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Spatio-temporal changes of snowmelt in Greenland ice sheet based on SSM/I (SSMIS) data (1988-2016)

X D Wang [a,b], K Zhang*[,a,b], D H Shangguan[c] & Y H Wang[a,b]

[a]Key Laboratory of Grain Information Processing and Control (Henan University of Technology), Ministry of Education, Zhengzhou – 450 001, China

[b]Henan Key Laboratory of Grain Photoelectric Detection and Control, (Henan University of Technology), Ministry of Education, Zhengzhou – 450 001, China

[c]State Key Laboratory of Cryospheric Science, Lanzhou – 730 000, China

*[E-mail: 212323818@qq.com]

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The snowmelt of the Greenland ice sheets is of great significance to the study of global climate change. This paper is based on the 19.35 GHz horizontal polarization data and 37.00 GHz vertical polarization data of the Special Sensor Microwave/ Imager Sounder (SSMIS) and Special Sensor Microwave/ Image (SSM/I) carried by National Defense Meteorological Satellite Program (DMSP) from 1988 to 2016, by cross-polarization ratio (XPGR) algorithm (threshold value is -0.0158). The inter-annual trends of snowmelt area, annual average snowmelt onset, end date and duration in Greenland were studied. The results showed that the maximum snowmelt area was 2,080,000 km^2 in 2012, and the minimum was 1,115,000 km^2 in 1992. From 1988 to 2016, the snowmelt area of the Greenland ice sheets was increased by 2.8×10^5 km^2, with a growth rate of 9.66×10^3 km^2/year. In the annual average change rate, there were earlier snowmelt onset date (0.16 days earlier each year), longer snowmelt duration (0.36 days longer each year) and later snowmelt end date (0.06 days later each year), and the snowmelt area was in the marginal region. The snowmelt area of the southern margin is the largest, and there are obvious regional differences. The snowmelt of Greenland ice sheets changes greatly and shows a periodic change rule in the annual mean snowmelt variation.

[**Keywords**: Snowmelt of ice sheet, SSM/I, Spatio-temporal changes, XPGR algorithm]

Introduction

Glaciers can absorb heat, and the presence of glaciers plays an important part in maintaining the Earth's climate balance. Because the terrain of the polar region is less undulating and small changes in temperature will cause changes in the surface humidity of large areas of snow, accelerating the movement of the ice shelf, and cause sea-level rise[1]. The ice-sheet freeze-thaw changes will cause changes in the composition and temperature of the seawater, which in turn will trigger ocean currents and evaporation. Besides, changes in the surface reflectivity caused by the ice-sheet freezing and thawing will affect the radiation balance and temperature changes, which in turn affects the atmospheric circulation and global water vapour transport[2]. In recent decades, the global sea-level rise contributed by the Greenland has doubled due to the accelerated melt of its ice sheets[3-4]. If all Greenland ice sheet melted, oceans would be 15-20 feet higher[5]. Due to the Greenland's ice-sheet melt, the rate of sea-level rise doubled to 0.74 mm/year[6-8]. At this rate, the Greenland's ice-sheet melt is expected to raise sea level by more than 20 cm by 2100[refs. 9,10]. The study of polar ice-sheet snowmelt detection is of great significance to the study of global climate changes.

The microwave radiometer SSM/I is a multi-frequency dual-polarized surface radiation measurement with high time resolution and data acquisition capability. Many scholars have done a lot of research work on the surface snowmelt of ice sheet based on the large-scale spaceborne SSM/I data. Steffen *et al*.[11] used horizontal polarized 19.35 GHz and 37.00 GHz data to detect the snowmelt in the Greenland ice sheet by normalized gradient ratio (GR). Abdalati & Steffen[12] proposed a method for detecting snowmelt in ice sheet surface by XPGR (threshold value is -0.025), and the threshold value was revised to -0.0158 in 1997. Cheng *et al*.[13] analyzed the time series of brightness temperature changes of Antarctic snowmelt by 19.35 GHz band of vertical polarization of microwave radiometer SSM/I. Further, Torinesi *et al*.[14] studied the ice-sheet snowmelt detection methods, and obtained the melt data of ice sheet in Antarctica from 1980 to 1999, and analyzed the spatio-temporal changes. In 2005, Liu *et al*.[15] proposed a new method for detecting snowmelt of ice sheet based on wavelet transform, and in 2006, Liu *et al*.[16] analyzed and studied the melt of the ice sheet in Antarctica from 1978 to 2004. Based on four kinds of microwave radiometer data and the characteristics of different data and time obtained by different microwave radiometers every day, a diurnal variation model of Antarctic snowmelt was established by Picard & Fily[17]. Liang *et al*.[18,19] used Scanning Multichannel Microwave Radiometer (SMMR) data and SSM/I data to analyze the temporal and spatial changes of ice-sheet surface snowmelt in Antarctica from 1978 to 2010. Similarly, using the microwave radiometer SMMR, SSM/I and microwave scatterometer QuikSCAT data, Bhattacharya *et al*.[20] probed the surface snowmelt area change of the Greenland ice sheet from 1979 to 2008. Further, Tedesco *et al*.[21] explored the trend of pan-Arctic land snowmelt from 1979 to 2008 by using the variation of diurnal temperature difference. Tedesco[22] utilized the fixed threshold method of a brightness temperature difference between ascending and descending orbits to investigate the Greenland's ice-sheet snowmelt change from 1992 to 2005. The above researches based on a long-term series of snowmelt detection only studied the snowmelt change of ice sheet but neglected the change rate of snowmelt onset date, end date, and duration.

This paper is based on the 19.35 GHz horizontal polarization data and 37.00 GHz vertical polarization data of the SSMIS and SSM/I in the Greenland ice sheet from 1988 to 2016, and the snowmelt temporal and spatial changes was obtained by the classic XPGR snowmelt detection algorithm. Based on this, the snowmelt spatial and temporal trend change characteristics in the Greenland ice sheet were analyzed.

Materials and Methods

Study areas and data sets

Greenland is the largest island in the world with an area of about 216,000 km^2, which is located in the Northeastern part of North America and between the Arctic Ocean and the Atlantic Ocean. Its annual average temperature is below zero. The summer temperature in coastal areas can reach above zero, while the inland part is perennially frozen. Greenland is about 2670 km long from North to South, and about 1050 km wide from East to West. Nearly 80 % of the island is in the Arctic Circle, and about 83.7 % of Greenland is covered by ice and snow. The average thickness of the Greenland ice sheet is about 2300 m. Greenland's total ice and snow is about 3 million km^3, accounting for 5.4 % of the world's total freshwater. In recent years, the amount of snowmelt in Greenland is increasing year by year due to the global warming trend. The Greenland ice sheet covers on a basin in Greenland, most edges of the basin are about the same height as the sea level. Mountains and plateaus lie in the East and South of Greenland. The mountain area is parallel to the East and West sides of Greenland, with the highest Gunnbjorns Fjeld at 3700 m above the sea level. The plateau area has an average elevation of 1900 m and an area of 1.87 million km^2. In the coastal area of Greenland, the long and tortuous bays penetrate the island, forming a complex and huge bay system.

This paper uses the 19.35 GHz horizontal polarization data of the SSM/I carried by the American DMSP and the 37.00 GHz vertical polarization data to analyze the Greenland's ice-sheet surface snowmelt. SSM/I is carried on F8, F11, F13, and F17 platforms, in which F8 runs from July 1987 to December 1991, F11 runs from December 1991 to September 1995, F13 runs from March 1995 to April 2009, and F17 runs from December 2006 to the present. Therefore, it is necessary to normalize different types of sensor data into the same platform to study the snowmelt changes of long time series and continuous monitoring. The data from four different platforms can be processed by regression based on their overlapping time. Formula (1) can be used to calibrate the data of F11, F13, and F17 to F8 platform. T_1 is the brightness temperature of platform F8, and T_2 is the corresponding brightness temperature of platform F11, F13, and F17. In the following formula, a and b are defined as the regression parameters, respectively.

$$T_1 = a * T_2 + b \quad \ldots (1)$$

The conversion of SMMR and SSM/I, and the conversion of F11 and F8, and F13 were calculated using Liu *et al*.[15]. Data conversion parameters of different sensors are shown in Table 1. In this paper, the regression coefficients are used to return all data

Table 1 — Regression parameters for different platforms and sensors

Data platforms	*a*-value	*b*-value	Correlation coefficient
F11 and F13 of SSM/I	1.008	-1.17	R > 0.99
F17 of SSM/I	1.0286	-3.0094	R > 0.99

to the F8 platform. After data normalization, 29-year snowmelt information of the Greenland ice sheet was extracted by XPGR algorithm.

XPGR algorithm

XPGR algorithm mainly uses the brightness temperature date of 37.00 GHz vertical polarization (37.00V) and 19.35 GHz horizontal polarization (19.35H) of microwave radiometer for normalization calculation, enlarging the difference between wet snow and dry snow, thereby performing the snowmelt detection of the ice sheet[12]. Since the real dielectric part of wet snow will increase, it will affect different polarization modes to varying degrees. When the snow humidity is less than 1 %, the emissivity of horizontal polarization is lower than that of vertical polarization (as shown in Fig. 1)[23] . So when the dry snow melts into the wet snow, the horizontal polarization data is more pronounced than the upward trend of vertical polarization. When the dry snow melts into the wet snow, the difference between 19.35H and 37.00V is the largest of the seven band differences, and the sum of 19.35H and 37.00V is the smallest of the seven bands. So the sharper ratio information can be obtained by using the data of two chosen channels, which is more conducive to the snowmelt detection of the ice sheet, thereby improving the image contrast and improving the snowmelt detection accuracy of the ice sheet. The definition of XPGR is as follows:

$$XPGR = \frac{T_{b19.35H} - T_{b37.00V}}{T_{b19.35H} + T_{b37.00V}} \quad \ldots (2)$$

In which, $T_{b19.35H}$ is the brightness temperature of the 19.35H band, and $T_{b37.00V}$ is the brightness temperature of the 37.00V band.

The XPGR algorithm is sensitive to the water content of the snow and ice. Therefore, the XPGR algorithm can clearly identify that the snow is in a frozen or melted state (defined as a melt state when the surface snow humidity is greater than 1 %, otherwise defined as a frozen state). When the XPGR value of a certain pixel point is greater than -0.0158

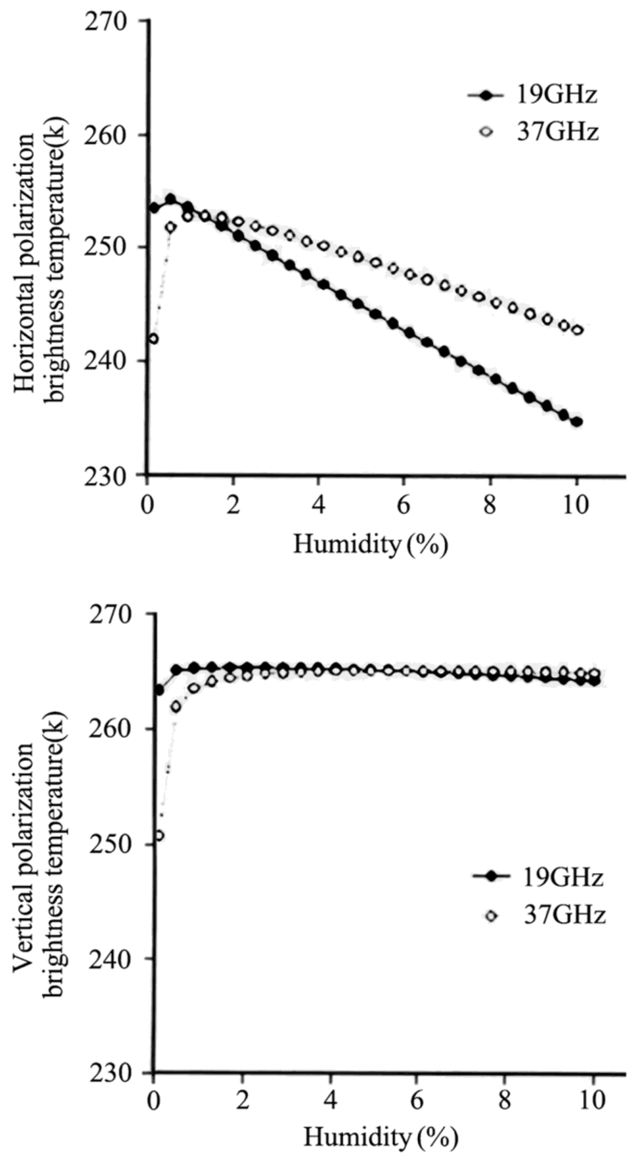

Fig. 1 — 19 GHz and 37 GHz polarization brightness temperature changes with humidity

(classification threshold of dry snow and wet snow), the surface of the ice sheet is in a thawed state; otherwise, the surface of the ice sheet is in a frozen state.

Results and Discussion

Analysis of spatio-temporal changes

Spatial changes

Based on the above process, the spatial variation maps (Fig. 2) of the average snowmelt onset date, duration and end date in the Greenland ice sheet from 1988 to 2016 are obtained. As can be seen from Figure 2, the snowmelt of the Greenland ice sheet occurred in most regions in the past 29 years. The

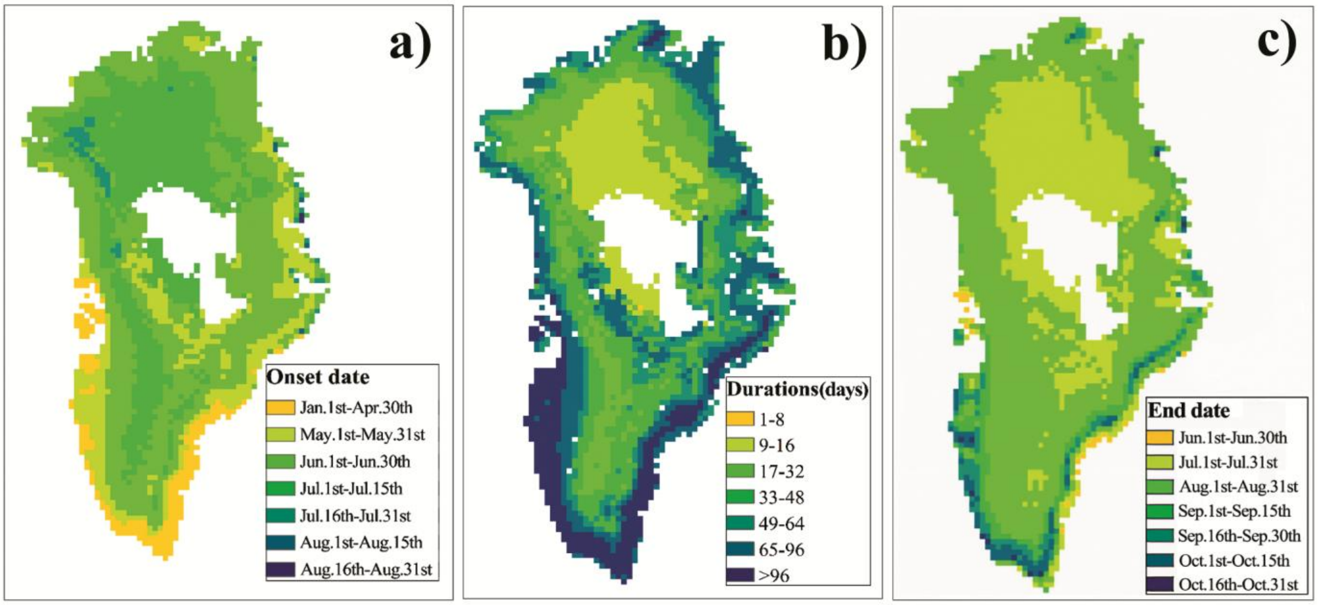

Fig. 2 — Average snowmelt onset date, duration, and end date of the Greenland ice sheet (1988-2016): a) onset date, b) duration (days), and c) end date

total melt area reached 2,006,875 km^2, accounting for 89.57 % of entire Greenland. Besides, there are apparent regional differences in the snowmelt of the Greenland ice sheet. The closer the melt region is to the edge, the earlier the snowmelt onset date is, the longer the snowmelt duration is, and the later the snowmelt end date is. Overall, the southern edge of Greenland has the highest melt intensity, and the average melt onset date is before May, and the melt duration is more than 96 days, and the melt end date is after October. Only a small part of Greenland's interior has not melted in 29 years.

Temporal changes

Based on the statistical analysis of the temporal changes from 1988 to 2016, the annual melt area variation map was obtained (Fig. 3). As can be seen from Figure 3, the melt area of the Greenland ice sheet showed an increased trend, with an increased rate of 1.0×10^4 km^2/year. The largest melt area is 2,080,000 km^2 in 2012, and the smallest melt area is 1,115,000 km^2 in 1992. From 1988 to 2016, the snowmelt area in the Greenland ice sheet is increased by 2.8×10^5 km^2, with a growth rate of 9.66×10^3 km^2/year. From 1988 to 1994, the melt area was relatively small. From 1995 to 2012, the melt area obviously changed and the overall melt extent slightly increased. The melt area began to decrease significantly after 2012.

In order to study the melt regularity of the onset date, duration and end date of the Greenland ice sheet, the snowmelt regions of each year in the Greenland ice sheet from 1988 to 2016 are obtained as shown in Figure 4, and the blue areas around are the parts that melt every year from 1988 to 2016.

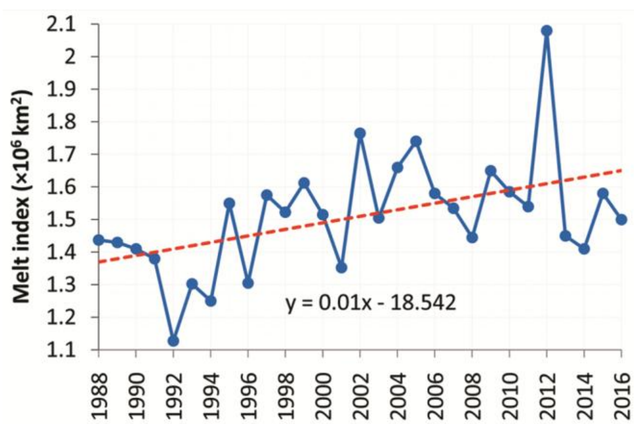

Fig. 3 — Melt index map of the Greenland ice sheet (1988-2016)

To explore the melt trend of the Greenland ice sheet, Figures 5(a – c) were plotted to study the change maps of the average snowmelt onset date, duration and end date in the Greenland ice sheet from 1988 to 2016.

The average snowmelt onset date is obtained by averaging the snowmelt onset date of all pixels in the study area from 1988 to 2016. It is clear from Figure 5(a) that the average snowmelt date of the ice sheet is getting earlier and earlier, with a change rate of -0.16

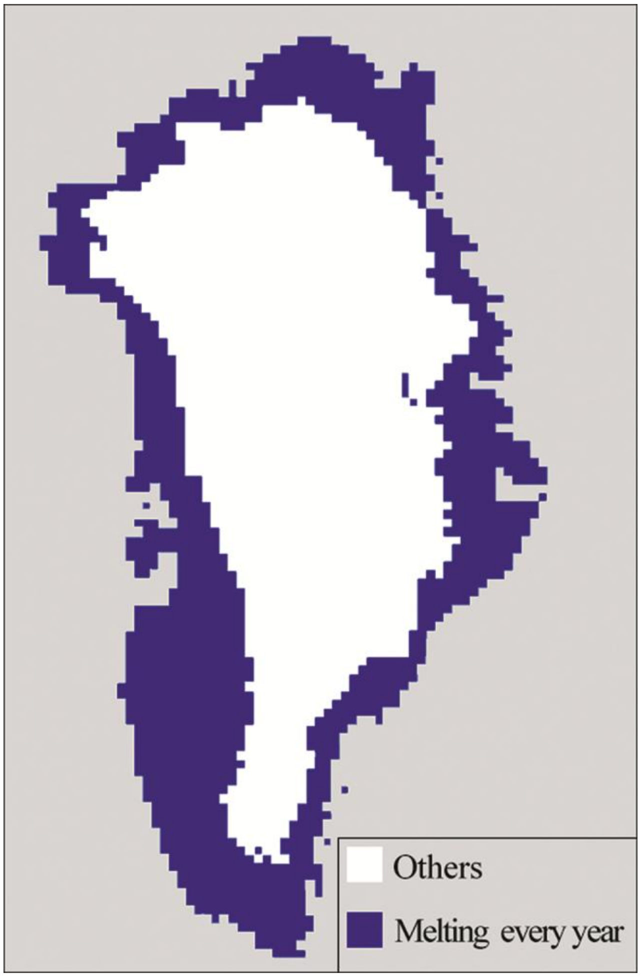

Fig. 4 — Snowmelt regions of each year in the Greenland ice sheet (1988-2016)

days/year, and the change rule of 'peak' appeared every 7 years (the 'peak' is represented by red dots, which are 1992, 1999, 2006 and 2013, with the snowmelt onset date on the 165th, 164th, 158th and 160th days, respectively), and the average snowmelt onset date of ice sheet in 2015 was abnormally delayed.

In general, since 1998, the minimum value in each cycle has suddenly increased to the 'peak' value in the next year, and the minimum value in the cycle is getting smaller and smaller.

As can be seen from Figure 5(b), the average snowmelt duration of the Greenland ice sheet shows an increasing trend, with an increased rate of about 0.36 days/year. Also, the shortest snowmelt duration (64 days) was in 1992 and the longest snowmelt duration (100 days) in 2010. The change rate of snowmelt duration from 1988 to 2007 was small, while from 2008 to 2016 was large. From 1988 to 2001

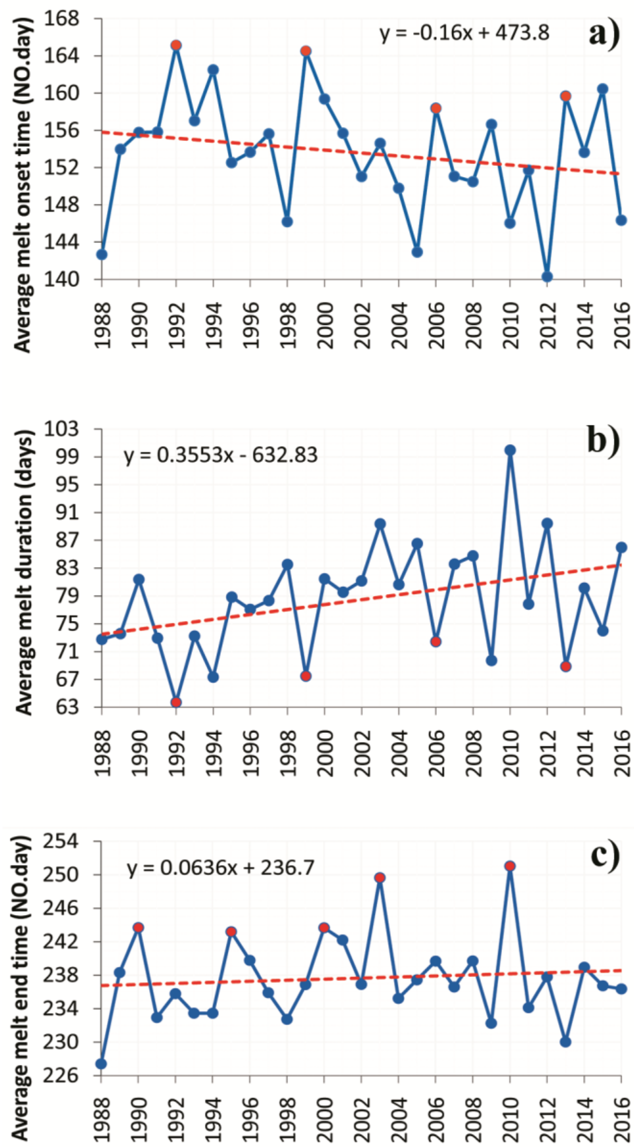

Fig. 5 — Changes in the average snowmelt in the Greenland ice sheet (1988-2016): a) onset date, b) duration, and c) end date

the average snowmelt duration was about 75.08 days, and from 2002 to 2016 the average snowmelt duration was about 81.63 days.

As can be seen from Figure 5(c), the average snowmelt end date in Greenland shows a delayed trend, with a change rate of about 0.06 days/year. Compared with the average snowmelt onset date and duration, the change rate is smaller. It means that the average snowmelt end date in the Greenland ice sheet is relatively stable. It reflects that the average snowmelt end date for the Greenland ice sheet is not large due to global warming. Since the snowmelt end date occurs in the second half of the year, it means that the climate in Greenland is relatively stable in the second half of the year. The snowmelt end date in 1988 is the earliest (227th day), and in 2010 is the latest (251st day). Besides, from 1988 to 2001 the 'peak' of the snowmelt end date occurs every six years, and from 2002 to 2016 the 'peak' of the snowmelt end date occurs every seven years, and from 2002 to 2016 the 'peak' of the average snowmelt end date is 6.82 days more than from 1988 to 2001.

Conclusion

From the spatial variation maps of snowmelt onset date, duration and end date of the Greenland ice sheet from 1988 to 2016, it can be seen that the Southern edge of Greenland has the largest snowmelt intensity. The closer the snowmelt region is to the edge of Greenland, the earlier the snowmelt onset date is, the later the snowmelt end date is, and the longer the snowmelt duration is. The interannual variations of the average snowmelt onset date, duration and end date of the Greenland ice sheet are dramatic and show a periodic rule. The snowmelt area gradually increased, snowmelt onset date gradually advanced, snowmelt duration gradually increased, and the snowmelt end date gradually delayed.

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Conflict of Interest

Authors declare no competing or conflict of interest.

Author Contributions

The authors likely to certify that, XDW & KZ had contributed towards the preparation of this paper such as data collection, data analysis, manuscript drafting and supervision; DHS & YHW contributed in editing the contents of writing and guidance, modifications, suggestions and review.

References

1 Wang L, Deriving spatially varying thresholds for real-time ice sheet detection from space-borne passive microwave observations, *Remote Sens Lett*, 3 (2012) 305-313.
2 Li X W, Zhang Y & Liang L, Snowmelt detection on the Greenland ice sheet using microwave scatterometer measurements, *Int J Remote Sens*, 38 (2016) 796-807.
3 Li Y & Flanner M, Investigating the Impact of Aerosol Deposition on Snow Melt over the Greenland Ice Sheet Using a New Kernel, *Agu Fall Meeting*, 2018, pp. 1-39.
4 Muntjewerf L, Petrini M, Vizcaino M, da Silva C E & Sellevold R, Greenland Ice Sheet Contribution to 21st Century Sea Level Rise as Simulated by the Coupled CESM2.1-CISM2.1, *Geophy Res Lett*, 47 (2020) p. e2019GL086836.
5 Kintisch E, Meltdown, *Science*, 355 (2017) 788-791.
6 Shepherd A, Ivins E R & Geruo A, A Reconciled Estimate of Ice-Sheet Mass Balance, *Science*, 338 (2012) 1183-1189.
7 Rignot E & Kanagaratnam P, Changes in the velocity structure of the Greenland ice sheet, *Science*, 311 (2006) 986-990.
8 Rignot E, Velicogna I & Van d B M R, Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophy Res Lett*, 38 (2011) 132-140.
9 Van d B M, Bamber J, Ettema J, Rignot E, Schrama E, *et al*., Partitioning recent Greenland mass loss, *Science*, 326 (2009) 984-986.
10 Dumont M, Brun E, Picard G, Michou M, Libois Q, *et al*., Contribution of light-absorbing impurities in snow to Greenland/'s darkening since 2009, *Nat Geosci*, 7 (2014) 509-512.
11 Steffen K, Abdalati W & Stroeve J, Climate sensitivity studies of the Greenland ice sheet using satellite AVHRR, SMMR, SSM/I and in situ data, *Meteorol Atmos Phys*, 51 (1993) 239-258.
12 Abdalati W & Steffen K, Passive microwave -derived snow melt regions on the Greenland Ice Sheet, *Geophy Res Lett*, 22 (2013) 787-790.
13 Cheng X, Zhang Y M, Li Z & Shao Y, Time series analysis of SSM / I microwave radiometer brightness temperature in Antarctica, *Adv Water Sci*, 16 (2005) 265-273.
14 Torinesi O, Fily M & Genthon C, Variability and trends of the summer melt period of Antarctic Ice margins since 1980 from microwave sensors, *J Climate*, 16 (2003) 1047-1060.
15 Liu H, Wang L & Jezek K C, Wavelet-transform based edge detection approach to derivation of snowmelt onset, end and duration from satellite passive microwave measurements, *Int J Remote Sens*, 26 (2005) 4639-4660.
16 Liu H, Wang L & Jezek K C, Spatiotemporal variations of snowmelt in Antarctica derived from satellite scanning multichannel microwave radiometer and Special Sensor Microwave Imager data (1978-2004), *J Geophys Res*, 111 (2006) 1-20.
17 Picard G & Fily M, Surface melting observations in Antarctica by microwave radiometers Correcting 26-year time series from changes in acquisition hours, *Remote Sens Environ*, 104 (2006) 325-336.
18 Liang L, Guo H D & Li X W, Analysis of spatio-temporal variation of snowmelt in Antarctica derived from microwave radiometer data, *J Remote Sens*, 17 (2013) 423-438.

19 Liang L, Li X W & Zheng F, Spatio-Temporal Analysis of Ice Sheet Snowmelt in Antarctica and Greenland Using Microwave Radiometer Data, *Remote Sens-Basel*, 11 (1838) (2019) pp. 13.

20 Bhattacharya I, Jezek K C, Wang L & Liu H X, Surface melt area variability of the Greenland ice sheet 1979-2008, *Geophys Res Lett*, 36 (2009) 1437-1454.

21 Tedesco M, Brodzik M, Armstrong R, Savoie M & Ramage J, Pan arctic terrestrial snowmelt trends (1979-2008) from spaceborne passive microwave data and correlation

22 with the Arctic Oscillation, *Geophys Res Lett*, 36 (2009) 272-277.

23 Tedesco M, Snowmelt detection over the Greenland ice sheet from SSM/I brightness temperature daily variations, *Geophys Res Lett*, 34 (2007) 155-164.

24 Bai Y J, Lu L, Li X & Che T, Sensitivity analysis of snow cover microwave radiation brightness temperature to snow cover parameters: Taking the multi-layer snow cover microwave radiation model as an example, *Remote Sens Technol Appl*, 24 (2009) 622-630.