Extracting Time-Series of Wet-Snow Facies in Greenland Using Sentinel-1 SAR Data on Google Earth Engine

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Abstract—Accurate information on the dynamic change of wet-snow facies (WSF) in Greenland is important in investigating the mass balance of Greenland ice sheets and assessing global sea level rise. In this study, we proposed a rapid WSF extraction algorithm, referred to as difference method, for extracting WSF at a continental scale and with high spatial resolution using the Sentinel-1 synthetic aperture radar (SAR) data available on Google Earth Engine. We used this method to extract the WSF in Greenland from May to October in recent 6 years. Accuracy of the extracted results was evaluated using air temperature data from Greenland automatic weather station. Results suggested that the difference method has good precision in extracting WSF from Sentinel-1 SAR data, and can process a large amount of data simply, quickly, and effectively.

Index Terms—Big data, Google Earth Engine (GEE), Greenland, synthetic aperture radar (SAR), wet-snow facies (WSF).

I. INTRODUCTION

Nmeteorological, climatological and global change research, long-term monitoring of snow cover is a key topic of great importance [1]. Greenland ice sheets (GrIS) continuously loses mass at a high rate, research showed that the mass loss of the GrIS has accelerated due to increases in both ice discharge and surface meltwater runoff [2]. Surface melting is extensive on the GrIS, and spatial variation in the effects of this melting [3] enabled us to divide the snow pack of the GrIS into distinct diagenetic facies, or zones [4], such as dry-snow facies, percolation facies, wet-snow facies (WSF), ice facies, etc. Wet snow is an import indicator of snow melting in an area [5], accurate acquisition of time-series of WSF information is crucial in investigating the uncertainty of GrIS mass balance and assessing global sea level change [6], [7].

Using variations in C-band synthetic aperture radar (SAR) image intensity to map zones of dry snow, percolation, wet snow, and bare ice [4], extending the early facies work of Benson [3] into the satellite era [8]. A large number of GrIS surface melting monitoring methods were developed by using active microwave data [9]–[11], passive microwave data [7], [12], [13], and scatterometer data [10], [14], [15] in subsequent studies. However, these methods are difficult to satisfy the requirements of large scale, high spatial resolution, and time series at the same time. Now, more recent developments in SAR technology have enabled access to ultra-wide, high-resolution data at a continental scale [16]. For example, Sentinel-1 A/B series SAR satellites of the European Space Agency have an extra-wide swath (EW) of 410 km and a spatial resolution of 20 m × 40 m. The satellites can collect thousands of images in a single month and cover most of the WSF of the Greenland multiple times. Sentinel-1 images of the Greenland collected over a span of several years constitute a massive dataset. However, there are few studies on WSF of Greenland with time series, large scale, and high spatial resolution using this dataset due to the limitations of storage, sharing, and processing resources of big data. Google Earth Engine (GEE) is a cloud-based platform that makes it easy to access high-performance computing resources for processing very large geospatial datasets [17], providing an efficient path for WSF extraction with large area, time-series, and high resolution.

A rapid extraction method of WSF—“difference method” was proposed in this study, to generate a time-series of WSF maps in Greenland of recent 6 years using Sentinel-1 SAR data on GEE. This article is outlined as follows. The “difference method” process procedure and the method of accuracy evaluation were described in Section II. The WSF extraction results, and accuracy evaluation were presented in Section III. In Section IV, The advantage and limitations of WSF extraction over Greenland using the Sentinel-1 SAR data were described. Lastly, Section V gives the conclusions of this article.

II. METHODS

GEE has ground range detection (GRD) product that was processed using Sentinel-1 Toolbox. The data for each scene were processed through thermal noise removal, radiometric calibration, terrain correction using SRTM and mostly in ASTER...
DEM, and conversion of intensity to decibel units (dB) [5]. The Sentinel-1 A/B GRD product in descending and ascending modes, HH copolarization, repeat pass images acquired in EW mode from 2015 to 2020 were selected to extract Greenland WSF on GEE in this study. The spatial resolution of the images is $20 \times 40$ m, and the width is 410 km. Sentinel-1 data do not cover the entire Greenland, however, such as ice sheets in the center of inland, where also experience snowmelt in major melt events. The technical route of WSF extraction in Greenland is shown in Fig. 1.

A. Data Preprocessing

Gamma map filter [18] was applied to remove speckle noise from Sentinel-1 SAR images on GEE. Sentinel-1 images have invalid edges with different distances that may extend up to tens of kilometer wide, and usually appear on one side of the image [16]. Pixels with backscattering coefficient less than $-10$ dB in the area 10 km from the edge of the image were masked on GEE to avoid the influence of invalid black edge on the extraction of WSF.

B. Extraction Method of WSF

The backscattering echo received by Sentinel-1 radar antenna is the result of surface scattering and volume scattering from different ground objects. Dry-snow facies, WSF, percolation facies, and ice facies in Benson’s original glacier facies designations [3] were considered in this study.

Dry-snow facies is present at high altitudes in Greenland, where snow is gradually compacted by its own weight or deformed under the influence of wind [19]. There is no surface melting in these regions except for major melt events. The grain-size of dry fresh snow is smaller compared to the wavelength of C-band SAR and has a low backscattering coefficient in SAR images [20].

Below the dry-snow facies (at lower elevations) is a region with the brightest returns from the ice sheet. This region is the percolation facies, where surface meltwater percolates downward, occasionally spreading out into layers [20]. The ice lenses and pipes in percolation facies can have dimensions comparable to the wavelength of the SAR and can produce high radar returns [19]. This results in intense scattering and a high backscattering coefficient in SAR imagery [Fig. 2(a)]. There would be a smooth gradation of backscatter from the dry-snow facies to the percolation facies, rather than a sharp boundary [20].

Below the percolation facies is a narrow zone: the WSF. Here, the snow has reached the melting point as a result of latent heat released by extensive refreezing of meltwater [20]. The backscatter from the WSF was much more strongly varying than from the percolation facies [19]. During the ablation season, the WSF will reduce markedly in backscatter intensity. Therefore, WSFs can be identified by comparing the change of backscattering coefficient of SAR images between summer and winter.

Ice facies is mainly distributed at low altitudes, and the ice surface is covered with dry snow in winter. Bare smooth ice will be exposed after surface snow melts away in summer [19]. Therefore, the backscattering coefficient of ice surface both in winter and summer is low [Fig. 2(a) and (b)].

The SAR image of winter 2019 (January 14) [Fig. 2(b)] was selected as a reference image, Fig. 2(c) shows the difference image between SAR image from summer 2019 (July 25) [Fig. 2(a)] and the reference image. We can see that WSF has significant difference in texture from other glacier facies in the difference image.

Combined with the characteristics of the four different glacier facies discussed earlier, samples were selected for the statistics of backscattering coefficients. Fig. 3(a) and (b) showed the histograms of backscattering coefficients of the four glacier facies in the SAR image in summer and difference image, respectively. The backscattering coefficients of the dry-snow facies, WSF, and ice facies in summer SAR image showed little difference. For instance, the backscattering coefficients of the WSF are mainly distributed between $-28$ and $-7$ dB in the difference image, while those of non-WSF are mainly distributed...
between $-7$ and $15$ dB. Therefore, a threshold of $-7$ dB is appropriate to differentiate WSF from non-WSF. Fig. 2(d) shows the binary classified image using the threshold for the extraction of WSF.

C. Monthly WSF Extraction

All Sentinel-1 SAR images covering Greenland were divided into reference images (January and February) and snow-melting images (May–October). The median composite results of all January and February images were used as reference image. Such processing ensures that there are enough data to form a winter reference image. Even if temperature anomalies occur between January and February, the median filter can filter them out to ensure the validity of the winter reference image. The monthly minimum value of the snow-melting images is synthesized because WSF in SAR images has a low backscattering coefficient. Monthly variation of the WSF in Greenland

Fig. 2. Characteristics of different glacier facies in Sentinel-1 EW HH polarization SAR images. (a) SAR image from summer 2019 (July 25). (b) SAR image of winter 2019 (January 14). (c) Image of the difference between summer and winter 2019. (d) WSF extracted from (c).

Fig. 3. Statistics of backscattering coefficients of four glacier facies (a) before and (b) after difference treatment.
from May–October was then obtained by using the “difference method.” Finally, the extracted results were processed by mosaicking, median filtering, and masking. These processes were carried out for images acquired by the same satellites (Sentinel-1 A and Sentinel-1 B) in order to reduce the influence of SAR observation geometry and terrain fluctuations in the extraction of WSF. Given that the descending data covering the GrIS are much less than the ascending data, they were not processed separately in this study.

D. Precision Assessment

The programme for monitoring of the Greenland ice sheet (PROMICE) has been measuring Greenland’s climate and ice sheet properties since 2007. Currently, the PROMICE automatic weather station (AWS) network includes 25 instrumented sites in Greenland [21]. However, most of the stations in this network are generally located near the ice sheet margins where bare land conditions around some sites may affect the verification of the extracted WSF using the AWS data. Therefore, we screened 6 PROMICE AWS products processed by [21] as an in-situ metric of melting conditions. The locations of the stations are shown in Fig. 4. The daily maximum temperature data were used to determine whether a snow melting event has occurred in the pixel where AWS is located: as long as the maximum temperature is greater than 0 °C on any day in a month, a snow melting event is considered to have occurred in that month; otherwise, no snow melting event. Based on the confusion matrix (Table I), (1) was used to calculate the accuracy of WSF extraction using SAR and PMW data, respectively.

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\text{Accuracy} = \frac{(TP + TN)}{(TP + TN + FP + FN)}.
\] (1)

III. Result and Analysis

A. Extracted Time-Series of WSF in Greenland

The extracted WSF in Greenland based on SAR data using the “difference method” (Fig. 5) show that WSF mainly occurred in May to October every year, they occurred earlier in southern Greenland than northern Greenland, and earlier at the margin zones than central Greenland. The WSF in May was mainly distributed in the southern periphery of the GrIS. In June, a large portion of WSF appeared outside the GrIS. The area of WSF in southern Greenland in June 2019 was much larger than the other years. The largest area of WSF occurred in July, with a large abnormal snow melting event in northern GrIS in July 2015. The July snowmelt in 2018–2020 covered almost the entire southern Greenland. The area of WSF showed a decreasing trend from July to October, and the decreasing rate was higher in the west than in the east. Only a few area of WSF were distributed along the periphery of Greenland in October.

B. Accuracy Evaluation Results

The accuracies of WSF extraction obtained by the “difference method” validated using the AWS temperature in Greenland are showed in Table II. For instance, the overall accuracy of WSF extraction obtained by the “difference method” is 88.57%, the lowest accuracy is 80.00% occurred at the KAN_M site, and the highest accuracy is 97.14% occurred at the KPC_U site. The results suggested that the extraction results of WSF have high reliability.

IV. Discussion

The difference method performed very well to generate WSF maps in Greenland. This method can process a large amount of data simply, quickly, and effectively. It can supplement and extend other algorithms for snowmelt monitoring. The sentinel-1 SAR sensor with high stability provided EW data of large width and high resolution that effectively improved the quality of the WSF maps in Greenland. The application of the gamma map filter reduced speckle uncertainty of SAR data. WSF extraction using SAR data of the same satellite can effectively reduce the
Fig. 5. WSF extracted from the Sentinel-1 SAR data during 2015–2020.
The WSF could be affected by major melt events. For instance, an abnormal atmospheric ridge (high-pressure ridge) concentrated over the Arctic Ocean in July 2015 was the main reason for a large surface runoff and high land surface temperature moving northward in Greenland [22]. This high-pressure ridge may also be the main cause of the large area of WSF in northern Greenland (Fig. 5). GrIS experienced an unusually intense snow melting event in late July 2019, with widespread snowmelt covering central Greenland [23]. However, this event did not show up in the WSF maps we extracted. The major melt event of 2019 produced large area of WSF in the middle of GrIS, but was not observed due to the insufficient Sentinel-1 SAR data coverage over the central Greenland region.

The availability of the Sentinel-1 SAR data over Greenland depends on locations. The number of SAR images along the periphery was greater than that over the central Greenland, over the north was much larger than over the south. For instance, there were more than 30 scenes per month over the north and periphery of Greenland, while over the central Greenland, there were fewer than 10 scenes per month (Fig. 6). Thus, the uncertainty caused by insufficient data over central Greenland makes it possible to underestimate the extent of the WSF extracted in this study, especially during major melt event. Combining Sentinel-1 SAR data with other data sources of high-frequency coverage over central Greenland may overcome this difficulty.

V. CONCLUSION

In this study, we proposed to use the “difference method” to rapidly extract time-series of WSF in Greenland, making full use of the sentinel-1 SAR data covering Greenland on GEE. The median composite image of SAR data in winter (January and February) was taken as the reference image, and the monthly minimum synthetic images of SAR data from May to October were taken as snow-melting images. The difference between each snow image and the reference images was then taken. Lastly, we used uniform thresholds to produce monthly WSF maps over Greenland.

The spatiotemporal distribution of the WSF in Greenland was not uniform. Snow melting mainly occurred from May to October, and the maximum extent of WSF occurred in July. Melting occurred earlier in the south than in the north, and earlier over the periphery than over central Greenland.

The allover accuracy of the WSF extracted by the “difference method” from the Sentinel-1 SAR data as verified by the AWS temperature data is 88.57%. WSF extraction results may be affected by the insufficient Sentinel-1 SAR data coverage over the central Greenland region, the southern of GrIS is more affected than the northern part, and the central part is more affected than the ice sheet edge.

REFERENCES

[1] J. Pan, L. Jiang, and L. Zhang, “Wet snow detection in the south of China by passive microwave remote sensing,” in Proc. IEEE Int. Geosci. Remote Sens. Symp., 2012, pp. 4863–4866.
[2] D. K. Hall, J. C. Comiso, N. E. Digirolamo, C. A. Shuman, J. E. Box, and L. S. Koenig, “Variability in the surface temperature and melt extent of the Greenland ice sheet from MODIS,” Geophys. Res. Lett., vol. 40, no. 10, pp. 2114–2120, 2013.
[3] C. S. Benson, “Stratigraphic studies in the snow and firn of the Greenland ice sheet,” Ph.D. dissertation, Cold Regions Res. Eng. Lab, Hanover, NH, USA, 1962.
[4] F. Mark, B. Robert, K. Ron, and J. Ken, “Greenland ice sheet surface properties and ice dynamics from ERS-1 SAR imagery,” Science, vol. 262, no. 5139, pp. 1530–1534, Dec. 1993.
[5] F. Irshad, J. Malik, and R. M. Z. Khalil, “Mapping wet snow using SAR C-band through Google Earth Engine,” in Proc. 6th Int. Conf. Aerosp. Sci. Eng., 2019, pp. 1–5.
[6] F. Gillet-Chaulet et al., “Greenland ice sheet contribution to sea-level rise from a new-generation ice-sheet model,” Cryosphere, vol. 6, no. 6, pp. 1561–1576, Dec. 2012.
[7] D. Houtz, C. Mätzler, R. Naderpour, M. Schwank, and K. Steffen, “Quantifying surface melt and liquid water on the Greenland ice sheet using L-band radiometry,” Remote Sens. Environ., vol. 256, Apr. 2021, Art. no. 112341.
[8] M. G. Cooper and L. C. Smith, “Satellite remote sensing of the Greenland ice sheet ablation zone: A review,” Remote Sens., vol. 11, no. 20, pp. 10–13, 2019.

[9] K. C. Jezeck, P. Gegineni, and M. Shanableh, “Radar measurements of melt zones on the Greenland ice sheet,” Geophys. Res. Lett., vol. 21, no. 1, pp. 33–36, Jan. 1994.

[10] I. S. Ashcraft and D. G. Long, “Comparison of methods for melt detection over Greenland using active and passive microwave measurements,” Int. J. Remote Sens., vol. 27, no. 12, pp. 2469–2488, Jun. 2006.

[11] A. Johnson, M. Fahnestock, and R. Hock, “Evaluation of passive microwave melt detection methods on Antarctic Peninsula ice shelves using time series of sentinel-1 SAR,” Remote Sens. Environ., vol. 250, Dec. 2020, Art. no. 112044.

[12] W. Abdalati and K. Steffen, “Passive microwave-derived snow melt regions on the Greenland ice sheet,” Geophys. Res. Lett., vol. 22, no. 7, pp. 787–790, Apr. 1995.

[13] X. Fettweis, M. Tedesco, M. van den Broeke, and J. Ettema, “Melt zones on the Greenland ice sheet (1958–2009) from spaceborne microwave data and regional climate models,” Cryosph., vol. 5, no. 2, pp. 359–375, May 2011.

[14] S. V. Nghiem, K. Steffen, R. Kwok, and W. Y. Tsai, “Detection of snowmelt over the Greenland ice sheet using diurnal backscatter change,” J. Glaciol., vol. 47, no. 159, pp. 539–547, 2001.

[15] L. Zheng, C. Zhou, and K. Wang, “Enhanced winter snowmelt in the Antarctic Peninsula: Automatic snowmelt identification from radar scatterometer,” Remote Sens. Environ., vol. 246, 2020, Art. no. 118835.

[16] D. Liang, H. Guo, L. Zhang, Y. Cheng, Q. Zha, and X. Liu, “Time-series snowmelt detection over the Antarctic using Sentinel-1 SAR images on Google Earth Engine,” Remote Sens. Environ., vol. 256, Apr. 2021, Art. no. 112318.

[17] N. Gorelick, M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau, and R. Moore, “Google Earth Engine: Planetary-scale geospatial analysis for everyone,” Remote Sens. Environ., vol. 202, pp. 18–27, 2017.

[18] A. Baraldi and F. Parmiggiani, “A refined gamma MAP SAR speckle filter with improved geometrical adaptivity,” IEEE Trans. Geosci. Remote Sens., vol. 33, no. 5, pp. 1245–1257, Sep. 1995.

[19] K. C. Partington, “Discrimination of glacier facies using multi-temporal SAR data,” J. Glaciol., vol. 44, no. 146, pp. 42–53, 1998.

[20] M. Fahnestock, R. Bindschadler, R. Kwok, and K. Jezeck, “Greenland Ice sheet surface properties and ice dynamics from ERS-1 SAR imagery,” Science, vol. 262, no. 5139, pp. 1530–1534, 1993.

[21] R. S. Fausto et al., “Programme for monitoring of the Greenland ice sheet (PROMICE) automatic weather station data,” Earth Syst. Sci. Data, vol. 13, no. 8, pp. 3819–3845, 2021.

[22] M. Tedesco et al., “Arctic cut-off high drives the poleward shift of a new Greenland melting record,” Nature Commun., vol. 7, no. 1, Jun. 2016, Art. no. 11723.

[23] S. Mousavi et al., “Melt detection over Greenland using SMAP radiometer observations,” in Proc. IEEE Int. Geosci. Remote Sens. Symp., 2020, pp. 2972–2974.

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