Hindawi
Advances in Meteorology
Volume 2020, Article ID 4532478, 10 pages
https://doi.org/10.1155/2020/4532478

Research Article

Intercomparison and Validation of MIRS, MSPPS, and IMS Snow Cover Products

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Received 16 October 2019; Revised 3 February 2020; Accepted 11 February 2020; Published 23 March 2020

Academic Editor: Hiroyuki Hashiguchi

We evaluate the agreement between automated snow products generated from satellite observations in the microwave bands within NESDIS Microwave Integrated Retrieval System (MIRS) and Microwave Surface and Precipitation Products System (MSPPS), on the one hand, and snow cover maps produced with manual input by the NOAA's Interactive Multisensor Snow and Ice Mapping System (IMS), on the other. MIRS uses physically based retrievals of atmospheric and surface state parameters to provide daily global maps of snow cover and snow water equivalent at 50 km resolution. The older MSPPS delivers daily global maps at the spatial resolution of 45 km and utilizes mostly simple empirical algorithms to retrieve information. IMS daily maps of snow and sea ice cover for the Northern Hemisphere are produced interactively through the analysis of satellite imagery in the visible, infrared, and microwave spectral bands. We compare the performances of these products across the Northern Hemisphere for 2014–2017, using IMS as the standard. In this intercomparison, the daily overall agreement of the automated snow products with IMS ranges between 88% and 99% for MIRS and 87% and 99% for MSPPS. However, daily snow sensitivity is lower, ranging between 36% and 90% for MIRS and 26% and 91% for MSPPS. We analyze this disagreement rate as a function of terrain and land cover type, finding that, relative to IMS, MIRS shows fewer false positives but more false negatives than MSPPS over high elevation and grassland areas.

1. Introduction

Snow cover plays an important role in Earth's climate, water resources, and weather. Seasonal snow cover is found primarily in the Northern Hemisphere, where its area can reach 46 million km^2. Snow cover increases the earth's surface albedo, recharges reservoirs and rivers in certain regions, and affects the land surface temperature [1]. Thus, snow properties are important for applications in climate, hydrology, water management, agriculture, transportation, and recreation [2–4].

Information about snow properties, particularly the snow depth and the snow water equivalent, can be acquired from traditional in situ measurements. This point-specific data is limited to populated or accessible locations. Unlike in situ data, observations from weather satellites provide continuous wide area coverage and therefore offer a tool for mapping and monitoring of the snow cover on a global and continental scale.

There is a considerable number of satellite-based snow cover products developed both for operational and climate applications. The retrieval techniques for these products employ both interactive and automated data processing approaches and utilize satellite observations in the visible/infrared spectral bands [5–8], passive microwave observations [9–13], or a synergy of observations in the visible/infrared and in the microwave [14–17].

Since 2000, an automated image classification algorithm has been used to produce global daily snow cover maps from observations in the visible and infrared spectral bands of

Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua satellites. A similar technique has been applied to observations of the Visible and Infrared Imaging Radiometer Suite (VIIRS) onboard SNPP and NOAA-20 satellites. Snow maps derived from this type of observations are characterized by high spatial resolution, on the order of several hundred meters, and high accuracy, typically ranging between 92 and 97% [18, 19]. However, gaps in coverage due to clouds and darkness reduce the value of satellite-based visible/infrared snow products and hamper their use in model applications.

One of the most widely used snow cover datasets are the snow and ice cover maps generated by NOAA within Interactive Multisensor Snow and Ice Mapping System (IMS) [20, 21]. IMS maps are prepared by human analysts who rely primarily on the visual analysis of imagery from operational polar orbiting and geostationary satellites. Analysts also have access to several other datasets including satellite-based snow products and surface measurements and web-camera imagery. IMS maps are available daily and cover the Northern Hemisphere at the spatial resolution of about 1 km (since 2014). These maps are used to generate coarser-resolution daily snow and ice charts at 4 km and 24 km.

Satellite observations using passive microwave sensors have coarse spatial resolution, typically 10–50 km. However, they are not affected by most types of clouds and do not require daylight and thus can provide spatially continuous (gap-free) maps of snow cover properties. Besides the presence of the snow cover on the ground, these observations are also sensitive to physical properties of the snow pack, including the snow water equivalent. Automated satellite microwave-based snow products can be updated more frequently than products such as IMS that require human analyst input and can provide information not only on the snow cover extent but also on the snow depth and/or snow water equivalent [11, 22].

National Oceanic and Atmospheric Administration (NOAA) satellite observations in the microwave present an important component of the operational snow cover monitoring system. Since the mid-1990s, information on the global snow cover properties from satellite observations has been obtained from satellite data using a semiempirical decision-tree retrieval algorithm and, later, its modified version [9, 23]. Using a set of threshold-based tests involving spectral and polarization indices inferred from satellite-observed brightness temperature values, the algorithm differentiates the snow cover from the snow-free land surface, precipitating clouds, glaciers, and cold rocky surfaces. For snow-covered areas, the snow depth is then estimated from the spectral gradients of the brightness temperature at 19 and 37 GHz and at 37 and 89 GHz. These algorithms have been incorporated in the National Environmental Satellite, Data, and Information Service (NESDIS) Microwave Surface and Precipitation Products System (MSPPS) system, where a similar semiempirical approach and threshold-based algorithms were used to infer a set of other atmospheric, land surface, and sea surface parameters. Snow cover products within MSPPS include daily maps of global snow extent and snow depth generated at about 50 km resolution.

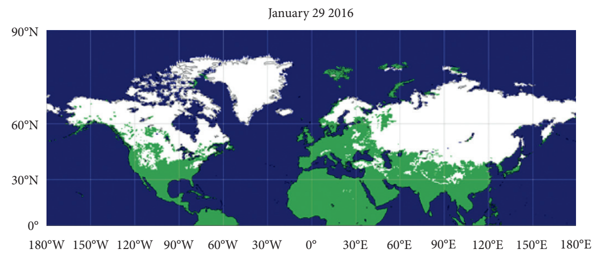
Since 2011, satellite observations in the passive microwave have been processed at NESDIS with the MIRS system [24]. This system generates a set of atmospheric, land surface, and sea surface parameters to a large extent similar to the one of MSPPS. However, unlike MSPPS, MIRS employs a physically based one-dimensional variational satellite data assimilation technique where atmospheric and surface geophysical parameters are estimated simultaneously. This technique is applied to the data from AMSU and MHS instruments onboard NOAA satellites. Similar to MSPPS, the spatial resolution of the MIRS products, including information on the snow cover and the snow depth is about 50 km.

There is a reasonable expectation that a more justified physically based retrieval approach in the MIRS system would provide a better quality of derived environmental parameters and, in particular, of the snow products as compared to MSPPS. This expectation has contributed to a large extent to a recent NESDIS decision to retire the MSPPS system and to terminate its data production while retaining MIRS operations. Advantages of MIRS products over MSPPS, at least with respect to the snow cover characterization, have not yet been clearly demonstrated and documented. Operational snow cover products delivered by the two systems have never been compared under the same set of environmental conditions and against the same reference dataset. The MIRS system has only been operational for the last decade, meaning that generating consistent long-term time series of microwave-based snow cover products will inevitably require combining earlier, pre-2011, MSPPS with later MIRS retrievals. Therefore, a detailed comparison of MIRS and MSPPS snow products and evaluation and assessment of their differences are also important from the point of view of generating a consistent long-term climate dataset.

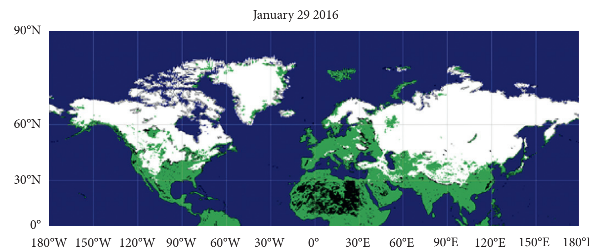
The principal objective of this study consists in the comparison and accuracy assessment of the snow extent maps generated within MSPPS and MIRS systems. Assessment of the accuracy is performed by comparing the two microwave automated snow products with IMS snow cover maps, considered as a standard due to their higher spatial resolution and incorporation of different satellite and ground-based data. The overall agreement between MSPPS, AIRS, and IMS was examined over the 2014–2017 period. The incidence of disagreement with regard to snow cover was analyzed with respect to the surface elevation and the land cover type.

2. Datasets

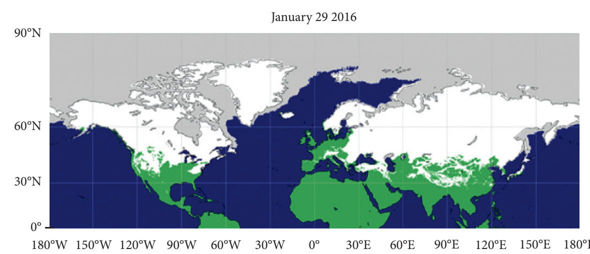
Three snow cover products: Microwave Integrated Retrieval System (MIRS), NOAA Microwave Surface and Precipitation Products System (MSPPS), and NOAA Interactive Multisensor Snow and Ice Mapping System (IMS) are used in this study (Figure 1). The agreement of NESDIS MIRS and MSPPS are evaluated with NOAA IMS for January 1, 2014, to April 24, 2017. Daily global snow products generated by MIRS and MSPPS systems were acquired from the NOAA Comprehensive Large Array-data Stewardship System



(a)



(b)



(c)

Figure 1: Example (a) MIRS, (b) MSPPS, and (c) IMS maps for January 29, 2016. MIRS shows sea, land, and snow classes. MSPPS shows other (black), sea, land, and snow classes. IMS shows sea, land, sea ice (grey color), and snow cover classes.

(CLASS) in the NOAA-18 Satellite in Polar Stereographic projection. Daily Northern Hemisphere snow and ice cover data from IMS were acquired from the National Snow and Ice Data Center FTP archives at a 24 km resolution.

MIRS uses physically based retrieval of atmospheric and surface state parameters: temperature and water vapor profiles, cloud and precipitation parameters, vertical profiles (nonprecipitating cloud water, rain, ice, snow, and graupel), and skin temperature and emissivity spectrum. It intended to be an "enterprise" solution (a common physics package for snow cover and property retrieval) that can be used for microwave sensors from various satellites with different configurations. The operational products are currently generated from microwave sensors onboard six polar-orbiting satellites: the Advanced Microwave Sounding Unit-A (AMSU-A) and Microwave Humidity Sounder (MHS) onboard National Oceanic and Atmospheric Administration-18 (NOAA-18), National Oceanic and Atmospheric Administration-19 (NOAA-19), Meteorological Polar Orbit satellite (Metop-A and Metop-B), Advanced Technology Microwave Sounder Suomi-National Polar-orbiting Partnership (ATMS S-NPP), and Special Sensor Microwave Imager/Sounder onboard the Defence Meteorological Satellite Program-Series (SSMIS DMSP F18). Two daily products are generated in both polar and cylindrical projections, from observations on the ascending node and descending node, respectively. The products come in 50 km spatial resolution, global coverage, and daily frequency.

MSPPS is the original NOAA AMSU-based product, representing an older generation of snow retrieval methods soon to be replaced by MIRS. It incorporates mostly simple empirical algorithms. The product comes in 45 km spatial resolution, global coverage, and daily frequency. It is only available in polar projection and combines satellite data obtained both on ascending and descending nodes. It uses antenna temperatures from AMSU-A and AMSU-B/MHS onboard NOAA's and EUMETAT's polar orbiting satellites [25].

IMS uses a combination of geostationary and polar orbiting satellites in the visible, infrared, and microwave spectrums, as well as manual analyst input. The product provides daily maps of snow and sea ice extent over the Northern Hemisphere and is derived from a combination of sources including satellite imagery and in situ data. The visible and infrared spectral data from Polar and Geostationary Operational Environmental Satellites are used to generate snow cover data [26]. Persistent cloud cover inhibits the visible and infrared spectrum; thus, microwave products from Special Sensor Microwave Imager (SSM/I) and Advanced Microwave Scanning Radiometer for EOS (AMSR-E) are also incorporated in IMS. Snow Data Assimilation System (SNODAS) and station-mapped products are also integrated in IMS [21, 26]. IMS analysts start charting using the map from the previous day and then utilize the satellite inputs [26]. IMS comes in 1 km, 4 km, and 24 km resolutions in polar stereographic projection [12].

3. Methodology

The validation and comparison of these microwave products (Figure 2) is performed by first resampling the MIRS, MSPPS, and IMS products into a latitude-longitude (Plate Carrée) grid over the Northern Hemisphere [27] with a pixel size of approximately 0.02778° (~3 km in the equator). The resampling is done by replicating the closest pixel value of the original as that of the finer grid cells. This provided the base grid in which all comparisons are executed. Although we would expect the global snow products to have lower accuracy at this finer resolution, the main purpose of the current study is to compare the performance of the different products, for which a common fine resolution is suitable.

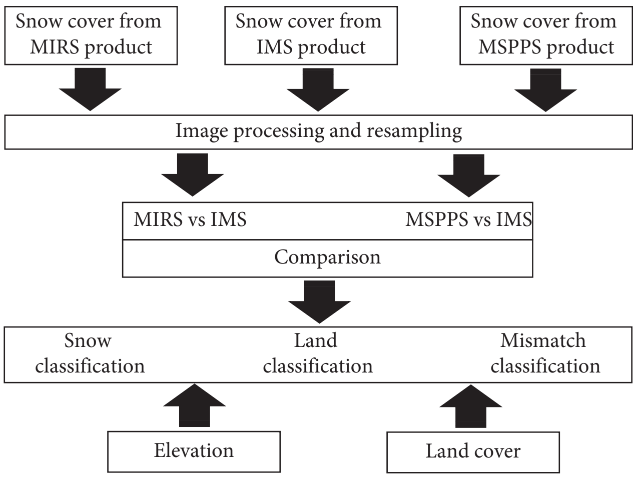


Figure 2: Flow chart showing the overall comparison process of MIRS and MSPPS with IMS snow cover and further analysis of elevation and land cover effects on snow identification.

The agreement evaluation of the newly resampled MIRS and MSPPS snow cover data is performed by comparing each grid cell of microwave product to that of the IMS and given a classification of false positive/negative (FP/FN) or true positive/negative (TP/TN). Snow cover is taken as the positive classification. Truth or falsity is imputed based on whether MIRS or MSPPS matches IMS in detecting snow cover (Figure 3). A confusion matrix is used to organize the different classifications, and the total area of each classification is used for the calculation of overall agreement and snow sensitivity for each daily microwave product. Agreement measures the overall accuracy of the model classification. Sensitivity measures how often the products agree where IMS shows snow cover [28, 29]. The equations used are as follows:

$$\text{overall agreement } (\%) = \frac{A_{\text{TN}} + A_{\text{TP}}}{A_{\text{TN}} + A_{\text{FP}} + A_{\text{FN}} + A_{\text{TP}}},$$
$$\text{snow sensitivity } (\%) = \frac{A_{\text{TP}}}{A_{\text{TP}} + A_{\text{FN}}}, \quad (1)$$

where A_X is the total area in each classification.

To better understand the sources of disagreement of the microwave products with IMS, the false classifications are compared over elevation and land cover classes. Mountains interfere in the identification of snow because snow distribution and density may be very irregular in complex terrain, while vegetation introduces the problem of masking [30]. For elevation, the GTOPO30 dataset was used. GTOPO30 is a global digital elevation model with a horizontal grid spacing of 30 arc seconds (~1 km). This was resampled to the same, coarser resolution grid used for the snow products (Figure 4(a)). The resampling was performed by aggregating and averaging the original GTOPO30 data within the larger base grid cells. For the analysis, it is assumed that elevations greater than one km, or 1000 meters, above sea level constitute mountainous terrain.

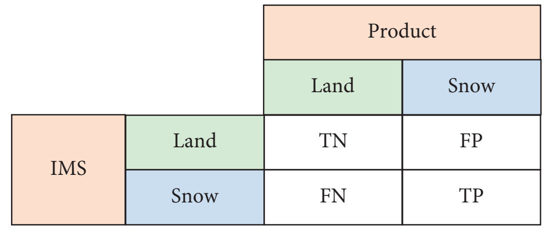


Figure 3: Classification used in the intercomparison of snow cover products, where product refers to either MSPPS or MIRS.

The MODIS Land Cover Type Product (MCD12Q1) and the International Geosphere Biosphere Programme (IGBP) land cover classification system are used to characterize the land surface cover type [31]. For the analysis, the MODIS Land cover map at $5'$ resolution was resampled to the base grid. MODIS provides greatly enhanced spectral, spatial, radiometric, and geometric quality data that gives a basis for current global land cover maps applicable for this study [32]. The original land surface cover types are aggregated into three larger categories: Forest, Short Trees, and Grassland (Figure 4(b)). Forest includes evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, and mixed forest. Short trees include closed and open shrublands and woody savannas. Grassland includes savannas, grassland, permanent wetlands, croplands, cropland/natural vegetation mosaics, and barren or sparsely vegetated. Other land cover types not included in the Forest, Short Trees, and Grassland classifications were grouped as Other. The same procedure is done for finding the percentage of errors in elevation areas and is also done with land cover identification.

4. Results and Discussion

The comparison of daily NESDIS MIRS and MSPPS microwave snow cover products with IMS was performed throughout the years 2014 to 2017. The results of the comparison were reported in terms of the corresponding areas of the True/False Positive/Negative classifications.

As an example, Figures 5 and 6 show these classifications for MIRS and MSPPS products for the 29th day of the months of January (winter), April (spring), July (summer), and October (fall) of 2016, respectively. It is observed that both microwave products make very similar mistakes as compared to IMS; false negatives dominate in winter, spring, and fall while false snow pixels are minimal in the summer. The microwave products tend to often miss snow cover identified by IMS, likely due to a general lack of sensitivity of passive microwave observations to melting snow [30]. On the other hand, MSPPS tends to overestimate snow over Tibet, whereas MIRS provides a more accurate characterization of snow cover over mountainous areas.

The overall agreement of both products during the entire 2014–2017 period with IMS is similar. MIRS has an agreement of 93% (true positive and true negative area fraction) while MSPPS has an agreement of 92% (Figure 7). However, their agreement changes drastically across seasons. Over the winter, agreement varies from 88% to 93%. It

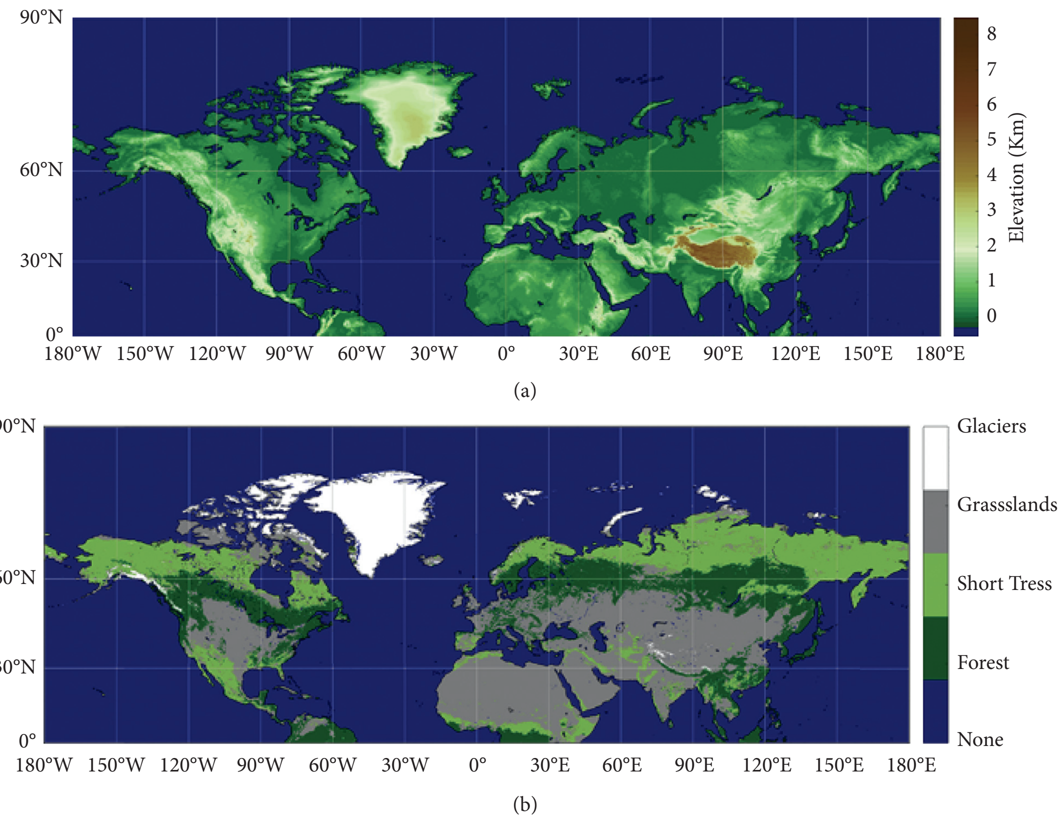


Figure 4: (a) GTOPO30 elevation and (b) MODIS land cover category (forest, short trees, and grassland classes).

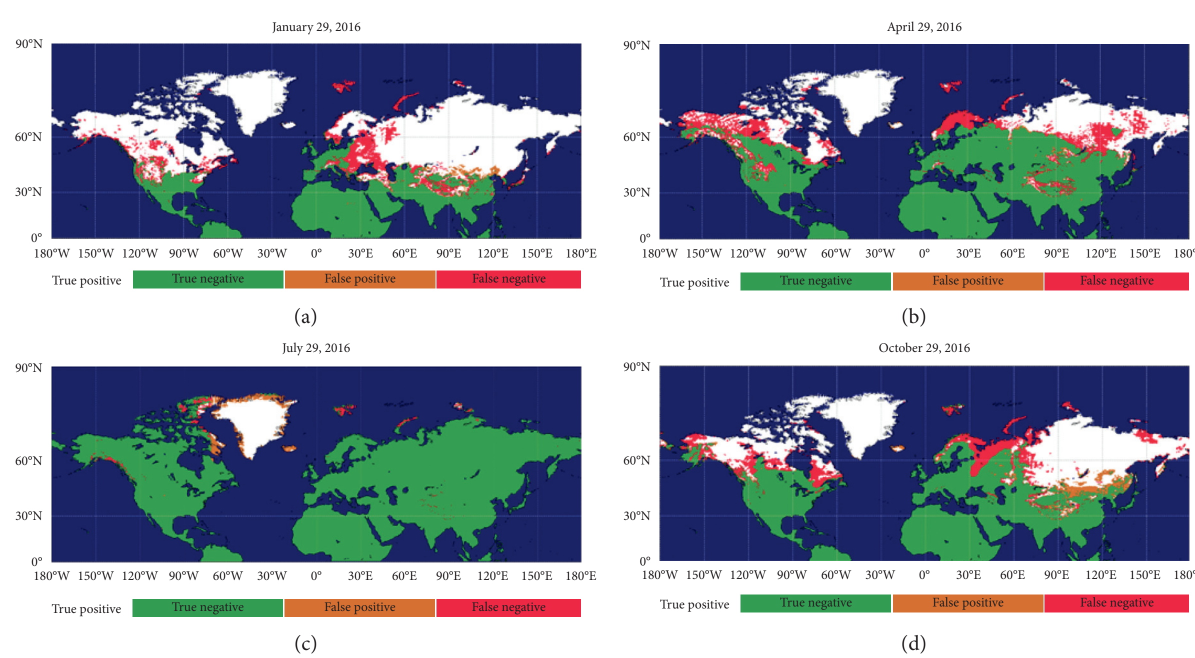


Figure 5: MIRS vs IMS maps showing the classifications of the comparison on 29th of January, April, July, and October of 2016, respectively. Red areas show where MIRS misses snow or underestimates snow cover.

further increases over spring and reaches its maximum agreement percentage of 99% over summer months. This is because during summer the likelihood of a mismatch, or false classification, is lower due to low snow cover present. Generally, MIRS shows better agreement with IMS than MSPPS during the study period.

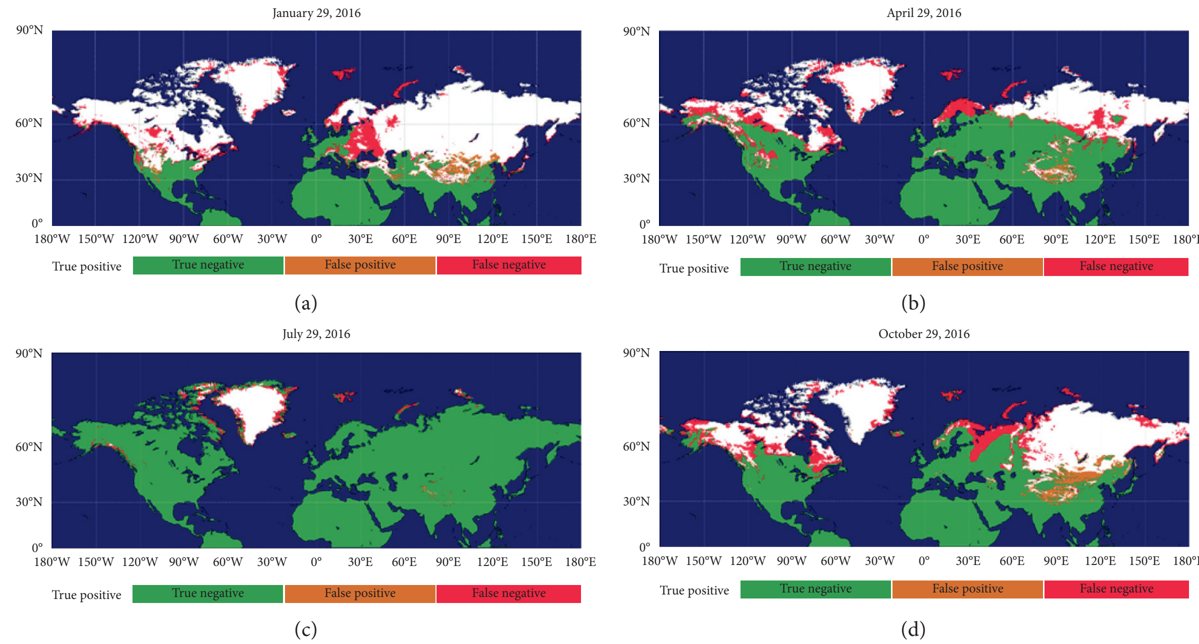


FIGURE 6: MSPPS vs IMS maps showing the classifications of the comparison on 29th of January, April, July, and October of 2016, respectively. Red color-product misses snow or underestimates snow cover.

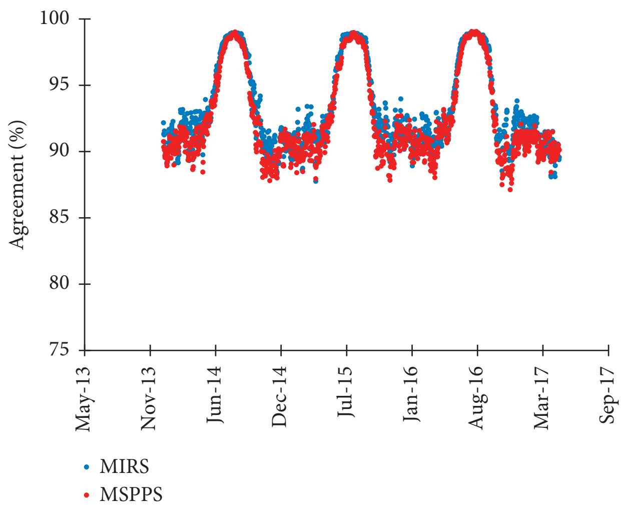


FIGURE 7: Daily rate of overall agreement for MIRS and MSPPS.

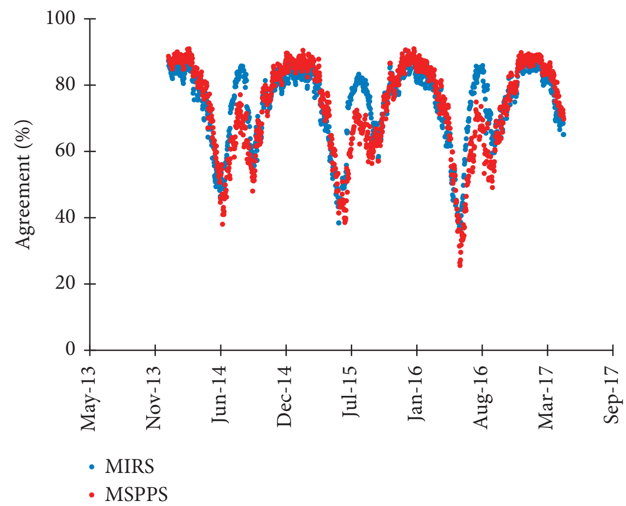


FIGURE 8: Daily rate of snow sensitivity for MIRS and MSPPS.

Nevertheless, when studying the rate of true positives divided by all positives (snow sensitivity), the agreement presents a different behavior than the previous one. Snow sensitivity ranges from 26% to 91% across the years (Figure 8). Unlike the overall agreement, this peaks during winter when there is greater accumulation and coverage. It significantly decreases during spring, when more snowmelt occurs. This corresponds to the challenges melting snow presents for microwave remote sensing. The agreement improves again over summer since less snow is present. Both products have the same seasonal patterns, but MIRS has a better rate of agreement, which is apparently due to the physical nature of the MIRS retrieval.

One important aspect in the comparison of these two products is identifying the source (s) of disagreement by finding the percentage of false negative and false positive indicators (Figure 9). In a case of a mismatch, this helps understand which type of mismatch is more likely to occur in each individual product. MIRS has a lower rate of overestimating snow cover since it has less percentage of false positive indicators. Although false negative indicators (underestimation of snow cover) are the predominant characteristic of both microwave-based products, MSPPS has a slightly lower likelihood of missing snow than MIRS.

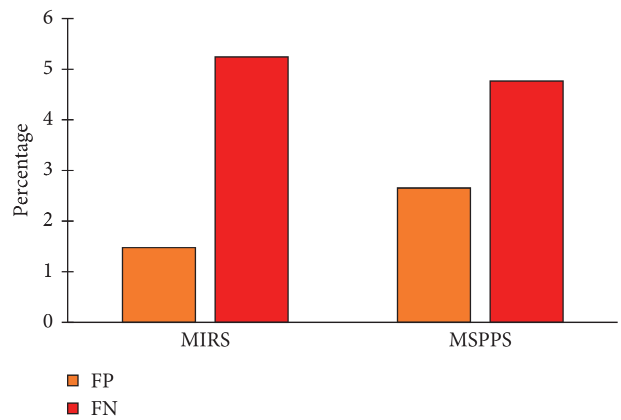


Figure 9: Percentage area of false indicators for MIRS and MSPPS. Red color shows the false negative (underestimation) percentage and orange color shows the false positive (overestimation) percentage.

Table 1: Percentage of total false classification of each land cover type.

	MIRS	MSPPS
Total F	6.72	7.42
Total F in $H > 1$ km	2.29	3.14
Total F in $H < 1$ km	4.44	4.29
Total F in Forest	1.50	1.41
Total F in Short Trees	1.19	1.08
Total F in Grassland	2.90	3.38
Other	1.13	1.56

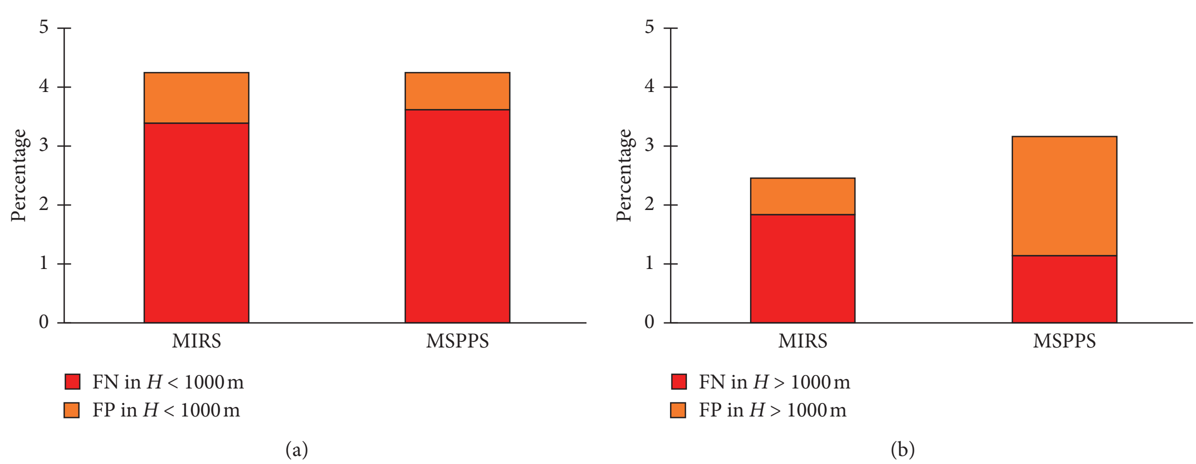


Figure 10: Percentage of false positive (FP) and negative (FN) classification present in (a) low elevation (<1000 m) and (b) high elevation (>1000 m terrain).

4.1. Effects of Terrain. Vegetation emits microwave radiation, thus increasing the surface emissivity sensed by satellite sensors. This tends to mask the signal of the underlying snow, leading to an underestimation of snow cover. The more the vegetation, the less snow cover the microwave sensors can identify [33]. Terrain also affects how snow accumulates on the ground and how wind can redistribute it. On mountainous terrain, the direction that the slope faces, time of the day, temperature, and cloud cover determines how snowpack depth evolves. In the Northern Hemisphere, south facing slopes get more solar radiation, which leads to frequent and rapid snowmelt. The upwind side of the mountain receives greater precipitation. The wind can cause a denser layer of wind deposited snow that enhances sublimation of the top layer of the snowpack and snow metamorphism. Generally, in slopes greater than 45 degrees, snow does not accumulate much. All of these processes occurring on mountainous terrain could lead to mischaracterization of snow cover.

The effects of terrain on the microwave snow cover retrieval are evaluated by determining the number of false, or mismatching, pixels of each product located above or

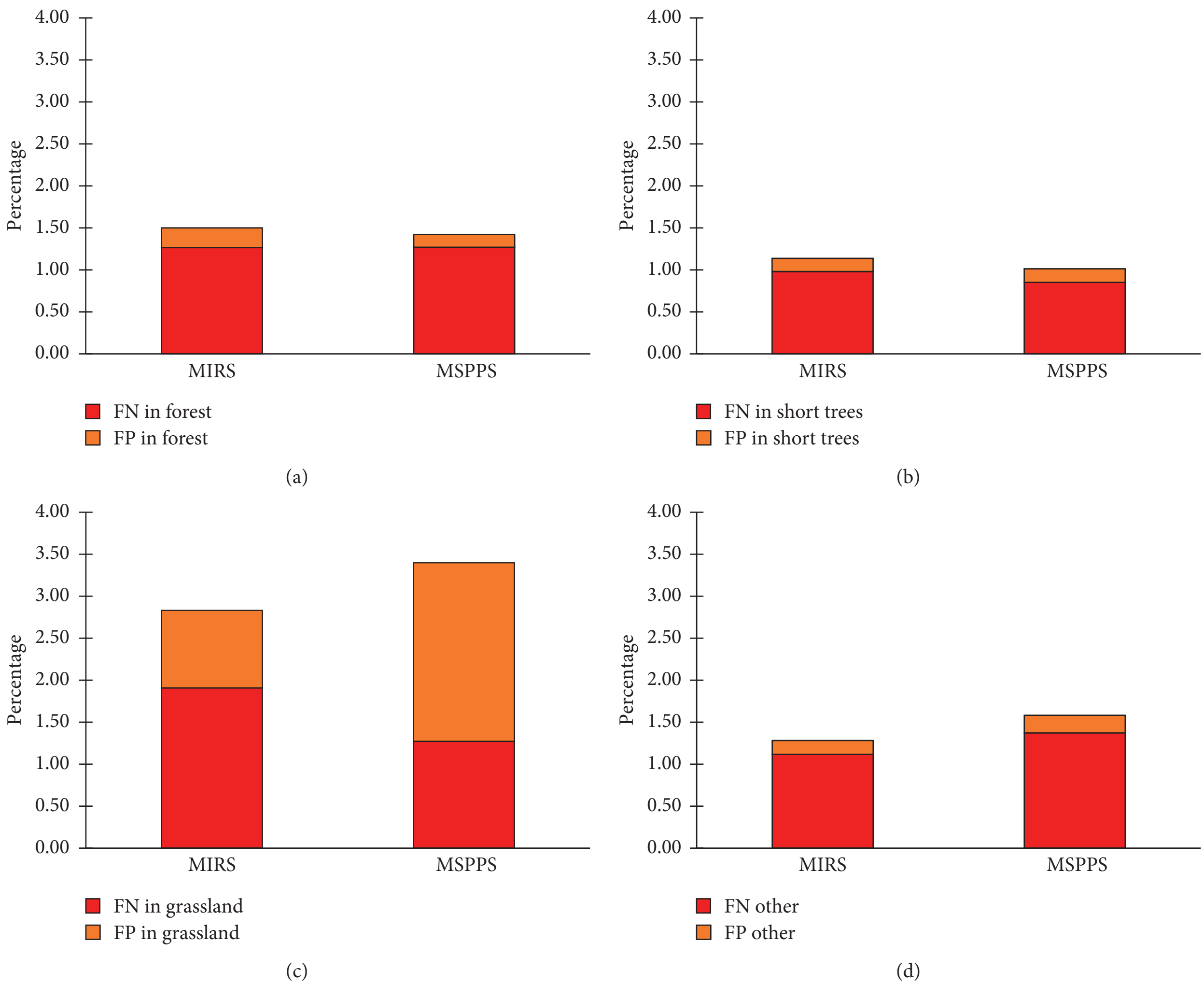


Figure 11: Percentages of false negatives (FN) and false positives (FP) by land cover type: (a) Forest, (b) Short Trees, (c) Grassland, and (d) Other.

below a determined height threshold. It is assumed that elevations greater than one km, or 1000 meters, above sea level are considered mountainous terrain. Although topography is taken into consideration in the algorithm of each product, it is still found to be associated with the mischaracterization of snow cover. As shown in Table 1, high elevation terrain, characterized by elevations greater than one km in this study, has greater impact on the MSPPS product. In high elevation terrain, or elevation greater than one km, MSPPS has 3.14% error while MIRS has 2.29% error. Thus, MIRS outperforms MSPPS over the mountainous terrain (Figure 10). MIRS tends to underestimate snow cover in high elevations; MIRS has 1.84% FN error in high elevation areas. On the other hand, MSPPS tends to overestimate snow cover in high elevations; MSPPS has 2.03% FP error in high elevation areas. In lower elevations, or less than one km, MSPPS has 4.29% error while MIRS has 4.44% error. Therefore, MIRS and MSPPS are found to act similarly in lower elevations. The majority of mischaracterization present at lower elevations is from underestimating snow. In lower elevations, MIRS has 3.4% FN error and MSPPS has 3.62% FN error.

4.2. Effects of Land Cover. Although land cover is taken into consideration in the algorithm, vegetation is still characterized as a challenge for microwave snow cover characterization. The majority of the disagreements come from underestimating snow coverage wherever there are trees in "Forest" and "Short Trees" classifications. However, in the case of "Grassland" classification, overestimating snow coverage is most likely. MSPPS has 2.14% FP error and MIRS has 0.92% FP error over Grasslands, suggesting that MSPPS has a greater likelihood of overestimating snow coverage for those areas (Figure 11). MSPPS performs better over forested and short-tree areas than MIRS; MSPPS has 1.41% and 1.02% error while MIRS has 1.51% and 1.14% error over forest and short trees, respectively (Figure 11). Pixels pertaining to the "Other" classification also have a greater percentage of underestimating snow: FN error in "Other" was 1.09% and 1.36% while the FP error in "Other" was 0.16% and 0.21% for MIRS and MSPPS, respectively. This applies especially to the MSPPS product, which has the second greatest percentage of its false identifiers over "Other."

5. Conclusion

Characterization of the agreement and sources of false classifications of MIRS and MSPPS snow cover products is useful for many purposes. The understanding of disagreement of these microwave products can help develop a technique and algorithm to combine microwave products to improve characterization of snow cover. Furthermore, estimation of snow properties through microwave band retrievals carries added value beyond what is feasible with optical and infrared sensing alone and is important to better model and plan for climate, hydrology, water management, agriculture, transportation, and recreational changes and impacts. This study shows an overall hemisphere-wide agreement with IMS of over 90% in both products, which is mostly attributed to the lack of snow cover at low latitudes and during summer months. However, the rate of snow characterization (sensitivity) varies drastically from season to season, ranging from 26% to 91%. Terrain at high elevation has a negative effect on the match of both products with IMS; it leads to an underestimation of snow cover in MIRS and overestimation of snow cover in MSPPS. Land cover type also has an impact on both products, which leads to underestimation of snow cover. However, disagreement in snow identification mainly comes from the "Grassland" type, which is less dense vegetation, with 43% and 45% of the total false identification (or 2.9% and 3.38% error) corresponding to this type for MIRS and MSPPS, respectively.

One limitation that should be taken into account when interpreting the findings of this study is that the MIRS and MSPPS classifications are compared to the IMS product and not directly to in situ snow observations, which are only available for relatively few stations. Unlike point-specific data, IMS provides continuous wide area coverage of snow cover, which aids in the comparison for our large study area of the Northern Hemisphere. Furthermore, IMS incorporates surface snow observations where these are available. Previous work has found that during the summer months, IMS is highly accurate due to the lack of snow accumulation, but accuracy is lower during the other seasons, ranging from 79 to 100% [26].

The variation of agreement for the microwave products and how terrain and land cover type affect them can be attributed to different factors. The retrieval algorithm plays a large role in this; however, the node in which the data is retrieved for analysis may also have an impact. Overnight passes are better for snow cover monitoring since there is less of a chance of snow melting, which makes snowpack harder to detect in microwave wavelengths. MIRS uses the ascending node for its results in polar projection, which are during night-time, while MSPPS uses a combination of ascending and descending nodes, which are day and night measurements. Thus, further comparison with ground-based stations to identify frozen soil, shallow snowpacks, and melting snow are needed to study how time of observation affects the microwave snow cover products.

Data Availability

Publicly available previously reported remote sensing snow cover, elevation, and land cover data were used to support this study. These prior datasets are cited at relevant places within the text.

Disclosure

The statements contained within this research article are not the opinions of the funding agency or the U. S. government, but reflect the authors' opinions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported and monitored by the National Oceanic and Atmospheric Administration–Cooperative Science Center for Earth System Sciences and Remote Sensing Technologies under the Cooperative Agreement Grant No. NA16SEC4810008. The authors would like to thank the City College of New York and NOAA Office of Education, Educational Partnership Program with Minority Serving Institutions (EPP/MSI) for full fellowship support for Jessica Chiu and Stephany Paredes-Mesa. The statements contained within the research article are not the opinions of the funding agency or the U.S. government, but reflect the author's opinions.

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