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Snow Cover Dataset by Multi-source Data Fusion Algorithm: A Case Study in the Northwestern United States

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Abstract: A comprehensive understanding of snow cover is of great significance with respect to the measurement of changes in snow cover, the development of coping strategies, the management of regional water resources under continuous climate warming, and for acquiring a better understanding of climate change at the global level. Based on the latest MODIS NDSI data, IMS snow/ice data and snow measurements at 192 SNOTEL stations, a suitable NDSI threshold for snow recognition based on the snow characteristics occurring in the Northwestern United States was established. Subsequently, various fusion rules based on data performance for different time periods were formulated. Finally, the snow cover dataset by a multi-source data fusion algorithm for the Northwestern United States region (2000–2020) was developed. A validation study indicated that the data fusion could improve the accuracy and snow recognition performance compared with the source data. The dataset included: (1) the boundary data of the test area; (2) the daily snow cover data of the test area from 2000 to 2020 (spatial resolution 500 m). In addition, the data for the verification points for snow depth were included. The formats for storage of the data were .tiff, .shp, .xlsx and .txt, and consisted of 7,688 data files with a data size of 170 GB (compressed into one file, 421 MB).

Keywords: snow cover; multisource data; daily data; 2000–2020; Northwestern United States

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The dataset supporting this paper was published and is accessible through the *Digital Journal of Global Change Data Repository* at: https://doi.org/10.3974/geodb.2022.02.08.V1 or https://cstr.escience.org.cn/CSTR:20146.11.2022.02.08.V1.

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1 Introduction

Ninety eight percent of snow cover throughout the world is distributed in the Northern Hemisphere, and the maximum snow cover on the land in winter is about 4.7% × 10^7 km^2[1], this figure accounting for 50% of the land area of the Northern Hemisphere[2]. Snow cover in the Northern Hemisphere is distributed mainly in the Arctic and high-latitude regions. Large amounts of seasonal snow cover also exist in the Alpine mountains near the Mediterranean[3], mountains in the Northwestern United States[4], Northeastern China[5], northern Xinjiang[6] and other regions[7,8]. The area of interest in the Northwestern United States ranges from 105°W–140°W, 40°N–50°N, and 600–3,100 m a.s.l., and is dominated by crops and grasslands at lower elevations, shrubs and grasslands at middle elevations, and forests at higher elevations. The snow cover in the high-altitude regions of the Northwestern United States, is dominated by the Cordillera and Rocky Mountains, and the area is one of the main sources of fresh water for Washington, Oregon, Idaho, Nevada, Utah, Wyoming, and Montana[9]. Continuous warming limits the amount of seasonal snow cover in the winter, and snow-free or mountains with less snow will become more common by the second half of this century[10]. The accumulation of snow and research on snow cover data in the Northwestern United States is of great practical significance to the management of local water resources; moreover, this topic holds great scientific significance in comparative studies of snow cover in the Tibet Plateau which is at similar latitudes.

Methods for observation and monitoring of snow include mainly ground observation and remote sensing measurements. Ground observation can yield accurate and high-precision data, while remote sensing observations can cover a larger area and obtain more comprehensive snow information[11]. Optical and microwave radiation are the most commonly used energy bands for remote sensing observation. The resolution of snow data obtained by optical remote sensing observation is relatively high, but surfaces enveloped in cloud cover cannot be observed. Microwave remote sensing can operate in all-weathers, but the spatial resolution is low[12]. Multi-source fusion of datasets has become an effective method to integrate and exploit the advantages of the various data sources to realize comprehensive and high-precision snow cover data[13–16]. The interactive multisensory snow and ice mapping system (IMS) is one of the most commonly used fusion data systems[17]. Studies have shown that the accuracy of the IMS snow/ice data in the Northwestern United States is lower than that of the MODIS (Moderate-resolution Imaging Spectroradiometer) snow cover data[18]. In the present study, we first analyze the characteristics and accuracy of MODIS and IMS in three stages based on the spatial resolution of the IMS snow/ice data; then we define a suitable NDSI threshold for snow recognition according to the snow characteristics in the Northwestern United States; and finally we formulate various fusion rules based on data performance in different time periods. Finally, the snow cover dataset provided by a multi-source data fusion algorithm was developed for a case study which targeted the Northwestern United States.

2 Metadata of the Dataset

The metadata of the Snow cover dataset by multi-source data fusion algorithm—a case study in the Northwestern United States[19] is summarized in Table 1. It includes the dataset full name, short name, authors, year of the dataset, temporal resolution, spatial resolution, data format, data size, data files, data publisher, and data sharing policy, etc.

Table 1 Metadata summary of the Snow cover dataset by multi-source data fusion algorithm—a case study in the Northwestern United States

Items	Description
Dataset full name	Snow cover dataset by multi-source data fusion algorithm—a case study in the Northwestern United States
Dataset short name	SnowCoverTest_2000-2020
Authors	Gao, Y. AFX-6602-2022, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, yanggao@itpcas.ac.cn Dong, H. W., Shandong University of Science and Technology, donghw@itpcas.ac.cn
Geographical region	The Northwestern United States
Year	2000–2020
Temporal resolution	1 day
Spatial resolution	500 m
Data formats	.tif, .shp, .xlsx, .txt
Data size	170 GB（Compressed into 1 file of 421 MB）
Data files	Boundary data of test area; binary dataset for snow; data for verification points of snow depth
Foundations	Ministry of Science and Technology of P. R. China (2017YFA0603303); National Natural Science Foundation of China (42171136)
Data publisher	Global Change Research Data Publishing & Repository, http://www.geodoi.ac.cn
Address	No. 11A, Datun Road, Chaoyang District, Beijing 100101, China
Data sharing policy	***Data*** from the Global Change Research Data Publishing & Repository includes metadata, datasets (in the *Digital Journal of Global Change Data Repository*), and publications (in the *Journal of Global Change Data & Discovery*). ***Data*** sharing policy includes: (1) ***Data*** are openly available and can be free downloaded via the Internet; (2) End users are encouraged to use ***Data*** subject to citation; (3) Users, who are by definition also value-added service providers, are welcome to redistribute ***Data*** subject to written permission from the GCdataPR Editorial Office and the issuance of a ***Data*** redistribution license; and (4) If ***Data*** are used to compile new datasets, the 'ten per cent principal' should be followed such that ***Data*** records utilized should not surpass 10% of the new dataset contents, while sources should be clearly noted in suitable places in the new dataset[7]
Communication and searchable system	DOI, CSTR, Crossref, DCI, CSCD, CNKI, SciEngine, WDS/ISC, GEOSS

3 Methods

3.1 Raw Data

The development of this dataset used remote sensing data and ground observation data. Remote sensing data included Terra/Aqua MODIS snow data and IMS snow/ice data. The MODIS/Terra snow cover 8-day L3 global 500 m sin grid dataset version 6 (MOD) during the period from January 1 2000 to December 31 2020 and the MODIS/Aqua snow cover daily L3 global 500 m sin grid dataset version 6 (MYD) from May 4 2002 to December 31 2020 were used[21,22]. Different from the values of "snow" and "no snow" in version 5, the MODIS snow cover data version 6 provide the Normalized Difference Snow Index (NDSI) and parameters which represent the quality of snow detection[23,24]. The user can define a more suitable NDSI threshold for snow recognition according to the regional snow characteristics, and thus obtain more accurate snow data. The spatial resolution of MODIS NDSI data is 500 m, and the temporal resolution is 1 day. The data acquisition time is 10:30 a.m. or 1:30 p.m. The consistency of these two data is 10% in summer and 30% in winter, up to 62%[25].

The IMS snow/ice data is a multi-source fusion dataset of snow and sea ice for the Northern Hemisphere, distributed by the National Snow Ice Data Center. The source datasets include data from NOAA's Very Low Orbit, Geostationary Operational Environment Satellites, Geostationary Meteorological Satellite, United States Department of Defense Polar Satellites Orbiters, Multi-Function Transport Satellites, and European Meteorological

Satellites. Also, the data of various radar sources from European countries, Japan, China, South Korea, Canada, the United States, and snow observations in many countries were combined[26]. The spatial resolution of IMS is 24 km, 4 km, and 1 km, during the periods from January 1 2000 to February 23 2004, from February 24 2004 to December 2 2014 and after December 2 2014, respectively. The temporal resolution of the IMS is 1 day[27].

The ground data represent the observations of snow depth during the snow years 2001–2003, 2009–2011, 2016–2018 (snow years are defined as being from September 1 to August 31 of the following year, e.g., snow year 2001 is from Sepember1 2000 to August 31 2001) at SNOTEL (snow telemetry) stations[1][28]. After discarding stations with short time or discontinuous observation, 192 stations in the Northwestern United States were chosen. These stations, located in the area of the Cordillera Mountains or the Rocky Mountains range in height from 650 m to 3,031 m. 72.4% of the stations located in the area are within 1,000–3,000 m. The stations encompassed all the key altitudes for the study area, and which were used to evaluate the fusion and improvement of the snow data in the various geographical locations. Thus, the observations at these stations can be viewed as the "true values" used to evaluate the accuracy and to verify the original remote sensing data and the improvements which result from using the fusion data.

3.2 Snow Recognition and Data Fusion

The purpose of this study is to create a new dataset with higher resolution, higher accuracy of snow recognition and less snow omission by integrating the effective information provided by the MODIS and IMS snow/ice data. The data processing consists of three parts. The first part is to define a suitable NDSI threshold according to the snow characteristics in the Northwestern United States and generate the MODIS snow cover binary dataset. The second part is the fusion of the two MODIS snow cover datasets. The information in MYD (Aqua) was used to compensate for the cloud coverage in MOD (Terra) and generate the MODIS fusion dataset MOYD (combined). In the third part, according to the data performance in the three periods, the corresponding fusion strategy was formulated and adopted to fuse the MODIS fusion data with IMS snow/ice data. Thereby, a new multi-source fusion snow cover dataset for the Northwestern United States was realized. The data processing steps are outlined in Figure 1.

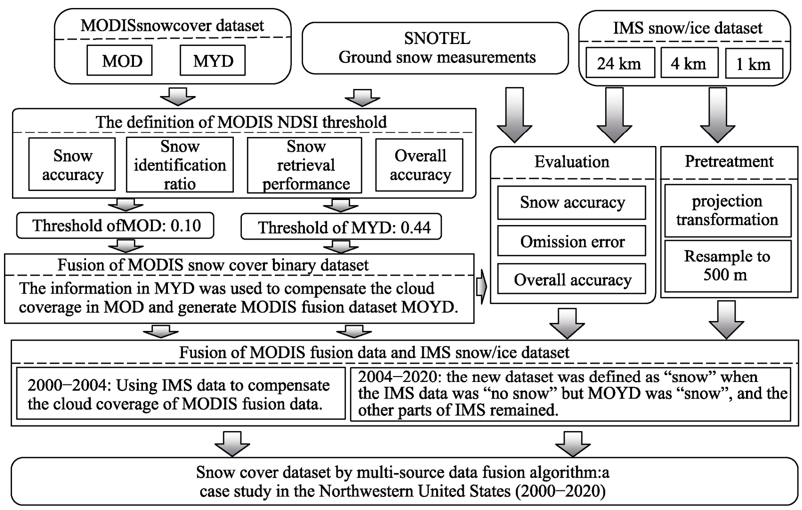

Figure 1 Flow chart for the development of the snow data

[1] https://www.nrcs.usda.gov/wps/portal/wcc/.

The "step-by-step iterative test" was used to define a suitable MODIS NDSI threshold for snow recognition. The NDSI threshold was based on carrying out 99 iterations between 0 and 1 in steps of 0.01[29]. The snow recognitions under each threshold were evaluated based on the ground observations by four indicators, i.e., the snow accuracy, the snow identification ratio, the snow retrieval performance, and the overall accuracy[6]. The snow accuracy is defined as the ratio between the number of correctly recognized snow samples and the number of snow samples identified by the remote sensing data, representing the correct snow recognition. The snow identification ratio is the ratio of the number of correctly recognized snow samples to the snow samples recorded by the ground observations; this represents the proportion of snow recognized by the remote sensing data. The snow retrieval performance is defined as the product of the snow accuracy and the snow identification ratio and is used to evaluate comprehensively the performance of data retrieval. The overall accuracy is defined as the ratio of the number of correctly classified samples to the total number of samples, and thus represents the overall accuracy for recognition in the data corresponding to "snow" and "no snow".

Verification indicated that the MOD and MYD for the Northwestern United States had the best snow retrieval performance being 78.3% and 67.9% when the NDSI threshold was 0.10 and 0.15, respectively. The snow accuracy for the MYD data was 87.1%, which was 5.5% lower than that of the MOD data which had a value of 92.6%. To ensure the highest snow accuracy for these two data fusion results, the NDSI threshold of MYD was reset as 0.44 to achieve a snow accuracy of 94.7%, a value which is comparable to that for the MOD. Therefore, 0.10 and 0.44 were set as the NDSI thresholds for MOD and MYD in the Northwestern United States, respectively. When the NDSI was greater than or equal to this value, the grid was recognized as "snow", and when the NDSI was less than this value, it was recognized as "no snow". In the multi-data fusion, the MOD dataset was given the highest priority. The MYD dataset served to compensate for cloud coverage in the MOD and generate the MODIS fusion dataset MOYD.

The IMS snow/ice data has three different spatial resolution settings, that is, 24, 4, and 1 km, respectively. For data with different spatial resolutions, the data from September 1 2000 to August 31 2003, September 1 2008 to August 31 2011, and September 1 2015 to August 31 2018 were selected. Three indicators, namely, the snow accuracy, the omission error and the overall accuracy were used to evaluate the MODIS and the IMS dataset. The snow accuracy and overall accuracy were defined as previously mentioned above. The omission error is the ratio of the number of samples that misjudged "snow" as "no snow" based on remote sensing retrieval versus the number of snow samples verified by ground observations, thus giving a measure of the snow missed by remote sensing observation. The results indicated that in the first stage when the spatial resolution of IMS was 24 km, the snow accuracy of IMS was slightly lower than that of the MODIS fusion dataset, and the omission error was higher. Thus, the MODIS fusion dataset should have the highest priority in the next fusion. The data fusion rule was defined as using the IMS data to compensate for the cloud coverage of the MODIS fusion data. In the second stage, when the spatial resolution of the IMS was 4 km, the snow accuracy of the IMS was higher than that of MODIS fusion dataset, but the omission error was still higher. Therefore, the data fusion rule was that the new dataset was defined as "snow" when the IMS data was "no snow" but MOYD was "snow", and the other parts of the IMS remained. In the third stage when the spatial resolution of the IMS was 1 km, the snow accuracy of the IMS was higher than that of the MODIS fusion data, and the omission error was lower than that of the MODIS. However, the overall accuracy of the IMS was lower, and a higher level of snow omission still existed.

To further reduce the snow omission, the data fusion rule was adjusted to be the same as that in the second stage.

4 Data Results and Validation

4.1 Data Products

The dataset consists of 7,688 files and covers the period from January 1 2000 to December 31 2020. The time resolution is on a daily basis and the spatial resolution is 500 m. The data file format is .tif. The grid consists of snow binary data, where one represents "snow" and zero represents "no snow". The data size was 170 GB and was compressed into 1 file of 421 MB.

4.2 Data Results

The snow cover in the Northwestern United States exhibited different distribution characteristics for the various regions (Figure 2). For example, the western coastal areas were almost snow free. In the Cordillera Mountains near 122°W, snow cover increased with increase of altitude, and the number of snow cover days over 2,000 m on an annual basis was more than 120 days. Perennial snow cover existed in the areas above 3,000 m, where the number of snow cover days (annual basis) was more than 330. Most areas of the Rocky Mountains above 1,500 m, in the location 115°W to 105°W, had more than 180 days of snow cover (annual basis). The lower elevations between the two mountainous regions had fewer numbers of snow cover days, typically being less than 60 (annual basis).

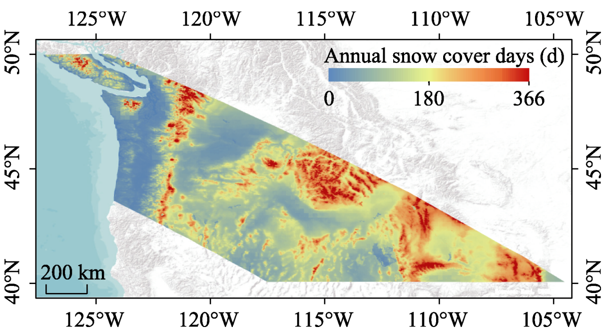

Figure 2 Average annual snow cover days for the Northwestern United States

The annual variation of snow cover for the Northwestern United States is presented in Figure 3. From September there were 1–2 days with sporadic snow in the high-altitude regions. In October, the snow cover days at high altitude increased to 6–10. In November, a large area experienced snow cover, the number of days being 6–10. In December, more areas were covered with snow, and the duration of snow cover in the high-altitude regions increased to more than 20 days. In January and February, most areas higher than 1,000 m were covered continually with snow. In March, the snow at low altitude (< 1,000 m) melted first, and in April, the snow at mid-altitude (1,000–2,000 m) melted. In May, the snow in other areas had melted except for some regions above 2,000 m. After June, the snow had disappeared except for small amounts of snow on the top of the northern Cordillera Mountains. The Cordillera Mountains are a north-south mountain range. The data for snow in November and May indicated that snow cover started earlier and ended later in the northern part of the Cordillera Mountains. In addition, snow cover in the Rocky Mountains, which is far from the Pacific Ocean, started earlier and ended later than expected based on comparisons of the snow cover variations for other regions at a similar latitude and altitude.

From 2000 to 2020, the snow cover days (monthly basis) revealed a decreasing trend at the different altitudes as illustrated in Figure 4. The snow cover days on a monthly basis was defined as the average snow cover days in one month per square kilometer in the region of interest (d·km^{-2}). Based on altitude, the study area was divided into four regions: <1,000 m, 1,000–2,000 m, 2,000–3,000 m and >3,000 m, which corresponds to areas of 1.6 × 10^5 km^2,

2.8×10^5 km^2, 1.0×10^5 km^2 and 0.6×10^5 km^2, respectively. Irrespective of the altitude, the seasonal fluctuations in the number of snow cover days (monthly basis) for the

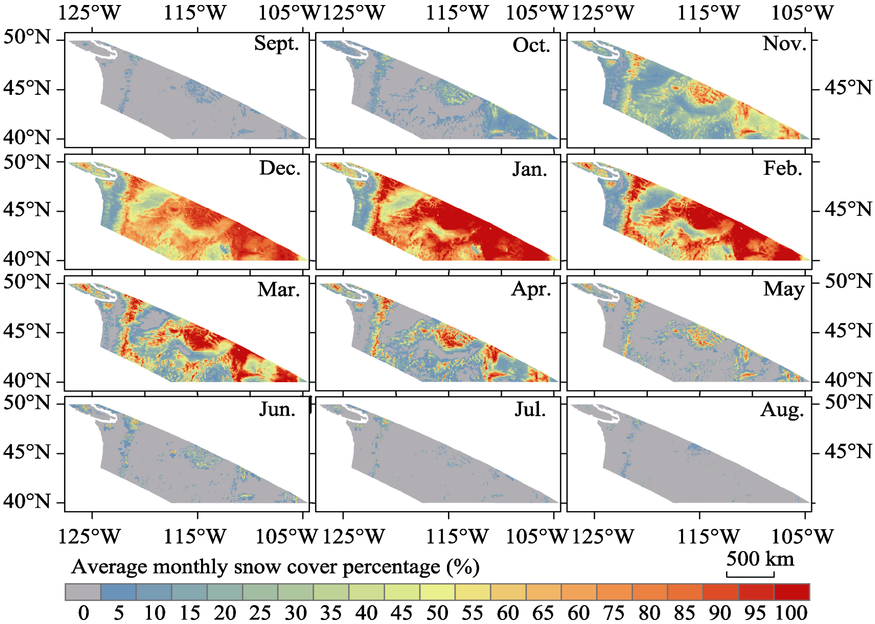

Figure 3 Average monthly snow cover percentage for the Northwestern United States

Northwestern United States is quite clear; that is, there is almost no snow from June to September, and some snow from December to March. The number of snow cover days generally reached a peak in January being 41.3, 86.1, 110.3 and 110.8 d·km^{-2} for the four regions, respectively. The inter-annual fluctuations were particularly clear for the region <1,000 m, and less for the region > 2,000 m except in 2019 and 2020.

The trends for the number of snow cover days (monthly basis) in the four regions during the period from 2000 to 2020 were –0.45, –0.73, –0.74 and –0.54 d·km^{-2}·y^{-1}, respectively. These decreasing trends were clearly affected by the low number of snow cover days in 2019 and 2020. Therefore, the snow changes during the period from 2000 to 2018 were recalculated in order to better represent the snow fluctuations over a long-time series. The results showed that the trends for the number of snow cover days (monthly basis) in the four regions were –0.29, –0.30, –0.04 and 0.66 d·km^{-2}·y^{-1}, respectively. During these 19 years, the number of

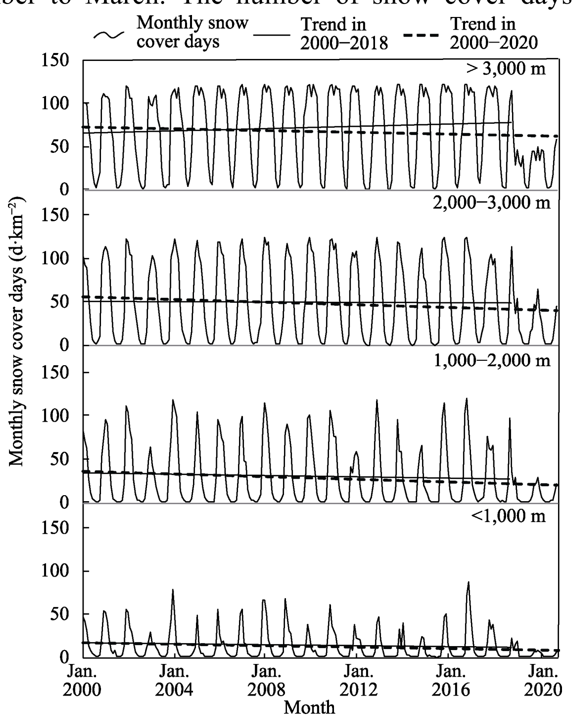

Figure 4 Variation of monthly snow cover days at different altitudes for the Northwestern United States during the period 2000 to 2020

snow cover days (monthly basis) decreased by 5.5, 5.7 and 0.7 d·km^{-2} in the region <1,000 m, 1,000–2,000 m, and 2,000–3,000 m, respectively, while it increased by 12.5 d·km^{-2} in the region >3,000 m. It can be seen that since the start of this century, snow cover in areas less than 2,000 m in the Northwestern United States has exhibited a decreasing trend, snow cover in the area 2,000–3,000 m basically has remained unchanged, while the snow cover in the area >3,000 m has clearly shown an increasing trend.

4.3 Data Validation

The accuracy of MODIS, the IMS snow data and the two fusion snow datasets were evaluated based on the ground observations at 192 SNOTEL stations. It was found that all the data exhibited a high level of accuracy for snow recognition (above 90%), whether it was the original data or the fusion data (Figure 5). The first MODIS data fusion aimed to remove the effect of cloud cover and increase the area of study. Compared with the raw MOD, the accuracy of the fusion data decreased slightly by 0.4%–0.5%, however, the extent of cloud cover decreased substantially. The cloud cover on a monthly basis decreased by 6.7% (2.7–9.1%), and the maximum daily decrease in cloud cover could reach 57.8%. The omission error for the MOYD fusion data was still lower than that of the IMS snow/ice data. All of these findings indicated that the fusion of the two MODIS datasets can effectively reduce the impact of cloud cover, and this method was confirmed to be feasible and efficient for the Northwestern United States.

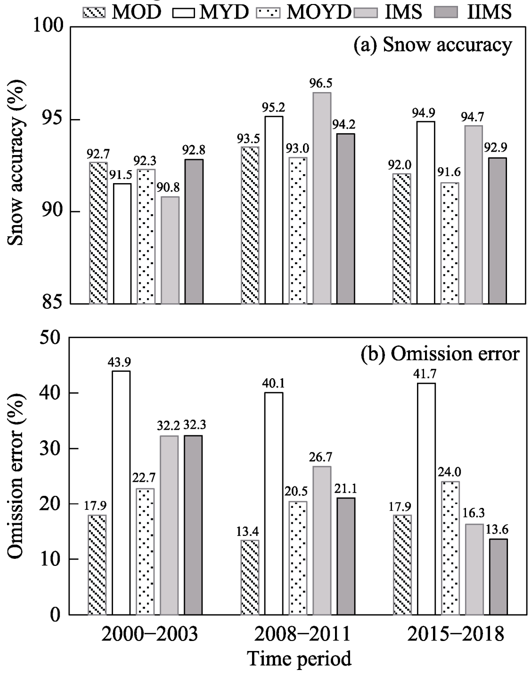

Figure 5 Evaluation of accuracy and verification of the results of MODIS. IMS raw data and the fusion datasets: (a) snow accuracy; (b) omission error

The purpose of the fusion of the MOYD and IMS was to improve the spatial resolution and reduce the snow omission errors. Two strategies were adopted for the data fusion in the different time periods. The data fusion of 2000–2004 firstly improved the IMS spatial resolution from 24 km to 500 m, which resulted in an improvement in the accuracy by 2.0%. The data fusion of 2004–2020 also at first increased the IMS spatial resolution from 4 km or 1 km to 500 m. Also, the snow omission error decreased significantly, i.e., by 5.6% and 2.7%, although the snow accuracy decreased by 2.3% and 1.8%. The snow accuracies were still at a high level, 94.2% and 92.9%, respectively. The above verifications showed that the second fusion of MODIS and IMS not only effectively improved the spatial resolution, but also maintained high snow accuracies and reduced the omission errors to some extent. The comprehensive performance of the new multi-source fusion snow cover dataset resulted in improvements compared with the source datasets.

5 Discussion and Summary

Snow cover is an important element of the global climate system, and affects the surface energy budget, regulates temperature, promotes atmospheric teleconnection, and controls the hydrology system. A comprehensive understanding of snow cover is of great significance to the measurement of changes in snow cover and the associated coping strategies, the management of regional water resources under continuous warming, and for obtaining a deeper understanding of global climate change. Based on the latest MODIS NDSI data, and the IMS snow\ice data, this study formulated various fusion rules based on the snow recognition performance for each dataset in the different periods, and this led to a snow cover dataset based on the use of a multi-source data fusion algorithm being developed; the algorithm was then successfully applied to a case study of the Northwestern United States for the period 2000–2020.

The daily snow measurements at 192 SNOTEL stations were used in accuracy and verification studies. The stations were distributed in 4 altitude ranges within the study area, and the observations of snow cover were shown to represent the snow characteristics of the study area. Data evaluation and verification indicated that use of the multi-source fusion snow cover dataset resulted in a higher snow accuracy, a lower snow omission error, and with a spatial resolution of 500 m. Moreover, the improved dataset can fully reflect the spatial differences, and the inter-annual and intra annual variations of snow cover in the Northwestern United States. The analysis of the snow cover days on a monthly basis for the period 2000 to 2018 revealed various change trends for different regions, i.e., a decrease of snow cover in the area less than 2,000 m, an unchanged level of snow cover between 2,000 and 3,000 m, and an increasing level of snow cover at altitudes greater than 3,000 m.

In conclusion, the approach featuring the MODIS and IMS datasets provided a long-time series of snow cover and were used to study the spatial-temporal distribution and variation of snow cover in the area. Multi-source dataset fusion has been shown to be one of the most effective methods for improving comprehensively the performance of snow cover data. This study should provide a foundation for further research on long-time series snow cover datasets at the global level.

Author Contributions

Gao, Y. made the overall design for the dataset development and modified the data paper. Dong, H. W. processed MODIS and IMS datasets and verified these datasets. All authors wrote this data paper.

Conflicts of Interest

The authors declare no conflicts of interest.

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