustrat~~e~~ ~~ing~~ this can be seen on 26 April 2012 which was a day that had a large amount of clouds in the ~~primary~~ western~~our~~ U.S. study area ~~shown in Fig. 1~~ ~~of the western United States~~ (Fig. 11~~0~~). The patterns of cloud cover in the false-color imagery (not shown) of both Terra and Aqua MODIS show that the clouds ~~are in~~have the same shape ~~of~~ as many of the 'no-decision' regions on the Aqua CGF snow map. The clouds are probably very cold (possibly with ice) on top of lower-level clouds. The Aqua cloud mask fails to flag most of those clouds as 'certain cloud,' so they are processed as 'clear' in the MYD10A1 snow algorithm, and 'no decision' is the result. This is ~~an outcome of the fact that~~because the Aqua MODIS band 6 (with its non-functioning detectors) is not used in the Aqua MODIS cloud masking algorithm ~~because of the non-functioning detectors~~. Even though MYD10A1 uses the QIR for the C6 and C6.1 SCE algorithms, the C6 cloud masking algorithm, MYD35 developed by the University of Wisconsin, does not "restore" the non-functioning detectors of Aqua band 6, and therefore use~~sd~~ Aqua band 7 instead.

~~This is a common problem with the C6 Aqua CGF snow maps, and t~~The large number of 'no decision' pixels resulting from the Aqua C6 and C6.1 cloud mask would affect the continuity of a moderate-resolution SCE n ESDR. For that reason, we have decided to use of the Terra and VIIRS CGF maps only, as part ofto develop the ESDR.~~

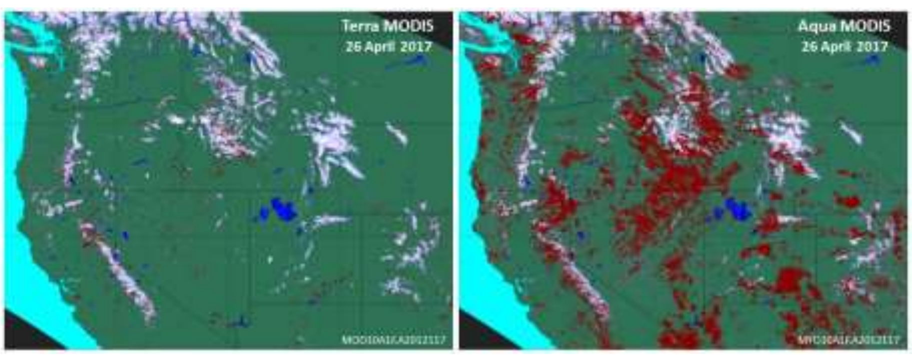

Figure 11~~0~~: Terra MODIS (left) and Aqua MODIS (right) cloud-gap-filled (CGF) snow-cover maps from 26 April 2012. Note that there are red pixels on both snow maps indicating 'no decision' by the algorithm, however there are many more red pixels on the Aqua MODIS snow map, primarily due ~~largely~~ to the inability of the Aqua MODIS cloud mask to identify large areas of cloud cover as 'certain cloud.' The location of this western United States study area is shown in Fig. 1.

There are greater uncertainties inherent in snow mapping using the Aqua MODIS vs. Terra MODIS for reasons mentioned above that are largely related to the non-functioning detectors in the Aqua MODIS band 6. The large number of 'no decision' pixels resulting from the Aqua C6 and C6.1 cloud mask would adversely affect the continuity of a moderate-resolution SCE ESDR. Based on this preliminary analysis, we recommend use of the Terra MODIS and S-NPP VIIRS CGF maps only, to develop the moderate-resolution SCE ESDR. Further analysis in other snow-covered areas is necessary to confirm this.

4.5 Development of Environmental Science Data Records using Cloud-Gap Filled Snow Maps

54 Discussion and Conclusion

Meltwater from mountain snowpacks provides hydropower and water resources to drought-prone areas such as the western United States. Accurate snow measurement is needed as input to hydrological models that predict the quantity and timing of snowmelt during spring runoff. SCE can be input to models to estimate snow-water equivalent (SWE) which is the quantity of most interest to hydrologists and water management agencies. Increasingly-accurate predictions save money because reservoir management improves as measurement accuracy of SWE increases.

In this paper, we describe some of the applications andsome uncertainties of the C6.1 MODIS and VIIRS cloud-gap filled (CGF) daily snow-cover maps, M*D10A1F and the C2 the C22 VIIRS CGF snow-cover map, VNP10A1F, respectively. The objective of this work tthe NASA MODIS and VIIRS algorithms products is to produce a daily, cloud-free snow-cover products along with appropriate QA information. These products will enable that can SCE can be used as the basis for that an Earth Science Data Record (ESDR) of snow cover tocan be produced at moderate spatial resolution for hydrological and climatological applications. Cloud-gap filled snow-cover products from MODIS and VIIRS have all of the uncertainties of the original products, that contain clouds, as well as additional uncertainties that are related to cloud the age of the snow measurementgap -filling, such as the age of the snow observation method. When using the MODIS and VIIRS CGF products, a user can specify how far back in time they want to look, using the Cloud-Persistence Count (CPC) which tells the age of the snow measurement in each pixel; the CPC, and is available as part of the product QA metadata for both the MODIS and VIIRS CGF snow-cover products. Uncertainty relating to cloud-gap filling is greater in areas with frequent and persistent cloud cover during the snow season such as in the northeastern U.S., or WRR vs. areas such as the Sierra Nevada Mountains where gaps in clouds occur more frequently during the snow season.

It is difficult to validate the MODIS and VIIRS CGF (and other) snow maps. Absolute validation can only be accomplished using NOAA daily snow depth station data when available. However, pwWe can also evaluate the pproduct accuracy can also be *evaluated* by comparing the CGF with MODISproducts with surface reflectance maps, higher-resolution maps such as derived from Landsat and Sentinel and using other satellite-derived snow maps.

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~~Comparisons of the daily MODIS and VIIRS CGF SCE products for a nearly 3-month time period in 2012 over a study area in the western U.S. (2,487,610 km^2) show excellent correspondence between the products with the VIIRS products, on average, mapping 11, 070 km^2 more snow as compared to the MODIS products on a given day, or 0.45 percent of the study area.~~

Comparisons of Terra and Aqua CGF snow maps in C6 reveal many more “no-decision” pixels in the Aqua snow maps, due to cloud masking, low illumination and terrain shadowing. Because of non-functioning detectors in band 6, the Aqua cloud mask is less accurate than the Terra cloud mask according to our preliminary validation over the western U.S. study area. Though the ~~Terra and~~ Aqua snow algorithms ~~are the same in C6 due to~~ use ~~of~~ the Quantitative Image Restoration (QIR) technique ~~technique~~ to map snow using ~~for~~the Aqua MODIS, the Aqua cloud mask does not use the QIR.~~but the accuracy of the Terra product is higher, and therefore the Terra~~ ~~MODIS CGF snow-cover maps of C6.1 are useful for development of an ESDR and ultimately a CDR (combined with S-NPP VIIRS and other JPSS VIIRS-derived snow maps now and in the future).~~

~~Time series of both the Terra and Aqua daily CGF snow-cover maps show pixels classified as ‘no decision,’ but on the Aqua CGF maps, there are many more ‘no decision’ pixels on the Aqua maps. Because of this issue with the Aqua MODIS cloud masking, as detailed above, ThereforeFor this reason we do not recommend using the C6.1 Aqua MODIS CGF snow maps as part of an ESDR at this time. In the future, if the Terra and Aqua cloud mask algorithms become more similar in future re-processing of the cloud mask, this recommendation will be reassessed.~~

Comparisons of the daily Terra MODIS and S-NPP VIIRS CGF SCE products for a 3-month time period in 2012 were undertaken for our study area in the western U.S. (2,487,610 km^2) covering all or parts of 11 states and part of southwest Canada. Though the MODIS and VIIRS SCE maps show excellent correspondence, the VIIRS maps, on average, show 11,070 km^2 more snow as compared to the MODIS maps on a given day which is only ~~~~<0.45 percent of the study area. MODIS CGF snow-cover maps of C6.1 are useful for development of an ESDR and ultimately a CDR (combined with S-NPP VIIRS and other JPSS VIIRS-derived snow maps now and in the future).

Snow cover is one of the Global Climate Observing System (GCOS) essential climate variables. The distribution, extent and duration of snow, along with knowledge of snowmelt timing, are critical for characterizing the Earth’s climate system and its changes. To ~~augment~~ complement the 53-year NOAA/Rutgers CDR of snow cover at 25-km resolution which is valuable for climate and other studies, the MODIS/VIIRS moderate-resolution ESDR will be available at 500-m resolution and as such will be~~is~~ useful for local and regional studies of snow cover and water resources, as well as for climate studies. The value of the ESDR will increase ~~as~~ as the length of the record increases.

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Acknowledgements

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