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Neither dust nor black carbon causing apparent albedo decline in Greenland's dry snow zone: Implications for MODIS C5 surface reflectance

Chris Polashenski
Dartmouth College

Jack E. Dibb
University of New Hampshire, jack.dibb@unh.edu

Mark G. Flanner
University of Michigan-Ann Arbor

Justin Y. Chen
Hanover High School, NH

Zoe R. Courville
Dartmouth College

See next page for additional authors

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Authors
Chris Polashenski, Jack E. Dibb, Mark G. Flanner, Justin Y. Chen, Zoe R. Courville, Alexandra M. Lai, James J. Schauer, Martin M. Shafer, and Mike Bergin

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Key Points:
- No significant change in deposition of light-absorbing impurities on Greenland found
- Albedo decrease by light-absorbing particles in snow is typically <0.005 in interior Greenland
- MODIS-observed albedo decline in Greenland dry snow partly due to instrument degradation

Supporting Information:
- Supporting Information S1

Correspondence to:
C. M. Polashenski,
chris.polashenski@gmail.com

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Neither dust nor black carbon causing apparent albedo decline in Greenland's dry snow zone: Implications for MODIS C5 surface reflectance

Chris M. Polashenski[1,2], Jack E. Dibb[3], Mark G. Flanner[4], Justin Y. Chen[5], Zoe R. Courville[1,2], Alexandra M. Lai[6], James J. Schauer[6], Martin M. Shafer[6], and Mike Bergin[7]

[1]USACE-CRREL, Ft. Wainwright, Alaska, USA, [2]Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, USA, [3]Earth Systems Research Center, EOS, University of New Hampshire, Durham, New Hampshire, USA, [4]Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, Michigan, USA, [5]Hanover High School, Hanover, New Hampshire, USA, [6]Environmental Chemistry and Technology Program, University of Wisconsin-Madison, Madison, Wisconsin, USA, [7]Civil and Environmental Engineering, Duke University, Durham, North Carolina, USA

Abstract Remote sensing observations suggest Greenland ice sheet (GrIS) albedo has declined since 2001, even in the dry snow zone. We seek to explain the apparent dry snow albedo decline. We analyze samples representing 2012–2014 snowfall across NW Greenland for black carbon and dust light-absorbing impurities (LAI) and model their impacts on snow albedo. Albedo reductions due to LAI are small, averaging 0.003, with episodic enhancements resulting in reductions of 0.01–0.02. No significant increase in black carbon or dust concentrations relative to recent decades is found. Enhanced deposition of LAI is not, therefore, causing significant dry snow albedo reduction or driving melt events. Analysis of Collection 5 Moderate Resolution Imaging Spectroradiometer (MODIS) surface reflectance data indicates that the decline and spectral shift in dry snow albedo contains important contributions from uncorrected Terra sensor degradation. Though discrepancies are mostly below the stated accuracy of MODIS products, they will require revisiting some prior conclusions with C6 data.

1. Introduction

Observations indicate that average summer albedo of the Greenland ice sheet (GrIS) has been declining [*Stroeve et al.*, 2013; *He et al.*, 2013; *Box et al.*, 2012]. The resulting changes to the energy balance of the GrIS are leading to increased surface mass losses and sea level rise [*Van Angelen et al.*, 2012; *Box et al.*, 2012; *Tedesco et al.*, 2011]. The albedo decline is most pronounced around the periphery of the GrIS where melt duration is increasing, dirty ice surfaces are increasingly exposed, and impurities are melt accumulated at the surface. Modest long-term summer albedo declines (0.01–0.04/decade) have also been found, however, in Moderate Resolution Imaging Spectroradiometer (MODIS) observations of the dry snow zone [*Dumont et al.*, 2014; *He et al.*, 2013; *Stroeve et al.*, 2013 p. 213; *Box et al.*, 2012]. These reductions in dry snow albedo occur even near the ice sheet summit where melt is rarely a factor and snow albedo is effectively reset each winter by new snowfall. Though the albedo trends are mostly of magnitude comparable to or below the stated accuracy of MODIS MOD/MYD09A1 and MCD43A3 surface reflectance products (0.05) [*Vermote and Kotchenova*, 2011; *Vermote and Saleous*, 2006; *Wang et al.*, 2012; Schaaf, personal communication], they are of magnitude sufficient to have large implications for GrIS energy balance and are consistent, statistically significant, and largely agree in sign with ground station observations [*Box et al.*, 2012]. Therefore, these observations suggest an interannual trend in one or more of the mechanisms controlling dry snow albedo, leading several authors to discuss the trends and speculate on their causes [e.g., *Dumont et al.*, 2014; *Stroeve et al.*, 2013 p. 211; *Tedesco et al.*, 2011].

Two properties dominate albedo in dry snow: (1) snow grain size (technically specific surface area) and (2) the presence of light-absorbing impurities (LAI), typically dominated by black carbon (BC) and mineral dust [*Warren and Wiscombe*, 1980; *Wiscombe and Warren*, 1980]. A trend in one or more of these properties appears necessary to explain the observed dry snow albedo decline. All have been discussed and supported in recent literature. Remote sensing and modeling evidence suggests that enhanced mineral dust transport to the GrIS may be playing a role in GrIS darkening since 2009. *Dumont et al.* [2014] demonstrate a red shift in MODIS reflectivity which would be consistent with enhanced dust concentrations. *Keegan et al.* [2014] suggest enhanced BC concentrations significantly contributed to an albedo feedback that triggered the widespread 2012 melt. Snow high on the GrIS typically has concentrations of BC too low to induce a significant albedo effect

[*Doherty et al.*, 2010; *Hagler et al.,* 2007a, 2007b], but above average spring fire activity in Canada and Siberia [*Giglio et al.*, 2013] and favorable atmospheric transport [*Häkkinen et al.*, 2014; *Fettweis et al.*, 2013] could have combined to cause exceptional BC deposition. Low-albedo anomalies in years with widespread melt events have been linked to snow grain growth and surface melt [*Tedesco et al.*, 2011]. Ongoing surface temperature increases [*Hall et al.*, 2013; *McGrath et al.*, 2013] would be expected to enhance grain metamorphosis.

In this study, we constrain the impact of LAI on GrIS albedo through direct measurement of their concentrations in snow over a wide area of the GrIS and model their impact on albedo. Comparing concentrations from 2012 to 2014 with historic concentrations places them in context. Finding that LAI cannot account for the observed albedo declines, we discuss the potential for grain size effects or MODIS sensor degradation to account for the observed change.

2. Methods

We examined and sampled the upper snow stratigraphy in the northwest sector of the GrIS during two traverses, conducted 1 May to 5 June 2013 and 8–30 April 2014 (see map, Figure S1 in the supporting information). A total of 67 snow pits were sampled at 3 cm depth resolution to characterize the deposition of LAI and snow microphysics over the prior 1–2 annual cycles. Dust and black carbon absorption was then modeled in the Snow, Ice, and Aerosol Radiation Model (SNICAR) [*Flanner et al.*, 2007] to derive the albedo impact of observed LAI concentrations. Our methods for sample collection, processing, and analysis are described in the supporting information.

3. Results

3.1. Concentrations of Light-Absorbing Impurities

Concentrations of black carbon (BC) and water soluble Ca^{+2} concentrations measured from snowpit samples are presented in Figure 1. A seasonal dependence in deposition is evident; mineral dust tracer Ca^{+2} concentrations peak in early spring (~April), and black carbon concentrations peak in summer (~June–August). Average BC and Ca^{+2} concentrations for a full annual cycle (May 2013–2014) are 2.6 ng/g and 13.7 ng/g, respectively, using the 23 sites where continuous samples were collected. Peak BC concentrations, typically found in June–August deposited layers, are 1.1–17.4 ng/g in summer 2012 and 2.8–43 ng/g in summer 2013, with an average peak of 4.0 ng/g during 2012 and 15 ng/g during 2013. The range of peak Ca^{+2} concentrations, typically found in March–May deposited layers, is 32–99 ng/g in spring 2013 and 7.4–290 ng/g in spring 2014 with an average peak of 49.5 ng/g during spring 2013, and 82 ng/g during spring 2014. BC concentrations above 3 ng/g are closely correlated with tracers that indicate a biomass burning source, such as NH_4 (Figure S2). BC concentrations show regional dependence with slightly enhanced BC deposition over central Greenland in summer 2012 and strongly enhanced BC deposition in our study area during summer 2013. Ca^{+2} concentrations are highest in samples collected near the periphery of the GrIS (below 1500 m elevation). This could potentially indicate some local dust sourcing, but is predominantly due to significant contributions of sea salt Ca^{+2} ($ssCa^{+2}$), that is removed before albedo impact analysis below.

3.2. Albedo Impact of Light-Absorbing Impurities

The albedo impact of observed impurity concentrations (relative to pure snow) is modeled and plotted in Figure 2 (see supporting information Text S3). We find albedo impacts of dust and BC are typically low. Average total albedo reduction is 0.0031 (0.0026–0.0035) in the central (low-high) scenarios of dust absorptivity. Albedo reduction, relative to pure snow, is less than 0.005 in 90% (83–92%) and less than 0.01 in 97.6% (96.5%–98%) of samples. In isolation, the albedo reduction attributed to dust averages 0.0009 and only rarely exceeds 0.005 (0.6% of samples), while BC impacts average 0.0016 with 5 times as many (3.3%) of samples indicating impact over 0.005. On average, therefore, LAI concentrations are roughly an order of magnitude too low to be the leading factor in MODIS-observed 0.01–0.04/decade dry snow albedo reduction noted by *Dumont et al.* [2014], *Stroeve et al.* [2013], *He et al.* [2013], and *Box et al.* [2012].

The few samples indicating high BC impact were mostly contained in a summer 2013 stratigraphic layer where BC was sufficient to reduce albedo by 0.01–0.02. Stratigraphic records and snow accumulation sensors on weather stations, however, show that the timing of this particular layer's deposition (well after peak annual insolation) and its subsequent burial (within several days) limited impact on surface energy balance.

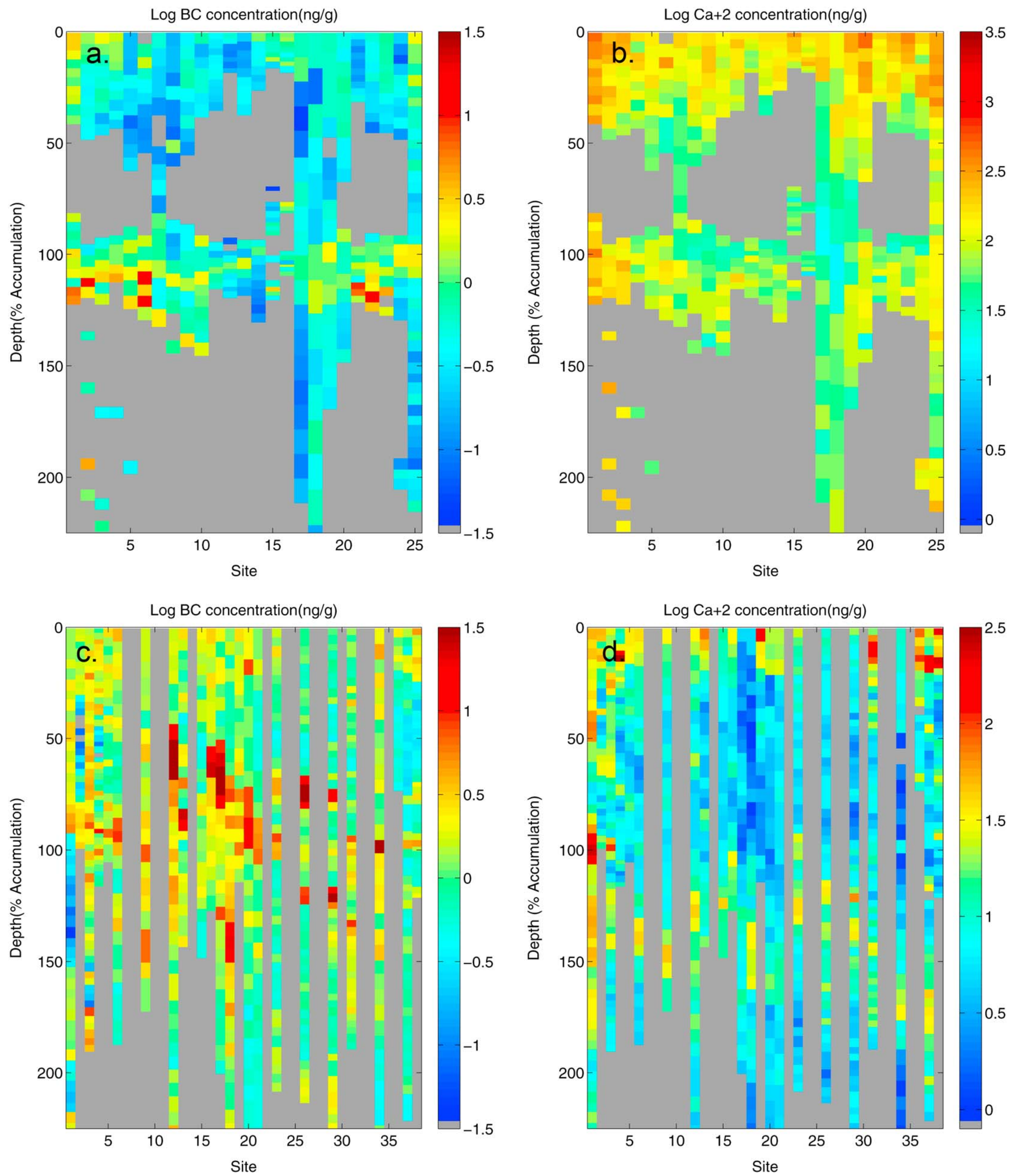

Figure 1. BC and Ca^{+2} concentrations from samples collected in (a, b) 2013 and (c, d) 2014. Depth (*y* axis) is plotted as a percentage of the accumulation since the prior summer melt/hoar layer; 100% corresponds to the depth of the prior mid-July–early August, and 0% is surface on the date of sampling in April/May. The previous April/May, 1 year prior to sampling, is near 130%. Grey indicates incomplete data. Peak Ca^{+2} occurs each spring, while peak BC occurs in summer.

Snow rich in BC fell primarily in an 8–9 August 2013 storm and was buried in subsequent storms on 11–13 and 28–30 August 2013. A similar layer deposited in spring or early summer and left unburied, however, could have significant impacts on annual energy balance and progression of melt.

4. Discussion

4.1. Comparison to Historical Observations of Impurities

The LAI-caused albedo impacts, calculated relative to pure snow, are small. We compare our measurements of LAI to prior studies of BC and dust in order to evaluate whether the impurity concentrations we observe are trending upward relative to historical averages. We also compare the makeup of these impurities to earlier

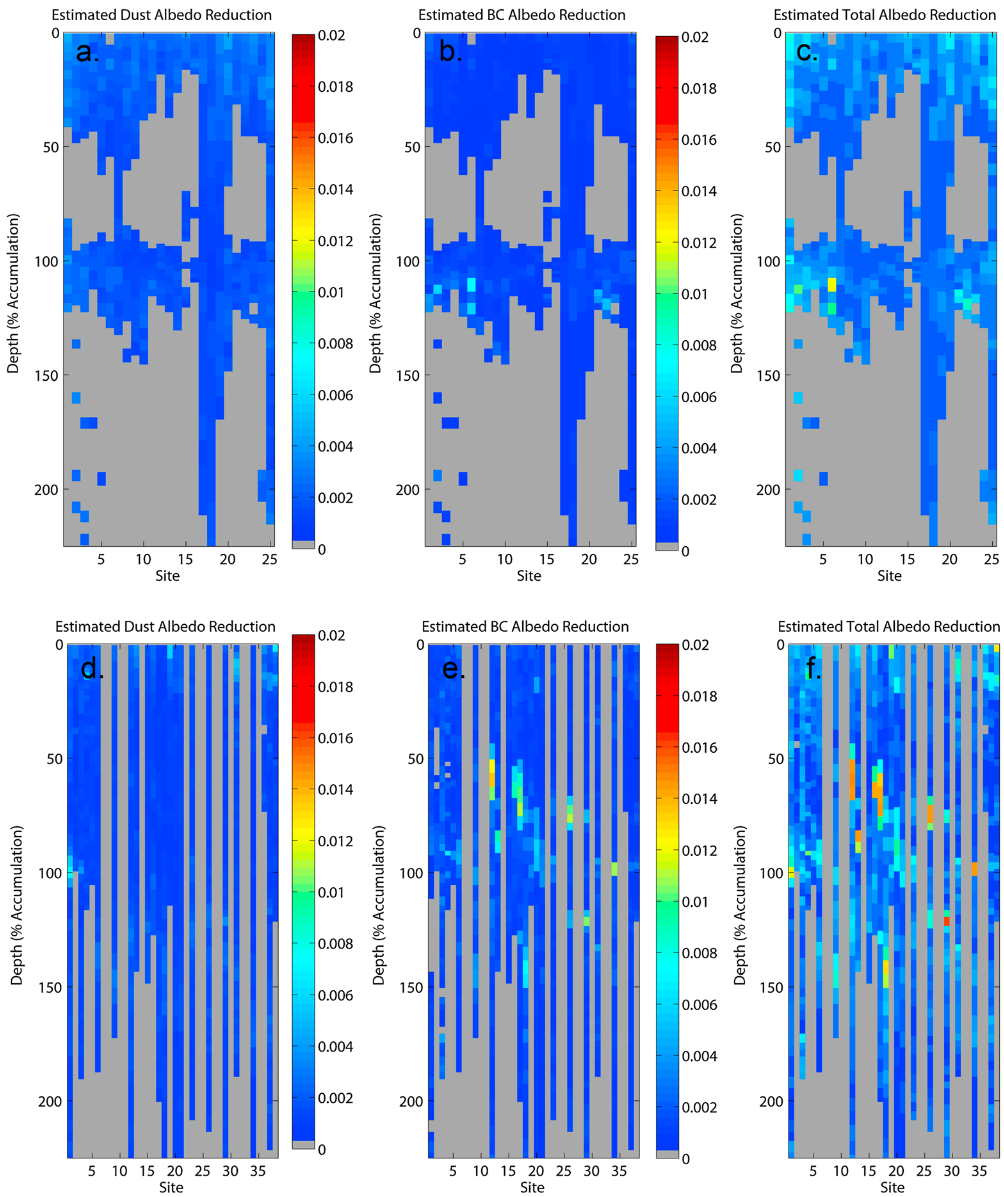

Figure 2. Modeled central scenario albedo reduction by (a) dust, (b) BC, and (c) combined dust and BC relative to pure snow for impurity observations collected in 2013; same for (d) dust, (e) BC, and (f) combined dust and BC for 2014 observations. As in Figure 1, depths are % of the accumulation since the prior summer melt or hoar layer.

studies to evaluate whether their composition has changed in a manner that would increase their absorptivity independent of changes in concentration. The best indications are that neither the quantity nor mineralogical makeup of LAI deposited on the GrIS has undergone significant optically relevant change from long-term averages in the past several years.

Black carbon observations, both in contemporary snows and ice core records, indicate stable or slightly declining BC concentrations on the GrIS of similar magnitude to our observations. A review of available observations (see supporting information Text S4.1) shows that BC concentrations high on the GrIS have been relatively stable since the 1950s, with annual averages typically in the 1.5–3 ng/g range, and episodic events depositing 5–10+ ng/g a few times a decade at a given site. Our observation of a mean 2013–2014 BC of 2.6 ng/g, with a mean peak of 15 ng/g, therefore, is consistent with historical estimates. Our observations in 2012–2013 do not capture a full annual cycle but do contain the 2012 summer peak concentrations (average peak, 4 ng/g), also indicating no significant departure from long-term norms, even in this year of record melt.

A wealth of prior observations is also available on dust and dust tracers, particularly on total elemental calcium (here referred to as Ca) and water soluble, typically IC-determined calcium (here Ca^{+2}) (see supporting information Text S4.2). Contemporary snow studies show a range in annual average concentrations from 5.3 to 14 ng/g Ca^{+2} at sites across the GrIS since 1950, similar to the longer-term stable range of 5.4–16 ng/g throughout Holocene ice core records. These ranges nicely bracket our 9.6 ng/g 2013–2014 interior GrIS annual average, again indicating we observed nothing trending out of normal variability ranges. Prior observations also show a clear seasonal signal with peak Ca^{+2} concentrations averaging 23–40 ng/g, slightly less than our 2014 spring mean peak (46.9 ng/g) but still comparable. Considering total dust rather than Ca^{+2} tracers, we use elemental analysis and a mineralogical mixing model (see supporting information Text S2 and S4.2) to show that our observations indicate a mean interior GrIS dust concentration of 33–45 ng/g, closely matching dust concentrations observed in contemporary snow (45 ng/g) [*Bory et al.,* 2002] and from core records collected at the GRIP site throughout the Holocene (33–53 ng/g) [*Steffensen*, 1997].

Finally, it appears that the optically relevant part of the mineralogical composition of the dust has remained stable. Average (median) observed concentrations of Fe, an indicator for the most absorptive parts of the dust mineralogy, were 10.6 (6.1) ng/g. The subset of our samples analyzed for metals overweights the high dust deposition (spring) layers, so we expect this to be somewhat high relative to full-year observations. With this in mind, our Fe concentration compares well with earlier observations, which mostly fall into the range of 1–10 ng/g (see supporting information Text S4.2). Similarly, the central estimate of hematite mass fraction in our measurements (5.6%) is consistent with the stable Fe_2O_3 fraction seen since prior to the last glacial maximum (7.0%, [*Laj et al.*, 1997]; 5.0% [*Lanci et al.*, 2004]).

The conclusion that our observations show no significant changes in dust composition is not surprising. A significant body of prior work points to stable composition and long-term sourcing of GrIS-deposited dust from East Asia, specifically the Taklamakan desert, for the majority of the dust reaching Greenland [*Biscaye et al.,* 1997; *Bory et al.*, 2002, 2003a, 2003b; *Grousset and Biscaye*, 2005; *Kahl et al.*, 1997], interrupted only by isolated events [*Donarummo et al.*, 2003; *Dibb et al.*, 2007]. Others have shown similar mineralogical composition of deposited dust in samples of contemporary snow and seventeenth century core segments [*Drab et al.*, 2002; *Bory et al.*, 2003b].

4.2. Other Mechanisms for Albedo Change

At least two physical mechanisms for dry snow albedo reduction remain: grain size growth [*Wiscombe and Warren*, 1980] and, potentially, algae and/or microbial growth [*Benning et al.*, 2014].

Snow grain size can cause direct reductions in albedo (mostly in the near-infrared) and indirect effects by enhancing the visible albedo reduction caused by LAI. It is also possible, though conjectural, that dust, BC, or ion concentrations might also alter the rates of grain metamorphosis to compound the albedo impact of an enhancement of a particular moiety [e.g., *Hörhold et al.*, 2012]. A decline in albedo from grain size changes during the MODIS record seems likely. Metamorphism rates increase with rising temperature, and trends of +1.35 ± 0.47C/decade are observed on the GrIS during the MODIS record [*Hall et al.*, 2013; *McGrath et al.*, 2013]. Increases in grain size have also been implicated in episodic events [*Tedesco et al.*, 2011]. Contradicting these expectations, however, the spectral character of MODIS albedo decline (discussed below) is not consistent with a significant change in grain size. Negative feedbacks such as increased snowfall, expected with warmer temperatures, could counterbalance enhanced metamorphosis by increased burial rates [*Box et al.*, 2013].

We have no observations of snow algae or microbial content but rule out significant albedo contribution in the dry snow zone based on studies of growth habits and the lack of seasonality in MODIS-observed albedo declines. Most biota require melting snow and air temperatures near or above 0°C for extended times for significant growth [*Hoham*, 1975; *Ling and Seppelt*, 1993]. Mean dry snow zone temperatures are well below 0°C even in midsummer, and albedo declines observed in the MODIS record occur even during the early spring [*Dumont et al.*, 2014, Figure 1] when surface temperatures are particularly inhospitable.

4.3. Reconciling Our Evidence With Observed MODIS Albedo Declines

The remaining hypothesis is that the spectral trends in MODIS-observed albedo are not physically real. Because the trends are mostly below the stated accuracy (0.05) of the MODIS surface reflectance products, this is not unlikely nor would it discredit the MODIS products. The fact that the trends are statistically

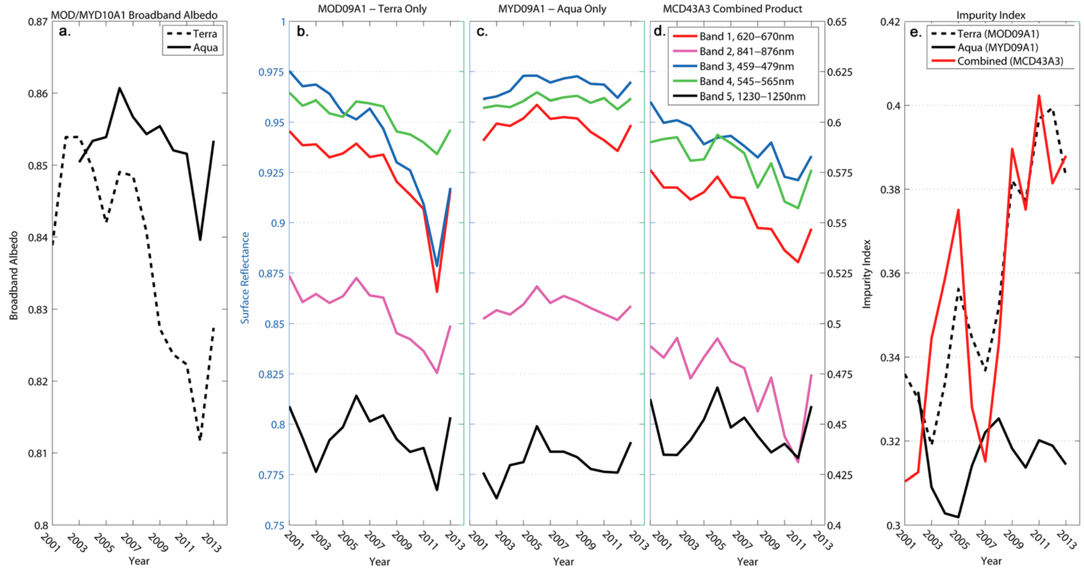

Figure 3. Average 15 May to 15 July MODIS surface reflectance, dry snow zone of the Greenland Ice Sheet (a) broadband albedo from MOD/MYD10A1. (b–d) Spectral bands 1–4 (left *y* axis) and 5 (right) for MOD09A1, MYD09A1, and MCD43A3 products, and (e) impurity index calculated from data in Figures 3b–3d.

significant and discussed in high profile GrIS literature [*Dumont et al.*, 2014; *Stroeve et al.*, 2013; *He et al.*, 2013; *Box et al.*, 2012], however, demands we investigate more closely. We examine in particular the possible role of uncorrected sensor degradation in Collection 5 (C5) MODIS data and demonstrate inconsistencies between the Terra and Aqua sensors which indicate its importance.

Average summer albedo (15 May to 15 July) is plotted for the GrIS dry snow zone using C5 MODIS data sets (Figure 3). An independent passive microwave melt mask [*Tedesco et al.*, 2011], elevation cutoff, and quality flag filtering ensure we strictly consider dry snow albedo changes and utilize only the best available data (see methods, supporting information Text S5). As expected from prior work [e.g., *Dumont et al.*, 2014], the MCD43A3 surface reflectance product shows declines in bands 1–4 albedo (Figure 3d), with little change in band 5 albedo, a spectral signature indicative of increases in dust and unchanged grain size. Following methods of *Dumont et al.* [2014], we calculate a spectrally derived impurity index from MCD43A3 data (Figure 3e, red line). Modeling carried out by *Dumont et al.* [2014, Figure S4] indicates that an increase of ~3000 ng/g dust along with ~5 ng/g BC would be required to create an impurity index shift of this magnitude. Highlighting the discrepancy which must be resolved, our in situ observations indicate only 33–45 ng/g (mean) dust, with no indication of significant trends.

Analysis of MODIS sensor degradation by *Lyapustin et al.* [2014] suggests that C5 data show systemic temporal trends in MODIS bands 1–7, which cover parts of the visible and NIR spectrum. Degradation is primarily on the Terra sensor, largest in the blue band (band 3), and decreases with wavelength. We plot GrIS dry snow zone albedo from the two MODIS sensors separately (Figures 3a–3c) to check for such trends. The result matches the pattern of uncorrected degradation presented by *Lyapustin et al.* [2014] and provides support for a hypothesis that uncorrected differential sensor degradation controls much of the observed trends. Terra (MOD10A1) shows a trend toward declining broadband albedo (−0.03/decade), while Aqua (MYD10A1) shows no significant trend (Figure 3a). The spectral reflectance bands 1–4 (red, NIR, blue, and green, respectively) show large declines (0.03–0.07/decade) for Terra (MOD09A1) (Figure 3b) but stable reflectance (−0.005 to +0.001/decade) for Aqua (MYD09A1) (Figure 3c). Neither exhibits a significant trend in band 5 (1230–1250 nm) albedo, a wavelength sensitive to changes in snow grains. The spectral differences result in near-zero trend in impurity index for Aqua and strongly positive trend for Terra (Figure 3e). Aqua's near-zero trend in dry snow albedo (Figures 3a and 3c) is consistent with our SNICAR calculations showing extremely small impacts on albedo from LAI.

MCD43A3, a more sophisticated surface reflectance product made using a full BRDF (Bidirectional Reflectance Distribution Function) inversion from multiple high-quality observations from both sensors (Figure 3d), also shows trends that fall between Aqua's stability and Terra's steep declines. Ideally, we would process separate

Terra and Aqua products from this data set as well, however, these data sets are not routinely produced or publicly available and producing them offline is problematic. The BRDF algorithm requires multiple angular observations for a full high-quality inversion, which are frequently unavailable within a 16 day window from only one sensor. We were able to examine separately processed MCD43A3 data at a test pixel in the dry snow zone, thanks to the generous help of members of the MODIS team (C. Schaaf and Q. Sun, personal communication, 2015). As expected, only a small fraction of high-quality retrievals were possible. The data showed a similar pattern of sensor-sensor discrepancy: declining albedo trends in Terra data and a lack of trends in Aqua, with the larger differences in shorter wavelength bands. The discrepancy between the sensors was, however, smaller than in the MOD/MYD09A1 data. Differences in trends were $<$0.035/decade, and absolute differences between sensors were mostly $<$0.025. Though smaller, these observed differences, combined with strong similarity between combined MOD/MYD09A1 trends and the full BRDF inversion product in MCD43A3 (Figure S3), lead us to conclude that the MCD43A3 product trends are also influenced substantially by the Terra degradation.

We considered the possibility that the Terra-Aqua discrepancy could be caused by environmental conditions instead. We rejected the possibility that different overpass times or loss in effectiveness of Aqua's cloud filter due to channel 6 failure might be the cause of the discrepancy in trends between the sensors. Terra and Aqua have daytime overpass times at 77 N, 55 W (near the center of our 2014 sites) of approximately 1300 and 1100 local solar time, respectively. These overpasses offer roughly equal solar zenith angle (SZA) and only a modest potential for diurnal variation in atmosphere properties. More importantly, differences caused by SZA or clouds would have the strongest impact in the NIR part of the spectrum, where our analysis shows good sensor agreement and almost no albedo trend.

We acknowledge that prior work has discussed the potential impacts of MODIS sensor degradation on GrIS albedo observations or evaluated MODIS trends against in situ data [e.g., *Stroeve et al.*, 2013; *Dumont et al.*, 2014; *Box et al.*, 2012] and concluded that the impact of Terra degradation is insignificant. *Stroeve et al.* [2013] used sensor-separated MOD/MYD43A3 products (calculated offline) in a small test area of northern Greenland to show that broadband albedo trends appear the same with both sensors. We did not have access to these data sets. Instead, we use spectral MOD/MYD09A1 products to show for a broader area, and over greater time, that significant discrepancies between the two sensors exist.

Box et al. [2012] and *Stroeve et al.* [2013] show agreement between MODIS and in situ GC-Net albedo decline, confirming a trend in ice sheet-wide albedo. We agree that these data are well correlated and indicate ice sheet-wide albedo decline, but note that this is mostly due to increased melt. Applying our melt filter to the GC-Net site locations excludes all but six sites (Humbolt, Summit, Tunu-N, NGRIP, NASA-E, and NEEM) due to regular occurrence of melt. Evaluating average June–August albedo trends at the dry sites shows three increasing and three declining, with a small, nonsignificant summer albedo trend of -0.007/decade (Table S2). In contrast, MOD10A1 observations trend downward with statistically significant trends averaging -0.036/decade [*He et al.*, 2013]. Earlier in spring, more of the stations are in dry snow. A somewhat larger array of sites (all six from above, plus CP1, DYE-2, Saddle, South Dome, and NASA-SE) can be examined in May while still excluding melt. These show a negative trend of -0.015/decade, with approximately 75% of sites trending downward (*Box et al.* [2012] and updated analysis through 2014) (J. Box personal communication, 2015). This provides some evidence that part of the dry snow zone albedo decline could be real, perhaps due to grain size effects. The GC-Net albedo trend, however, is still exceeded by the average MOD10A1 trends in May at this larger array of sites (-0.031/decade).

Finally, *Dumont et al.* [2014] consider the possibility of sensor degradation by selecting an area of Antarctica as a pseudoinvariant test case and, finding that MCD43A3 trends seen on the GrIS are absent there, conclude that the GrIS trends are genuine. Exploring whether Antarctic albedo is indeed invariant is beyond our scope. Instead, we point out that the spectral declines we observe in Greenland, particularly for Terra, are similar to those reported for the NASA-selected pseudoinvariant desert calibration sites during the derivation of C6/6+ calibrations, and that the desert sites are thoroughly evaluated for stability [e.g., *Sun et al.*, 2014; *Lyapustin et al.*, 2014].

5. Conclusions

We observe black carbon and dust tracer concentrations in the snow of NW Greenland during 2012–2014 which are consistent with observations over the past 60 years (BC) and throughout the Holocene (dust tracers).

Radiative transfer modeling shows that the direct impact of aerosol impurities on GrIS dry snow albedo is relatively small (mean −0.0031), though episodic aerosol deposition events can reduce albedo by 0.01–0.02. While the reduction is important for the energy balance of the GrIS and episodic deposition events could initiate significant albedo feedbacks if timed correctly, we find no evidence that would support a hypothesis that observed interannual to decadal *trends* in albedo are being caused by changes in the deposition of either class of LAI.

Examining the spectral signature of the dry snow zone albedo declines detected by MODIS satellites Aqua and Terra separately, we find conflicting trends which appear indicative of uncorrected sensor degradation in C5 products. Albedo decline is generally indicated by Terra but not by Aqua. These discrepancies occur in both MOD/MYD09A1 and MOD/MYD43A3 products, with larger discrepancies in MOD/MOD09A1 products. Though the magnitude of the trends is mostly below the 0.05 stated accuracy of the MODIS products, they have previously been used to both indicate changing GrIS dry snow zone albedo and diagnose its cause, making their discussion highly relevant [e.g., *Dumont et al.*, 2014; *Stroeve et al.*, 2013; *Tedesco et al.*, 2011; *Box et al.*, 2012]. After considering prior work on MODIS degradation and independent in situ albedo observations, we find the most likely means to reconcile the lack of increasing trend in LAI deposition with the apparent declines in MODIS visible band dry snow albedo is to attribute a significant fraction of the MODIS dry snow zone albedo trend to uncorrected sensor degradation, primarily on Terra. This conclusion is further supported by analysis of GC-Net data, which shows lower, nonsignificant trends in dry snow zone albedo than indicated in MODIS products. We expect, therefore, that the corrections for degradation in C6 data will greatly reduce or remove the MODIS trend in dry snow zone albedo. The same corrections would apply across other regions of the ice sheet, impacting trends. While the discrepancies identified are not large enough to alter the conclusion that overall ice sheet albedo is declining due to increased extent and duration of melt, the likely adjustment of MODIS albedo trends by 0.01–0.03+ (depending on product and band) may have significant implications for modeling efforts and broader reaching conclusions about ice sheet energy balance in a warming climate.

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