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Supplementary Materials for

Greenland Ice Sheet surface melt amplified by snowline migration and bare ice exposure

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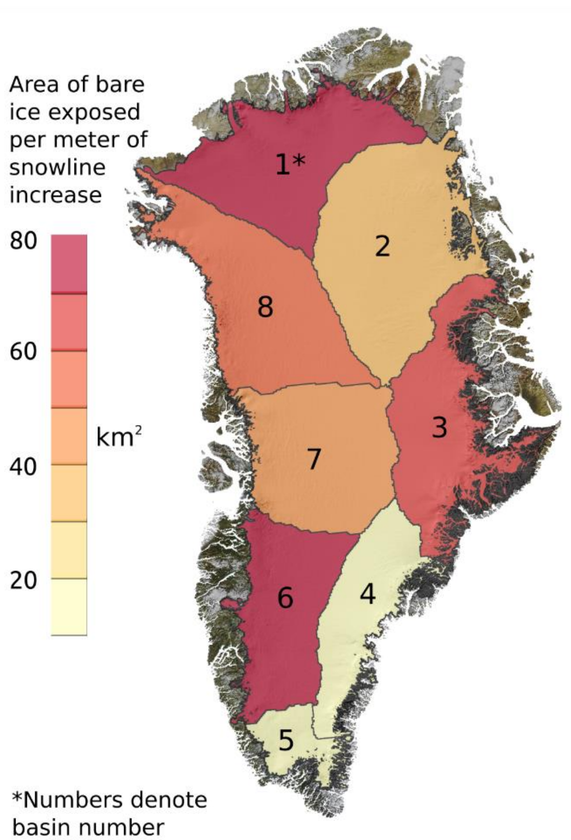

Fig. S1. Sensitivity of each IMBIE sector to the snowline-albedo feedback during the 2001–2017 study period.

The gently sloping topography of Southwest Greenland (IMBIE sector 6) makes it the most sensitive sector to snowline variability, averaging 78 km^2 of additional bare glacial ice exposure for every one-meter increase in snowline elevation. However, the surface topographic slopes of North, East, West and Northwest Greenland are nearly as flat as Southwest Greenland, signifying that the snowline-albedo feedback is an important control on melt from these sectors.

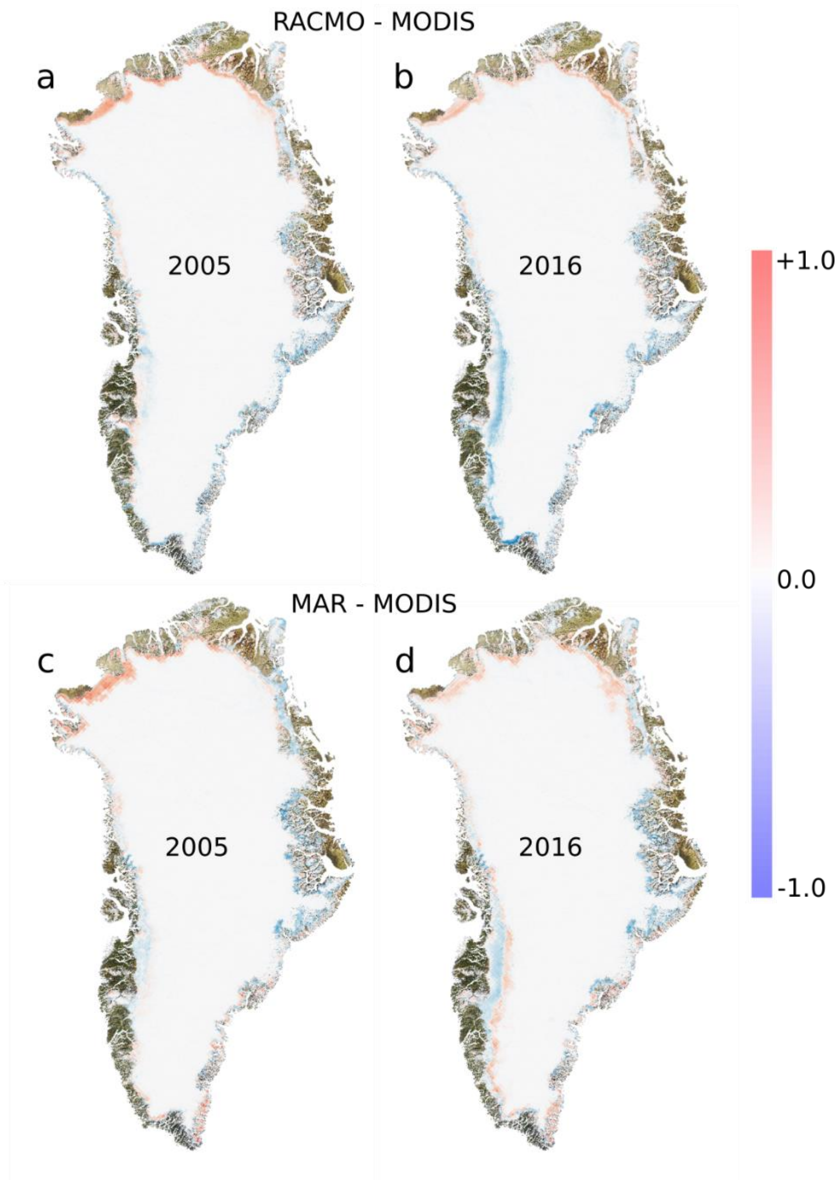

Fig. S2. Difference between observed (MODIS) bare ice presence index and that modeled by RACMO2.3p2 and MAR3.9 in an average melt year (2005) and high melt year (2016). A negative value (blue) indicates that bare ice duration or extent is underestimated by the models. (a) Difference between RACMO and MODIS in 2005, (b) difference between RACMO and MODIS in 2016, (c) difference between MAR and MODIS in 2005, and (d) difference between MAR and MODIS in 2016. We find that the difference between observed and modelled bare ice presence increases during high melt years.

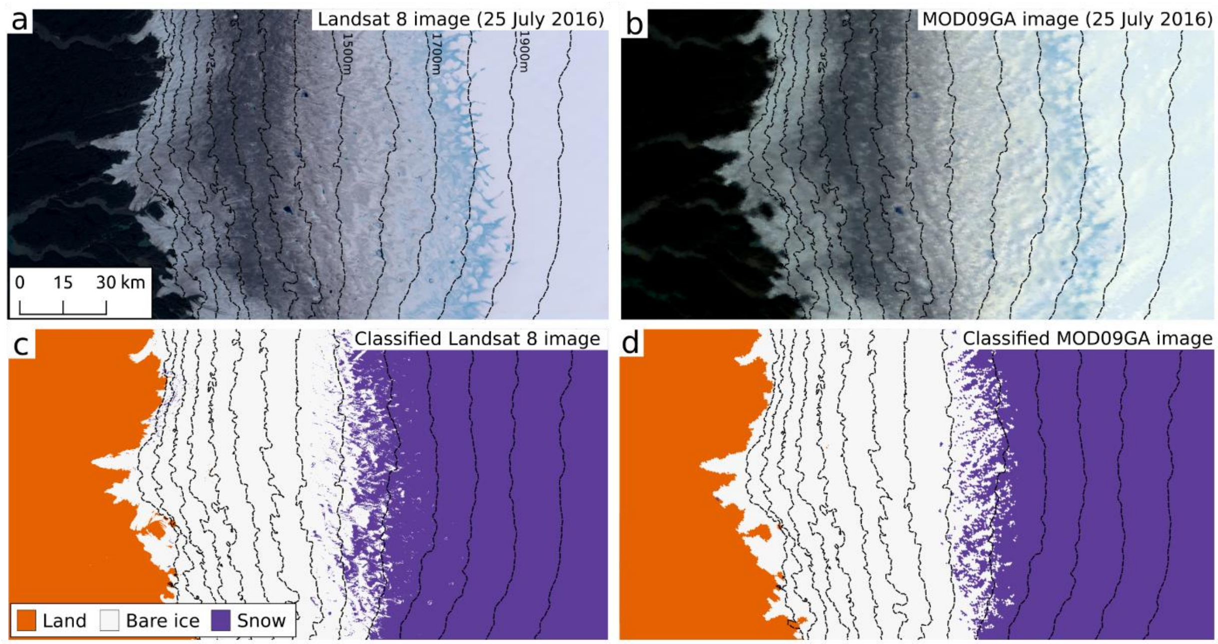

Fig. S3. Example of random forests classification of bare ice and snow in West Greenland on 25 July 2016. (a) Landsat 8 true color image with pixel resolution of 30 m. (b) MOD09GA true color image with pixel resolution of 500 m. (c) Classified Landsat 8 image with pixel resolution of 30 m. (d) Classified MOD09GA image. We find that bare ice is classified in MOD09GA images with an average accuracy of 97.8% based on comparison with Landsat imagery. We find errors of bare ice omission (i.e. bare ice incorrectly classified as snow) to be 4.6% and errors of bare ice commission (i.e. snow incorrectly classified as bare ice) to be 0.3%. The higher errors of omission may lead to a slight underestimation of the number of bare ice pixels and makes our bare ice extent and snowline metrics conservative.

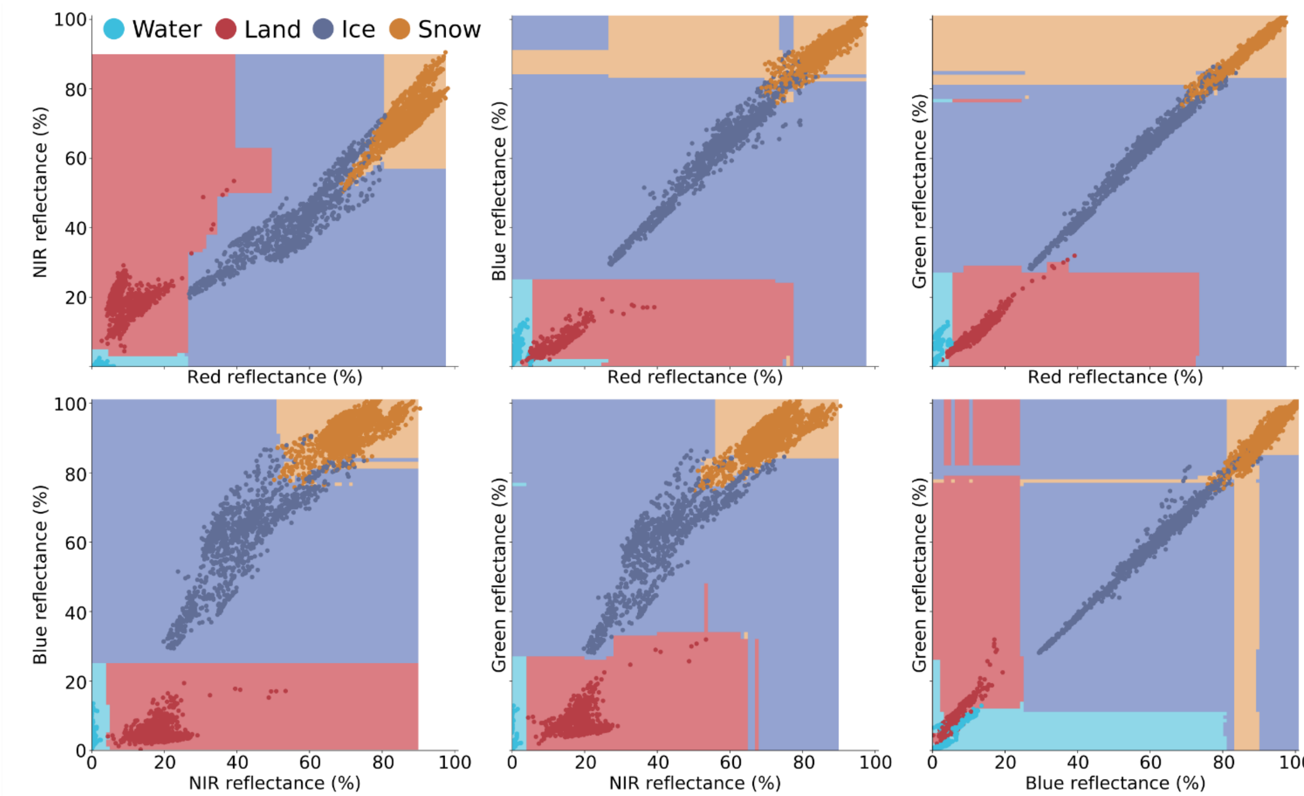

Fig. S4. Feature space occupied by water, land, bare ice, and snow in MOD09GA visible and near-infrared bands. Dots show the manually digitized pixel samples used to train the Random Forests classifier. The background shading shows the decision boundaries of the Random Forests classification. Snow and bare ice form are relatively easy to distinguish because they reflect different proportions of visible and near-infrared wavelengths and therefore form distinct clusters in the multi-dimensional feature space.

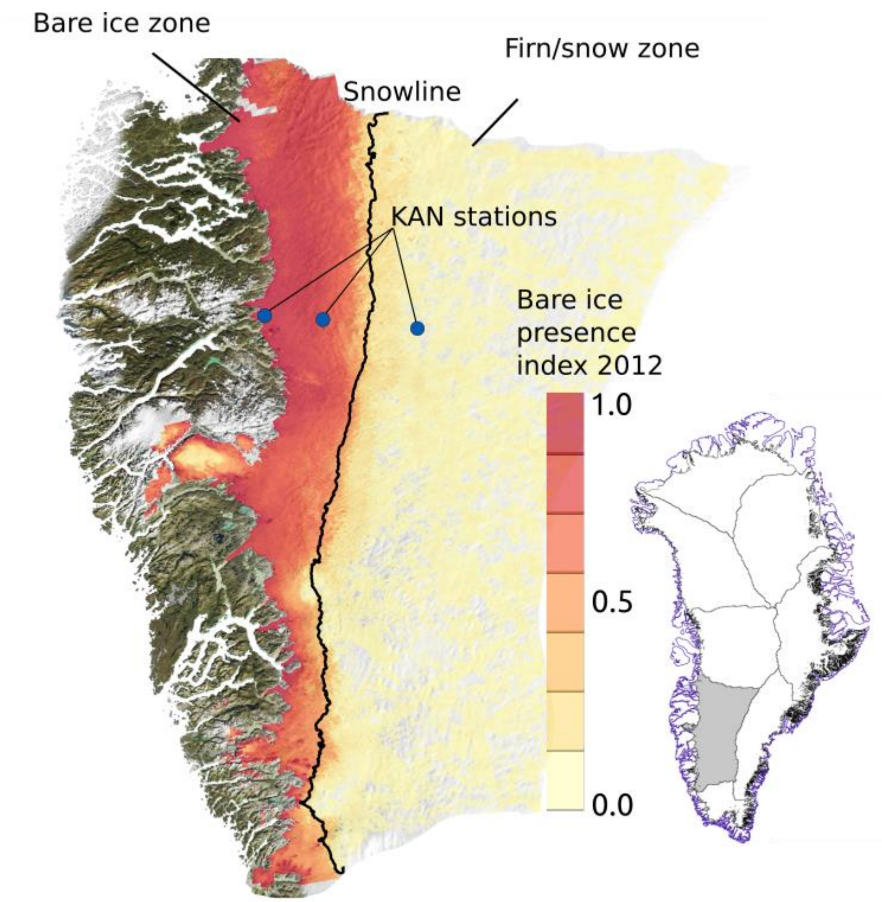

Fig. S5. Frequency of bare ice exposure (i.e., presence index) during summer 2012 in Southwest Greenland (IMBIE sector 6). The product was used to map the maximum snowline and extent of bare ice.

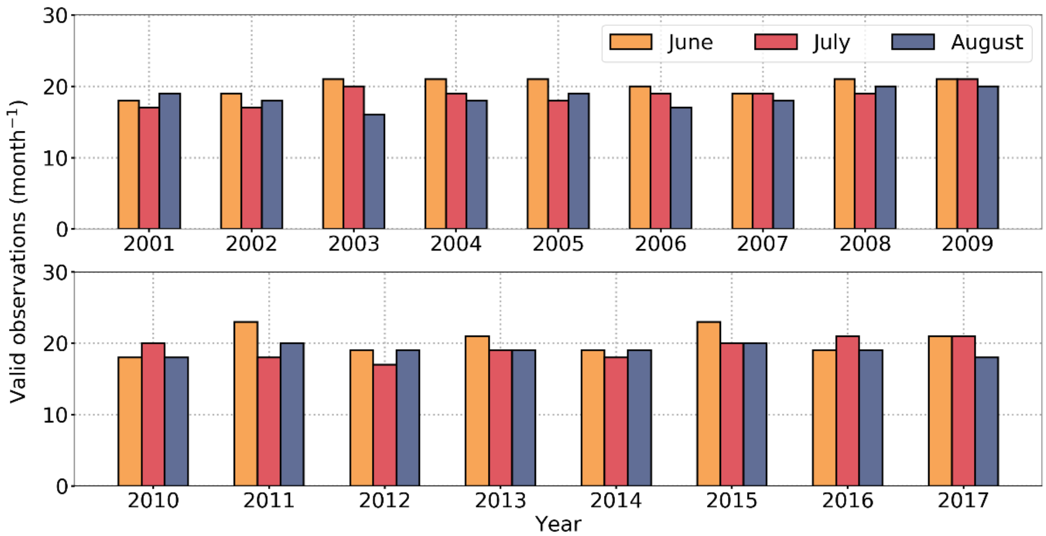

Fig. S6. Mean number of valid MODIS pixel observations across the Greenland Ice Sheet for each summer month between 2001 and 2017. The difference between the numbers of valid observations is small and cannot explain the patterns of bare ice presence or extent that we observe.

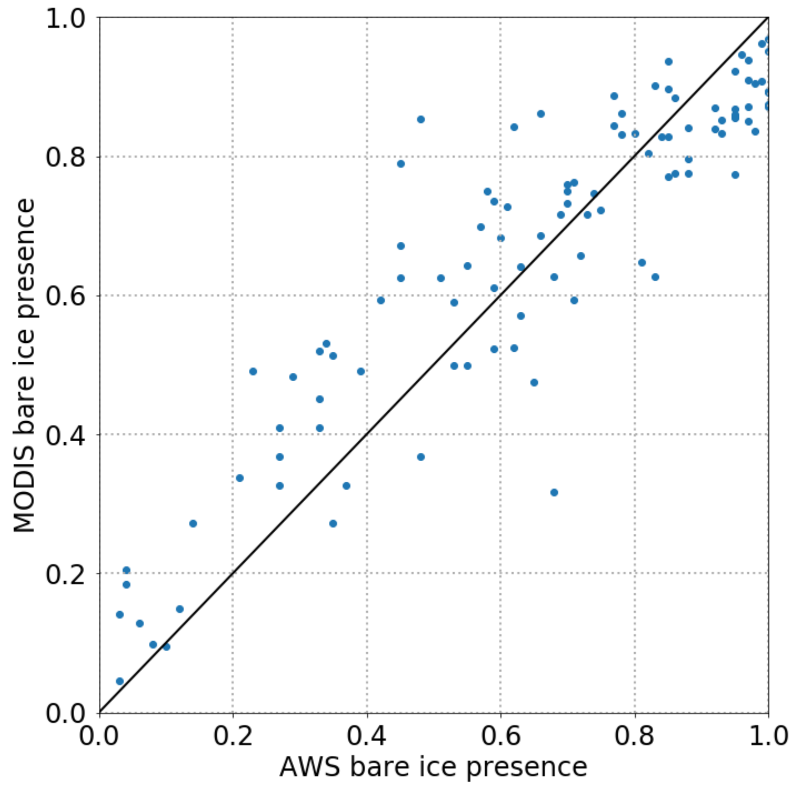

Fig. S7. Relationship between MODIS bare ice presence index with that derived from 21 AWSs situated across the Greenland Ice Sheet between 2009 and 2017. The strong correlation (R^2 = 0.82) provides validation of our remotely sensed bare ice classification and presence index, especially considering AWS albedo contain inherent uncertainties due to small sampling footprints in comparison to MODIS and tilt.

Table S1. Maximum (or end-of-summer) snowline and bare ice extent for IMBIE sectors 1 to 4 between 2001 and 2017.

	North (Sector 1)		**Northeast (Sector 2)**		**East (Sector 3)**		**Southeast (Sector 4)**	
Year	Snowline elevation (m)	Bare ice extent (km^2)	Snowline elevation (m)	Bare ice extent (km^2)	Snowline elevation (m)	Bare ice extent (km^2)	Snowline elevation (m)	Bare ice extent (km^2)
2001	1,004	23,464	993	18,720	1,673	23,858	1,392	8,208
2002	1,005	23,806	1,041	20,668	1,698	27,981	1,311	8,084
2003	976	22,725	1,039	20,098	1,680	22,371	1,362	6,505
2004	896	17,932	1,078	19,808	1,709	28,317	1,343	8,354
2005	961	21,910	1,053	20,232	1,716	32,367	1,321	9,779
2006	852	14,185	874	15,397	1,685	28,064	1,319	9,836
2007	894	17,693	1,006	18,618	1,749	33,531	1,415	11,271
2008	1,033	27,749	1,047	21,587	1,677	24,898	1,361	9,840
2009	976	22,465	1,030	19,247	1,658	23,491	1,372	9,477
2010	961	21,913	1,068	20,224	1,732	32,534	1,407	12,189
2011	987	23,982	1,078	20,203	1,733	31,320	1,407	11,343
2012	1,050	28,244	1,159	22,411	1,784	35,469	1,522	14,270
2013	888	12,485	1,081	19,259	1,726	29,951	1,505	9,374
2014	1,004	23,906	979	19,375	1,674	27,544	1,546	11,224
2015	1,109	32,301	1,026	18,595	1,684	22,181	1,374	7,777
2016	1,053	26,646	1,095	22,839	1,757	31,392	1,537	10,835
2017	1,006	19,779	1,077	20,725	1,652	20,804	1,410	9,216

Table S2. Maximum (or end-of-summer) snowline elevation and bare ice extent for IMBIE sectors 5 to 8 between 2001 and 2017.

	South (Sector 5)		**Southwest (Sector 6)**		**West (Sector 7)**		**Northwest (Sector 8)**	
Year	Snowline elevation (m)	Bare ice extent (km^2)	Snowline elevation (m)	Bare ice extent (km^2)	Snowline elevation (m)	Bare ice extent (km^2)	Snowline elevation (m)	Bare ice extent (km^2)
2001	1,410	10,682	1,468	39,873	1,290	11,856	1,066	18,512
2002	1,286	8,266	1,368	32,300	1,293	11,965	1,075	17,311
2003	1,492	11,589	1,554	47,254	1,343	13,784	1,094	20,557
2004	1,410	9,933	1,498	40,665	1,374	14,292	1,067	16,684
2005	1,224	7,198	1,420	33,986	1,358	13,845	1,138	20,164
2006	1,414	10,435	1,422	36,408	1,316	12,177	1,110	20,504
2007	1,516	12,221	1,633	54,688	1,463	17,567	1,161	23,761
2008	1,490	12,604	1,529	43,836	1,331	14,118	1,121	24,175
2009	1,319	8,659	1,387	33,977	1,338	13,362	1,117	24,358
2010	1,562	14,477	1,622	53,600	1,441	17,183	1,190	24,725
2011	1,512	12,892	1,627	55,497	1,479	18,625	1,206	28,202
2012	1,609	16,135	1,779	69,165	1,569	22,477	1,354	33,175
2013	1,370	9,563	1,490	42,709	1,367	14,889	1,063	15,003
2014	1,469	11,438	1,549	47,843	1,411	16,346	1,178	22,882
2015	1,304	7,973	1,437	33,184	1,434	16,671	1,265	31,012
2016	1,551	12,511	1,648	55,964	1,485	18,654	1,159	23,290
2017	1,470	11,455	1,415	37,245	1,360	14,172	1,063	17,437