Dr. Andrew Klein, Editor

Dear Dr. Klein,

We are attaching a response to all comments of the three reviewers of this manuscript, along with a version of the manuscript with track changes included. We have made changes to the structure of the manuscript following the comments of reviewers #1 and #2 by moving results material from the discussion section to the results section, and creating a new section discussing methods, and have made generally minor corrections throughout following the suggestions of the reviewers. Thanks very much to you and to the reviewers for your work towards the publication of this manuscript.

Sincerely,
Patrick Alexander
(On behalf of all co-authors)

Additional Corrections
In addition to the corrections made in response to the reviewers, we have identified and corrected an error in the manuscript as follows.

In particular, the spectral range of the K-Transect sensors is 0.3 – 2.8 μm, larger than the stated range of 0.3 – 1.1 μm. This affects the interpretation of the results and portions of the text have been changed accordingly. Specific corrections have been made as described below. Pages and line numbers refer to the version of the manuscript with track changes, provided below.

1. P. 12, 4-5. The spectral range of K-Transect data has been corrected: "K-Transect data are collected in the 0.3-2.8 μm band."

2. P. 12, Lines 15-17: The sentence "This bias likely also applies to K-Transect measurements, as the spectral sensitivity at K-Transect sites is comparable to the sensitivity at GC-Net locations." (P. 10 Lines 14-16) has been changed to "This bias does not apply to K-Transect measurements, as the spectral sensitivity at K-Transect sites is comparable to the sensitivity of MODIS sensors."

3. P. 13, Lines 28-33, P. 14, Lines 1-2: The following has been added:
"These results appear to be consistent with a positive bias in GC-Net measurements identified by Stroeve et al. (2005). However, we also find that the difference between in situ and satellite albedo is larger at K-Transect stations (+0.08) than at GC-Net sites (+0.04), and K-Transect data are not expected to exhibit the positive bias. It is likely that the high spatial variability of ablation area albedo contributes to the differences. In situ stations may be positively biased relative to satellite data because of a bias introduced by station locations: stations are unlikely to be placed within streams, lakes, or crevasses, which have a lower albedo. In the acccumulation zone, a lack of variation in surface features likely leads to smaller spatial variations in albedo."

4. P. 15, Lines 31-33; P. 16, Lines 1-2: "Data from in situ stations may be positively biased relative to satellite data because of a bias introduced by station locations: locations are not chosen to be within streams, lakes, or crevasses, which have a lower albedo. In the acccumulation zone, a lack of variation in surface features likely leads to smaller spatial variations in albedo."

5. P. 24, Line 20: "In situ" has been changed to "GC-Net".

Response to Reviewer 1:
Interactive comment on "Assessing spatio-temporal variability and trends (2000-2013) of modelled and measured Greenland ice sheet albedo" by P. M. Alexander et al.
Anonymous Referee #1

The following is a review of "Assessing spatio-temporal variability and trends (2000-2013) of modelled and measured Greenland ice sheet albedo" by P. M. Alexander, M. Tedesco, X. Fettweis, R. S. W. van de Wal, C. J. P. P. Smeets, and M. R. van den Broeke

This manuscript is a brief communication, investigating how modeled albedo compares with satellite-based and in situ observations. The authors focus on comparison between the spatial and temporal variability of albedo on the Greenland Ice Sheet surface during the summertime. The modeled albedo is a product of the latest version of the MAR Regional Climate Model (v3.2). For a comparison, the authors include results from a previous model version, which implements a different albedo scheme (v2.0). The study finds agreement amongst all products that low-elevation albedo has decreased over the last decade. They also find that, in this area, MAR exhibits a positive bias. In the accumulation area, they find that two different MODIS products show a decrease in surface albedo. However, this trend is neither reproduced in the model nor present in the in situ observations, suggesting that MODIS instrument degradation may play an increasingly significant role in these types of analyses.

As the authors point out, this is the first time an assessment of this kind has been presented with respect to surface albedo over Greenland Ice Sheet. The analysis presented here is thorough and well thought-out. Clearly, a good deal of work was put into trying to put model results on equal footing with different types of observations , so that they could be compared in this manner. Results are kindly presented in a variety of ways, n order to highlight product differences and to aid in the discussion. In addition, this study advances the scientific community's understanding of the biases that exists in regional climate models and at the same time, brings to light those that may be present in remote sensing products. Therefore, I recommend this paper for publication in The Cryosphere.

A few general comments for the authors' consideration:
- Title: The title is awkward, especially with placement of the years. Perhaps placing the years at the end might help this? ('Assessing spatio-temporal variability and trends of modeled and measured Greenland Ice Sheet albedo (2000-2013)'?)

The title has been changed to: "Assessing spatio-temporal variability and trends in modeled and measured Greenland ice sheet albedo (2000-2013)"

-Abstract: An additional final sentence about the significance of these results or repercussions they would have on the community would make the abstract stronger. Also, it is not necessary to define ablation and accumulation in the abstract.

As suggested, a final sentence has been added to the abstract highlighting the significance of the study's results. The definitions of ablation and accumulation areas have been removed.

- A number of times, model results are referred to as 'data'. Please refrain from this terminology when discussing ECMWF and MAR output fields.

We have replaced all references to MAR or ECMWF "data" with appropriate terms such as "outputs" or "results".

- Consider using the terms accumulation and ablation 'area' instead of zone, since you are usually assessing the entire area as a whole.

All references to "ablation zone" or "accumulation zone" have been changed to "ablation area" or "accumulation area." (Also suggested by Reviewer #3)

- You also may want to consider introducing results of the MAR3.2 and MAR2.0 comparisons earlier in the paper. If this was done in the results, it would make for a clearer and more direct discussion in section 4.2.3.

The results of the MAR3.2 vs. MAR 2.0 comparisons (Section 4.2.3) have now been moved to the results section (Section 3.4). Section 4.2.2 has been modified to incorporate discussion of the results in Section 3.4. The figures and tables have been rearranged appropriately.

- Some simple titles, or indicators on the figures would be helpful for fast reference. It would save the reader from having to constantly refer to the captions for a reminder of what is being compared.

Additional titles have been added to Figure 2, Figure 3, Figure 6 (Now Figure 7), Figure 7 (Now Figure 8), Figure 10 (Now Figure 13), Figure 11 (Now Figure 14), and Figure 14 (Now Figure 12). We feel the others do not need additional titles as they already have axis labels.

- I found myself getting confused about the values of min and max dry snow and bare ice albedo values for the different models. A simple table of these values would be very helpful for reference and maybe make the albedo ranges clearer to the reader. Then you would not have to always insert the values into the text. (For example, 'maximum bare ice albedo' is equal to .55 but bare ice albedo can range up to 0.6 – section 4.2.3).

Table 1 now provides the range of values for snow, ice and firn for MAR v3.2 and v2.0 and values have been removed from the text in some instances. The statement that bare ice albedo can "range up to 0.6" was incorrect. This has been revised to read "range up to 0.55".

Below, I offer some more specific comments/suggestions:

Page 3735, line 23-29: Please consider rephrasing. This sentence is awkward.
The sentence has been removed and replaced with the following two sentences:
"Nevertheless, given their relatively high temporal and spatial resolution, these products are useful for evaluating albedo derived from regional climate models (RCMS). RCMs are an important tool for estimating both current and future changes in the GrIS SMB (Box and Rinke, 2002; Box et al., 2006; Ettema et al., 2009; Fettweis et al., 2007, 2011; Rae et al., 2012, Tedesco and Fettweis, 2012), and the surface albedo schemes employed by these models have a substantial impact on their simulation of the SMB (Rae et al., 2012; van Angelen et al., 2012; Lefebre et al., 2005; Franco et al., 2012)."

Page 3736, line 23: Reference for ERA? (Uppala, 2005)
References to Uppala et al. (2005) for ERA-40 and Dee et al. (2011) for ERA-Interim have been added in the text and the reference list.

Page 3737, line 23: The use of 'vice versa' here is not clear.
The relationship between these grain properties and optical diameter is in fact somewhat complex, and unnecessary to include here. We have simply revised the text to read "MAR snow albedo (α) depends on the optical diameter of snow grains (d), which is in turn a function of other snow grain properties, such as grain size, sphericity and dendricity." Readers who are interested in further details can refer to the references provided.

Section 2.3: It would be nice to specify that MODIS is available 2000-2013, since state the years in the MAR and the in situ sections.
The range of dates for the MODIS products is now provided in section 2.3.

Page 3746, line 1: Please be more specific that the term 'close to'.
The sentence has been removed. We have added a more specific mention of biases at K-Transect and GC-Net sites.

Page 3748, line 2: Typo, 'products'
The typo has been corrected.

Page 3751, line 1: Reference for snow metamorphism?
The paper Wiscombe and Warren (1980), which was already provided in the reference list, has now been cited in section 4.1.

Page 3751, line 11: This statement suggests that these papers showed that albedo trends are driven by atmospheric circulation changes. It is my understanding they connect the melt to circulation change (but not actually the albedo trends to the circulation). Please review this sentence for clarity.
Yes, this was the intended meaning of the sentence, but we agree that the meaning was ambiguous. The sentence has been split into two:
"…captured by models (Fettweis et al., 2011; Ettema et al., 2009) and in situ observations (van de Wal et al., 2012). Increased melting has been linked to warmer regional atmospheric air temperatures, associated with atmospheric circulation changes (Fettweis et al., 2013a; Häkkinen et al., 2014)."

Page 3759, line 11: Perhaps 'confirm' instead of 'prove'?
The reviewer must have been referring to Page 3757, line 11. "Prove" has been changed to "confirm" as suggested.

Response to Reviewer #2

Interactive Comment on "Assessing spatio-temporal variability and trends (2000-2013) of modelled and measured Greenland ice sheet albedo"

This paper is an important contribution to understanding mass loss from the Greenland ice sheet as albedo is one of the central variables in this process. In this paper, several different products of Greenland ice sheet albedo are compared, including satellite, regional climate model and in situ data. The insights provided in this paper are highly valuable as many scientists use these datasets and models. The methods and data interpretations are sound. Most of my comments are about presentation of the material and organizing the manuscript.

Major comments 1. Follow the Introduction-Methods-Results-Discussion manuscript structure, which many readers expect of this kind of paper by making the following corrections:
a. Add new sections to the methods section that describe your comparison methodology and analysis of trends. For example, describe the method you used to calculate trends (linear regression or non-parametric methods?).

Section 2.5, "Methods of Analysis" has been created. Some of the material from the original sections describing comparison methods has been moved here, and a new section (2.5.5) discusses statistical techniques.

b. Several new analyses and their methods are introduced in the discussion section. Consider moving the presentation of the analysis shown in Figure 12-14 to the result section, and explain the methodology of these two analyses in the methods section.

The structure of the manuscript has been altered as suggested by reviewers 1 and 2. The discussion of MAR v3.2 vs. 2.0 (originally section 4.2.3) has been moved to section 3.4. The new material originally presented in section 4.2.1 has been moved to section 3.1. Various statements with regard to methodology have been removed in the discussion section and are now included in the new methods section.

2. Paper can be rewritten to be more concise. For example, figure caption text sometimes appears in several figures or both in the caption and the text. It may be sufficient to only write it once. Furthermore, you do not have to explain what the figure shows in the text (e.g. sentences starting with "In Fig. X, we show" since this is made clear in the figure caption. I have pointed out some but not all occurrences below.

The suggested changes have been made wherever possible, and have improved the flow of the manuscript.

3. Could the correlation in Figure 7 be close to zero in the accumulation zone because the standard deviation is close to zero? If the data has no variation, no correlation is expected. If so, the correlation analysis is not suitable to describe the similarity between the datasets in this region.

Yes, we intended to imply this in the statement:
"Within the accumulation area, correlation between MAR and MODIS products is generally poor ($r^2 < 0.2$) and not significant at the 95% confidence level. Again, in this region, variability is smaller than the assumed uncertainty for MCD43A3."

To be clearer, the final paragraph of section 3.2 now begins with:

"For areas south of 70°N and in the ablation area north of 70°N, the two MODIS products are highly correlated (for MCD43A3 16 day periods, $r^2 > 0.5$), but in the accumulation area north of 70°N this correlation decreases (Fig. 8a). Poor correlation in this area is likely a result of the low standard deviation of albedo which falls within the uncertainty range for MODIS."

And ends with:
"Again, in the accumulation area, it is difficult to draw any conclusions regarding correlation, as the variability in albedo is smaller than the assumed uncertainty for the MODIS products."

Minor comments

P3734. L26. Consider rewriting this sentence. There is not 'direct' relationship between temperature and melt. It is the surface energy balance that drivers surface melting.
The sentence has been changed to read: "Increased melt over Greenland has been associated with both changes in temperature and an amplifying ice-albedo feedback: increased melting and bare ice exposure reduce surface albedo, thereby increasing the amount of absorbed solar radiation and, in turn, further amplifying melting (Box et al., 2012; Tedesco et al., 2011)."

P3736. L1-4. Be more specific about what products you are using in your comparison and provide more insights to your methods to give a roadmap of the paper here. State the number and exact MODIS products used, as well as the two AWS datasets, also clarify that you are using MAR 2.0 and 3.2 as RCM. Mention that you have regridded data and calculated averages over the same time interval to make intercomparison possible. Here you can also state the study period and what part of the ice sheet you are considering. Finally, explain that you are also investigating potential errors due to differences in albedo spectral range, MAR albedo scheme, etc etc. You can remove lines 5-8 since it follows the standard structure for a scientific paper.
Further details have been added here following the above suggestions. The sentences referring to the paper structure have been removed.

P3736. L4. The reference to Fettweis does not seem necessary unless you explain why he used MAR 2.0 over 3.2 in his 2013 papers.
(We assume the reviewer was referring to P3737). The reference has been removed there.

P3736. L18. Rewrite. You are using both MAR 3.2 and 2.0 in this paper.

The sentence and portions of the subsequent paragraph have been revised to indicate that we focus primarily on MAR v3.2, but also consider MAR v2.0 outputs.

P3737. L10. Remove "some". Presumably "all" ice edge stations with less than 100% MAR ice covered where analyzed in this way. If not, you need to list which stations you applied this method too and explain why only 'some' ice edge station were analyzed this way.
This sentence has been removed from this section. We now provide more specific details in section 2.5.3. Indeed, we use data from the MAR "ice-covered" sector in the comparison in *all* cases where a station falls within a MAR grid box with less than 100% ice cover.

P3737. L25. Repetitive
The sentence has been revised to read:
"Albedo has been defined in MAR for three spectral intervals:"

P3738. L7. Consider substituting "bands" with "ranges".
We have chosen to use the word "interval", which is also used at a later point in the text.

P3744. L1-8. This belongs in the method section. You can be more assertive, there is little doubt that surface albedo in JJA is most important for SMB.
The methods material here has been moved to section 2.5.5. "Is likely to have the largest impact on SMB" has been changed to "has the largest impact on SMB".

P3744. L8-10. Consider remove sentences like this to make article more concise. This information is given in the figure and table captions. I propose you go straight to your results and refer to figures in parenthesis.
The sentences have been removed here, and wherever possible the suggested revisions have been made.

P3744. L13. Add a reference to Figure 2 at the end of this sentence.
The section now begins with this sentence, and it refers to Figure 2.

P3744. L20. Instead of "compared to Fig 3a" spell out what product differences are shown in Fig 3a.
The sentence has been revised as noted in the response to the next comment.

P3744. L20. I disagree with your interpretation of Figure 3. It is difficult to see if the spatial variability in 3a is less than in 3b and 3c. While 3a does not have the strong positive anomalies in Fig 3b and 3c, it appears to have the strongest negative anomalies.
The intent was to point out differences in patterns of spatial variability rather than the magnitude of spatial variations in albedo. The sentence now reads:
"The pattern of differences between MAR v3.2 and the two satellite products (Fig. 3b and c) appears to vary with both elevation and latitude, while the difference between the two satellite products varies primarily with latitude (Fig. 3a).

P3745. L18-24. Consider removing to make the paper more concise. This is "methods" and I believe it is already explained there.

These sentences have been removed and some of the information has been moved to the Methods section.

P3746. L6-7. This sentence is also in the figure text. It only needs to appear once.
The sentence has now been removed.

P3746. L23-25. Rewrite. Replace standard deviation with spatial variability. The figure "indicate" something about spatial variability.
The sentence has been revised to read:
"Within the low elevation ablation area of the ice sheet, both MAR and the MODIS products exhibit a relatively high standard deviation for the 2000-2013 period (0.07 on average for 16 day periods; Fig. 7, Table 3)."

P3747. L15. Specify what kind of correlation (e.g. Pearson or Spearman). Spearman correlation may be warranted given that the data does not have a normal distribution.
We use Pearson's correlation, which is now specified in the Methods section (2.5.5). We calculated the Spearman correlation as well, but found a relatively small effect on correlation in the ablation area, where the data are least likely to be normally distributed, but a more substantial effect where the data are not normally distributed. We feel that calculating Pearson's correlation is sufficient for our purposes and provides a better indicator of correlation in the accumulation area.

P3747. L18. Be careful how you refer to R2 throughout the paper. R2 is the coefficient of determination, while R is the correlation coefficient.
"Correlation" or "correlation coefficient" has been changed to "coefficient of determination" when referring to what is plotted in Fig. 7 (now Fig. 8).

P3748. L13-17: Move to methods. Make a new section to explain your methodology to analyze trends.
We assume the reviewer is referring to P3749. The sentence has been moved to Section 2.2.5 where we discuss methodology for computing trends.

P3749. L7-8. This sentence is unnecessary. It is clear from the figure captions.
The sentence has been removed.

P3756. L4-5. Clarify if this is a recommendation or something that will be implemented.
This has been implemented in the latest version of MAR. This has been stated and further discussion has been added.

P3757. L1-2. Why not show this analysis in this paper. Rewrite, remove or add the analysis.
Since the analysis did not reveal statistically significant differences, we feel that it is unnecessary to include a figure here. The paragraph has been shortened to a single sentence:
"We also investigated the possibility that the smaller spectral interval of GC-Net data influences trends by comparing MCD43A3 visible vs. shortwave albedo trends, but did not find the trends to be significantly different from each other."

Table 2 and 3 captions: Consider removing “Summary of” or use “Summary statistics”
“Summary of” has been removed.

Figure 1: Clarify that the black stippled line in the inset represents elevation contours (not ELA as in the larger figure)
The black stippled lines in the inset have been changed to solid lines to be consistent with the larger figure.

Figure 3: Explain what the ‘hatched’ areas represent.
Statement added: “MAR grid boxes where the difference is not statistically significant at the 95% confidence level are marked with a grey ‘x’.”

Figure 4: Graph can be improved so that different data can be distinguished more clearly. For example, give each line a unique color and show poor quality by using spilled lines instead of symbols. Consider removing the good or all quality data from the figure since it is not discussed in the text and it clutters the figure.
Lines on the figures have been made thicker and the symbols have been made smaller so that the lines are now more clearly visible. The good vs. all quality data are mentioned in the discussion section 4.2.1. Therefore we prefer to keep all data on the figure.

Figure 5: Figure 4b and 5 are extremely similar. Consider removing Figure 4b from the manuscript.
We would prefer to keep Figure 4b in the manuscript, as Figure 5 is useful for comparing station data to data for all MAR grid boxes in the accumulation area, but Figure 4b provides a summary of icesheet-wide albedo as a function of latitude. Figure 4b is also mentioned in the discussion section in the context of MODIS data quality.

Figure 7: Rewrite. R2 is the coefficient of determination, and R is the correlation coefficient.
“Correlation coefficient” has been changed to “coefficient of determination” on the figure and in the text. (This is now Figure 8).

Figure 10: Correct “95% level” to “95% confidence level”.
Corrected. (This is now Figure 13).

Figure 11: Here the y axis labels denotes unitless with “(-)”. This is different from how albedo was presented in previous figures (the unitless only mentioned in the caption). Either way is fine, however, be consistent throughout the paper. Consider using the same axis interval for all graphs to make it easier to compare the trends between the three plots.
“(-)” has been changed to “(unitless)” on the y-axis. The same axis interval (0.45) was originally used on all graphs but the axis on Fig. 14c is offset by 0.1 as the average ablation zone albedo is lower. A note has been added to the caption stating: “Note that the y-axis interval is the same for all graphs, but is shifted by 0.1 for **(c)**.” (This is now Figure 14)

Figure 13: Shouldn’t the density distributions for MAR 2.0 in panel a and c be the same? The same goes for MAR 3.2 in panels b and d.

An error in the code used to create this figure was discovered that results in a different bin size for histograms for the comparison with MOD10A1 data. This has been corrected so that the bin size for all histograms is 0.0099. The distributions are still slightly different, because only coincident MODIS and MAR data are used for each plot, and missing values from MOD10A1 do not necessarily correspond to missing values from MCD43A3. Statistics for the data (such as those presented in Table 5) remain unchanged. (This is now Figure 11).

Figure 14: Consider adding a sentence that explain that the average SMB is negative, which means a positive bias is "less" negative and results in "less" mass loss.
A sentence has been added stating this:
"Note that in the ablation area, where net SMB is negative (Fig. 1), a positive SMB bias indicates a smaller amount of average mass loss." (This is now Figure 12).

Response to Reviewer #3 (Jason Box)

Interactive comment on "Assessing spatio-temporal variability and trends (2000-2013) of modelled and measured Greenland ice sheet albedo" by P. M. Alexander et al.

Jason E Box (Referee)

Summary It is nice to see a rigorous study of Greenland albedo. The paper is of significance for findings that include 1.) "difference in mean albedo of up to 0.08 between the two remote sensing products north of 70 N 2.) a disagreement in the trend magnitude between the two MODIS albedo products for the accumulation area, and 3.) likely positive bias in MAR simulated bare-ice albedo.

major critique
The use of relatively coarse 25 km horizontal resolution when the MODIS data are available at a much higher resolution raises the question of resolving the ablation area and fine structures [e.g. Wieltjes and Oerlemans 2010] observed in the ablation area.

The MODIS data are aggregated to the MAR 25 km grid in order to conduct comparisons with MAR. For analyses involving in situ stations, MODIS data at the original resolution of the MODIS products (463x463m) have been used. The focus of this study is not to reveal all details of spatial variability in Greenland Ice sheet albedo, but rather to use multiple datasets and model results to capture variability at the scales examined. We now indicate the importance of capturing albedo variations at a higher spatial resolution in the concluding paragraph.

page 3734 lines 20-21 "not confirmed by either the model or in situ observations" untrue an accumulation area albedo decline is documented in in situ observations. See Box et al. (2012) for MODIS see section 4.2 Albedo trend verification 4th paragraph.

As noted in section 4.2.3, it is not clear why there is a discrepancy between the results presented here and those of Box et al. (2012). We have added a sentence to the abstract to indicate that the findings contradict with a previous study.

“Nevertheless, satellite products show a decline in JJA albedo of -0.03 to -0.04 per decade for regions within the accumulation area that is not confirmed by either the model or in situ observations. These findings appear to contradict a previous study that found an agreement between accumulation area in situ and MODIS trends during individual months.”

page 3735 lines 22-23 incoporate critique of Wang and Zender using Schaaf et al. (2011)

This critique has been discussed in section 4.2.1. We feel that the argument that in general, high solar zenith angles lead to less accurate albedo measurements is not affected by this critique, but have removed the reference to Wang and Zender (2002) in this portion of the paper as it is not essential to include here.

page 3745 line 1 While MAR abackground albedo has not yet been mentioned in the article, I suspect that “large positive bias in MAR albedo” are because a background albedo that ‘reflects’ [pun intended] MAR not incorporating impurities from, for example, outcropping dust [Wientjes et al. 2010]?

We agree that the fact that MAR does not account for impurities in the ablation area contributes to the bias in this region. The “dark zone” is discussed in section 4.2.2, and we have expanded this discussion somewhat in the revised manuscript.

It is unfortunate PROMICE.org weather station data were not used. Presumably the authors saw Cryolist emails from Dirk van As on the data availability. PROMICE AWS have [usually] more accurate radiometers than GC-Net radiometers. PROMICE AWS compliment GC-Net by being concentrated in the ablation area where the albedo change signal is the largest.

We were aware of this dataset, but were not aware of its availability online when data analysis for this study was conducted. While the use of additional measurements would certainly improve this study, we do not feel that the measurements would substantially alter the findings presented here. Given limited time and resources we cannot include the data but are open to utilizing it in the future.

page 3746 lines 10-11 The hypothesis: “MOD10A1 may also be positively biased north of 70 N” could be tested using PROMICE.org data from the KPC_U and KPC_L station data.

These stations are placed along the edges of the ice sheet. To assess variability with latitude at local stations (Fig. 5) we have focused on stations within the MAR-defined accumulation area, with a record of at least 9 years. We have deliberately avoided ablation area stations for this analysis as albedo there is subject to high variability and is influenced by processes such as melting, bare ice and dust exposure. While the data from these stations might provide some indication as to the validity of the hypothesis, we don’t think they would provide definitive conclusions regarding a positive bias in MOD10A1.

page 3750 section 4.1 1st paragraph seems unnecessary and speculative. Regarding “datasets”, it would be useful to make more distinction between simulation from MAR and observational datasets. The framing should perhaps be how well or not MAR performs relative to this and that observational dataset.

We do not think this discussion is speculative, as it is consistent with previous literature. Some additional references have been added.

We now refer to MAR model “outputs” or “results” rather than “data.”

section 4.2.1 Variation of albedo with latitude. it’s hard to conclude anything with confidence because all datasets (perhaps not MAR in this case) will have some solar and viewing geometry dependent bias.

We have noted this in section 4.2.1:
“Part of the reasons for discrepancies in the latitudinal dependence of albedo may be associated with biases resulting from viewing geometry or sun angle, which vary with latitude, making it difficult to draw conclusions from the various observational datasets as to ‘true’ variations in albedo with latitude.”

minor critique

throughout, consider replacing + “zone” with “area” to adopt a standard suggested by Dorothy Hall, one that is more accurate since, in my view, a zone is a latitude interval.
This change has been made throughout the manuscript.

“mean” with “average”, the former is more jargon than the latter.
We prefer to use the term “mean” as it refers to the arithmetic mean, which we have calculated here, while the term “average” seems more ambiguous.

page 3734 line 3 delete “crucial”, unneeded
The word “crucial” has been removed.

page 3735 3 replace “accelerating” with “amplified”
“Accelerating” has been replaced with “amplify”.
11 “increasing” instead of “record”
The suggested change has been made.

page 3736 lines 4-5 “To our knowledge, this is the first-time that a multi-tool integrated assessment of albedo over Greenland is presented.” why is this important? Each publishable study does several things for the first time, no? This sentence should be removed.
We think that it is important to state why this study is different from previous evaluations, so that the reader is aware of the contribution of this study to the existing literature.

Page 3741 midday instead of noontime
“noontime” has been replaced with “midday”.

page 3744 line 13 not just "meltwater and bare ice" but dust and algae. There are several papers of the topic such as: Bøggild, C.E., Brandt, R.E., Brown, K. J., and Warren, S.G.: The ablation zone in Northeast Greenland: ice types, albedos and impurities, J. Glaciol., 56, 101-113, 2010. Wienjes, I.G.M. and Oerlemans, J.: An explanation for the dark region in the western melt zone of the Greenland ice sheet, The Cryosphere, 4, 261-268, doi:10.5194/tc-4-261-2010, 2010. Wientjes, I.G.M., R.S.w. van de Wal, G.J. Reichart, A. Sluijs and J. Oerlemans, 2011. Dust from the dark region in the western ablation zone of the Greenland ice sheet. The Cryosphere, 5, 589-601. Doi: 10.5194/tc-5-589-2011
We have also referred to the presence of impurities and have cited these references.

page 3746 17-18 remove "Therefore," unneeded
The sentence has now been removed.

page 3746 17-18 "of the four datasets examined, only MCD43A3 appears to exhibit a decrease with latitude above 70°N. Only 3 datasets have a substantial latitude range. PROMICE.org data would be a 4th dataset.
The sentence has now been removed. Regarding PROMICE.org data, see responses at the start of the second page of this document.

Ablation vs. high latitudes.

first page 16 "indicates" instead of "points to"
"point to" has been changed to "indicate"

page 3749 "undergoes" or "exhibits" instead of "experiences" which is a sentient phenomenon
"Experiences" has been changed to "undergoes".

page3753 6 "above 0.84" comes from Konzelmann, T. and Omura, A.:, J. Glaciol., 41, 490-502, 1995. where albedo was measured to a Swiss standard, i.e., extremely carefully and therefore their maximum values for fresh snow are credible.
The reference has been cited here and included in the reference list.

Page 3756 21 remove "in"
"in ablation zone areas" has been changed to "within the ablation area" .

page 3758 16 refer also to Stroeve et al. (2013)
The reference has been added.

ps. I am sorry for taking so long to make the review after accepting the assignment.
No problem, thanks for taking the time to review it!

Assessing spatio-temporal variability and trends ~~(2000-2013) of~~ in modelled and measured Greenland ice sheet albedo (2000-2013)

P. M. Alexander[1,2], M. Tedesco[2,1], X. Fettweis[3], R. S. W. van de Wal[4], C. J. P. P. Smeets[4], and M.R. van den Broeke[4]

[1]{Graduate Center of the City University of New York, 365 5th Ave., New York, NY, 10016 USA}

[2]{City College of New York, City University of New York, 160 Convent Ave., New York, NY, 10031 USA}

[3]{Department of Geography, Université de Liège, Place du 20-Août, 7, 4000 Liège, Belgium}

[4]{Institute for Marine and Atmospheric research Utrecht, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands}

Correspondence to: P. M. Alexander (palexander@gc.cuny.edu)

Abstract

Accurate measurements and simulations of Greenland Ice Sheet (GrIS) surface albedo are essential, given the ~~crucial~~ role of surface albedo in modulating the amount of absorbed solar radiation and meltwater production. In this study, we assess the spatio-temporal variability of GrIS albedo (during June, July, and August) for the period 2000-2013. We use two remote sensing products derived from data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS), as well as outputs from the Modèle Atmosphérique Régionale (MAR) regional climate model (RCM) and data from in situ automatic weather stations. Our results point to an overall consistency in spatiotemporal variability between remote sensing and RCM albedo, but reveal a difference in mean albedo of up to ~0.08 between the two remote sensing products north of 70°N. At low elevations, albedo values simulated by the RCM are positively biased with respect to remote sensing products ~~and in situ measurements~~

by up to ~0.1 and exhibit low variability compared with observations. We infer that these differences are the result of a positive bias in simulated bare-ice albedo. MODIS albedo, RCM outputs and in situ observations consistently ~~point to~~indicate a decrease in albedo of -0.03 to -0.06 per decade over the period 2003-2013 for the GrIS ablation area~~zone (where there is a net loss of mass at the GrIS surface)~~. Nevertheless, satellite products show a decline in JJA albedo of -0.03 to -0.04 per decade for regions within the accumulation ~~zone~~area ~~(where there is a net gain of mass at the surface)~~ that is not confirmed by either the model or in situ observations. These findings appear to contradict a previous study that found an agreement between in situ and MODIS trends for individual months. The results indicate a need for further evaluation of high elevation albedo trends, a reconciliation of MODIS mean albedo at high latitudes, and the importance of accurately simulating bare ice albedo in RCMs.

1 Introduction

Over the past decade, the Greenland Ice Sheet (GrIS) has simultaneously experienced accelerating mass loss (van den Broeke et al., 2009; Rignot et al., 2011) and records for the extent and duration of melting (Tedesco et al., 2008, 2011, 2013; Nghiem et al. 2012). ~~Besides the direct relationship between temperature and melting, I~~Increased melt over Greenland has been associated with both changes in temperature and an amplifying ice-albedo feedback: increased melting and bare ice exposure reduce surface albedo, thereby increasing the amount of absorbed solar radiation and, in turn, further ~~accelerating~~amplifying melting (Box et al., 2012; Tedesco et al., 2011). Recent studies (van den Broeke et al., 2011; Vernon et al., 2013) also indicate that albedo plays an essential role in the GrIS surface energy balance, and consequently, the surface mass balance (SMB) of those regions where considerable melting occurs. Because of the impact of albedo on the surface energy balance, it is crucial to assess the performance of models that simulate albedo over the GrIS and the quality of albedo estimates from remote sensing or in situ observations. These assessments are pivotal for improving our understanding of the physical processes leading to accelerating ~~record~~ mass loss, and for improving projections for the next decades.

Several studies that have investigated GrIS albedo trends and variability have primarily relied on satellite measurements, particularly those collected by the Moderate Resolution Imaging

Spectroradiometer (MODIS) (e.g. Stroeve et al. 2005, 2006, 2013; Box et al. 2012). Remote sensing measurements can capture changes at large spatial scales and for long periods, continuously (with the exception of cases when the surface is obscured by clouds). Previous studies have found MODIS albedo products to agree reasonably well with in situ data, especially with regards to capturing the seasonal albedo cycle and mean seasonal values in regions where variability is small (Stroeve et al., 2005, 2006, 2013), but lower accuracy at high solar zenith angles has been identified (Stroeve et al. 2005, 2006~~; Wang and Zender, 2009~~), limiting the periods and locations for which these data can be used. Nevertheless, given their relatively high temporal and spatial resolution, these products are useful for evaluating albedo derived from regional climate models (RCMS). ~~On the other hand, we note that regional climate models (RCMs)~~RCMs are an important tool for estimating both current and future changes in the GrIS SMB (Box and Rinke, 2002; Box et al., 2006; Ettema et al., 2009; Fettweis et al., 2007, 2011; Rae et al., 2012, Tedesco and Fettweis, 2012), ~~with~~ and the surface albedo schemes ~~(and in particular the bare ice albedo parameterizations)~~ employed by these models have ~~aving~~ a substantial impact on their simulation of the SMB (Rae et al., 2012; van Angelen et al., 2012; Lefebre et al., 2005; Franco et al., 2012).

In this paper, we report the results of an assessment of GrIS albedo spatio-temporal variability and trends for the period 2000-2013. To our knowledge, this is the first time that a multi-tool integrated assessment of albedo over Greenland is presented. We use (1) data –from two remote sensing products from the Moderate Resolution Imaging Spectroradiometer (MODIS), the MOD10A1 daily albedo product (Hall et al., 2012) and MCD43A3 16 day albedo product (Schaaf et al., 2002), (2) in situ albedo data from the Greenland Climate Network (GC-Net, Steffen et al., 1996) and Kangerlussuaq-Transect (van de Wal et al., 2005), and (3) outputs from two versions (v2.0 and v3.2) of the Modèle Atmosphérique Régionale (MAR; Fettweis et al., 2013a,b). In order to carry out comparisons between products, MODIS data have been regridded to the MAR model grid in some instances daily data have been averaged over 16 day periods when necessary. The role of potential errors associated with differences in spectral range between satellite and in situ data and cloud cover have been considered and corrected for when possible. ~~through the analysis of different remote sensing products, in situ measurements and the outputs of two different versions of an RCM, featuring different albedo schemes. To our knowledge, this is the first-time that a multi-tool integrated assessment of albedo over Greenland is presented. We introduce the MAR model, the MODIS products and the GrIS in situ data in Sect. 2. In Sect. 3, we compare spatio-temporal variability of the two~~

~~MODIS satellite products, in situ data, and MAR outputs, and discuss these results in Sect. 4. Conclusions are presented in Sect. 5.~~

2 Data and Methods

2.1 The MAR model

The Modèle Atmosphérique Régionale (Gallée and Schayes 1994; Gallée, 1997; Lefebre et al., 2003), abbreviated MAR, is a coupled land-atmosphere regional climate model featuring the atmospheric model described by Gallée and Shayes (1994) and the Soil Ice Snow Vegetation Atmosphere Transfer scheme (SISVAT) surface model. SISVAT incorporates the multilayer snow model *Crocus* (Brun et al., 1992), which simulates fluxes of mass and energy between snow layers, and reproduces snow grain properties and their effect on surface albedo. The model setup used here is described in detail by Fettweis (2007). We primarily use a recent version of MAR (v3.2), which features changes to the albedo scheme relative to previous versions (v1 and v2), detailed in Section 2.2, but also examine differences between MAR v3.2 and a previous version, MAR v2.0. MAR v3.2 (v2.0) has been run at a 25 km horizontal resolution for the period 1958-2013 (1958-2012)~~present~~. ~~The model~~Both model versions are ~~is~~ forced at the~~its~~ lateral boundaries and ocean surface and initialized with 6-hourly reanalysis ~~data~~ outputs from the European Centre for Medium-Range Weather Forecasts (ECMWF), using the ERA-40 reanalysis (Uppala et al., 2005) for the period 1958-1978 and the ERA-Interim reanalysis (Dee et al., 2011) for the period 1979-present. Here we focus on the 2000-2013 period for comparison with satellite data. The MAR v3.2 ice sheet mask (which gives the fraction covered by ice for each grid box) and surface elevation are defined using the Greenland digital elevation model of Bamber et al. (2013). ~~Originally,~~ MAR v2.0 uses~~d~~ the elevation model of Bamber et al. (2001), and the land surface classification mask from Jason Box (sites.google.com/site/jboxgreenland/datasets).

In MAR v3.2, in contrast with MAR v2.0 ~~(used by Fettweis et al., 2013a,b),~~ , sub-grid scale parameterizations make it possible to have fractions of different land cover types within a single grid box. Quantities are computed for the sectors within each grid box and a weighted average of these quantities is used to represent the average value for a grid box. ~~Here, we conduct comparisons with satellite data only for pixels classified as 100% covered by ice (to avoid including satellite pixels over tundra in the comparison). For some in situ stations~~

~~along the edges of the ice sheet, we have compared in situ and satellite data with MAR estimates of albedo within the "ice-covered" sector of the encompassing MAR grid box.~~

For the reader's convenience, we show the mean September 2000 - August 2013 SMB from MAR v3.2 in Fig. 1, along with the equilibrium line dividing positive and negative SMB, together with the locations of the weather stations used in this study. In this study, areas below the mean 2000-2013 equilibrium line as defined by MAR are collectively referred to as the "ablation ~~zone~~area", while areas above this line are referred to as the "accumulation ~~zone~~area".

2.2 The MAR albedo scheme

The basis for the MAR albedo scheme is described in detail by Brun et al. (1992) and Lefebre et al. (2003). MAR snow albedo (α) depends on the optical diameter of snow grains (d), which is in turn a function of other snow grain properties, such as grain size, sphericity and dendricity.~~.~~ ~~Larger, more spherical, less dendritic particles result in a higher optical diameter, and vice versa.~~ In the model, the sphericity, dendricity, and size of snow grains are a function of snowpack temperature, temperature gradient, and liquid water content. ~~MAR~~ Albedo~~albedo (α) is a function of snow grain optical diameter (d) in meters for~~ is defined in MAR for three spectral interval~~band~~s ~~for visible, near infrared and far infrared radiation~~:

~~Band~~ Interval 1, visible (0.3 – 0.8 µm): $\alpha_1 = \max(0.94, 0.96 - 1.58\sqrt{d})$ (1)

~~Band~~ Interval 2, near infrared (0.8 – 1.5 µm): $\alpha_2 = 0.95 - 15.4\sqrt{d}$ (2)

~~Band~~ Interval 3, far infrared (1.5 – 2.8 µm): $\alpha_3 = 364 * \min(d, 0.0023) - 32.31\sqrt{d} + 0.88$ (3)

where α_1, α_2, and α_3 are wavelength dependent albedo values~~ over the three spectral bands~~. The integrated snow albedo (α_S) for the range 0.3 to 2.8 µm is a weighted average of albedo over these ~~bands~~ intervals based on solar irradiance fractions:

$$\alpha_S = 0.580\alpha_1 + 0.320\alpha_2 + 0.1\alpha_3 \quad (4)$$

The minimum albedo of snow is set to 0.65. In MAR v2.0, bare ice albedo was simply assigned a fixed value~~ of 0.45~~. In MAR v3.2 (the version primarily used here), bare ice albedo is a function of accumulated surface water following the parameterizations of Lefebre et al. (2003), described below. In the case of bare ice (which occurs in MAR when the surface snow density is greater than 920 kg m^{-3}) ice albedo (a_I) is given by:

$$\alpha_I = \alpha_{I,\min} + (\alpha_{I,\max} - \alpha_{I,\min})e^{-\left(\frac{M_{SW}(t)}{K}\right)} \quad (5)$$

Where $\alpha_{I,min}$ and $\alpha_{I,max}$ are the minimum and maximum bare ice albedo~~ (set to 0.45 and 0.55 respectively for MAR v3.2),~~, K is a scale factor (set to 200 kg/m^2), and $M_{SW}(t)$ is the time-dependent accumulated amount of excessive surface meltwater before runoff (in kg m^{-2}). According to the parameterization of Zuo and Oerlemans (1996), there is delay in MAR v3.2 between the production of meltwater and evacuation towards the oceans (Lefebre et al., 2003), in order to account for the reduction of bare ice albedo due to the presence of surface water. The ice surface albedo (α_I) will therefore be lower if the melt rate is higher, asymptotically approaching the minimum bare ice albedo.

Additionally, to ensure temporal continuity in simulated albedo, values of albedo between the maximum bare ice and minimum snow albedo ~~(0.55 and 0.65 respectively for MAR v3.2)~~ are possible when the surface (or near-surface) snow density lies between 830 and 920 kg m^{-3}. In this case (which corresponds to the presence of firn), albedo (α_I) is a function of density as follows (Lefebre et al., 2003):

$$\alpha_I = \alpha_{I,\max} + (\alpha_{S,\min} - \alpha_{I,\max})\left(\frac{\rho_I - 920kgm^{-3}}{\rho_C - 920kgm^{-3}}\right) \quad (6)$$

where $\alpha_{S,min}$ is the minimum albedo of snow~~ (0.65)~~, ρ_I is the density of the upper firn layer, and ρ_C is the density at which pores within firn close off (830 kg m^{-3}). For the reader's convenience, Table 1 provides the range of possible albedo values for ice, firn, and snow in MAR v2.0 and v3.2.

In cases where there is a snowpack with a thickness of <10 cm overlaying ice or firn (with a density greater than 830 kg m^{-3}), excluding the case of ice lenses, albedo is interpolated between the ice albedo and the surface snow albedo as a linear function of snowpack thickness, to produce an "integrated" surface albedo of snow, ice and water (α_{SI}):

$$\alpha_{SI} = \alpha_I + \alpha_S(H_S/0.1) \quad (7)$$

where H_s is the snowpack height in meters. In cases where a snowpack thicker than 0.1 m lies above ice, or there is bare ice at the surface, α_{SI} is simply set equal to the snow albedo (α_s), or bare-ice albedo (α_I), respectively.

~~Snow albedo is generally higher during cloudy conditions due to the masking of a portion of the incoming solar spectrum by clouds (Greuell and Konzelman, 1994). MAR accounts for this factor by applying a correction to the integrated surface albedo (α_{SI}) as a function of cloud fraction, following Greuell and Konzelman (1994):~~

$$\cancel{\alpha_{CL} = \alpha_{SI} + 0.05(n - 0.5)} \qquad \cancel{(8)}$$

~~where n is the cloud fraction computed by MAR, and α_{CL} is the cloud-corrected albedo. Satellite data can only provide cloud-free measurements, and therefore we re-correct MAR surface albedo to produce estimates of cloud-free surface albedo. We use this particular technique rather than excluding "cloudy" data from MAR because MAR does not necessarily replicate the actual cloud fraction observed by MODIS. The correction factor applied here reverses the correction applied in MAR, then corrects albedo for the case where there is a cloud fraction of 0:~~

$$\cancel{\alpha_{MAR,clear-sky} = \alpha_{MAR,daily} - 0.05(n_{MAR,daily} - 0.5) - 0.025} \qquad \cancel{(9)}$$

~~In this case $\alpha_{MAR,\ daily}$ is the daily mean MAR albedo, $n_{MAR,\ daily}$ is the daily mean cloud fraction from MAR, and $\alpha_{MAR,\ clear-sky}$ is the daily mean clear-sky albedo. All following analyses with MAR data are conducted using $\alpha_{MAR,\ clear-sky}$.~~

2.3 Satellite-derived albedo

We use the daily MODIS albedo product (MOD10A1, Version-5) distributed by the National Snow and Ice Data Center (Hall et al., 2012; available at http://nsidc.org/data/mod10a1.html), available for the period March 2000 - present, and the 16-day (MCD43A3, Version-5) product from Boston University (Schaaf et al., 2002; available at https://lpdaac.usgs.gov/), available for the same period.

The MOD10A1 Version-5 product contains daily albedo (0.3 - 3 µm) based on the "best" daily MODIS observation, defined as the observation that covers the greatest percentage of a grid cell. Corrections are also applied to account for anisotropic scattering, for the influence of the atmosphere on surface albedo, and for the limited spectral range of MODIS bands (Klein and Stroeve, 2002; Stroeve et al., 2006). Here we use MODIS data from the TERRA satellite, as MODIS data from the AQUA satellite are less reliable due to an instrument failure in the near infrared band (Stroeve et al., 2006; Box et al., 2012).

The MCD43A3 Version-5 product makes use of all atmospherically-corrected MODIS reflectance measurements over 16-day periods to provide an integrated albedo measurement every 8 days. A semi-empirical bidirectional reflectance function (BRDF) model is used to compute bi-hemispherical reflectance as a function of these reflectance measurements (Schaaf et al., 2002). The MCD43A3 product contains, in addition to albedo values for each MODIS instrument band, "shortwave" albedo values calculated over a wavelength interval of 0.3-5.0 μm and "visible" albedo values for the 0.3-0.7 μm interval, calculated using the BRDF parameters. Here we primarily make use of "shortwave" MCD43A3 albedo, as its wavelength interval is consistent with those of MAR and MOD10A1, but briefly consider "visible" albedo as well. The MCD43A3 product provides, over each wavelength interval, an integrated diffuse White Sky Albedo (WSA) and a direct Black Sky Albedo (BSA) for a specific viewing geometry (from above when the local solar zenith angle is at a maximum). A linear combination of WSA and BSA can be used to compute the true "blue-sky albedo". Stroeve et al. (2005) suggest that there is little difference between BSA and WSA for typical summer ~~noontime~~ midday solar zenith angles over Greenland. Simulation of blue-sky albedo requires models or observations of aerosol optical depth (e.g. Stroeve et al., 2013) that are not available for this study and therefore, the following results consider BSA only.

Both MODIS products provide quality flags indicating "good quality" vs. "other quality" data. In the case of MCD43A3, "other quality" data are produced using a "backup" algorithm. When few observations are available, the backup algorithm is used to scale an archetypal BRDF function that is based on past observations (Schaaf et al., 2002). In order to understand the influence of data quality on our results, we present results for both "all quality" as well as "good quality" data. ~~For our purposes, MODIS albedo products are re-gridded to the MAR 25 km resolution grid from the original 463 m spatial resolution at which they are distributed. Re-gridded values contain the median value of all the MODIS values falling within a MAR grid box. As mentioned, we restrict our analysis to the GrIS, excluding areas where the MAR sub-grid level ice cover percentage is less than 100%, except for comparison with in situ data, in which case we use data from individual MODIS pixels, in situ measurements, and MAR ice-covered sector data.~~

2.4 Weather station data

We use Automatic Weather Station (AWS) data from two sources, the Greenland Climate Network (GC-Net, Steffen et al., 1996) and the Kangerlussuaq Transect (K-Transect, van de Wal et al., 2005). The locations of the weather stations are shown in Fig. 1, and a list of the weather stations used and their period of coverage is provided in Table 2~~1~~. We use all available GC-Net and K-transect June-July-August (JJA) data within the period 2000-2012 for comparison with MODIS and MAR albedo. (GC-Net data for the summer of 2013 were not yet available when data analysis for this study was conducted.) We follow a procedure similar to that employed by Stroeve et al. (2005) to generate albedo timeseries' from GC-Net and K-Transect data. Mean daily albedo was computed as the sum of daily incident shortwave (SW) radiation divided by the sum of daily outgoing SW radiative flux. Instances where hourly upward SW radiative flux exceeds downward SW radiative flux were excluded. Upward and downward hourly radiative fluxes were excluded when downward fluxes were smaller than 250 W/m^2 to reduce the impact of relative errors on measured albedo, especially during cases of low incident radiation. (We investigated the sensitivity of our results to this threshold, and did not find a considerable effect on the results). Data from several locations and time periods were excluded from this analysis. These stations are included in Table 2~~1~~. In particular, measured albedo at Swiss Camp for the year 2012 appeared to be unrealistically high relative to previous years and was excluded (mean measured JJA albedo for 2012 was 0.99, 3.5 standard deviations above the mean 2000-2011 value of 0.64). Measured albedo at Crawford Point-2 undergoes a step change after 2004 (mean albedo is 0.81 ± 0.03 for 2000-2004 and 0.90 ± 0.04 for 2005-2010) and therefore we excluded data after 2004, as was done by Stroeve et al. (~~,~~2013). At the stations NASA-U and NGRIP, leveling errors produce a low bias in upward radiation for all years (Stroeve et al., 2013) resulting in measured albedo values that are unrealistically low for snow outside of the ablation ~~zone~~area (0.30 ± 0.01 at NASA-U and 0.33±0.01 at NGRIP), and are therefore excluded. At the Peterman Glacier and Peterman ELA, missing MODIS data prevented us from including all weather station data in this analysis.

~~As in the case of the original MAR albedo data, in situ measurements also include measurements made during cloudy conditions while MODIS albedo data do not. Given a lack of available measurements, we do not explicitly correct in situ data for the presence of clouds in this study, but only consider data where coincident satellite and in situ measurements are~~

~~available. Stroeve et al. (2013) applied a correction to GC-Net data using a radiative transfer model, but found that the correction did not significantly impact their results.~~

~~The GC-Net LI-COR sensors are sensitive within the 0.4-1.1µm band, and K-Transect data are collected in the 0.3-1.1 µm band. These bands are narrower than the MOD10A1 interval of 0.3-3µm and the MCD43 shortwave albedo interval of 0.3-5µm, and the interval of 0.3-2.8µm over which albedo is calculated in the MAR model. GC-Net incoming and outgoing radiation values are calibrated to represent radiation for a spectral interval of 0.28 to 2.8 µm (Wang and Zender, 2009). However, because snow has a high spectral reflectance over the 0.3 to 1.1 µm interval, and a much lower reflectance above 1.1 µm, measured albedo over the smaller interval will be higher for snow-covered areas (Stroeve et al., 2005). Stroeve et al. (2005) compared albedo derived with GC-Net LI-COR pyranometers to measurements from pyranometers with a larger spectral range, and found that the smaller wavelength interval results in a positive albedo bias of between 0.04 and 0.09, for GC-Net data relative to MODIS albedo, depending on the location and time period (Stroeve et al., 2005). This bias likely also applies to K-Transect measurements, as the spectral sensitivity at K-Transect sites is comparable to the sensitivity at GC-Net locations. Because this bias may be smaller or larger depending on multiple factors, we do not apply any correction here, but provide an indication of spatial variability of this bias in Section 4.2.1 by comparing MCD43A3 visible albedo (0.3 – 0.7 µm) with MCD43A3 shortwave (0.3-5.0 µm) albedo.~~

2.5 Methods of analysis

2.5.1 Corrections to MAR albedo

Snow albedo is generally higher during cloudy conditions due to the masking of a portion of the incoming solar spectrum by clouds (Greuell and Konzelman, 1994). Both MAR v3.2 and MAR v2.0 account for this factor by applying a correction to the integrated surface albedo (α_{SI}) as a function of cloud fraction, following Greuell and Konzelman (1994):

$$\alpha_{CL} = \alpha_{SI} + 0.05(n - 0.5) \qquad (8)$$

where n is the cloud fraction computed by MAR, and α_{CL} is the cloud-corrected albedo. Satellite data can only provide cloud-free measurements, and therefore we re-correct MAR surface albedo to produce estimates of cloud-free surface albedo. We use this particular technique rather than excluding pixels from MAR because MAR does not necessarily replicate the actual cloud fraction observed by MODIS. The correction applied here reverses the correction applied in MAR, then corrects albedo for the case where there is a cloud fraction of 0:

$$\alpha_{MAR,clear-sky} = \alpha_{MAR,daily} - 0.05(n_{MAR,daily} - 0.5) - 0.025 \qquad (9)$$

In this case $\alpha_{MAR,\ daily}$ is the daily mean MAR albedo, $n_{MAR,\ daily}$ is the daily mean cloud fraction from MAR, and $\alpha_{MAR,\ clear-sky}$ is the daily mean clear-sky albedo. All analyses with MAR results are conducted using $\alpha_{MAR,\ clear-sky}$.

2.5.2 Aggregation of MODIS data to the MAR grid

For the purpose of comparing model results and satellite data, MODIS albedo products are re-gridded to the MAR 25 km resolution grid from the original 463 m spatial resolution at which they are distributed. Re-gridded values contain the median value of all the MODIS values falling within a MAR grid box. When comparing satellite datasets and satellite data against model results, we restrict our analysis to the GrIS. For all comparisons including MAR v3.2 results, areas where the MAR sub-grid level ice cover percentage is less than 100% are excluded. For all comparisons including MAR v2.0 results, the same mask from MAR v3.2 is used, except that pixels classified as 100% ice covered in MAR v3.2, but classified as non-ice-covered in MAR 2.0 are also excluded from the analysis.

2.5.3 Comparisons at in situ stations

Comparisons at in situ stations are conducted between weather station data and data or outputs from the MODIS or MAR grid box that encompasses the in situ station. In this case we use the original (463x463m) MODIS grid box containing the station rather than the MODIS data aggregated to the encompassing 25x25 km MAR grid box to reduce potential errors associated with spatial variations of albedo. In cases where an in situ station is contained within a MAR grid box classified as less than 100% ice-covered in MAR v3.2, we compare in situ data to MAR v3.2 data from the ice-covered sector of that grid box rather than data from the entire grid box.

As in the case of the original MAR albedo outputs, in situ measurements also include measurements made during cloudy conditions while MODIS albedo data do not. Given a lack of available measurements, we do not explicitly correct in situ data for the presence of clouds in this study, but only consider data where coincident satellite and in situ measurements are available. Stroeve et al. (2013) applied a correction to GC-Net data using a radiative transfer model, but found that the correction did not significantly impact their results.

2.5.4 Spectral differences

The GC-Net LI-COR sensors are sensitive within the 0.4-1.1μm band, and K-Transect data are collected in the 0.3-2.8 μm band. The GC-Net bands are narrower than the MOD10A1 interval of 0.3-3μm and the MCD43 shortwave albedo interval of 0.3-5μm, and the interval of 0.3-2.8μm over which albedo is calculated in the MAR model. GC-Net incoming and outgoing radiation values are calibrated to represent radiation for a spectral interval of 0.28 to 2.8 μm (Wang and Zender, 2009). However, because snow has a high spectral reflectance over the 0.3 to 1.1 μm interval, and a much lower reflectance above 1.1 μm, measured albedo over the smaller interval will be higher for snow-covered areas (Stroeve et al., 2005). Stroeve et al. (2005) compared albedo derived with GC-Net LI-COR pyranometers to measurements from pyranometers with a larger spectral range, and found that the smaller wavelength interval results in a positive albedo bias of between 0.04 and 0.09, for GC-Net data relative to MODIS albedo, depending on the location and time period (Stroeve et al., 2005). This bias does not apply to K-Transect measurements, as the spectral sensitivity is comparable to the sensitivity of MODIS sensors. Because this bias may be smaller or larger depending on multiple factors, we do not apply any correction here, but provide an indication of spatial variability of this bias in Section 4.2.1 by comparing MCD43A3 visible albedo (0.3 – 0.7 μm) with MCD43A3 shortwave (0.3-5.0 μm) albedo.

2.5.5 Calculation of bias, correlation, and trends

In the following analysis, we focus on the JJA period because MODIS data are less reliable during other months, when solar zenith angles are high, as discussed by Box et al. (2012), and because this is the period when surface albedo has the largest impact on SMB.

In order to compare spatial variations in albedo we calculated the mean 2000-2013 JJA MOD10A1, shortwave MCD43A3 BSA albedo, and MAR clear-sky albedo using all available measurements or model outputs over the specified period, excluding cases where greater than 25% of data were missing for a given pixel. When differences between datasets or between satellite data and model results are calculated, we only use measurements or results that overlap in time and space, to avoid the possibility of biases introduced by missing data. The mean difference between two samples for a given grid box was deemed to be statistically significant if the p-value for a two-sample Student's t-test was smaller than 0.05. Unless otherwise specified, we use only "good quality" MODIS data in comparisons.

In some cases, observational data or model results have been spatially averaged or aggregated within the ablation and accumulation areas defined using MAR v3.2 or v2.0. The ablation (accumulation) area is defined as the area that experienced a net loss (gain) of mass over the 2000-2013 period as simulated by either version of the model.

For analyses of temporal variability, we consider daily variability, for which MOD10A1 data, in situ values, and MAR outputs available, as well as variability over 16-day MCD43A3 periods. In the case of the analysis of 16-day data, MOD10A1, MAR, and in situ daily data are averaged to produce a value for each overlapping MCD43A3 16-day period. We examine the correlation between daily satellite data and between satellite data and model results using Pearson's coefficient of determination (r^2).

To compare the distribution of ablation area albedo for satellite data and MAR model outputs, we produced frequency histograms for ablation area albedo using a bin width of 0.0099. Parameters for the best fit of a bimodal distribution to the histograms was obtained using the maximum likelihood estimation function in MATLAB, assuming a bimodal normal distribution for the fit.

Box et al. (2012) investigated changes in GrIS albedo using the MOD10A1 albedo product, finding that between 2000 and 2012, surface albedo decreased over almost the entire ice sheet. Here, we build on the analysis of Box et al. (2012) and extend the analysis to include MCD43A3, MAR v3.2 and in situ JJA data for the period 2000-2013. Trends in albedo have been obtained by performing linear regression on 16-day albedo values for satellite products, in situ data, and model outputs, excluding albedo values outside of the JJA period. We have also computed trends for annual JJA average values. A trend was determined to be statistically different from 0 if the p-value for a Student's t-test was smaller than 0.05. For in situ stations, only stations with a record of at least 9 years of data are included in the analysis, and only trends for albedo from the encompassing MAR v3.2 (25x25 km) grid box and MODIS (463x463m) grid boxes over the same range of years are considered.

3 Results

3.1 Albedo spatial variability

~~We first examine spatial variations in mean 2000-2013 JJA MODIS daily (MOD10A1) and 16 day (MCD43A3) shortwave BSA albedo, as well as clear-sky albedo from MAR v3.2. We focus on the JJA period because MODIS data are less reliable during other months, when solar zenith angles are high, as discussed by Box et al. (2012), and because this is the period when surface albedo is likely to have the largest impact on SMB. Figure 2 shows mean 2000-2013 GrIS JJA albedo for MOD10A1, MCD43A3 and MAR v3.2. Table 2 provides mean albedo for each product within the ablation and accumulation zones. All three~~MAR v3.2 and the two MODIS datasets show coherent spatial patterns of JJA mean 2000-2013 albedo (Fig. 2) that are consistent with previous studies (e.g., Box et al., 2012), with low-elevation areas in the ablation ~~zone~~area dominated by lower albedo values (<0.7 on average, Table 3) due to the presence of meltwater and bare ice, and high elevation areas by relatively higher albedo (>0.74~~5~~). The most obvious discrepancy between ~~all~~ the satellite products ~~datasets~~ occurs north of 70°N, where the MOD10A1 daily product exhibits an increase in albedo with latitude, while MCD43A3 points to the opposite. The difference between the two satellite products (Fig. 3a) is statistically significant (at the 95% confidence level) above 70°N, reaching ~0.08 (for albedo ranging between 0 and 1) at the highest latitudes.

The pattern of differences between MAR v3.2 and the two satellite products (Fig. 3b and c) ~~exhibits a higher degree of spatial variability when compared to~~appears to vary with both elevation and latitude, while the difference between the two satellite products varies primarily with latitude (Fig. 3a). Because any systematic biases in the satellite products are likely to be relatively consistent across space (at least as a function of longitude), it is likely that MAR v3.2 biases contribute to some of the elevational differences seen in Figs. 3b and c. Within the accumulation ~~zone~~area south of 70°N, MAR v3.2 albedo (0.77 on average) is comparable to MODIS albedo (average of 0.78 for MOD10A1 and 0.77 for MCD43A3). At low elevation areas, especially along the west coast ablation ~~zone,~~area, MAR v3.2 overestimates albedo (up to ~0.1) relative to both satellite products. The mean ablation ~~zone~~area albedo from MOD10A1 (0.68 ± 0.07) is identical to MAR mean ablation ~~zone~~area albedo (Table 3~~2~~), despite the large positive bias in MAR albedo within the west coast ablation ~~zone~~area that can be seen in Fig. 3. This is likely a result of a positive bias for MOD10A1 at high latitudes, as will be discussed further below. For areas north of 70°N, the discrepancy between satellite products makes it impossible to determine the magnitude and direction of MAR biases.

~~Spatial variations in albedo are further examined in Fig. 4, in which mean 2000-2013 JJA albedo for MAR and the MODIS products is plotted as a function of elevation (binned into 150 m segments) and latitude (binned into 2° segments).~~ MAR v3.2, MOD10A1 and MCD43A3 mean 2000-2013 JJA albedo values show a similar logarithmic dependence of albedo with elevation (Fig. 4a); below 2000 m, albedo increases relatively rapidly with elevation (both MAR and the MODIS products show a statistically significant albedo increase of ~0.01 to ~0.02 per 100 m increase in elevation), while above 2000 m, the change is smaller (no statistically significant increase for MAR, and an increase of ~0.002 to ~0.003 per 100 m for both MODIS products). The discrepancies between ~~datasets~~ MODIS products north of 70°N are evident in Fig. 4b: MCD43A3 decreases with latitude while MOD10A1 increases, and MAR v3.2 shows little change.

~~Data from in situ stations are compared with MODIS and MAR albedo values that are coincident in space and time in Table 3. Data have been spatially aggregated into ablation and accumulation zones of the GrIS defined by MAR v3.2, and temporally averaged over the same 16-day periods as the MCD43A3 product. In this case, we compare in situ measurements with MODIS data for the pixel closest to each weather station using the original (463x463m) MODIS grid, and do not average data to the MAR grid (25 km x 25 km).~~ For in situ stations~~locations~~ in the ablation ~~zone~~area (Table 4), in situ mean albedo (0.56 ± 0.08) is higher than coincident average MOD10A1 ~~albedo~~ (0.51 ± 0.09) and MCD43A3 ~~albedo~~ (0.50 ± 0.07) albedo values, and is comparable with MAR v3.2 clear sky mean albedo for sectors classified as ice-covered (0.57 ± 0.07). Within the accumulation ~~zone~~area, in situ albedo is larger by 0.01 to 0.06 relative to MAR and the MODIS products (Table 4). These results appear to be ~~are~~ consistent with a positive bias in GC-Net measurements identified by Stroeve et al. (2005). ~~Given that GC-Net albedo values are likely positively biased, and MAR mean ablation zone albedo values are close to GC-Net values, MAR is also likely positively biased in the ablation zone.~~ However, we also find that the difference between in situ and satellite albedo is larger at K-Transect stations (+0.08) than at GC-Net sites (+0.04), and K-Transect data are not expected to exhibit the positive bias. It is likely that the high spatial variability of ablation area albedo contributes to the differences. Data from in situ stations may be positively biased relative to satellite data because of a bias introduced by station locations: locations are not chosen to be within streams, lakes, or crevasses, which have a lower albedo. In the acccumulation zone, a lack of variation in surface features likely leads to smaller spatial variations in albedo.

Mean 2000-2012 JJA albedo values for ablation area GC-Net stations with a record of at least 7 years does not appear to exhibit a clear variation with latitude when compared with satellite data and model results (Fig. 5). GC-Net albedo at stations north of 70°N is on average larger by 0.02 relative to stations south of 70°N (Table 4), suggesting that GC-Net albedo does not confirm the decrease in albedo with latitude indicated by MCD43A3. ~~In Fig. 5, we show mean 2000-2012 albedo for selected individual stations in the accumulation zone as a function of latitude, along with 2000-2012 values for all MODIS and MAR grid boxes in the accumulation zone. We only show stations for which at least 7 years of data are available for 2000-2012. Error bars on station measurements indicate the range of biases (0.04 to 0.09) that have been observed by Stroeve et al. (2005). Figure 5 and Table 3 indicate that~~ MOD10A1 accumulation ~~zone~~area measurements are comparable (within 0.01 for aggregated station data) to uncorrected GC-Net data north of 70°N ~~(within 0.01 for aggregated station dat~~ (Fig. 5, ~~a~~Table 4). This suggests that the MOD10A1 may also be positively biased north of 70°N. ~~Table 3 indicates that GC-Net albedo at stations north of 70°N is on average larger by 0.02 relative to stations south of 70°N, suggesting that GC-Net albedo does not confirm the decrease in albedo with latitude indicated by MCD43A3.~~

It appears possible from Fig. 5 that the bias at GC-Net sites (between 0.04 and 0.09 according to Stroeve et al., 2005) could increase with latitude, rendering corrected GC-Net ~~measurements comparable to MCD43A3 measurements~~mean 2000-2013 albedo comparable to MCD43A3 albedo. In order to indicate how the GC-Net albedo bias is likely to vary spatially, the mean difference between MCD43A3 visible BSA (for the interval 0.3-0.7 µm) and MCD43A3 shortwave BSA (for the interval 0.3-5.0 µm) was computed (Fig. 6). The difference is larger than the biases observed by Stroeve et al. (2005) at GC-Net stations likely because the MCD43A3 visible wavelength interval is smaller than that for GC-Net stations. The difference does not vary with latitude, but is rather lowest in the ablation area, where bare ice is exposed during summer months, is largest in regions where melting occurs, but bare ice exposure is infrequent, and is relatively small at high elevations.

The spatial variability of the difference appears to be associated with the differences in spectral albedo between different materials. Because ice does not exhibit the spectral dependence of albedo that snow does (Hall and Martinec, 1985), the difference between

MCD43A3 visible and shortwave albedo is lower in the albation area, where bare ice is exposed during summer. In locations where melting occurs, snow grains tend to be larger because of constructive metamorphism, reducing reflectance mostly in the near infrared band (Wiscombe and Warren, 1980), resulting in a larger difference between visible and near infrared reflectance. ~~Through an examination of MCD43A3 visible and shortwave albedo we show that this is not likely to be the case (Sect. 4.2.1). Therefore, of the four datasets examined, only MCD43A3 appears to exhibit a decrease with latitude above 70°N.~~This suggests that in situ albedo values do not exhibit the decrease of albedo with latitude suggested by MCD43A3.

3.2 Albedo temporal variability

The standard deviation of albedo time-series provides information on the magnitude of its temporal variability. ~~Figure 6 shows maps of 2000-2013 JJA standard deviations for MAR and the two MODIS products, over the 16-day MCD43A3 periods (Fig. 6a-c) as well as for daily periods (Fig. 6d and e). Figure 6 and Table 2 indicate that~~ W~~w~~ithin the low elevation ablation ~~zone~~area of the ice sheet, both MAR and the MODIS products exhibit a relatively high standard deviation for the 2000-2013 period (0.07 on average for 16 day periods; ~~)~~Fig. 7, Table 3). At high elevations, variability is smaller (0.02 to 0.03 on average for 16 day periods). The MCD43A3 and MOD10A1 products show similar spatial patterns of standard deviation when the daily product is averaged over 16 day MODIS periods (Fig. 7a and c). Table 3~~2~~ suggests that MAR v3.2 ablation ~~zone~~area temporal variability is identical to MODIS variability on average, but Fig. 7~~6~~ ~~indicates~~ shows that there are locations, particularly within the west coast ablation ~~zone~~area, where MODIS variability is considerably higher. MAR v3.2 albedo variability in low elevation areas reaches a maximum of 0.09, while MODIS variability for the same regions is 0.15 at maximum. At a daily temporal resolution, MOD10A1 daily variability in the ablation ~~zone~~area (0.17 maximum, 0.07 on average) is considerably larger than the variability of MAR v3.2 albedo (0.12 maximum, 0.04 on average). As will be discussed in section 4.2, this may be the result of a positive bias in bare-ice albedo from MAR, but may also be associated with errors introduced by cloud artifacts in the MOD10A1 product. For the accumulation ~~zone~~area, the standard deviation of albedo for MAR and MODIS generally falls within the 16 day uncertainty of 0.04 for MCD43A3 high-quality albedo and daily uncertainty of 0.067 for MOD10A1 albedo estimated by Stroeve et al. (2005, 2006). This limits the comparison among MAR and the MODIS products for high elevations.

~~Figure 7 shows maps of correlations (on a pixel by pixel basis) between the two MODIS products, and between MAR and each of the MODIS products.~~ For areas south of 70°N and in the ablation ~~zone~~area north of 70°N, the two MODIS products are highly correlated (for MCD43A3 16 day periods, $r^2 > 0.5$), but in the accumulation ~~zone~~area north of 70°N this correlation decreases (Fig. 8a). Poor correlation in this area is likely a result of the low standard deviation of albedo which falls within the uncertainty range for MODIS. Maps of ~~correlation~~ the coefficient of determination between MAR and MODIS (Fig. 8~~7~~b and c) indicate that MAR v3.2 captures more than 50% of the ablation ~~zone~~area variability ~~captured~~ detected by satellite products for 16 day periods and more than 25% for daily periods. It is, however, important to note that the daily variability from MOD10A1 is partially driven by cloud artifacts retained in the MOD10A1 product (Box et al., 2012). Again, in the accumulation area, it is difficult to draw any conclusions regarding correlation, as the variability in albedo is smaller than the assumed uncertainty for the MODIS products. ~~Within the accumulation zone, correlation between MAR and MODIS products is generally poor (r^2 < 0.2) and not significant at the 95% confidence level. Again, in this region, variability is smaller than the assumed uncertainty for MCD43A3.~~

3.3 Albedo spatio-temporal variability

Further insights into the consitency of spatio-temporal variations in albedo between MODIS products and between MAR and MODIS products can be drawn from ~~The consistency of spatio-temporal variability in albedo between MODIS products and between MAR and MODIS prodcuts is investigated further by plotting scatter plots for all 2000-2013 JJA albedo values (Fig. 8). The~~ scatter plots for all MCD43A3 vs. MOD10A1 2000-2013 JJA albedo values (Fig. 9a) and MAR vs. MODIS values (Fig. 9b-d). Figure 9a indicates that ~~are consistent with conclusions drawn from previous analyses. For example~~ MCD43A3 albedo is lower (by 0.03 on average) compared to MOD10A1 albedo, ~~(Fig. 8a),~~ consistent with the significant difference between the products at high latitudes seen in Fig. 3a. There is a fairly good correlation between MCD43A3 and MOD10A1 (r^2 = 0.66) and the slope of the best linear fit (0.83) is close to 1.

When MAR is compared with MCD43A3 and MOD10A1 over 16 day periods (Fig. 9~~8~~b and c), the correlation between MAR and satellite data is as good or better than the correlation between MOD10A1 and MCD43A3 (r^2 = 0.66 vs. MOD10A1 and 0.81 vs. MCD43A3). However, there is less agreement about the 1 : 1 line; a linear fit reveals a slope of 0.58 for MAR vs. MCD43A3 and 0.51 for MAR vs. MOD10A1. MAR overestimates low values of albedo (below 0.6) relative to satellite data, which is consistent with the apparent positive MAR bias in the ablation ~~zone~~area seen in Fig. 3b and c. On a daily basis, there is a poor agreement between MAR and MOD10A1 (Fig. 9~~8~~d, r^2=0.35), consistent with the poor correlations observed in Fig 8~~7~~d. (Note that MOD10A1 albedo is only accurate to two decimal places, resulting in the apparent vertical lines in Fig. 8d.)

Scatter plots of 2000-2012 JJA albedo values for both satellite products and MAR v3.2 vs. all weather station measurements (Fig. 10~~9~~) indicate a strong correlation between in situ data and the two satellite products over 16 day periods (Fig. 10~~9~~a and b; r^2 = 0.80 for MOD10A1, r^2=0.81 for MCD43A3), as well as a good agreement about the 1 : 1 line (slope = 0.95 for MOD10A1 and 0.88 for MCD43A3). MAR agrees reasonably well with in situ data, but the correlation is lower (r^2 = 0.78), and the slope (0.66) is further from 1. Again, it appears that MAR also overestimates low albedo values relative to in situ measurements, in consistency with Fig. 9~~8~~b and c.

On a daily basis, MOD10A1 albedo exhibits a nearly 1 : 1 relationship with daily in situ albedo (Fig. 10~~9~~d; slope = 0.99), although there is increased scatter (r^2=0.75) due to higher variability on daily timescales (~~, as shown in~~ Fig. 7~~6~~). Similarly, when MAR is compared with daily in situ measurements, the correlation is lower relative to the 16 day comparison (r^2=0.74), while the slope of the best fit line does not change substantially (slope = 0.65).

~~In Figs. 8 and 9, blue points indicate locations within the MAR-defined accumulation zone. All datasets~~In situ and satellite data and MAR v3.2 outputs ~~agree~~ all indicate that spatiotemporal variability of albedo is higher in the ablation ~~zone~~area (where the standard deviation of albedo is ~0.13) than in the accumulation ~~zone~~area (standard deviation of ~0.04). This is to be expected, given that the ablation ~~zone~~area ~~experiences~~ undergoes a substantial seasonal cycle in melting.

3.4 MAR v3.2 vs. MAR v2.0 albedo

In order to further examine some of the discrepancies between MAR and observations, we find it useful to examine differences between MAR v3.2 and MAR v2.0, which has been validated against satellite and in situ data (e.g. Fettweis et al., 2005, 2011) and used for making future projections (Fettweis et al., 2013b; Tedesco and Fettweis, 2012). A major difference between MAR v3.2 and MAR v2.0 is in the scheme for calculating the albedo of bare ice; MAR v2.0 bare ice albedo is set to 0.45, while in MAR v3.2, it ranges between 0.45 and 0.55 as a function of surface melt (Table 1).

Scatter plots for MAR vs. MODIS 2000-2012 JJA albedo in the ablation area, along with frequency histograms and best fit curves of the distribution (Fig. 11) suggest that there is a bimodal distribution of ablation area albedo, which we attribute to the presence of two main surface types, ice (and firn) and snow. Pixels classified by MAR as having bare ice (or firn, surface density > 830 kg m^{-3}) for at least 8 days of each 16 day period coincide with one of the peaks in the bimodal distributions (Fig. 11).

There are differences in the observed distributions, however. MAR v2.0 exhibits a clustering of albedo values above 0.65 and below 0.55 (Fig. 11a). MCD43A3 exhibits an overlap in the distribution of the two modes, and there is a wider range of low albedo values (σ=0.10 for MCD43A3 and 0.05 for MAR for the best fit of the lower albedo peak; Table 5). The MAR v3.2 distribution exhibits a slightly wider range of low albedo values (σ=0.06 for the low albedo peak) with a mean that is positively shifted relative to MAR v2.0 (μ=0.61 vs. 0.50) (Fig. 11b). MOD10A1 does not appear to exhibit a bimodal distribution with two distinct peaks, but the best-fit curve agrees qualitatively with the observed distribution (Fig. 11c). The higher uncertainty and therefore increased variability for the MOD10A1 product (Fig. 6; Stroeve et al., 2006) may possibly mask the two peaks of the distribution. Indeed, the best-fit bimodal distribution from MOD10A1 has a higher standard deviation of albedo for the higher albedo peak (σ = 0.06 for MOD10A1 vs. 0.04 for MCD43A3; Table 5).

We compare MAR v2.0 mean 2000-2012 clear-sky JJA albedo with albedo from MAR v3.2 and MODIS in Figs. 12a-c. MAR v3.2 albedo is significantly larger in the ablation area compared with MAR v2.0 (Fig. 12a). Rather than being positively biased relative to MODIS (as is the case for MAR v3.2 as shown in Fig. 3), MAR v2.0 albedo is either negatively biased or is not significantly different from MODIS data (Fig. 12b and c). The difference in albedo scheme is the major difference between MAR v3.2 and MAR v2.0, and it results in a significant difference in SMB (Fig. 12d). The average ablation area JJA SMB for MAR v3.2 is higher by 0.53 mWE yr^{-1} compared with the average for MAR v2.0, a considerable fraction (roughly 25%) of the mean ablation area JJA SMB from MAR v3.2, which is on average -2.02 mWE/yr for the period 2000-2013. This highlights the importance of a model's albedo scheme in determining the ablation rate and size of the ablation area (van Angelen et al., 2012).

~~3.4~~3.5 Greenland Ice Sheet albedo trends

~~Box et al. (2012) investigated changes in GrIS albedo using the MOD10A1 albedo product, finding that between 2000 and 2012, surface albedo decreased over almost the entire ice sheet. Here, we build on the analysis of Box et al. (2012) and extend the analysis to include MCD43A3, MAR and in situ JJA data for the period 2000-2013. Maps of GrIS trends for 2000-2013 for MCD43A3, MOD10A1, and MAR are shown in Fig. 10 and timeseries' of annual average albedo are shown in Fig. 11.~~ MAR v3.2, MCD43A3, and MOD10A1 consistently agree that there has been a significant decrease in albedo within the ablation ~~zone~~area over 2000-2013, and that the largest decreases in albedo have occurred below 2000 m a.s.l. (Figs. 13 and 14). MCD43A3 shows a decrease of up to -0.1 per decade for pixels in the ablation ~~zone~~area, as does MOD10A1 (both products show a decrease of -0.06 per decade for the entire ~~zone~~area). MAR v3.2 agrees with these trends, but the overall magnitude is smaller (-0.03 per decade for the entire ~~zone~~area).

Within the accumulation ~~zone~~area, ~~the~~ MAR v3.2 disagrees with the two MODIS products as to the direction and magnitude of trends. MCD43A3 shows a decrease of -0.03 per decade on average, and MOD10A1 trends are somewhat larger (-0.04 per decade on average), while for MAR v3.2, trends are generally not statistically significant at the 95% level for grid boxes above 2500 m a.s.l., and are slightly positive in some high-elevation areas.

~~We also compare decadal trends at weather stations where there is a record of at least 9 years in Table 4.~~ For locations within the GrIS ablation ~~zone~~area, trends at ~~weather stations~~GC-Net stations with a record of at least 9 years are consistent with significant decreases in albedo indicated by MODIS and MAR ~~over the periods specified~~the periods covered (2000-2012 or 2004-2012; Table 6). The magnitude of the trends varies between ~~datasets~~ MAR v3.2, MODIS and in situ data at individual stations. These differences can be attributed in part to the high spatio-temporal variability of albedo within the ablation ~~zone~~area. This can potentially lead to trends at a weather station that are substantially different from trends within a 500 m MODIS grid box containing the location of that weather station. At higher elevations, this factor is less important as there is less spatio-temporal variability in albedo (~~as shown in~~ Figs. 9~~8~~ and 10~~9~~). Within the accumulation ~~zone~~area, trends at weather stations are generally within ±0.01 per decade of MAR trends; they are generally not statistically significant and are close to zero, unlike MODIS estimates, which show trends ranging between -0.01 and -0.07 per decade (Table 6).

4 Discussion

4.1 Albedo properties of the Greenland Ice Sheet ~~captured by all datasets~~common to all observations and model results

The results presented above highlight certain features of Greenland ice sheet albedo variability that are common to in situ, satellite data, and model ~~data~~results. ~~All datasets~~MAR, MODIS and in situ data capture general spatial patterns of low albedo in the ablation ~~zone~~area, which increases with increasing elevation below ~2000 m and is relatively insensitive to elevation at higher elevations (Figs. 2 and 4a, Table 4~~3~~). This spatial variability is consistent with the presence of meltwater and ~~and~~ bare ice exposure at low elevations, which are a function of surface air temperatures, and therefore elevation (Tedesco et al., 2011; Fettweis et al., 2011). Bare ice in the ablation area is often covered with dust, further reducing low elevation albedo (Bøggild et al., 2010; Wientjes and Oerlemans, 2010; Wientjes et al., 2011). ~~.~~ At high-elevation areas that are permanently snow covered, particularly at northern sites, melting is infrequent (Nghiem et al., 2012; Tedesco et al., 2011) and albedo variability is primarily associated with accumulation,~~n and~~ subsequent dry snow grain size metamorphism (Wiscombe and Warren, 1980), and possibly impurities (Dumont et al., 2014). Low elevation melting and bare ice exposure during warm summer months reduces surface albedo relative to snow albedo, resulting in a seasonal cycle that increases local variability. As Fig. 7~~6~~ and Tables 3~~2~~ and 4~~3~~ show, ~~all datasets show~~there is higher variability in ~~the~~ ablation ~~zone~~area albedo (where the mean standard deviation of albedo at in situ stations ranges between ±0.06 and ±0.09) relative to the accumulation ~~zone~~area (where standard deviations range between ±0.02 and ±0.04).

As noted in Section 3.5, ~~all datasets~~MAR, MODIS, and in situ data agree that there has been a significant decline in ablation ~~zone~~area albedo between 2000 and 2013. These trends in surface albedo are associated with increased melting and bare ice exposure resulting in a declining ablation ~~zone~~area SMB, captured by models (Fettweis et al., 2011; Ettema et al., 2009) and in situ observations (van de Wal et al., 2012). Increased melting has been linked to ~~, and are driven by warmer~~ higher regional atmospheric air temperatures, associated with atmospheric circulation changes (Fettweis et al., 2013a; Häkkinen et al., 2014).

4.2 Insights from differences between datasets

4.2.1 Variation of albedo with latitude

Results from sect. 4.1 indicate that above 70°N, MOD10A1 shows an increase in albedo with latitude, MCD43A3 exhibits a decrease, MAR shows little change, and there is also a small increase with latitude at local weather stations (Figs. 2, 4b, 5, Table 4~~3~~). The increase with latitude at local stations is likely unaffected by differences in spectral range between MODIS and in situ sensors (Fig. 10).~~.~~

~~In section 3.1 we mentioned the possibility that the bias at GC-Net stations could vary with latitude, rendering corrected GC-Net mean 2000-2013 JJA albedo comparable to MCD43A3 albedo. In order to indicate how the GC-Net albedo bias is likely to vary spatially, Fig. 12 shows the difference between MCD43A3 visible BSA (for the interval 0.3-0.7 µm) and MCD43A3 shortwave BSA (for the interval 0.3-5.0 µm). The difference between MCD43A3 visible and MCD43A3 shortwave BSA (which ranges between 0.1 and 0.2) is larger than the biases observed by Stroeve et al. (2005) at GC-stations (which range between 0.04 to 0.09), likely because the MCD43A3 visible wavelength interval is smaller than that for GC-Net stations. The difference is lowest in the ablation zone where bare ice is exposed during summer months, is largest in regions where melting occurs, but bare ice exposure is infrequent, and is relatively small at high elevations.~~

~~Because ice does not exhibit the spectral dependence of albedo that snow does (Hall and Martinec, 1985), the difference between MCD43A3 visible and shortwave albedo is lower in the ablation zone, particularly along the west coast of Greenland, where bare ice is exposed during summer. In locations where melting occurs, snow grains tend to be larger because of constructive metamorphism, reducing reflectance mostly in the near infrared band (Wiscombe~~

~~and Warren, 1980), hence resulting in a larger difference between visible and near infrared reflectance. At high elevations, there is little or no melting, and therefore a smaller difference between albedo in different bands. The difference is not a function of latitude, but rather appears to be related to surface properties. This suggests that in situ albedo values do not exhibit the decrease of albedo with latitude suggested by MCD43A3.~~

Theoretically, snow albedo is expected to increase with increasing solar zenith angle, particularly for high solar zenith angles (Wiscombe and Warren, 1980) and therefore will increase slightly with latitude at high latitudes, as long as other factors do not contribute to lower albedo values. Wang and Zender (2009) compared 16 day MCD43C3 albedo with GC-Net measurements and suggest that the MCD43C3 product is unrealistic at higher latitudes, in particular for solar zenith angles > 55°. (The MCD43C3 product differs from the MCD43A3 product used here only in its grid.) Schaaf et al. (2011) and Stroeve et al. (2013) suggest that the findings of Wang and Zender (2009) are inaccurate, partially because they did not separate results for high- vs. low-quality albedo. We have considered this in our study: results for all MCD43A3 data are shown along with good quality MCD43A3 data in Fig. 4b. While the use of only good quality data increases MCD43A3 albedo above 70°N, it does not fundamentally change the dependency of MCD43A3 albedo on latitude. For MOD10A1, excluding low quality data has little effect on the binned values.

It should also be noted that the MOD10A1 product, to the contrary, may be positively biased above 70°N, given that it is comparable with uncorrected ~~in situ~~GC-Net data, which are likely positively biased (Fig. 5). We do not have a reasonable explanation for this potential bias, but as noted by Box et al. (2012), the MOD10A1 product contains artifacts that have not been removed during quality control, even for "good quality" data. The ~~Box et al. (2012) also suggest that~~ in situ observations of Konzelmann and Omura (1995) also suggest that values of albedo ~~from MOD10A1~~ above 0.84 are unrealistic for snow under clear-sky conditions. Part of the reason for discrepancies in the latitudinal dependence of albedo may be associated with biases resulting from viewing geometry or sun angle, which vary with latitude, making it difficult to draw conclusions from the various observational datasets as to "true" variations in albedo with latitude.

4.2.2 Differences between MAR v3.2, MAR v2.0 and observations

The major difference between MAR v3.2 albedo and observed albedo is an overall positive bias in the ablation ~~zone~~area. This bias can be seen most clearly as a difference of ~0.1 between MAR v3.2 and the two MODIS products along the west coast ablation ~~zone~~area in Fig. 3b and c, and in a difference between MAR v3.2 and both MODIS products of 0.06 at in situ stations (with low elevation stations mostly located in the west coast ablation ~~zone~~area). Mean ablation ~~zone~~area albedo from local stations is also comparable with coincident MAR v3.2 albedo (Table 4~~3~~), but local station measurements are likely positively biased, further confirming a positive MAR bias in this area.

Scatter plots of ablation ~~zone~~area albedo appear to confirm this: when MAR v3.2 is compared with both MODIS data and in situ measurements (Figs. 9~~8~~b, c and 10~~9~~c) the result is a best fit line with a slope smaller than one. Additionally in the same area where MAR v3.2 appears positively biased in the west coast ablation ~~zone~~area, MODIS exhibits relatively high variability compared with MAR v3.2 (as discussed in Sect. 3.3; Fig. 7~~6~~).

Biases in MAR ablation area albedo are related to its ability to capture the observed bimodal distribution in ablation zone albedo (Fig 11) associated with two main surface types, ice and snow.

The positive bias from MAR v3.2, as well as the relatively low modeled variability in the ablation ~~zone~~area is the result of the albedo values set for bare ice ~~(ranging between 0.45 and 0.55)~~ in MAR v3.2 (Table 1) that may be too high on average~~, as will be discussed further in the following section~~.~~.~~ MAR v2.0 albedo, by contrast, which has a fixed bare ice albedo of 0.45, generally exhibits a negative bias in most portions of the ablation zone. ~~-~~A bare ice albedo that is too high will also ~~, indeed,~~ lead to a smaller difference between the albedo values of melting snow and bare ice, reducing temporal variations in ablation ~~zone~~area albedo, resulting in the relatively low variability from MAR v3.2 (Fig. 7). ~~.~~

An examination of Fig. 11 indicates that the low albedo peak for MAR v3.2 is closer to being normally distributed compared with the peak for MAR v2.0, and therefore better matches the distribution from MCD43A3. However, the MAR v3.2 parameterization overestimates the bare ice albedo, as already discussed, and still does not fully capture the variability in the low albedo peak for MODIS albedo (σ=0.06 for MAR v3.2 and σ=0.10 for both MODIS products). The results suggest that although MAR v3.2 appears to correct a low albedo bias present in MAR v2.0, and introduces a somewhat more realistic distribution of albedo in the ablation area, it also introduces a positive albedo bias, particularly along the west coast ablation zone, which is rich in impurities.

~~Also,~~ MAR ~~v3.2~~ albedo is only a function of accumulated meltwater and does not explicitly take into account the presence of dust, surface lakes and surface streams, including the West Greenland "dark zone" (van de Wal and Oerlemans, 1994; Wientjes and Oerlemans, 2010), which reduces bare ice albedo and likely introduces increased ablation ~~zone~~area albedo variability. Assigning a wider range of MAR albedo values for bare ice (which has been implemented in most recent release of MAR, v3.4) may improve its representation of the distribution of bare ice albedo, but may not necessarily improve its ability to capture the spatial distribution of ablation area albedo. This could potentially be achieved through the inclusion of an explicit representation of dust and sub-grid-scale hydrology in the model.

~~1.1.1 MAR v3.2 vs. MAR v2.0 albedo~~

~~In order to further examine some of the discrepancies between MAR and observations, we find it useful to examine differences between MAR v3.2 and a previous version (MAR v2.0), which has been validated against satellite and in situ data (e.g. Fettweis et al., 2005, 2011) and used for making future projections (Fettweis et al., 2013b; Tedesco and Fettweis, 2012). Comparisons are conducted for the 2000-2012 period, as MAR v2.0 data are available only through 2012. A major difference between MAR v3.2 and MAR v2.0 is in the scheme for calculating the albedo of bare ice. As noted in section 2.2, MAR v2.0 assumes a fixed value of 0.45 in the case where surface densities exceed 920 kg m^{-3}, while in MAR v3.2, bare ice albedo ranges between 0.45 and 0.6 as a function of surface melt.~~

~~In Fig. 13, we show scatter plots for MAR vs. MODIS 2000-2012 JJA ablation zone albedo on 16 day timescales for both versions of MAR along with frequency histograms of albedo values for MAR and the two MODIS products, and distributions of the best-fit of these histograms obtained using maximum likelihood estimation. Statistics for the mean (μ) and standard deviation (σ) of these best-fit distributions are shown in Table 5. MAR v2.0 exhibits a clustering of albedo values above 0.65 and below 0.6, resulting in a bimodal distribution of albedo values (Fig. 13a). MCD43A3 also shows a bimodal distribution of albedo, but the distributions of the two modes overlap, and there is a wider range of low albedo values (σ=0.10 for MCD43A3 and 0.05 for MAR for the best fit of the lower albedo peak). The~~

~~MAR v3.2 distribution exhibits a slightly wider range of low albedo values (σ=0.06 for the low albedo peak) with a mean that is positively shifted relative to MAR v2.0 (μ=0.61 vs. 0.50) (Fig. 13b). MOD10A1 does not appear to exhibit a bimodal distribution with two distinct peaks, but the best-fit curve agrees qualitatively with the observed distribution (Fig. 13c). The higher uncertainty and therefore increased variability for the MOD10A1 product (Fig. 6; Stroeve et al., 2006) may possibly mask the two peaks of the distribution. Indeed, the best-fit bimodal distribution from MOD10A1 has a higher standard deviation of albedo for the higher albedo peak (σ = 0.06 for MOD10A1 vs. 0.04 for MCD43A3).~~

~~The bimodal distribution of albedo appears to be related to the presence of two main surface types within the ablation zone, ice (and firn) and snow. Pixels classified by MAR as having bare ice (or firn, surface density > 830 kg m^{-3}) for at least 8 days of each 16 day period are shown in red in Fig. 13, and the location of these points coincides with one of two peaks in the bimodal distributions. MAR v2.0 logically exhibits a smaller range of low albedo values compared with MODIS, given that its bare-ice albedo is fixed at 0.45. An examination of Fig. 13 indicates that the low albedo peak for MAR v3.2, for which bare-ice albedo ranges between 0.45 and 0.6, is closer to being normally distributed compared with the peak for MAR v2.0, and therefore better matches the distribution from MCD43A3. However, the MAR v3.2 parameterization overestimates the bare ice albedo, as already discussed, and still does not fully capture the variability in the low albedo peak for MODIS albedo (σ=0.06 for MAR v3.2 and σ=0.10 for both MODIS products).~~

~~We compare MAR v2.0 mean 2000-2012 clear-sky JJA albedo with albedo from MAR v3.2 and MODIS in Figs. 14a-c. Fig. 14a shows that MAR v3.2 albedo is significantly larger in the ablation zone compared with MAR v2.0. Rather than being positively biased relative to MODIS (as is the case for MAR v3.2 as shown in Fig. 3), MAR v2.0 albedo is either negatively biased or is not significantly different from MODIS data. The difference in albedo scheme is the major difference between MAR v3.2 and MAR v2.0, and it results in a significant difference in SMB, as shown in Fig. 14d. The average ablation zone JJA SMB for MAR v3.2 is higher by 0.53 mWE yr^{-1} compared with the average for MAR v2.0, a considerable fraction (roughly 25%) of the mean ablation zone JJA SMB from MAR v3.2, which is on average -2.02 mWE/yr for the period 2000-2013. This highlights the importance of a model's albedo scheme in determining the ablation rate and size of the ablation zone (van Angelen et al., 2012). The results suggest that although MAR v3.2 appears to correct a low~~

~~albedo bias present in MAR v2.0, and introduces a more realistic distribution of bare ice albedo, it also introduces a positive albedo bias, particularly along the west coast ablation zone, which is rich in impurities. A reduction of the minimum bare ice albedo (0.45 currently) in the next MAR version may reduce this bias by more realistically representing the GrIS surface.~~

4.2.3 Discrepancies in ~~ablation~~accumulation ~~zone~~area trends

As noted in section 3.5, there is a discrepancy between ~~different~~ the satellite products, in situ data, and model results ~~datasets~~ regarding albedo trends in the accumulation ~~zone~~area of the ice sheet. MOD10A1 and MCD43A3 show significant decreases in accumulation ~~zone~~area albedo (-0.04 to -0.03 per decade) while MAR v3.2 trends are generally not statistically significant, and in situ trends are generally small (not larger than -0.01 per decade) or not significant.

A possible explanation for this discrepancy is that MODIS trends are negatively biased as a result of declining instrument sensitivity of the MODIS sensors (Wang et al., 2012). In particular, a larger degradation has been observed for the MODIS Terra satellite (Wang et al., 2012). The MCD43A3 product uses data from both the Terra and Aqua satellites, while MOD10A1 only uses data from Terra. This could potentially explain the larger trends for MOD10A1 relative to MCD43A3 (Table 6~~4~~, Fig. 13~~0~~). Box et al. (2012) conclude that declining instrument sensitivity does not substantially affect GrIS albedo trends, because they find larger trends in GC-Net data relative to MOD10A1 for 70% of cases where trends are deemed to be significant. We do not find JJA GC-Net trends larger than those of MODIS, except within the ablation ~~zone areas~~area, with high local variability, in ~~contrary~~ contrast to the findings of Box et al. (2012). The analysis performed here is somewhat different from that employed by Box et al. (2012). Differences in trends may result from the fact that here we have focused on trends for the entire JJA period rather than on monthly trends, and calculate trends for 16 day albedo values rather than calculating a monthly albedo from integrated fluxes over a 1-month period, as was done by Box et al. (2012).

We also investigated the possibility that the smaller spectral interval of GC-Net data influences trends by comparing MCD43A3 visible vs. shortwave albedo trends, but did not find the trends to be significantly different from each other. ~~(not shown here). We find that MCD43A3 visible albedo shows differences of smaller than ±0.05 per decade compared with~~

~~MCD43A3 shortwave and the differences are not statistically significant. The largest differences are found in the west coast ablation zone. This is likely associated with more frequent bare ice exposure, which substantially reduces visible albedo, but does not have as large of an effect on near infrared albedo, due to the low reflectance of snow at near infrared wavelengths. This may therefore have some impact on ablation zone stations that experience bare ice exposure (e.g. JAR2 and S9) contributing to larger trends observed at these locations relative to MAR and MODIS (Table 4), but again, the overall impact is small.~~

We are not able to ~~prove~~ confirm that the larger trends from MODIS are associated with declining instrument sensitivity, as this analysis is outside the scope of this study. However, the findings of this study seem consistent with this possibility and this is suggested as a topic for future research.

5 Conclusions

We have examined spatio-temporal variability and trends in GrIS albedo using in situ measurements, satellite products obtained from MODIS data, and outputs of a regional climate model (MAR v3.2). The results presented here reveal areas of agreement as well as discrepancies between observational and model estimates of GrIS albedo spatio-temporal variability. Examining ~~all of these~~ local measurements, satellite data, ~~datasets~~and model results concurrently reveals information about the GrIS albedo and potential biases that would not be revealed by examining ~~any of the datasets~~ the observational datasets or model results individually.

The results presented here show that albedo varies spatially as a function primarily of surface properties, in particular melting and bare-ice exposure in the ablation ~~zone~~area. These factors are also associated with temporal variations in albedo, resulting in high variability in low elevation regions. The differences in variations with latitude indicated by satellite products appear likely to be a function of inaccuracies associated with the products themselves, rather than a record of actual variations in surface albedo, particularly as the two products are derived from the same MODIS sensors.

Both satellite products and MAR model ~~data~~ outputs (for v2.0 and v3.2) suggest that there is a bimodal distribution of surface albedo within the ablation ~~zone~~area of the ice sheet. Based on model results, we infer that this distribution is associated with the presence of two primary surface types within the ablation ~~zone~~area, snow and bare ice. The model's inability to capture the full range of low elevation albedo leads to inaccuracies in the representation of spatiotemporal variations in albedo, which can substantially impact the representation of SMB. The MAR version examined here (v3.2) appears to better represent the full range of bare-ice albedo in the ablation ~~zone~~area relative to a previous version (v2.0), but a lower minimum bare ice albedo value (as is implemented in the next version of MAR, v3.4), may produce results that are more consistent with observations. Even so, it may be necessary to account for the presence of impurities and sub-grid scale hydrology in order to fully capture spatial variations in albedo.

~~A comparison between multiple datasets~~The analysis performed here indicates a statistically significant decrease in ablation ~~zone~~area albedo over the period 2000-2013 that is consistent with previous studies (Box et al., 2012; Tedesco et al., 2011, 2013; Str~~e~~oeve et al., 2013). This decrease is consistent with a coincident decline in ablation ~~zone~~area SMB recorded by both models and observations (e.g. Fettweis et al., 2011; Ettema et al., 2009~~; van de Wal et al., 2012~~). Our results are inconclusive regarding high elevation trends in albedo; we observe inconsistencies between satellite-derived trends and trends obtained from in situ measurements and MAR v3.2 results. We are therefore unable to confirm previously reported decreases in surface albedo at high elevations.

Future research should be directed towards understanding the reasons for discrepancies between ~~datasets~~satellite products, in situ data and model results, in order to better understand changes in GrIS albedo. This includes resolving discrepancies ~~between datasets~~ regarding high-elevation trends, and discrepancies in mean satellite-derived surface albedo at high latitudes. Models such as MAR appear to be effective at capturing surface albedo, but refinements are necessary for representation of surface albedo in low elevation areas. ~~(~~In particular, the representation of bare ice albedo is critical.~~)~~ Sensitivity studies, such as those performed by van Angelen et al. (2012) of the impact of surface albedo on SMB variability, may help to quantify the accuracy with which surface albedo must be modeled for a given region. Analysis of spatiotemporal variations in albedo across different spatial scales (including at a higher spatial resolution than has been examined here) may also become increasingly important as models operate at higher spatial resolutions, and as we seek to understand the GrIS surface mass and energy budget in greater detail. Given the strong relationship between surface albedo and SMB, these future studies are crucial for efforts aiming at estimating and predicting the impact of current and future climate change on GrIS SMB.

Acknowledgements

This research is supported by NSF Grant 0909388. In situ data along the K-transect are financed over time by Utrecht University, and several grants from the Polar Program of the Netherlands Organization for Scientific Research (NWO) including the Spinoza Program, and by the Royal Netherlands Academy of Sciences (KNAW). The authors would like to thank Rajashree Datta, Jason Box, and two anonymous reviewers for comments and suggestions that improved the manuscript. Part of this work was performed while Marco Tedesco was serving as Program Director at the National Science Foundation.

References

Bamber, J.L., Ekholm, S., and Krabill, W.B.: A new, high-resolution digital elevation model of Greenland fully validated with airborne laser altimeter data, J. Geophys. Res., 106, B4, 6733-6745, 2001.

Bamber, J.L., Griggs, J.A., Hurkmans, R.T.W.L., Dowdeswell, J.A., Gogineni, S.P., Howat, I., Mouginot, J., Paden, J., Palmer, S., Rignot, E., and Steinhage, D.: A new bed elevation dataset for Greenland, The Cryosphere, 7, 449-510, doi:10.5194/tc-7-499-2013, 2013.

Bøggild, C. E., Brandt, R. E., Brown, K. J., Warren, S. G.: The ablation zone in northeast Greenland: ice types, albedos and impurities, J. Glaciol., 56, 2010.

Box, J. E. and Rinke, A.: Evaluation of Greenland Ice Sheet surface climate in the HIRHAM Regional Climate Model using automatic weather station data, J. Climate, 16, 1302-1319, 2002.

Box, J.E., Bromwich, D.H., Veenhuis, B.A., Bai, L.-S., Stroeve, J.C., Rogers, J.C., Steffen, K., Haran, T. and Wang, S.-H.: Greenland Ice Sheet surface mass balance variability (1988-2004) from calibrated Polar MM5 output, J. Climate, 19, 2783-2800, 2006.

Box, J.E., Fettweis, X., Stroeve, J.C., Tedesco, M., Hall, D.K., and Steffen, K.: Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers, The Cryosphere, 6, 821-839, 2012.

Brun, E., David, P., Sudul, M., and Brunot, G.: A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting, J. Glaciol., 38, 128, 13-22, 1992.

Dee, D. P., Uppala, S. M., Simmons, A. J., et al.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. R. Meteorol. Soc., 137: 553-597, doi: 10.1002/qj.828, 2011.

Dumont, M., Brun, E., Picard, G., Michou, M., Libois, Q., Petit, J-R., Geyer, M., Morin, S., and Josse, B.: Contribution of light-absorbing impurities in snow to Greenland's darkening since 2009, Nature, doi:10.1038/NGEO2180, 2014.

Ettema, J., van den Broeke, M.R., van Meijgaard, E., van de Berg, W.J., Bamber, J.L., Box, J.E., Bales, R.C.: Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, Geophys. Res. Lett., 36, L12501, doi:10.1029/2009GL038110, 2009.

Fettweis, X.: Reconstruction of the 1979-2006 Greenland ice sheet surface mass balance using the regional climate model MAR, The Cryosphere, 1, 21-40, doi:10.5194/tc-1-21-2007, 2007.

Fettweis, X., Gallée, H., Lefebre, F., and van Ypersele, J.-P.: Greenland surface mass balance simulated by a regional climate model and comparison with satellite-derived data in 1990-1991, Clim. Dynam., 24, 623-640, 2005.

Fettweis, X., van Ypersele, J.-P., Gallée, H., Lefebre, F., and Lefebvre, W.: The 1979-2005 Greenland ice sheet melt extent from passive microwave data using an improved version of the melt retrieval XPGR algorithm, Geophys. Res. Lett., 34, L05502, doi:10.1029/2006GL028787, 2007.

Fettweis, X., Tedesco, M., van den Broeke, M., and Ettema, J.: Melting trends over the Greenland ice sheet (1958-2009) from spaceborne microwave data and regional climate models, The Cryosphere, 5, 359-375, doi:10.5194/tc-5-359-2011, 2011.

Fettweis, X., Hanna, E., Lang, C., Belleflamme, A., Erpicum, M., and Gallée, H.: *Brief communication* "Important role of the mid-tropospheric atmospheric circulation in the recent surface melt increase over the Greenland ice sheet", The Cryosphere, 7, 241-248, doi:10.5194/tc-7-241-2013, 2013a.

Fettweis, X., Franco, B., Tedesco, M., van Angelen, J. H., Lenaerts, J. T. M., van den Broeke, M. R., and Gallée, H.: Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR, The Cryosphere, 7, 469-489, doi:10.5194/tc-7-469-2013, 2013b.

Franco, B., Fettweis, X., and Erpicum, M.: Impact of spatial resolution on the modelling of the Greenland ice sheet surface mass balance between 1990-2010, using the regional climate model MAR, The Cryosphere, 6, 695-711, doi:10.5194/tc-6-695-2012, 2012.

Gallée, H.: Air-sea interactions over Terra Nova Bay during winter: simulation with a coupled atmosphere-polynya model, J. Geophys. Res., 102, D12, 13835-13849, 1997.

Gallée, H., and Schayes, G.: Development of a three-dimensional meso-γ primitive equation model: katabatic winds simulation in the area of Terra Nova Bay, Antarctica, Mon. Weather Rev., 122, 671-685, 1994.

Greuell, W., and Konzelman, T.: Numerical modelling of the energy balance and the englacial temperature of the Greenland Ice Sheet. Calculations for the ETH-Camp location (West Greenland, 1155 m.a.s.l.), Global and Planetary Change, 9, 91-114, 1994.

Häkkinen, S., Hall, D. K., Shuman, C. A., Worthen, D. L., and DiGirolamo, N. E.: Greenland ice sheet melt from MODIS and associated atmospheric variability, Geophys. Res. Lett., 41, 1600-1607, 2014.

Hall, D. K., and Martinec, J.: Remote Sensing of Ice and Snow, Chapman and Hall, London, 1985.

Hall, D.K., Salomonson, V.V., and Riggs, G.A.: MODIS/Terra Snow Cover Daily L3 Global 500 m Grid. Version 5. [Tiles h15v02, h16v02, h17v02, h16v01, h17v02, h16v00, h17v00], National Snow and Ice Data Center, Boulder, Colorado USA, 2012.

Konzelmann, T., and Ohmura, A.: Radiative fluxes and their impact on the energy balance of the Greenland ice sheet, J. Glaciol., 41, 490-502, 1995.

Klein, A.G., and Stroeve, J.: Development and validation of a snow albedo algorithm for the MODIS instrument, Ann. of Glaciol., 34, 45-52, 2002.

Lefebre, F., Gallée, H., van Ypersele, J.-P.: Modeling of snow and ice melt at ETH Camp (West Greenland): a study of surface albedo, J. Geophys. Res., 108, 4231, doi:10.1029/2001JD001160, 2003.

Lefebre, F., Fettweis, X., Gallée, H., van Ypersele, J.-P., Marbaix, P., Greuell, W., and Calanca, P.: Evaluation of a high-resolution regional climate model simulation over Greenland, Clim. Dynam., 25, 99-116, doi: 10.1007/s00382-005-0005-8, 2005.

Nghiem, S. V., Hall, D. K., Mote, T. L., Tedesco, M., Albert, M. R., Keegan, K., Shuman, C. A., DiGirolamo, N. E., and Neumann, G.: The extreme melt across the Greenland ice sheet in 2012, Geophys. Res. Lett., 39, L20502, doi: 10.1029/2012GL053611, 2012.

Rae, J. G. L., Aðalgeirsdóttir, G., Edwards, T. L., Fettweis, X., Gregory, J. M., Hewitt, H. T., Low, J. A., Lucas-Picher, P., Mottram, R. H., Payne, A. J., Ridley, J. K., Shannon, S. R., van de Berg, W. J., van de Wal, R. S. W. and van den Breoke, M. R.: Greenland ice sheet surface mass balance: evaluating simulations and making projections with regional climate models, The Cryosphere, 6, 1275-1294, doi: 10.5194/tc-6-1275-2012, 2012.

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A. and Lenaerts, J.: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, Geophys. Res. Lett., 38, L05503, doi: 10.1029/2011GL046583, 2011.

Schaaf, C. B., Gao, F., Strahler, A. H., Lucht, W., Li, X., Tsang, T., Strugnell, N. C., Zhang, X., Jin, Y., Muller, J.-P., Lewis, P., Barnsley, M., Hobson, P., Disney, M., Roberts, G., Dunderdale, M., Doll, C., d'Entremont, R. P., Hu, B., Liang, S., Privette, J. L. and Roy, D.: First operational BRDF, albedo nadir reflectance products from MODIS, Remote Sens. Environ., 83, 135-148, 2002.

Schaaf, C.B., Wang, Z., and Strahler, A.H.: Commentary on Wang and Zender – MODIS snow albedo bias at high solar zenith anlges relative to theory and to in situ observations in Greenland, Remote Sens. Environ., 115, 1296-1300, 2011.

Steffen, K., Box, J.E., and Abdalati, W.: Greenland Climate Network: GC-Net, in: CRREL 96-27 Special report on glaciers, ice sheets and volcanoes, trib. to M. Meier, edited by: Colbeck, S. C., US Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire, 98-103, 1996.

Stroeve, J., Box, J.E., Gao, F., Liang, S., Nolin, A. and Schaaf, C.: Accuracy assessment of the MODIS 16-day albedo product for snow: comparisons with Greenland in situ measurements, Remote Sens. Environ., 94, 46-60, 2005.

Stroeve, J.C., Box, J.E. and Haran, T.: Evaluation of the MODIS (MOD10A1) daily snow albedo product over the Greenland ice sheet, Remote Sens. Environ., 105, 155-171, 2006.

Stroeve, J.C., Box, J.E., Wang, Z., Schaaf, C., and Barret, A.: Re-evaluation of MODIS MCD43 Greenland albedo accuracy and trends, Remote Sens. Environ., 138, 199-214, 2013.

Tedesco, M., and Fettweis, X.: 21st century projections of surface mass balance changes for major drainage systems of the Greenland ice sheet, Environ. Res. Lett., 7, 045050, doi: 10.1088/1748-9326/7/4/045405, 2012.

Tedesco, M., Serreze, M., and Fettweis, X.: Diagnosing the extreme surface melt event over southwestern Greenland in 2007, The Cryosphere, 2, 159-166, doi: 10.5194/tc-2-159-2008, 2008.

Tedesco, M., Fettweis, X., van den Broeke, M. R., van de Wal, R. S. W., Smeets, C. J. P. P., van de Berg, W. J., Serreze, M. C., and Box, J. E.: The role of albedo and accumulation in the

2010 melting record in Greenland, Environ. Res. Lett., 6, 014005, doi:10.1088/1748-9326/6/1/014005, 2011.

Tedesco, M., Alexander, P., Box, J. E., Cappelen, J., Mote, T., Steffen, K., van de Wal, R. S. W., Wahr, J., and Wouters, B.: Greenland Ice Sheet, in: State of the Climate in 2012, edited by: Blunden, J. and Arndt, D., B. Am. Meteorol. Soc., 94, S121-S123, 2013.\

Uppala, S. M., Kållberg, P. W., Simmons, A. J., et al.: The ERA-40 re-analysis, Q. J. R. Meteorol. Soc., 131, 2961-3012, doi: 10.1256/qj.04.176, 2005.

van Angelen, J. H., Lenaerts, J. T. M., Lhermitte, S., Fettweis, X., Kuipers Munneke, P., van den Broeke, M. R., van Meijgaard, E., Smeets, C. J. P. P.: Sensitivity of Greenland Ice Sheet surface mass balance to surface albedo parameterization: a study with a regional climate model, The Cryosphere, 6, 1175-1186, doi: 10.5194/tc-6-1175-2012, 2012.

van den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., Jan van de Berg, W., van Meijgaard, E., Velicogna, I., and Wouters, B.: Partitioning recent Greenland mass loss, Science, 326, 984-986, doi: 10.1126/science.1178176, 2009.

van den Broeke, M. R., Smeets, C. J. P. P., and van de Wal, R. S. W.: The seasonal cycle and interannual variability of surface energy balance and melt in the ablation zone of the west Greenland ice sheet, The Cryosphere, 5, 377-390, doi:10.5194/tc-5-377-2011, 2011.

van de Wal, R. S. W. and Oerlemans, J.: An energy balance model for the Greenland Ice Sheet, Global Planet. Change, 9, 115-131, 1994.

van de Wal, R. S. W., Greuell, W., van den Broeke, M. R., Reijmer, C. H., and Oerlemans, J.: Surface mass-balance observations and automatic weather station data along a transect near Kangerlussuaq, West Greenland, Ann. Glaciol., 42, 311-316, 2005.

van de Wal, R. S. W., Boot, W., Smeets, C. J. P. P., Snellen, H., van den Broeke, M. R., and Oerlemans, J.: Twenty-one years of mass balance observations along the K-Transect, West-Greenland, Earth Syst. Sci. Data, 4, 31-35, doi:10.5194/essd-4-31-2012, 2012.

Vernon, C. L., Bamber, J. L., Box, J. E., van den Broeke, M. R., Fettweis, X., Hanna, E., and Huybrechts, P.: Surface mass balance model intercomparison for the Greenland ice sheet, The Cryosphere, 7, 599-614, doi: 10.5194/tc-7-599-2013, 2013.

Wang, D., Morton, D., Masek, J., Wu, A., Nagol, J., Xiong, X., Levy, R., Vermote, E., and Wolfe, R.: Impact of sensor degradation on the MODIS NDVI time series, Remote Sens. Environ., 119, 55-61, 2012.

Wang, X. and Zender, C. S.: MODIS snow albedo bias at high solar zenith angles relative to theory and to in situ observations in Greenland, Remote Sens. Environ., 114, 563-575, 2009.

Wientjes, I. G. M., and Oerlemans, J.: An explanation for the dark region in the western melt zone of the Greenland ice sheet, The Cryosphere, 4, 261-268, 2010.

Wiscombe, W. J., and Warren, S. G.: A model for the spectral albedo of snow: pure snow, J. Atmos. Sci., 37, 2712-2733, 1980.

Zuo, Z. and Oerlemans, J.: Modelling albedo and specific balance of the Greenland ice sheet: calculations for the Søndre Strømfjord transect, J. Glaciol., 42, 305-317, 1996.

Table 1. Range of possible albedo values for different surface types in MAR v2.0 and v3.2

	MAR v2.0	MAR v3.2
Bare Ice	0.45	0.45 to 0.55
Firn	0.45 to 0.65	0.55 to 0.65
Snow	>0.65	>0.65

Table 2~~1~~. GC-Net and K-Transect weather stations used in this study and years of coverage.

Station Name	Coverage Period	Excluded data
Ablation ~~Zone~~Area		
Swiss Camp (GC-Net)	2000-2003, 2005-2011	2012
JAR 1 (GC-Net)	2000-2012	
JAR 2 (GC-Net)	2000-2005, 2007, 2009-2012	
JAR 3 (GC-Net)	2000-2003	
S5 (K-Transect)	2004-2012	
S6 (K-Transect)	2004-2012	
S9 (K-Transect)	2004-2012	
Peterman ELA (GC-Net)	2012	2003, 2005
Peterman Glacier (GC-Net)	Not Used	2002-2005
Accumulation ~~Zone~~Area, North of 70°N		
GIST (GC-Net)	2001, 2002, 2006, 2012	
Humboldt (GC-Net)	2002-2005, 2007, 2010-2012	
Summit (GC-Net)	2000-2012	
Tunu N (GC-Net)	2000-2002, 2005-2012	
NASA-E (GC-Net)	2000-2007, 2010-2012	
NEEM (GC-Net)	2006-2012	
NASA-U (GC-Net)	Not Used	2003-2012
NGRIP (GC-Net)	Not Used	2002-2004, 2007-2009
Accumulation ~~Zone~~Area, South of 70°N		
KULU (GC-Net)	2000	
S10 (K-Transect)	2010-2012	
Crawford Point 1 (GC-Net)	2000-2004	2005-2010
Crawford Point 2 (GC-Net)	2000	
Dye-2 (GC-Net)	2000-2012	
Saddle (GC-Net)	2000-2001, 2003-2008, 2010-2012	
South Dome (GC-Net)	2003-2012	
NASA SE (GC-Net)	2000-2007, 2009-2012	
KAR (GC-Net)	2000, 2001	
Aurora (GC-Net)	Not Used	

Table 3~~2~~. ~~Summary of mean~~Mean 2000-2012 JJA Greenland ice sheet albedo, for MOD10A1, MCD43A3 BSA shortwave, and MAR clear-sky albedo, averaged within the mass balance ~~zones~~ areas shown in Fig. 1 and Table 2~~1~~. Only good quality MODIS data are used here. All data have been averaged over the same 16 day periods of the MCD43A3 product. Only periods when coincident data for all datasets are available have been included.

Locations	MOD10A1	MCD43A3 BSA Shortwave	MAR Clear Sky
Ice-Sheet wide	0.77 ± 0.04	0.73 ± 0.04	0.75 ± 0.03
Ablation ~~Zone~~Area	0.68 ± 0.07	0.63 ± 0.07	0.68 ± 0.07
Accumulation ~~Zone~~Area	0.80 ± 0.03	0.75 ± 0.03	0.77 ± 0.02
Acc. ~~Zone~~ Area (N. of 70	0.80 ± 0.03	0.75 ± 0.03	0.77 ± 0.02
Acc. ~~Zone~~ Area (S. of 70	0.78 ± 0.03	0.77 ± 0.03	0.77 ± 0.02

Table 4~~3~~. ~~Summary of mean 2000-2012 JJA albedo (and average standard deviations) at in situ stations, for MOD10A1, MCD43A3 BSA shortwave, and MAR clear-sky albedo, aggregated into the mass balance zones shown in Fig. 1 and Table 1. Only good quality MODIS data are used here. All data have been averaged over the same 16 day periods of the MCD43A3 product. Only periods when coincident data for all datasets is available have been included. The closest pixel to the in situ station is used for MAR and MODI~~Same as Table 3, but for the average of 16 day data for all in situ stations within each region.~~S data.~~

Locations	MOD10A1	MCD43A3 BSA Shortwave	MAR Cloud-Corrected	In Situ
All stations	0.69 ± 0.06	0.67 ± 0.04	0.70 ± 0.04	0.74 ± 0.05
Ablation ~~Zone~~Area	0.51 ± 0.09	0.50 ± 0.07	0.57 ± 0.06	0.56 ± 0.08
Accumulation ~~Zone~~Area	0.79 ± 0.04	0.77 ± 0.02	0.76 ± 0.02	0.82 ± 0.03
Acc. ~~Zone~~ Area (N. of 70	0.82 ± 0.04	0.75 ± 0.02	0.78 ± 0.01	0.83 ± 0.02
Acc. ~~Zone~~ Area (S. of 70	0.77 ± 0.04	0.78 ± 0.03	0.75 ± 0.03	0.81 ± 0.03

Table 55. Mean and standard deviation for the best fit to the distributions of ablation ~~zone~~ area albedo shown in Fig. 124 (assuming that the appropriate distribution is a combination of two normal distributions).

	MOD10A1	MCD43A3 BSA Shortwave	MAR v2.0 Cloud-Corrected	MAR v3.2 Cloud-Corrected
First Mode (Ice)	0.57 ± 0.10	0.55 ± 0.10	0.50 ± 0.05	0.61 ± 0.06
Second Mode (Snow)	0.73 ± 0.06	0.71 ± 0.04	0.74 ± 0.04	0.74 ± 0.03

Table ~~6~~4. Trends (and 95% confidence intervals) in JJA albedo (fraction per decade) at GC-Net and K-Transect weather stations and the nearest~~,~~ MOD10A1, MCD43A3, and MAR pixels. In this case, MODIS data flagged as "other quality" have been included. Only 16 day periods when coincident estimates are available for all datasets have been used. Values in bold indicate trends significant at the 95% confidence level.

	Period	MCD43A3 BSA Shortwave	MOD10A1	MAR clear-sky	In Situ
Ablation Zone					
Swiss Camp (GC)	2000-2011	**-0.15** ± 0.05	**-0.15** ± 0.06	**-0.05** ± 0.03	**-0.06** ± 0.03
JAR 1 (GC-Net)	2000-2012	**-0.19** ± 0.06	**-0.21** ± 0.07	**-0.07** ± 0.03	**-0.22** ± 0.03
JAR 2 (GC-Net)	2000-2012	**-0.06** ± 0.02	**-0.08** ± 0.03	**-0.04** ± 0.02	<0.01 ± 0.02
S5 (K-Transect)	2004-2012	**-0.05** ± 0.03	**-0.09** ± 0.04	-0.04 ± 0.04	**-0.08** ± 0.04
S6 (K-Transect)	2004-2012	**-0.13** ± 0.07	**-0.19** ± 0.08	**-0.08** ± 0.06	**-0.14** ± 0.06
S9 (K-Transect)	2004-2012	**-0.15** ± 0.05	**-0.17** ± 0.06	**-0.12** ± 0.05	**-0.25** ± 0.05
Accumulation Zone, North of 70°N					
Humboldt (GC)	2002-2011	-0.01 ± 0.02	**-0.05** ± 0.02	**-0.02** ± 0.01	<0.01 ± 0.01
Summit (GC-Net)	2000-2012	**-0.02** ± 0.02	**-0.04** ± 0.02	**<0.01** ± <0.01	<0.01 ± < 0.01
Tunu N (GC-Net)	2000-2012	**-0.03** ± 0.01	**-0.05** ± 0.02	-0.01 ± 0.01	<0.01 ± 0.01
NASA-E (GC-Net)	2000-2011	**-0.02** ± 0.01	**-0.05** ± 0.02	<0.01 ± 0.01	**-0.03** ± 0.01
Accumulation Zone, South of 70°N					
Dye-2 (GC-Net)	2000-2012	**-0.05** ± 0.01	**-0.07** ± 0.02	**-0.01** ± 0.01	-0.01 ± 0.01
Saddle (GC-Net)	2000-2012	**-0.03** ± 0.01	**-0.05** ± 0.02	**-0.01** ± 0.01	-0.01 ± 0.01
South Dome (GC)	2003-2012	**-0.04** ± 0.01	**-0.06** ± 0.02	-0.01 ± 0.01	**-0.08** ± 0.01
NASA SE (GC)	2000-2012	**-0.04** ± 0.01	**-0.07** ± 0.02	**-0.02** ± 0.01	<0.01 ± 0.01

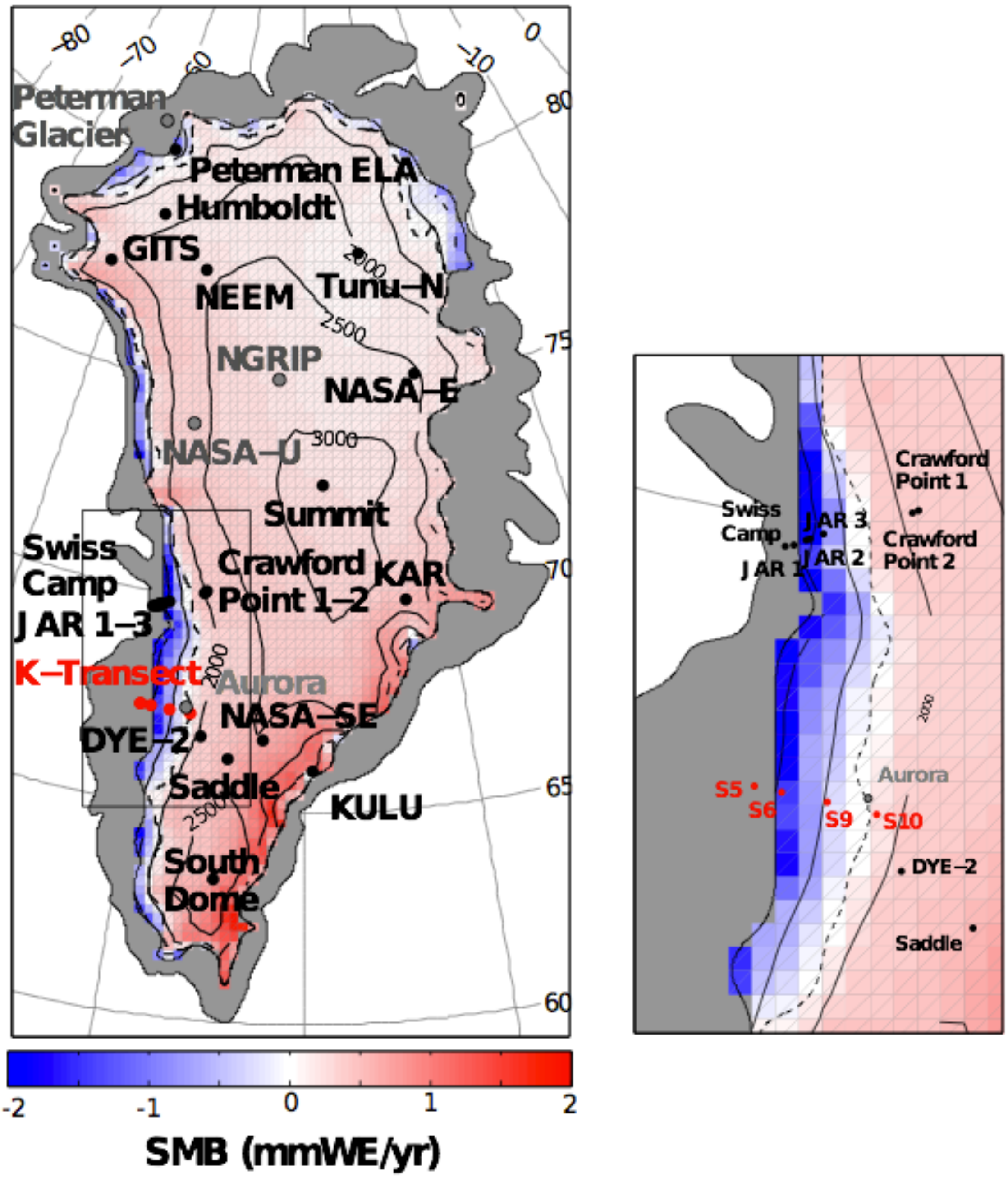

Figure 1. MAR v3.2 mean September 2000 - August 2013 SMB (mWE/yr) and locations of all GC-Net and K-Transect weather stations. Pixels not defined as 100% ice covered in MAR are masked out. The bold dotted black line shows the mean equilibrium line (where the mean SMB is 0). The K-transect stations (S5, S6, S9, S10) are colored red, while GC-Net stations are black. Stations in grey are GC-Net stations that have not been used in this study. Other contour lines indicate elevation in meters above sea level. The inset shows individual stations near the west coast ablation zone.

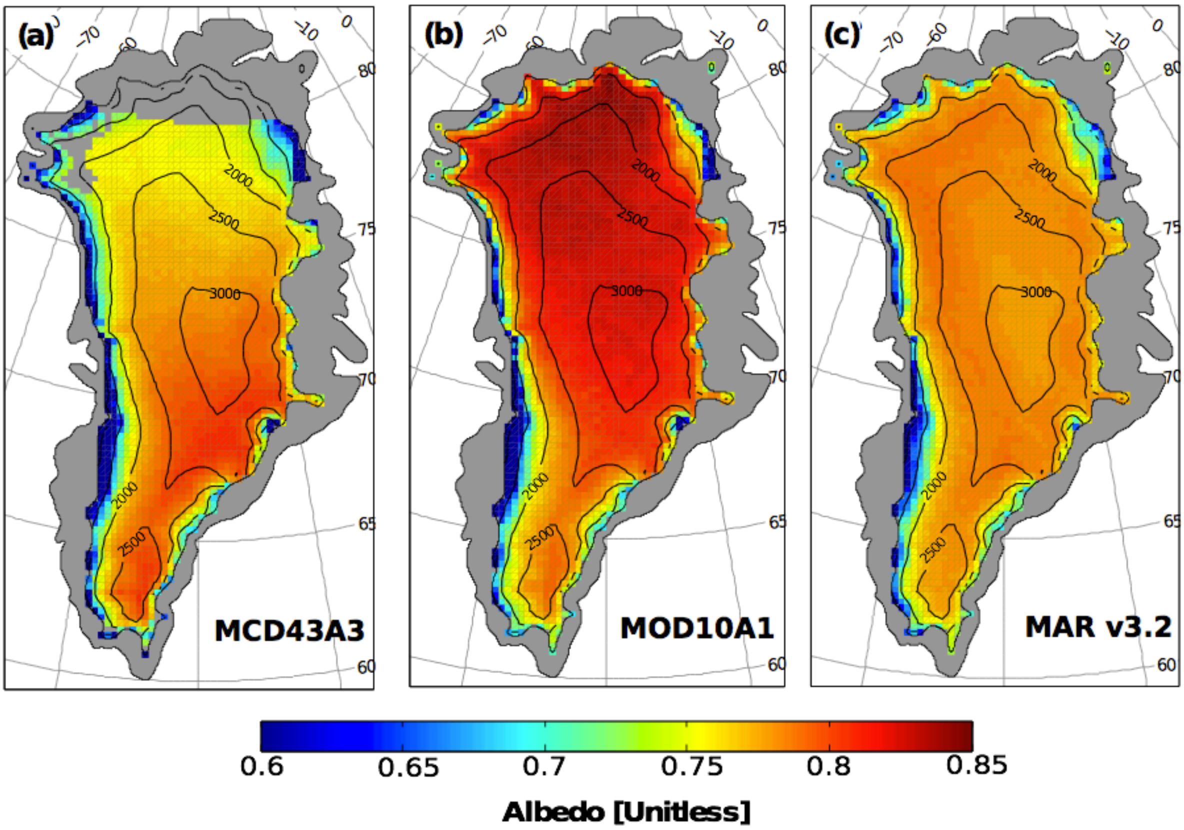

Figure 2. Mean 2000-2013 June, July, August (JJA) albedo (unitless) for **(a)** the MCD43A3 BSA shortwave product (on the MAR grid) **(b)** MOD10A1 product (on the MAR grid), and **(c)** MAR v3.2 clear-sky albedo. Only good quality data MODIS data are used here.

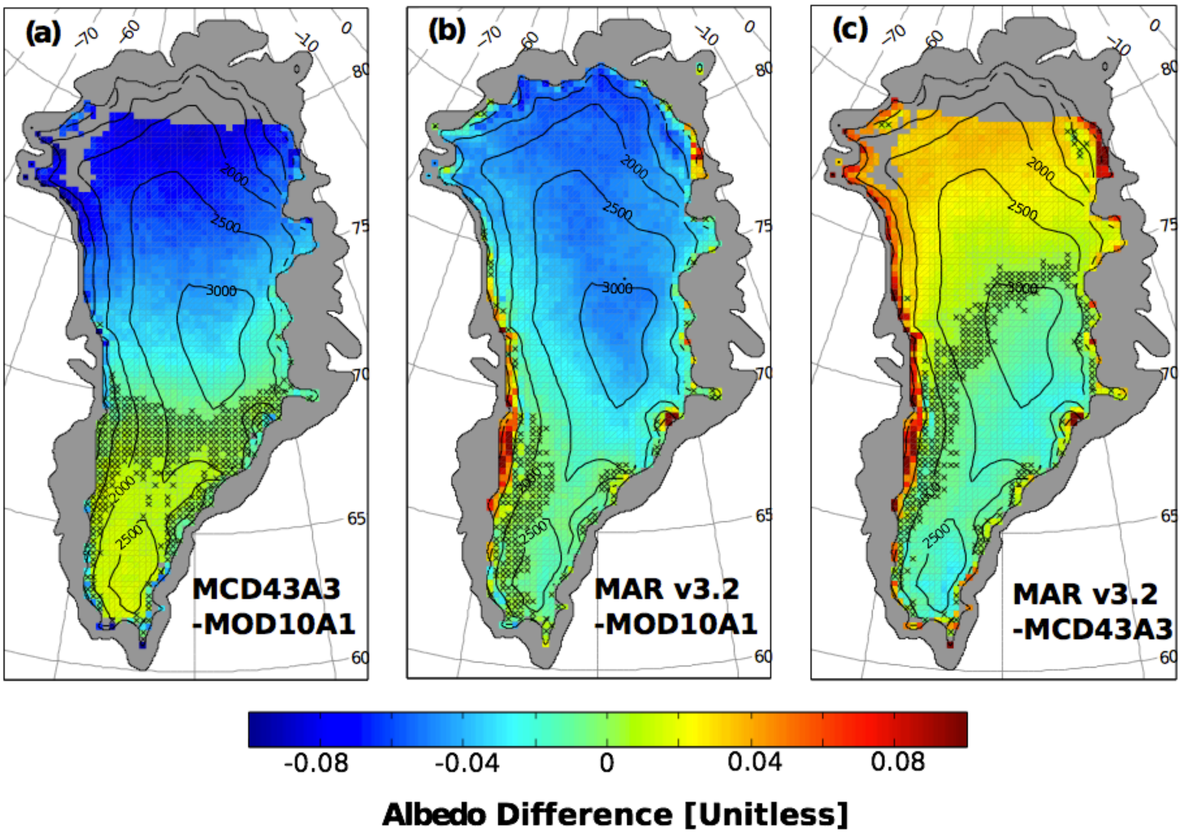

Figure 3. Mean difference in JJA albedo (unitless) for the 2000-2013 period: **(a)** MCD43A3 BSA shortwave minus MOD10A1 **(b)** MAR v3.2 clear-sky minus MOD10A1, and **(c)** MAR v3.2 clear-sky minus MCD43A3. In each case, only coincident data for each of the two datasets being compared is used. MAR grid boxes where the difference is not statistically significant at the 95% confidence level are marked with a grey “x”.

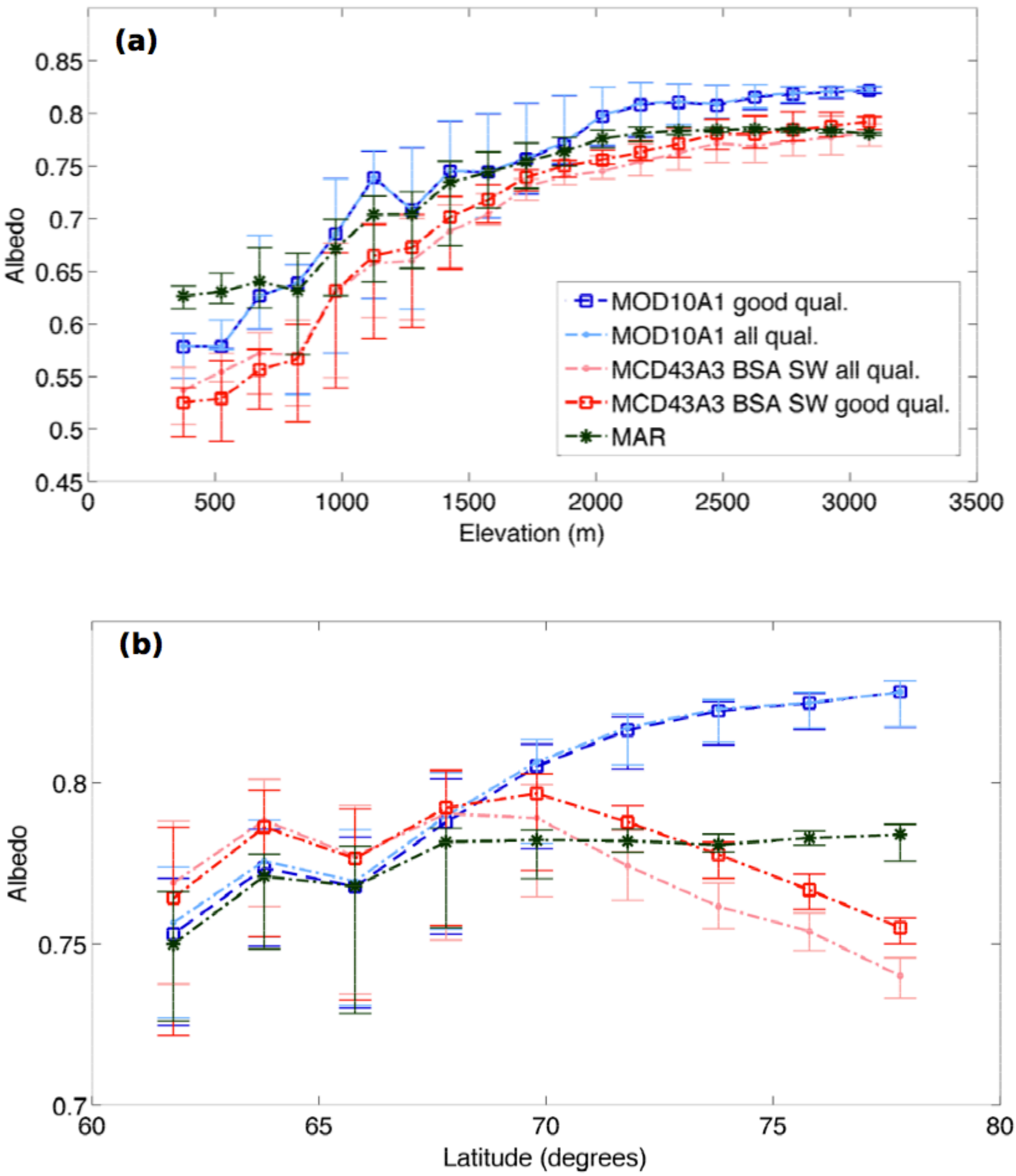

Figure 4. (a) Mean 2000-2013 JJA MOD10A1, MCD43A3 BSA shortwave (SW), and MAR v3.2 clear sky GrIS albedo (unitless) as a function of elevation divided into 150 m elevation bands. Error bars indicate standard deviation within each elevation band. **(b)** The same as **(a)** but for albedo as a function of latitude, divided into 2° Latitude bands. "Good qual." indicates results obtained by only using "good quality" MODIS data. "All qual." i~~I~~ndicates that all available MODIS observations have been used.

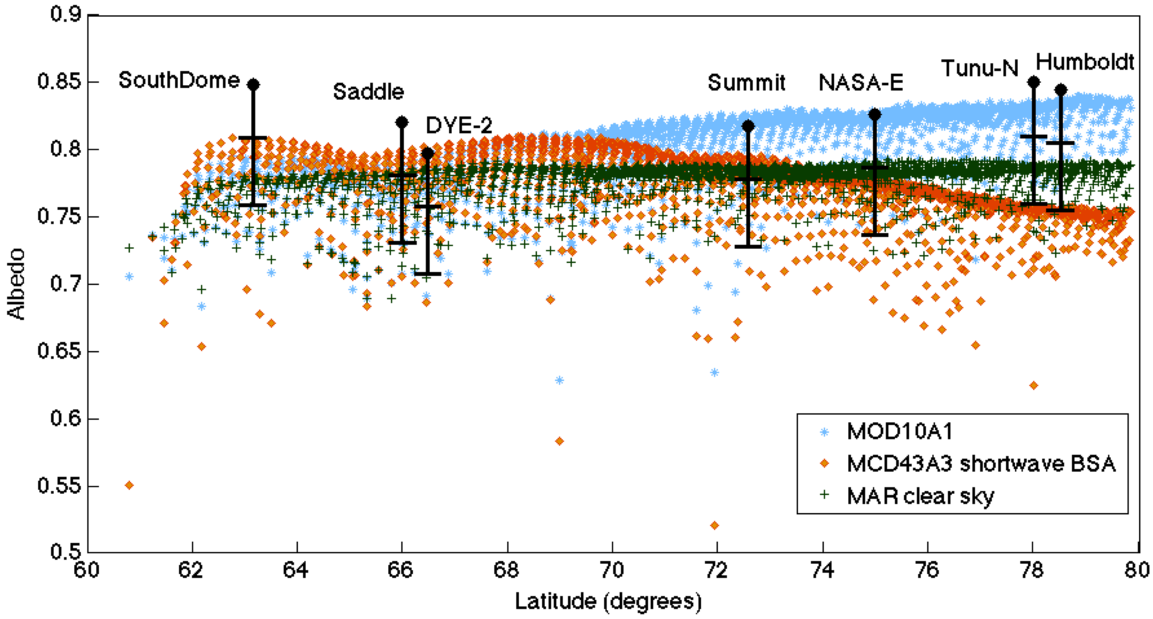

Figure 5. 2000-2012 mean JJA albedo (unitless) for the MAR accumulation zone vs. latitude, for MOD10A1, MCD43A3 BSA shortwave, MAR v3.2 clear-sky, and GC-Net station data (black circles) for stations with a record spanning at least 7 years of the 2000-2012 period. Only MODIS data flagged as "good quality" are used here. The error bars for GC-Net stations indicate the range of corrections to GC-Net data (between 0.04 and 0.09) employed by Stroeve et al. (2005).

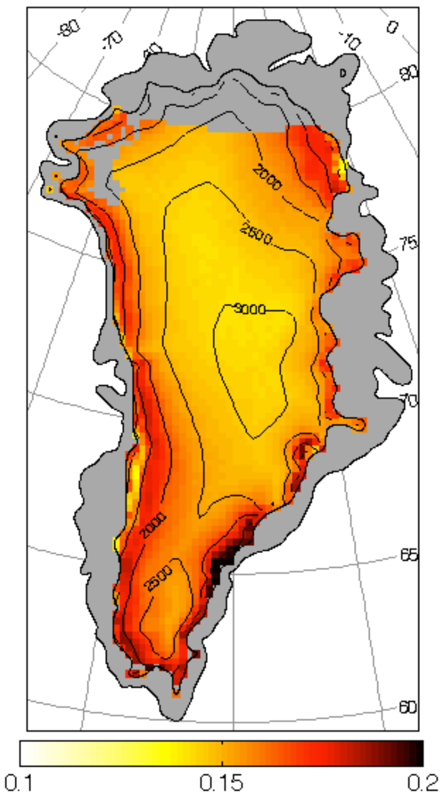

Figure 6~~2~~. MCD43A3 BSA visible (0.3–0.7 μm) minus MCD43A3 BSA shortwave (0.3–5 μm) 2000-2013 JJA mean albedo (unitless) on the MAR grid. Areas not defined as 100% ice covered in MAR v3.2 are excluded.

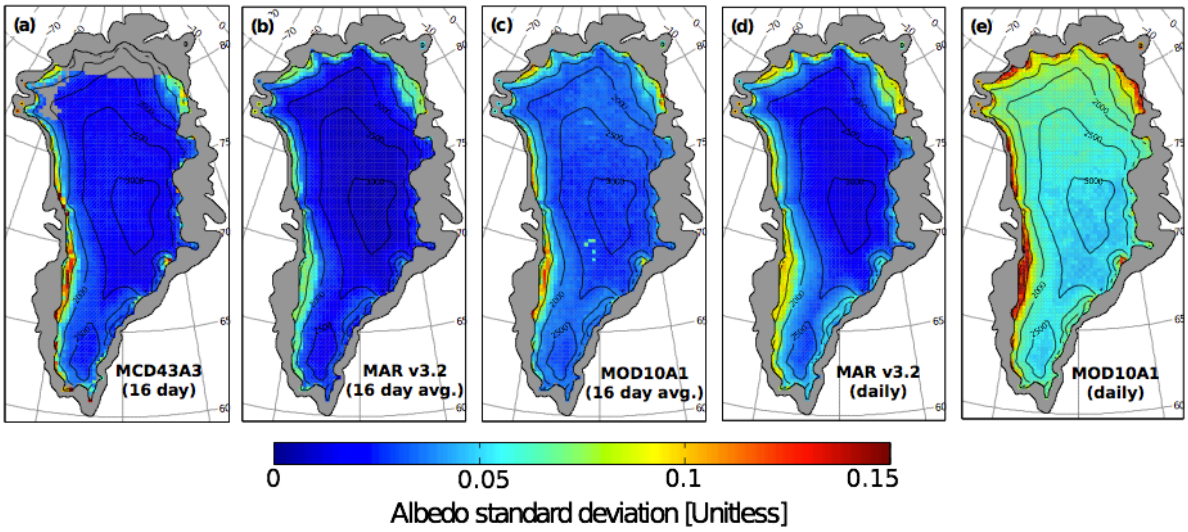

Figure 7~~6~~. Standard deviation of JJA albedo (unitless) (2000-2013) for **(a)** MCD43A3 shortwave BSA **(b)** MAR v3.2 clear sky 16 day averages **(c)** MOD10A1 16 day averages **(d)** MAR v3.2 clear sky daily, and **(e)** MOD10A1 daily.

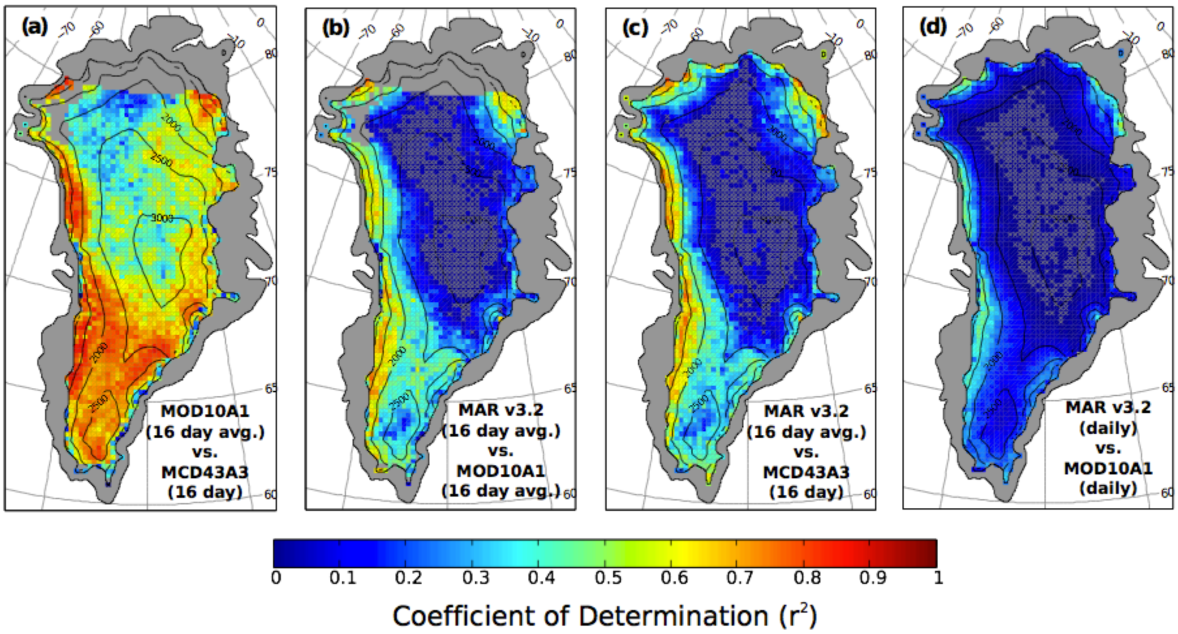

Figure 8~~7~~**.** ~~Correlation coefficients~~Coefficients of determination (r^2 values) for the 2000-2013 period during JJA for **(a)** MOD10A1 (averaged to 16 day periods) vs. MCD43A3 BSA shortwave **(b)** MAR v3.2 clear sky (16 day data) vs. MCD43A3 BSA shortwave, **(c)** MAR v3.2 clear sky (16 day data) vs. MOD10A1 (16 day data), and **(d)** MAR v3.2 clear sky (daily) vs. MOD10A1 (daily). MAR grid boxes where the correlation is not statistically significant are marked with a grey "x".

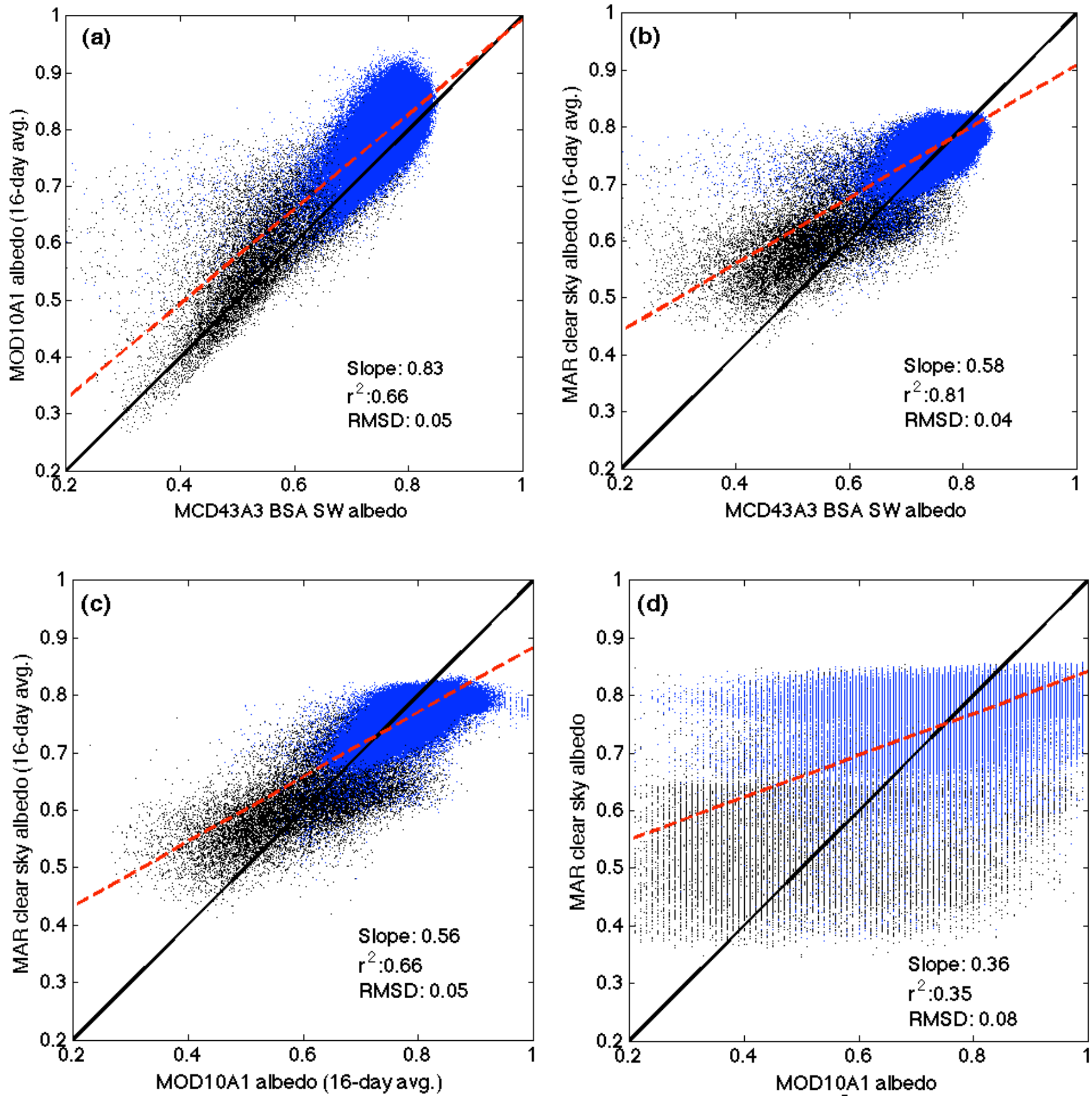

Figure ~~9~~8. Scatter plots for 2000-2013 JJA albedo for **(a)** MOD10A1 (16 day averaged) vs. MCD43A3 BSA shortwave albedo (unitless) **(b)** MAR v3.2 clear-sky (16 day) vs. MCD43A3 BSA shortwave albedo, **(c)** MAR v3.2 clear-sky (16 day) vs. MOD10A1 (16 day) albedo, and **(d)** MAR v3.2 clear-sky vs. MOD10A1 (daily) albedo. Black points indicate ablation zone locations, while blue points indicate locations within the accumulation zone as defined using MAR v3.2. A solid black line indicates the 1 : 1 line, and dashed red lines indicate the best linear fit.

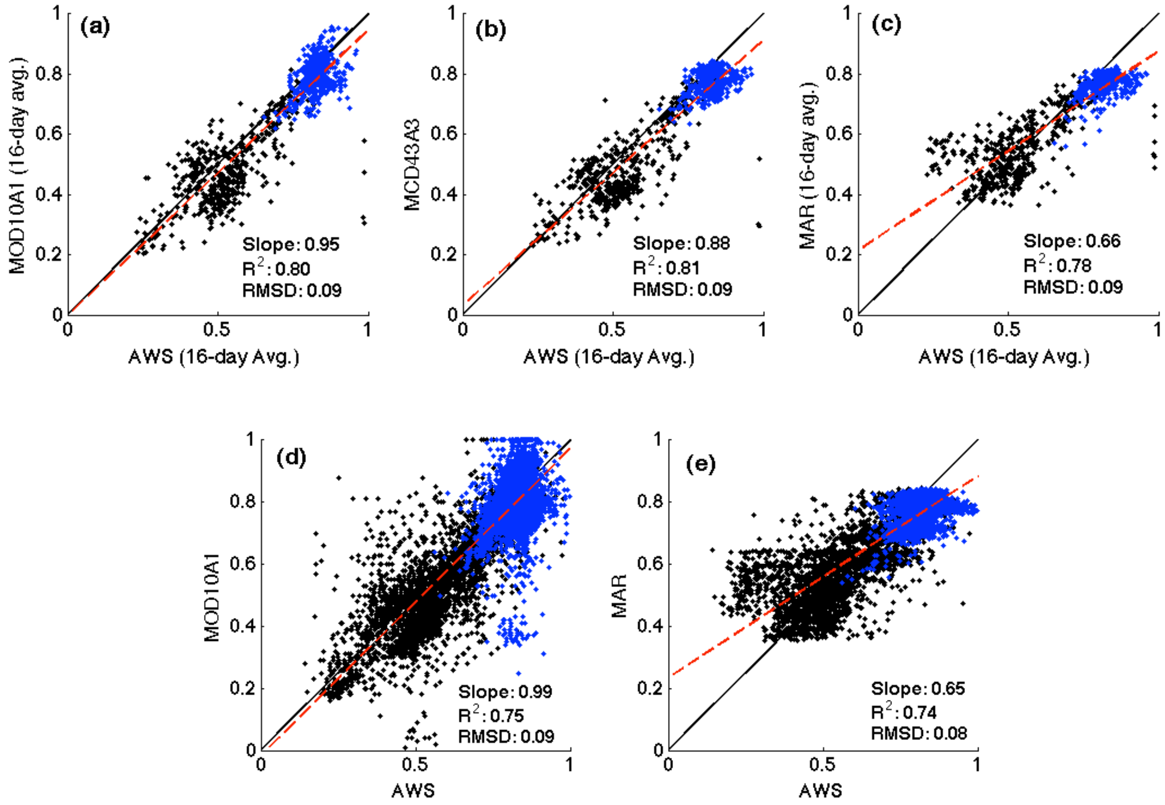

Figure 10~~9~~. Scatter plots of 2000-2012 JJA mean albedo [unitless] vs. automatic weather station (GC-Net and K-Transect) albedo: **(a)** MOD10A1 16 day averages vs. 16 day in situ **(b)** MCD43A3 BSA shortwave vs. 16 day in-situ **(c)** MAR v3.2 clear sky 16 day vs. 16 day in situ **(d)** MOD10A1 vs. in situ (daily) and **(e)** MAR v3.2 vs. in situ (daily). ~~The black lines in each figure indicate the 1 : 1 line. In this comparison, MODIS data have not been aggregated to the MAR grid. Black points indicate ablation zone locations, while~~ As for Fig. 9, blue points indicate locations within the accumulation zone as defined using MAR v3.2. ~~Solid black lines show the 1 : 1 line, and red dashed lines indicate the best linear fit.~~

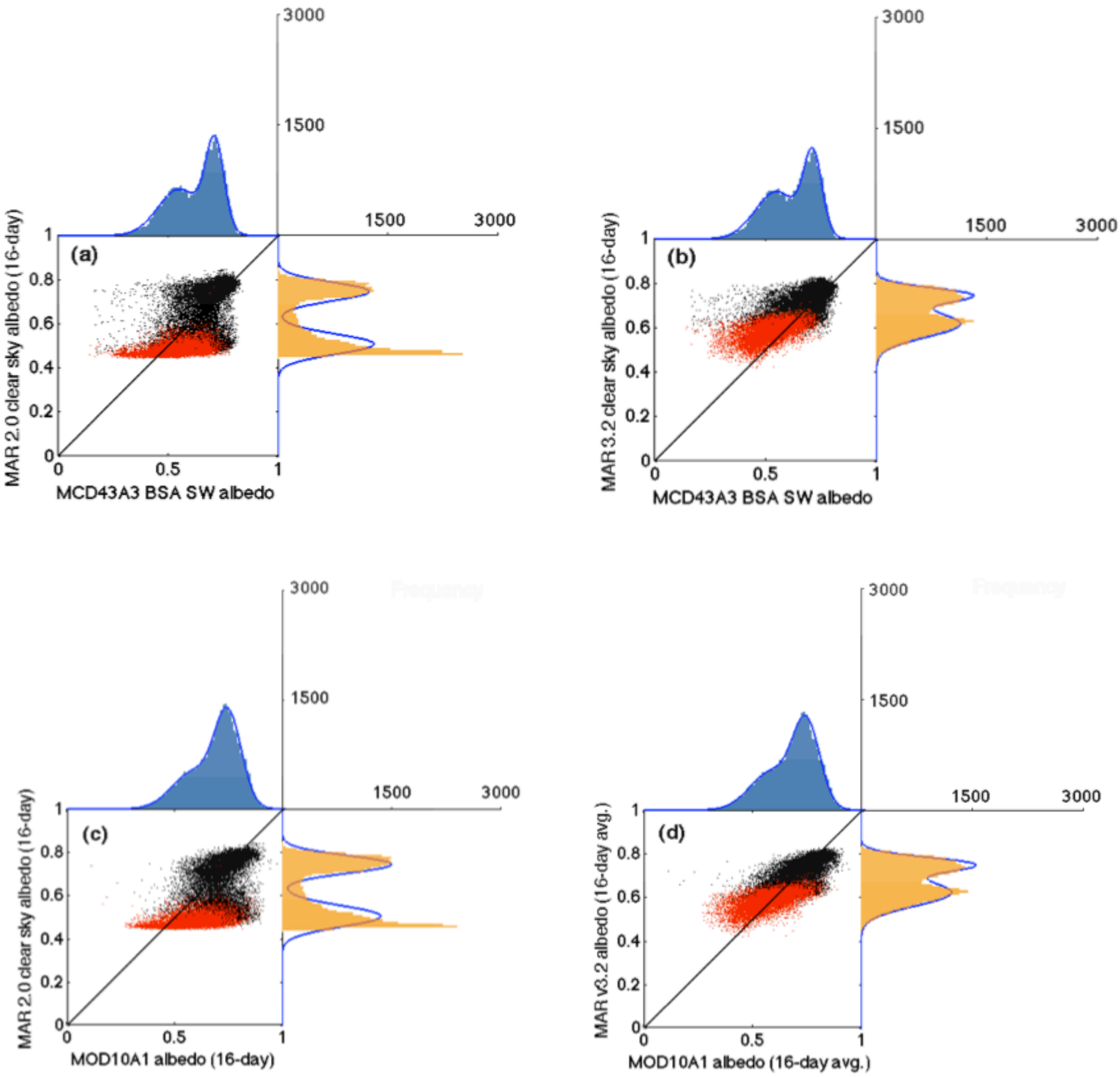

Figure 11~~3~~. Scatter plots and histograms for JJA 2000-2012 albedo [unitless] within the MAR v3.2-defined GrIS ablation zone, for **(a)** MAR v2.0 clear sky (16 day avg.) vs. MCD43A3 BSA shortwave. **(b)** The same as **(a)**, but for MAR v3.2. **(c)** The same as **(a)** but for MOD10A1 albedo (averaged to 16 day periods). **(d)** The same as **(c)** but for MAR v3.2. Points where there is snow or firn (surface snowpack density > 830 kg/m^3) for more than 8 days of a 16 day period are shown in red. ~~In the case of MAR v2.0, only pixels classified as 100% ice-covered by both MAR v2.0 and v3.2 are used.~~ Light blue curves show the best fit to each distribution obtained using maximum likelihood estimation.

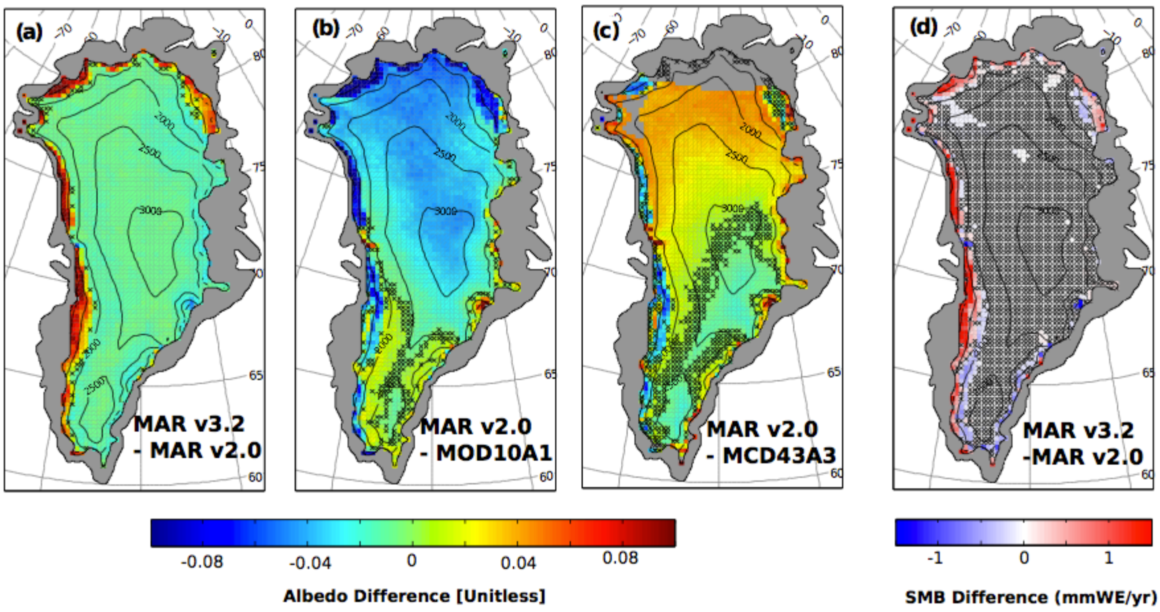

Figure 124. **(a)** MAR v3.2 clear-sky minus MAR v2.0 clear-sky mean JJA albedo **(b)** MAR clear-sky v2.0 minus MOD10A1 2000-2012 mean JJA albedo, **(c)** MAR clear-sky v2.0 minus MCD43A3 BSA shortwave 2000-2012 mean JJA albedo, and **(d)** MAR v3.2 minus MAR v2.0 mean JJA SMB (mWE/yr) for the same period. Note that in the ablation area, where net SMB is negative (Fig. 1), a positive SMB bias indicates a net mass loss that is reduced in magnitude. Grid boxes where differences are not significant at the 95% confidence level are marked with a black "x".

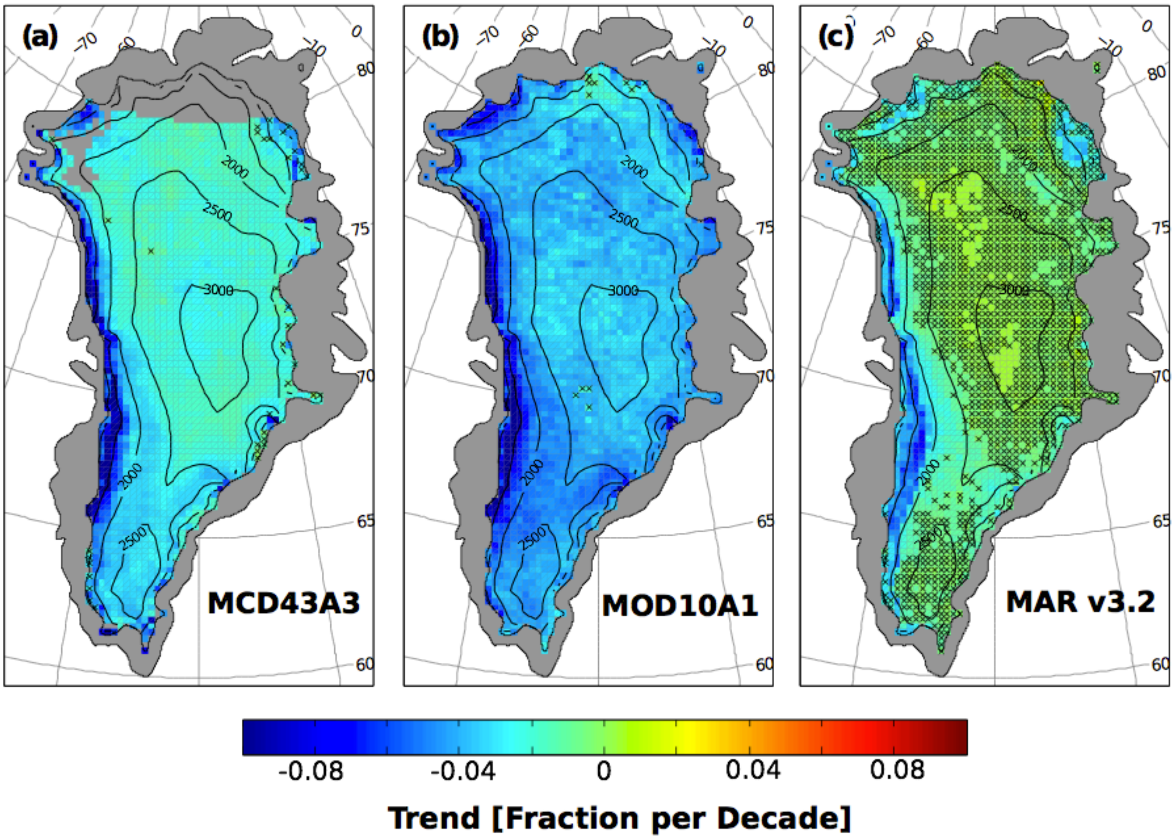

Figure 13~~0~~. JJA mean albedo trends (2000-2013) in units of fraction per decade for **(a)** MCD43A3 BSA shortwave albedo, **(b)** MOD10A1 albedo, and **(c)** MAR clear-sky albedo. Grid boxes where trends are not significant at the 95% confidence level are marked with a black “x”.

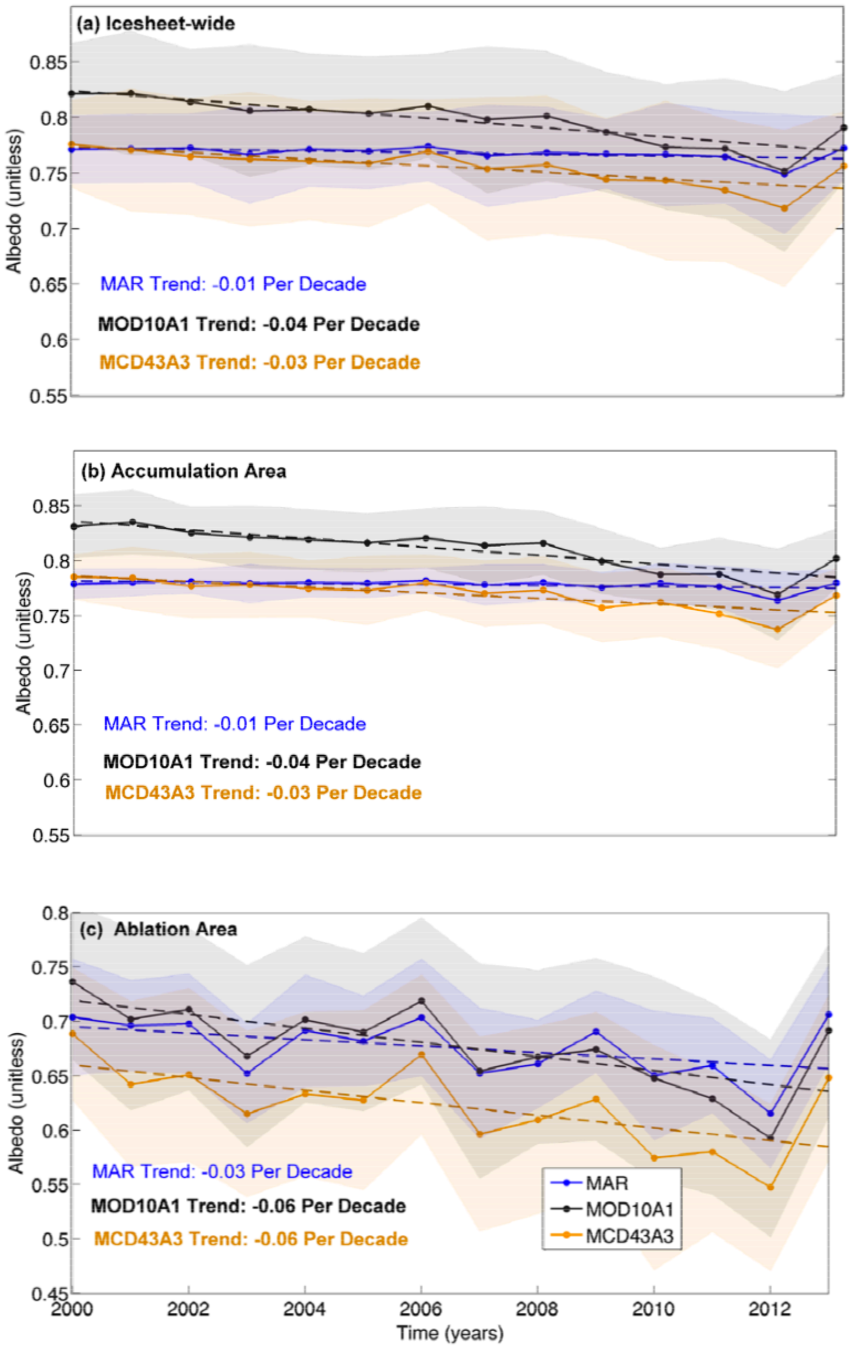

Figure 14~~1~~. Mean annual JJA ice sheet albedo (solid lines) simulated by MAR v3.2 (clear-sky) (blue), MOD10A1 (black) and MCD43A3 BSA shortwave (orange) for 2000-2013 and best linear fit (dashed lines) for **(a)** the entire ice sheet, **(b)** the accumulation zone, and **(c)** the ablation zone defined~~ using~~ with MAR v3.2~~ SMB~~. ~~All trends produced~~The trends shown ~~using annual data~~ are statistically significant at the 95% confidence level for the MODIS products, but are not statistically significant for MAR. Shaded areas show annual JJA standard deviation of albedo for 16 day periods from each dataset. Note that the y-axis interval is the same for all graphs, but is shifted by 0.1 for **(c)**.