nature geoscience

LETTERS

PUBLISHED ONLINE: 8 JUNE 2014 | DOI: 10.1038/NGEO2180

Contribution of light-absorbing impurities in snow to Greenland's darkening since 2009

M. Dumont[1*†], E. Brun[2†], G. Picard[3,4], M. Michou[2], Q. Libois[3,4], J-R. Petit[3,4], M. Geyer[2], S. Morin[1] and B. Josse[2]

The surface energy balance and mass balance of the Greenland ice sheet depends on the albedo of snow, which governs the amount of solar energy that is absorbed. The observed decline of Greenland's albedo over the past decade[1-3] has been attributed to an enhanced growth of snow grains as a result of atmospheric warming[1,2]. Satellite observations show that, since 2009, albedo values even in springtime at high elevations have been lower than the 2003–2008 average. Here we show, using a numerical snow model, that the decrease in albedo cannot be attributed solely to grain growth enhancement. Instead, our analysis of remote sensing data indicates that the springtime darkening since 2009 stems from a widespread increase in the amount of light-absorbing impurities in snow, as well as in the atmosphere. We suggest that the transport of dust from snow-free areas in the Arctic that are experiencing earlier melting of seasonal snow cover[4] as the climate warms may be a contributing source of impurities. In our snow model simulations, a decrease in the albedo of fresh snow by 0.01 leads to a surface mass loss of 27 Gt yr^{-1}, which could induce an acceleration of Greenland's mass loss twice as large as over the past two decades[5]. Future trends in light-absorbing impurities should therefore be considered in projections of Greenland mass loss.

The mass loss of the Greenland ice sheet (GrIS) has accelerated markedly over the past decade in response to both ice dynamics and surface melt increase[6]. GrIS mass loss is expected to raise global sea level by more than 20 cm by 2100 (ref. 5) and is consequently of tremendous importance for the entire population of the Earth. Over the period 1992–2010, a mean annual GrIS surface mass balance decrease of 12.9 Gt yr^{-1} was observed[5]. The recent GrIS surface mass balance decrease has been linked not only to changes in the Arctic atmospheric circulation but also to local feedbacks involving snow albedo[1,7].

Remotely sensed observations from the spaceborne MODerate resolution Imaging Spectroradiometer (MODIS) have shown that the GrIS broadband albedo has decreased significantly over the past decade in both ablation and accumulation areas[1,3]. This decrease has been attributed mainly to warmer conditions caused by anomalous atmospheric circulation patterns, and has been amplified by the intrinsic snow albedo feedback[1,3]. Snow is indeed involved in several feedbacks in the climate system; the primary one is linked to the presence or absence of highly reflective snow overlying dark surfaces such as ground or debris-covered ice[8]. Further, snow has an intrinsic albedo feedback. Warmer meteorological conditions enhance snow grain growth, inducing a decrease in snow albedo[9,10] and leading to increased energy absorption and, in turn, enhanced snow grain growth. This feedback is particularly efficient when surface melt occurs[1].

The amplification of the albedo decrease by the intrinsic snow albedo feedback largely explains extreme melt records in summer 2010 and 2012 (refs 1,2). However, a drastic snow albedo anomaly at elevations higher than 2,000 m is persistent over the whole period 2009–2013 in spring[1] (Fig. 1), even during periods with normal or colder than normal air temperatures. Winter and spring 2011 were the coldest since 2000 (ref. 11) and exhibited snow accumulation exceeding normals[7]. Hence another factor must be considered to explain the springtime anomaly. Year-to-year memory can be ruled out, as a few centimetres of fresh snow in winter are sufficient to cover the old snow that evolved during the previous summer and to reset the albedo to the high values characteristic of fresh snow (Supplementary Fig. 1c). To determine this factor, we ran the snow model Crocus[12] which predicts the evolution of grain size, albedo and other snow properties and is driven by near-surface meteorological data extracted from surface fields of a meteorological reanalysis (Methods). Crocus explicitly takes into account the processes involved in the intrinsic snow albedo feedback. Figure 2 shows May–June broadband albedo averaged over the ice sheet above 2,000 m a.s.l.—that is, leaving out areas prone to regular surface melt—using MODIS observations and results from Crocus assuming negligible impurity content in snow. The difference between Crocus and MODIS broadband albedo over the 2003–2012 period (Supplementary Fig. 7) is also shown. Although both signals in general show similar year-to-year variations, the difference between the two exhibits a statistically significant change point (p value $<10^{-6}$) in 2009, when it decreased markedly. This suggests that, from 2009 onwards, the intrinsic snow albedo feedback driven by meteorological conditions alone is not sufficient to explain the observed decrease in the GrIS albedo in spring.

Light-absorbing impurities, hereafter referred to simply as impurities, such as soot, mineral dust or micro-organisms (cyanobacteria and algae[13]) present in snow are known to decrease the albedo in the visible part of the solar spectrum. This usually results in a strong increase in the energy absorbed by snow even for a low impurity content[9,14]. We hypothesize that the behaviour depicted in Figs 1 and 2 was caused by a widespread increase in impurity content in snow. Among impurities, soot is by far the most efficient absorber: 1 ng g^{-1} of soot has approximately the same effect on albedo as 100 ng g^{-1} of dust at 500 nm (ref. 9), with variations depending on snow properties and dust particle size and refractive index. Recent measurements in Greenland have shown that the soot content is low, typically 3 ng g^{-1} (ref. 15). Dust is a less efficient absorber than soot, but measurements in Northern Greenland have shown late spring

[1]Météo-France–CNRS, CNRM-GAME UMR 3589, CEN, Grenoble F-38000, France, [2]Météo-France–CNRS, CNRM-GAME UMR 3589, GMGEC, Toulouse F-31057, France, [3]Univ. Grenoble Alpes, LGGE UMR 5183, Grenoble F-38000, France, [4]CNRS, LGGE UMR 5183, Grenoble F-38000, France. †These authors contributed equally to this work. *e-mail: marie.dumont@meteo.fr

© 2014 Macmillan Publishers Limited. All rights reserved.

NATURE GEOSCIENCE DOI: 10.1038/NGEO2180

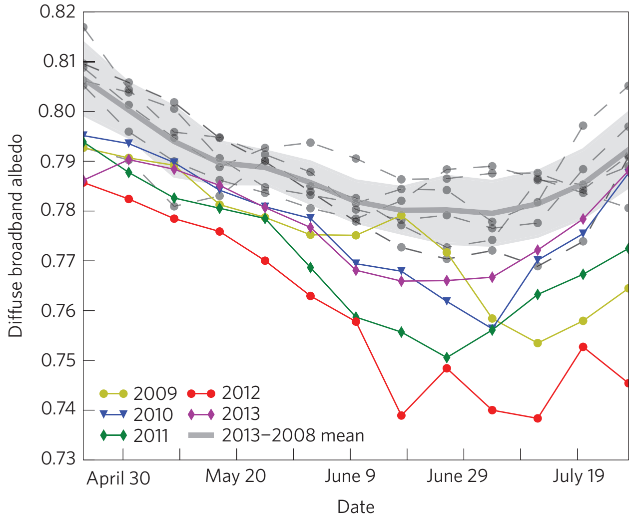

Figure 1 | Observed broadband diffuse albedo above 2,000 m a.s.l. Diffuse broadband albedo derived from MODIS MCD43A3 products for the May–July period from 2003 to 2013. The values are averaged over the GrIS above 2,000 m elevation. Only data with local solar elevation larger than 25° and labelled as high quality are used. The 2003–2008 mean and the standard deviation are indicated in grey shades. Individual 2003 to 2008 albedo series are shown as grey dashed lines.

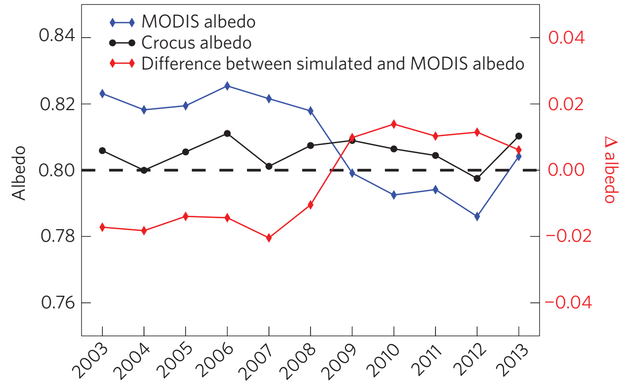

Figure 2 | Simulated and observed broadband albedo averaged over the GrIS above 2,000 m a.s.l for the May–June period from 2003 to 2013. The blue curve depicts the broadband albedo evolution provided by the MODIS MOD10A1 product. The red curve is the mean difference between the Crocus and MODIS broadband albedo. The black curve is the broadband albedo simulated by Crocus.

peak dust content reaching 500 ng g^{-1} at the NEEM site (Supplementary Fig. 5c; ref. 16). Even if this value cannot be extrapolated to the whole GrIS above 2,000 m altitude, it corroborates that dust is probably a significant absorber in Greenland snow (Supplementary Fig. 1a,b and Supplementary Table 2).

The evolution of the impurity content can be estimated from remote sensing observations by exploiting the high sensitivity of the albedo to impurity content in the visible spectrum. However, this sensitivity is modulated by the snow grain size, which varies widely in Greenland. To disentangle this interplay, we introduce the impurity index, $i_{imp} = \ln(\alpha_4)/\ln(\alpha_2)$, using albedo values from two MODIS spectral bands: α_4 at 545–565 nm and α_2 at 841–876 nm. By construction this index increases in parallel with the snow impurity content and is almost insensitive to grain size (Supplementary Fig. 2; ref. 17). The index also varies with the atmospheric aerosol content owing to uncertainties in the MODIS atmospheric correction. Figure 3 shows that i_{imp} has increased from 2000 to 2013, indicating an increase in impurity or aerosol content throughout this period, with highly positive anomalies larger than 0.06 from 2009 to 2013. At the same time, the i_{imp} index in Antarctica was constant, ruling out a spurious trend due to sensor degradation (Supplementary Figs 3 and 4). Reanalysis of the chemical composition of the atmosphere and atmospheric measurements indicate a slight increase of the atmospheric impurity content in recent years (Supplementary Fig. 5 and Supplementary Table 1). This may explain the increased i_{imp} in two ways: the direct effect of increased aerosols on the i_{imp} signal and increased impurity in snow resulting from enhanced scavenging from the atmosphere. Using radiative transfer calculations and Greenland *in situ* aerosol optical depth measurements we estimate that the direct contribution is at the most 30%, the remainder being due to the impurities in snow and ice. The radiative transfer model also shows that the impurity increase detected with i_{imp} is consistent with the broadband albedo anomaly in Fig. 1 (Supplementary Fig. 1a).

The Icelandic volcanic eruptions of Eyjafjallajökull in April 2010 and Grimsvötn in May 2011 are potentially important sources of impurities in the most recent years[16,18] (Supplementary Fig. 7). However, as the spring albedo anomaly started before 2010, other sources of impurities must be invoked. In the ablation area, the recent outcropping of old ice layers containing high amounts of dust[19] partially explains the anomaly in the ablation area, but this does not apply to the accumulation area. Moreover, dust contains nutrients for micro-organisms[13], which are commonly found in snow and ice and are even abundant at the margin of the GrIS (ref. 13). The unique ability of cyanobacteria to survive in snow during the winter and to migrate upwards in search of light[20] enables them to affect snow surface albedo very early in spring close to the ablation area, where liquid water is present for part of the year. The recent warming and the higher frequency and greater extension of melt events recorded over the past 15 years[7] may have favoured their development over a large part of the ablation and transient areas. Furthermore, recent warming in the Arctic has induced an earlier disappearance of the seasonal snow cover[4], uncovering large areas of bare soil and thus enhancing dust erosion[19,21,22] (Supplementary Fig. 5d). The earlier disappearance of snow cover also induces a spring maximum of fires in the Northern Hemisphere[23,24]. The hypothesis of a recent increase in snow dust content is supported not only by a reanalysis of atmospheric chemical composition (Supplementary Fig. 5b) but also by the spectral signature of the albedo anomaly, showing that the impurities are most certainly of reddish colour. Radiative transfer simulations using impurity content values recently measured at a few locations in Greenland snow (Supplementary Table 2 and Supplementary Fig. 5c; ref. 25) do not fully support a GrIS-wide albedo change of −0.01 (Supplementary Fig. 8). However, these calculations are simplified given the vertical resolution of available measurements, which thus calls for further field investigations.

Whereas the sign of the overall radiative forcing of aerosols in the atmosphere is uncertain[26], impurities in snow have been shown to have a positive impact on radiative forcing. To assess their potential impact on the GrIS surface mass balance, a numerical experiment was performed with Crocus over the period 2009–2012. To this end, we decreased the broadband albedo of fresh snow by 0.01; this change emulates the increase of snow impurity content. With respect to the base simulation, the results show enhanced sublimation everywhere and enhanced snow melt at low elevations. This decreases the total simulated annual accumulation by 12%, from 167 to 149 mm water equivalent per year, and induces a significant reduction of GrIS surface mass balance (SMB), corresponding to at least −27 Gt yr^{-1} (Fig. 4a). The enhancement of sublimation and melt is due not only to the direct decrease of albedo, but also to the amplification by the intrinsic snow albedo feedback, where warmer snow leads to accelerated grain growth and further albedo reduction. Figure 4b shows that this feedback amplifies the initial

© 2014 Macmillan Publishers Limited. All rights reserved.

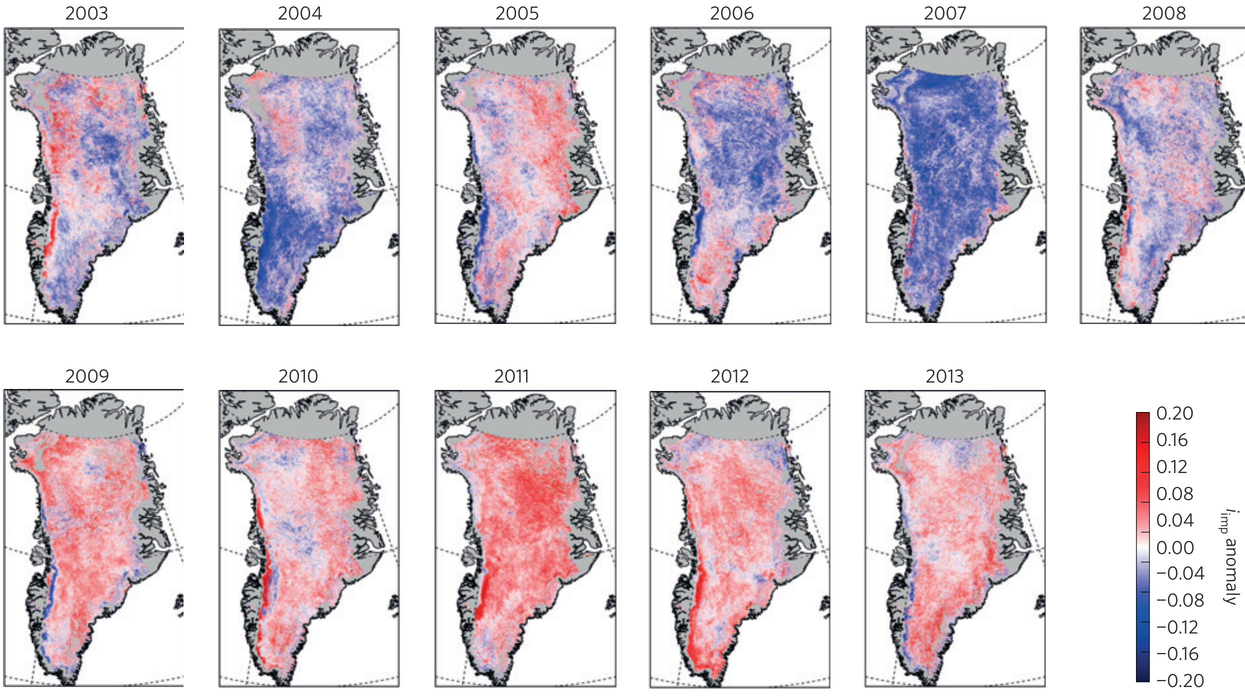

Figure 3 | Evolution of impurity index. Map of impurity index i_{imp} anomaly averaged over the May–June period. The anomaly is calculated with respect to the 2003–2013 average. The grey areas correspond to pixels outside the ice sheet or with insufficient high-quality data. Only data from 16 May to 26 June were used, to eliminate artefacts due to low solar elevation[3].

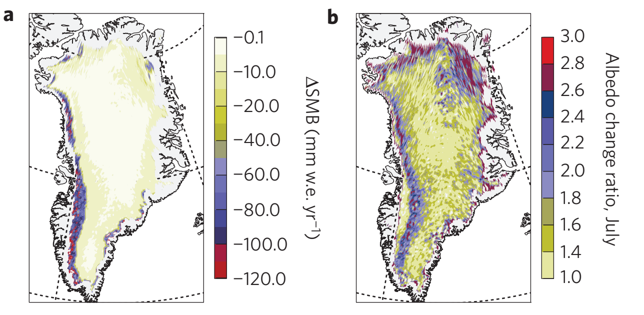

Figure 4 | Numerical estimation of the impact of increased impurity content on the surface mass balance (SMB). a, Decrease of the annual surface mass balance (in mm of water equivalent (w.e.) per year) induced by lowering the albedo of freshly fallen snow by 0.01 in Crocus. **b**, Amplification of this perturbation by the snow intrinsic albedo feedback in July. The map shows $\Delta\alpha/0.01$, where $\Delta\alpha$ is the decrease of broadband albedo caused by lowering the freshly fallen snow initial albedo by 0.01. The values are averaged over the period 2009–2012.

albedo reduction by a factor ranging from 1.5 to 3 in July over most of the GrIS.

This study reveals a significant impact of increased snow impurity on broadband albedo in May–June since 2009 over most of the GrIS. We estimate that this increase has contributed to a decrease in the GrIS surface mass balance of at least $-27\,\text{Gt yr}^{-1}$ in recent years. Because snow impurities tend to concentrate at the surface during melt[15,25], this creates a feedback loop that enhances surface melt. Furthermore, the intrinsic snow albedo feedback is amplified by the presence of impurities[25]. Both effects contribute to a reduction of GrIS albedo through a lower spring albedo and a higher rate of decrease. As these effects and the variations of impurity content are either not, or poorly accounted for in the prediction of the GrIS ice volume change[27], the additional decrease of SMB caused by impurities has been neglected in former assessments. If the hypothesis of enhanced dust transport is confirmed, the future accelerated shortening of the seasonal snow cover duration (−5 days per decade, ref. 28) can further increase the amount of mineral dust transported to the ice sheet and thus amplify the albedo decrease. This will amplify the impact of climate change on the GrIS surface energy and mass balance, accelerating Greenland surface melt and the corresponding sea level rise at a higher rate than currently predicted. Adequate modelling of the deposition, fate and effects of light-absorbing impurities in snow along with future field and remote sensing observation programmes to monitor their evolution are therefore urgently needed.

Methods

The broadband and spectral albedo observations are extracted from two MODIS products: MCD43A3 V005 (16 days synthesis product) at 500 m spatial resolution together with the quality information contained in MCD43A2 (ref. 3) and MOD10A1 (daily) at 500 m resolution[29]. MCD43A3 provides the diffuse albedo for seven spectral bands in the solar spectrum and MOD10A1 provides clear-sky broadband snow albedo. Both products have been evaluated with respect to field measurements[1,3]. MCD43A3 was used for the spectral analysis (i_{imp}) and MOD10A1 provides daily broadband albedo, allowing a precise comparison with albedo values simulated by Crocus. Only pixels located on the ice sheet are considered in this study[1,3]. MOD10A1 albedo data were processed similarly to ref. 1 to remove artefacts induced by clouds. For MCD43A, only 'high quality' data (according to the MODIS nomenclature) with local solar elevation angle larger than 25° were processed[3]. The impurity index was built using simulations of snow albedo with the radiative transfer model DISORT (ref. 30; Supplementary Fig. 1). MODIS spectral bands are subject to degradation over time and we demonstrated that the sensor degradation has no noticeable impact on the impurity index calculation by comparing time series over Antarctica and Greenland (Supplementary Figs 3 and 4) and by comparing MODIS and MERIS (Medium Resolution Imaging Spectrometer) time series (Supplementary Fig. 3i). The spring albedo change of −0.01 to −0.02 is lower than the accuracy of individual daily MODIS albedo observations, but it is statistically significant (Supplementary Information).

Numerical simulations with the detailed physically based snowpack model Crocus[12] were performed from 2003 to 2012 over the GrIS at 15 km resolution using 3-h meteorological conditions downscaled from the ERA-interim reanalysis (Supplementary Figs 6 and 7). The model represents the snowpack layering and accounts for the processes involved in the intrinsic snow albedo feedback.

© 2014 Macmillan Publishers Limited. All rights reserved.

The snow spectral albedo is computed as a function of the physical properties of surface snow. These original features have been used widely in many previous studies of the GrIS surface mass balance[1,2,27].

Received 12 March 2014; accepted 2 May 2014; published online 8 June 2014

References

1. Box, J. E. *et al.* Greenland ice sheet albedo feedback: Thermodynamics and atmospheric drivers. *The Cryosphere* **6,** 821–839 (2012).
2. Tedesco, M. *et al.* The role of albedo and accumulation in the 2010 melting record in Greenland. *Environ. Res. Lett.* **6,** 014005 (2011).
3. Stroeve, J., Box, J. E., Wang, Z., Schaaf, C. & Barrett, A. Re-evaluation of MODIS MCD43 Greenland albedo accuracy and trends. *Remote Sens. Environ.* **138,** 199–214 (2013).
4. Derksen, C. & Brown, R. Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections. *Geophys. Res. Lett.* **39,** L19504 (2012).
5. Rignot, E., Velicogna, I., Van den Broeke, M. R., Monaghan, A. & Lenaerts, J. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys. Res. Lett.* **38,** L05503 (2011).
6. Shepherd, A. *et al.* A reconciled estimate of ice-sheet mass balance. *Science* **38,** 1183–1189 (2012).
7. Tedesco, M. *et al.* Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data. *The Cryosphere* **7,** 615–630 (2013).
8. Imbrie, J. & Imbrie, J. Z. Modeling the climatic response to orbital variations. *Science* **207,** 943–953 (1980).
9. Warren, S. G. Optical properties of snow. *Rev. Geophys.* **20,** 67–89 (1982).
10. Picard, G., Domine, F., Krinner, G., Arnaud, L. & Lefebvre, E. Inhibition of the positive snow-albedo feedback by precipitation in interior Antarctica. *Nature Clim. Change* **2,** 795–798 (2012).
11. Hall Dorothy, K. *et al.* Variability in the surface temperature and melt extent of the Greenland ice sheet from MODIS. *Geophys. Res. Lett.* **40,** 2114–2120 (2013).
12. Vionnet, V. *et al.* The detailed snowpack scheme Crocus and its implementation in SURFEX v72. *Geosci. Model Dev.* **5,** 773–791 (2012).
13. Wientjes, I. G. M., Van de Wal, R. S. W., Reichart, G. J., Sluijs, A. & Oerlemans, J. Dust from the dark region in the western ablation zone of the Greenland ice sheet. *The Cryosphere* **5,** 589–601 (2011).
14. Painter, T. H. *et al.* Response of Colorado River runoff to dust radiative forcing in snow. *Proc. Natl Acad. Sci. USA* **107,** 17125–17130 (2010).
15. Doherty, S. J., Warren, S. G., Grenfell, T. C., Clarke, A. D. & Brandt, R. E. Light-absorbing impurities in Arctic snow. *Atmos. Chem. Phys.* **10,** 11647–11680 (2010).
16. Petit, J-R. *et al.* The NEEM record of aeolian dust: Contributions from Coulter counter measurements. *EGU Gen. Assem. Conf. Abstr.* **15,** 6255 (2013).
17. Zege, E., Katsev, I., Malinka, A., Prikhach, A. & Polonsky, I. New algorithm to retrieve the effective snow grain size and pollution amount from satellite data. *Ann. Glaciol.* **49,** 139–144 (2008).
18. Davies, S. M. *et al.* Widespread dispersal of Icelandic tephra: How does the Eyjafjöll eruption of 2010 compare to past Icelandic events? *J. Quat. Sci.* **25,** 605–611 (2010).
19. Wientjes, I. G. M. & Oerlemans, J. An explanation for the dark region in the western melt zone of the Greenland ice sheet. *The Cryosphere* **4,** 261–268 (2010).
20. Hoiczyk, E. & Baumeister, W. The junctional pore complex, a prokaryotic secretion organelle, is the molecular motor underlying gliding motility in cyanobacteria. *Current Biol.* **8,** 1161–1168 (1998).
21. Istomina, L. G., Hoyningen-Huene, W. V., Kokhanovsky, A. A., Schultz, E. & Burrows, J. P. Remote sensing of aerosols over snow using infrared AATSR observations. *Atmos. Meas. Tech.* **4,** 1133–1145 (2011).
22. Schultz, E. *et al.* Results of a pilot study on the climate relevant particle burden on Greenland. *Eur. Aerosol Conf.* T160A07 (2009).
23. Hegg, D. A., Warren, S. G., Grenfell, T. C., Doherty, S. J. & Clarke, A. D. Sources of light-absorbing aerosol in Arctic snow and their seasonal variation. *Atmos. Chem. Phys.* **10,** 10923–10938 (2010).
24. Stohl, A. *et al.* Pan-Arctic enhancements of light absorbing aerosol concentrations due to North American boreal forest fires during summer 2004. *J. Geophys. Res.* **111,** D22214 (2006).
25. Doherty, S. J. *et al.* Observed vertical redistribution of black carbon and other insoluble light-absorbing particles in melting snow. *J. Geophys. Res. Atmos.* **118,** 1–17 (2013).
26. Flanner, M. Arctic climate sensitivity to local black carbon. *J. Geophys. Res. Atmos.* **118,** 1840–1851 (2013).
27. Fettweis, X., Tedesco, M., Broeke, M. & Ettema, J. Melting trends over the Greenland ice sheet (1958–2009) from spaceborne microwave data and regional climate models. *The Cryosphere* **5,** 359–375 (2011).
28. Brutel-Vuilmet, C., Ménégoz, M. & Krinner, G. An analysis of present and future seasonal Northern Hemisphere land snow cover simulated by CMIP5 coupled climate models. *The Cryosphere* **7,** 67–80 (2013).
29. Klein, A. G. & Stroeve, J. Development and validation of a snow albedo algorithm for the MODIS instrument. *Ann. Glaciol.* **34,** 45–52 (2002).
30. Stamnes, K., Tsay, S-C., Wiscombe, W. & Jayaweera, K. Numerically stable algorithm for discrete ordinate-method radiative transfer in multiple scattering and emitting layered media. *Appl. Opt.* **27,** 2502–2509 (1988).

Acknowledgements

The authors are grateful to F. Domine, C. Carmagnola, R. Stones, M. Bergin, P. Wright, D. Voisin, C. Derksen, S. Nyeki, M. Tedesco, X. Faïn, A. Ribes and E. Pougatch for help and discussions. We thank B. Holben, AERONET PI, for his efforts in establishing and maintaining the Kangerlussuaq and Thule sites. This study was supported by the French ANR MONISNOW programme ANR-11-JS56-005-01 and by the European Commission's 7th Framework Programme, under Grant Agreement 226520, COMBINE project. MODIS data were kindly provided by the National Snow and Ice Data Center and by the US Geological Survey EROS Data Center. We thank J. Chappellaz and A. Wegner for collection of Greenland snow samples at NEEM site. The NEEM work was supported by the French ANR programme NEEM (ANR-07-VULN-09-001). LGGE and CNRM-GAME/CEN are part of LabEx OSUG@2020 (ANR10 LABX56).

Author contributions

M.D. processed satellite data and ran the radiative transfer code. E.B. and M.G. ran the mass balance simulations. G.P. and Q.L. contributed to the interpretation of satellite measurements. J-R.P. collected measurements at NEEM. M.M. and B.J. analysed the atmospheric chemical reanalysis. M.D., E.B., G.P. and S.M. wrote the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.D.

Competing financial interests

The authors declare no competing financial interests.

© 2014 Macmillan Publishers Limited. All rights reserved.