Responses to the reviews, including relevant changes made in the manuscript, and a marked-up manuscript version

The authors would like to thank all referees for the review of the manuscript, helpful comments, and the discussion involved in this process. The corresponding changes and improvements have been made in the revised paper and are also summarized in our reply below. Authors' responses are in blue. Reviewer's responses are in black.

Response to Reviewer 1

This study explores and compares the contributions of recent (satellite-era) changes in Arctic sea ice and snow cover to changes in absorbed solar energy at the surface, and finds that sea ice losses have contributed to a greater increase in solar heating than reduced Arctic snow cover. Similar analyses have been performed before, though this study carves out a niche by focusing exclusively on the Arctic (60-90 degrees) and comparing the terrestrial and sea ice contributions within this domain. An important point highlighted by the authors is that the major seasonal transition in albedo associated with sea ice loss is occurring near the summer solstice, whereas the terrestrial snow transition is shifting away from the solstice, implying greater solar forcing via sea ice loss in the recent past and near future. Overall, the paper is concise and very well-written, though there are several important aspects of the analysis that need to be revisited and/or clarified before publication. After these issues (described below) are addressed, I would support publication of this manuscript in The Cryosphere.

We thank the reviewer for their overall positive evaluation of the work and constructive comments, which were helpful in revising the manuscript. The point-by-point response to the comments is listed below.

(1) The discussion on p.7 lines 4-14 describes how lower-latitude changes in albedo drive larger changes in absorbed solar energy than equivalent albedo changes at higher latitudes. This is true for annual-mean albedo changes, but it is not true for the summer-solstice-season changes that are the focus of this section. This can be seen clearly in the authors' own Figure 5, which shows greater daily-mean solstice insolation at 80N than at 65N. The discussion on p.7 lines 4-14 is therefore largely inconsistent with Figure 5 (the latter of which is correct, I believe). The authors need to amend the discussion and re-consider potential causes of the statistics described on p.7. Differences in cloudiness and cloud trends may be a logical starting point for resolving this discrepancy

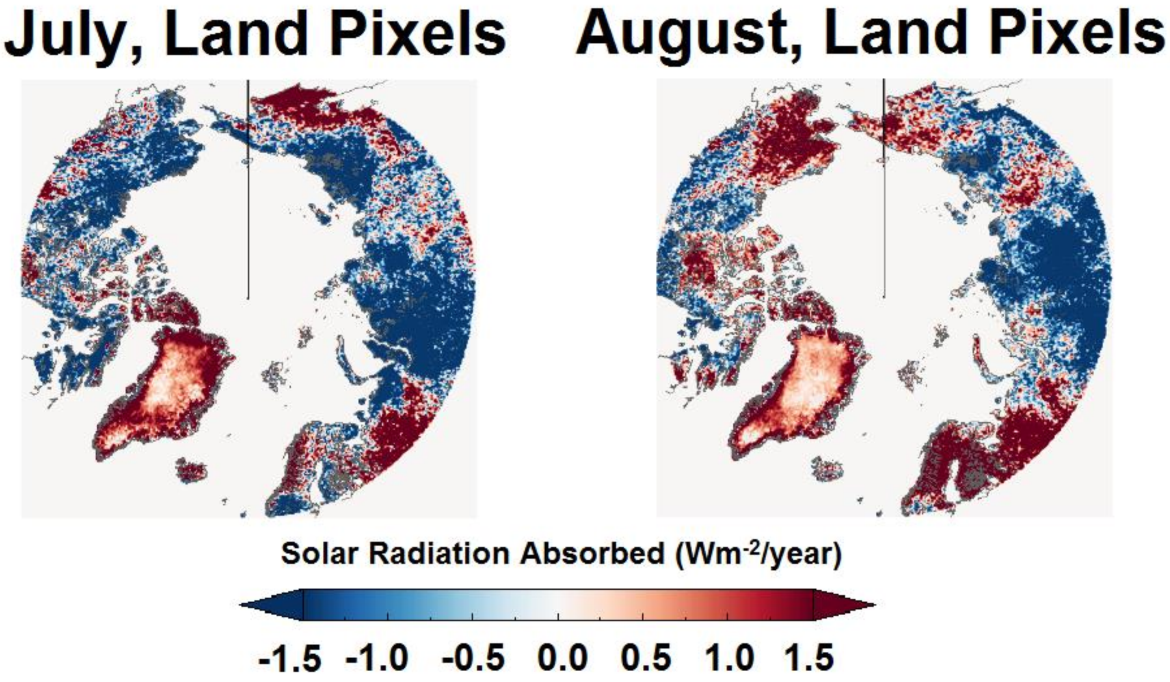
We acknowledge that the text described in your comment may have been misleading, and we have made substantial additions and alterations to the manuscript (see manuscript page 9, lines 18-26). The numbers in the paragraph are based on the instantaneous magnitude of insolation at 14:00 local solar time. We recognize, to your point, that the magnitude of the flux accumulated over the entire day around the summer solstice is larger at higher latitudes. Figure 5 was providing a simple illustration of changes in top-of-atmosphere accumulated incoming shortwave at 65° and 75°N, not the instantaneous surface absorption. Additional text has been added explaining this figure. In the text, we calculated accumulated flux increases over ocean and land (at both latitudes) for July 1 based on the changes in albedo between 1982 and 2015 and relate the accumulated flux increases to one another.

(2) The study focuses largely on changes in net shortwave flux at the surface, and the authors acknowledge at different points in the text that changes in clouds and sea ice thickness could contribute to net shortwave changes, in addition to the more obvious contributions of changing snow and sea ice coverage. Section 2 could be improved with a bit more quantification of how large these other contributions are. Perhaps such quantification is beyond the scope of the study, though I encourage the authors to consider ways in which they could quantify the contributions of these different drivers of shortwave flux trends. It seems that the cloud contribution could be isolated and quantified via existing APP-x data, though isolating the influence of sea ice thickness/age would be more challenging.

We believe that we have improved Section 2 based on your comment. We were able to quantify the contribution of clouds on the shortwave flux at the surface by performing a calculation that determined the maximum possible effect of clouds on downwelling shortwave radiation between 1982-2015 (see manuscript page 6, lines 17-34). This calculation used the 34-year average downwelling shortwave flux for the sunlit months (March-September) and the 34-year average cloud trend (during March-September) at each point to determine the changes instantaneous shortwave flux. Further details regarding the calculation and explanation of the assumptions made may be found in the added paragraph in the text. Ultimately, we find that changes in cloud cover from 1982-2015 (during March-September) resulted in an increase of surface absorption by $1.94 Wm^{-2}$ over land and $2.19 Wm^{-2}$ over ocean. The changes account for only a 0.5% increase in incoming shortwave over ocean and 0.4% increase over land.
We regret that changes in sea ice thickness' effect on shortwave absorption cannot be explicitly determined within the scope of this study, but we hope that the theoretical maximum contribution to surface absorption changes by cloud cover has shown that changes in surface type is the dominant term in the Arctic surface energy budget.

(2b) Related to the above point, the discussion on the top of p.4 highlights a trend of lower albedo over Greenland's near-coastal regions. Is this trend caused more by reduced snow cover over the (quite small) non-glaciated portion of Greenland, or more by darkening of the perennial ice surface?

According to the average monthly trends in shortwave absorption between 1982-2015, we believe that Greenland may be decreasing in albedo due to both of the reasons you mention. Since not all of the summer months are shown in Figure 2, we have included the trends in absorption for July and August in this response (below). The spatial pattern of increased absorbed shortwave radiation over Greenland shows that the largest increases due occur in the coastal areas, but lesser increases in absorption still occur spread out over the perennially snow-covered interior- particularly in southern Greenland.



Reviewer 1, Comment 2b Figure: Trends in absorbed solar radiation at the surface from 1982-2015 for the months of July (left) and August (right) over land.

(3) A companion analysis of MERRA2 data is referred to very briefly at the end of section 2. This is a nice addition to the study, but it would be helpful if this analysis was developed more. In particular, it would be helpful to state the shortwave trends obtained from MERRA2 and show companion figures to Figs 1 and 2, so that similarities and differences between the two products can be seen more clearly. Presenting results from two or more products will give the study more credence.

We agree that the comparison with MERRA2 results was more useful when expanded. A figure showing trends from MERRA2 for June has been added as well as relevant discussion pertaining to the trends displayed in the figure (see manuscript page 7, lines 15-24). We find that the spatial agreement between the two products' output is very convincing, and thank you for your comment.

(4) Figure 5 shows that the "Low Albedo midpoint" over oceans actually occurred *before* the solstice in 2015. If this is now the norm, it implies that future trends towards earlier melt will, as with terrestrial snow, cause the high-low albedo transition to move away from the solstice. In other words, the lag between snow and sea ice melt, in combination with melt trends, may have caused the snow/sea ice

forcing differences to have *already* peaked. In light of this (and if I have interpreted correctly), the authors may want to add a bit of nuance to the abstract and associated discussion.

We believe that you have correctly interpreted that the maximum difference between the absorption changes over land and ocean has recently occurred. We agree that as the albedo transition over ocean moves further from the summer solstice, the trends over ocean will approach those over land while the difference between the trends shrinks. We added text to mention this explicitly (see manuscript page 8, lines 30-34 and page 9, lines 1-2), and have revised language elsewhere that reflects this insight.

(5) The analysis of feedbacks in section 4 should either be removed, or methodological details of this analysis need to be clarified. Personally, I think this section could simply be removed, as it does not add much to the study, and is likely sensitive to methodological choices. If it is retained, more detail is needed on methodology, including how the spatial and temporal averaging of temperature (in particular) was conducted. Were monthly or annual trends in T used? Were gridcell-level or Arctic (or global) T trends used? (e.g., how exactly were the presented June feedback numbers calculated?) Personally, I think feedback analyses are only meaningful when large areas (e.g., hemispheric or global) are used for temperature averaging. More detail would also be needed on the technique used to determine: (d alpha_p / d alpha_s).

Methodological detail has been added (see manuscript page 11, lines 3-11) and clarification of monthly, gridcell-level trends were used for analysis.

(6) Conclusions, p8,13-17: This passage could be important, but needs clarification. To be clear, Flanner et al (2011) assumed constant seasonal cycles of the albedo of multiyear and first-year sea ice. Thus from interannual changes in sea ice extent and transitions multi-year to first-year ice did contribute to area-averaged albedo changes in that study, but changes in ice albedo due to thinning or earlier ponding (etc) did not. Line 15 states that "...here we find that the inclusion of inter-annual changes to surface albedo result in a significant change to the surface shortwave energy budget...". Do the "inter-annual changes to surface albedo" refer to changes in the albedo of the ice itself? If so, I do not recall seeing quantification of this contribution in the analysis (though I think it would be very useful!). The subsequent sentence also needs clarification: "Since 2010, for example, average ocean albedo in the study area during late June has been as low as mid-September albedo in 1982-1985." Are you referring to the ocean-wide albedo, or to the albedo of the sea ice itself? If the former, this is likely due simply to the reduction in June sea ice extent, and this would have been accounted for in the Flanner et al study. If not, this is a useful finding, but one that should be reported and further developed earlier in the study.

To clarify, our changes in shortwave absorption include real (observed) albedo changes in the ocean and sea ice using the retrieved instantaneous albedo of every pixel of sea ice as well as ocean. Therefore, the mentioned inter-annual changes to surface albedo referred to both changes in the morphology of the sea ice (thinning, ponding, etc.) and also the ocean-wide albedo. This is further shown in the figure added to this manuscript that shows the differences between MERRA2 and APP-x shortwave absorption trends during June. The assumption of a constant sea ice albedo by MERRA2 versus the observed month-by-month changes in ice albedo from APP-x illustrates the effect of including ice thickness/age and (presumably) liquid water or inhomogeneity at the surface of sea ice. It may very well be that the reduction of sea ice extent in June is a primary driver of this change, but the stronger, more positive trends in shortwave absorption in our results compared to MERRA2 indicate that there is some additional effect by the thinning or darkening of sea ice.

General: I appreciate the focus of this study on the "Arctic", defined here as 60-90N, but it is important to note that any conclusion about the relative magnitudes of sea ice vs. snow changes will be sensitive to the latitude bands selected. For example, if the latitude threshold for the analysis was adjusted equatorward, the relative contribution of land snow changes would clearly increase. I think this point should be acknowledged more clearly.

The selection of 60-90°N was intentional in hoping that we may capture the evolution of the Arctic surface over land and ocean over the satellite record. We agree, however, that analyzing the net changes in shortwave absorption from the pole to the equator could weaken or even refute our hypothesis. We attempt to make it clear in the manuscript that we are interested in the effects of changing snow and ice on the local surface energy budget, and only wish to consider pixels where the main drivers of change in the surface energy budget are such.

p1,21: A slightly clearer way to say this would be "September sea ice extent decreased by 45% from..."
p2,30: 1972 should be 1979, in reference to the Flanner et al study.
p6,22: This either needs "although" after the comma, or it should be two sentences.
p6,24-30: Please list the solstice DOY, for reference. Figure 1: It looks like there is only one point per year in this figure, so I assume you mean "Annual Absorption" instead of "Monthly Absorption".

Revisions based on the above minor comments have been made, and we thank the reviewer for their careful reading of the paper.

Figure 2: Could you speculate on the cause of the negative trend in April non-land albedo?

The negative trend in non-land albedo during April is possibly based on an increase in April cloud cover in the Arctic that spanned from the Canadian Archipelago through Alaska and into the East Siberian Sea. The increase in clouds reduced shortwave surface absorption. This increase in cloud cover did not occur over the central Arctic Ocean, however, and we cannot speculate what drove the decrease in absorbed radiation north of 80° in the Canadian-Russian Arctic.

Response to Reviewer 2

(1) It is stated that the time of the high-to-low albedo transition each year is moving toward the high sun of the summer solstice over ocean but moving away from the summer solstice over land. Some explanation is needed why this happens.

The manuscript was lacking a direct explanation of why snow on land (typically) melts earlier in the year than sea ice, which has been added. It has to do with higher temperatures and solar zenith angles at lower latitudes where more of the snow is compared to sea ice. Our explanation also mentions the tendency for snow-free land adjacent to snow-covered land to heat up faster than unfrozen ocean around sea ice (see manuscript page 8, lines 9-12).

(2) They claim that decreasing sea ice cover, not changes in terrestrial snow cover may play an even larger role in future Arctic climate change. The paper is not about prediction of future state of the arctic so there is no substantiation of what might happen in the future.

We have made adjustments to the abstract which removes any language referring to the changes in future ice and snow. We based this original statement on the movement of the ocean low albedo period toward the summer solstice, but we have since realized that the peak forcing of the sea ice albedo feedback may have already passed that point. The low albedo period has begun moving away from the solstice over ocean as well as land in recent years, though we expect the ice albedo feedback to remain relatively strong in the near future. The manuscript conclusion has been modified based on this explanation.

(3) There is confusion when dealing with the surface and top of the atmosphere (TOA). At TOA not only surface propertied matter but also clouds so it is a mixed signal (example to be given in Specific Comments).

The changes in shortwave absorption that were determined in the manuscript include real (observed) albedo changes at the surface using the retrieved instantaneous albedo of every pixel from the APP-x dataset. Some of this change in albedo may be due to changes in clouds, which, to your comment, makes the TOA incoming flux much different than the surface flux. A significant addition has been made to the manuscript to address the potential of cloud cover changes on absorbed shortwave at the surface (see manuscript page 6, lines 17-34). As mentioned in your specific comments, we use TOA (planetary) albedo change from the 2014 Pistone et al. study to highlight that the Arctic albedo has been generally decreasing. All other usage of the word “albedo” in the manuscript refers to albedo at the surface, unless stated otherwise.

(4) There is some lack of clarity about the impact of changes at the surface and the latitudinal changes in the solar radiation reaching the ground on the amount of absorption at the surface. How do you separate these two factors?

We do not try and normalize the differences in the amount of insolation at high vs. low latitudes in any way. Our goal is to assess the amount of absorbed solar radiation without adjusting it for the amount of incoming radiation. We hope that the text makes clear that the main driver of absorption changes is not based on latitudinal changes in insolation, but rather changes over time in surface albedo, cloud, and other variables. We interpret the "impact of changes at the surface" in your fourth comment to be concerning the changes in cloud cover or vegetation. Chapin et al. (2005) determine that on cloud-free summer days, broadband albedo has been reduced by 0.0002 per year due to changes in vegetation over the Alaskan North Slope region. Sturm et al. (2011) state that during the spring, land with more exposed shrub experienced albedo decreases earlier in the year than where there was less shrub or no vegetation at all. Some of the increasing absorption trends in the early spring over land may be caused by such changes in vegetation. Sturm et al. also point out that once temperatures became above-freezing, sensible heat flux overtook solar heating and the impact from lower albedo values was reduced, meaning that changes in absorption over land during the summer months are primarily driven by changes in snow cover, not vegetation. We have expanded the discussion on changes in vegetation and their impact on absorption (see manuscript page 5, lines 5-12) and removed redundant sentences at the end of the paragraph.

(5) MERRA-2 is also used in the analysis. Nothing is said about the differences in spatial and temporal scales of MERRA-2 and AVHRR. What impact does it have on the conclusions?

We have added a figure showing the results of MERRA2 absorption trends compared to results from APP-x and expanded the discussion of these results. Overall, the MERRA2 results are very similar to the APP-x results both spatially and with respect to the magnitude of the forcing.

Specific Comments:
Stated: Between 1979 and 2011, the Arctic top-of-atmosphere (planetary) albedo decreased from 0.52 to 0.48 (Pistone et al., 2014), and subsequent years with record or near-record low sea ice extent have further increased the amount of heat absorbed in the Arctic (Pistone et al., 2014). Comment The connection here between TOA and surface is confusing.

We have added a significant amount of explanation on manuscript pages 7-8 which talks about the difference between TOA incoming shortwave flux and accumulated flux at the surface. We also added text to the manuscript at the bottom of page five that addresses the changes in clouds and how they may cause TOA and surface downwelling shortwave flux to differ.

Stated: Snow extent has decreased over Eurasia and North America since the late 1980s Robinson & snow cover and the radiative balance over mid- and high-latitude land in the Northern Hemisphere (Groisman et al., 1994), in which retreating snow cover has led to a lower polar Comment The topic is the Arctic, so need to be focused.

Noted, but here we introduce the reader to literature that explains the trend of increasing absorption over land during spring, which our results agree with.

Stated: preconditioning of sea ice in the winter can influence the albedo into the fall of the following year, illustrating how changes in cloud cover during different seasons may affect the planetary albedo (Letterly et al., 2016; Liu & Key, 2014). Comment Above is a mixed bag of statements. Needs to be cleared.

This statement has been changed in the text. We intended to say that besides the effects of clouds on instantaneous absorption at the surface, they can influence sea ice changes, which in turn affects the non-land albedo. Thank you for bringing it to our attention!

Stated: This study focuses on the effects of snow and ice cover changes on the surface shortwave radiation budget of the Arctic - defined as the area poleward of 60◦N - not the remote effects of mid-latitudes on the Arctic Comment Why to invoke remote effects of mid-latitudes on the Arctic? This topic is not of relevance here and the comment does not add much to the discussion.

Other works, such as that of Flanner et al. (2011), perform a similar experiment but include the effects of changes in snow cover at lower latitudes. These changes in mid-latitudes are not considered in this study, which we mention here.

Stated: Furthermore, since terrestrial snow cover has mostly melted by June, the main drivers of absorption trends over land during the summer may be changes in cloud cover or vegetation (Chapin et al., 2005; Loranty et al., 2011). Comment: There is no discussion of changes in vegetation after melt and its impact on absorption.

Some discussion of these factors was in the original manuscript. Additional text on the effects of changing vegetation and its impact on broadband albedo has been added.

Stated: In contrast, most of the sea ice lasts through early summer, but changes in sea ice thickness still allow for changes in absorption (Perovich & Polashenski, 2012). Comment: The impact of ice thickness on absorption was not addressed in this paper. Needs more discussion.

We agree that the impacts of sea ice thickness on shortwave absorption are very important, and believe that they are a large reason for our absorption trend results from APP-x (which includes the effects of ice thickness in the surface albedo). Text and an additional reference addressing the changes of albedo with sea ice thickness has been added (see manuscript page 5, lines 18-19).

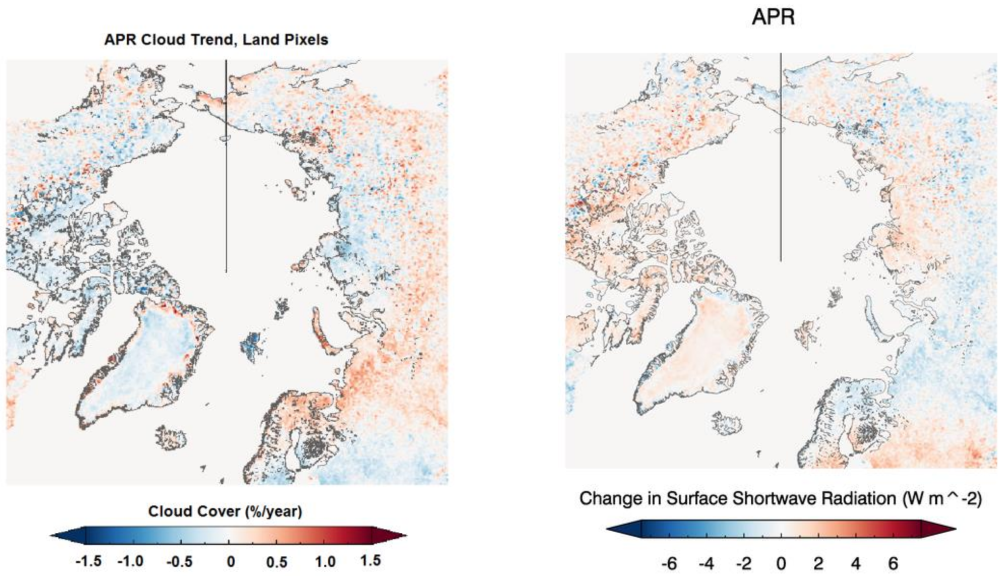
Response to Reviewer 3

(1) The analysis and discussion of albedo differences and trends over sea ice (beginning on p. 4, bottom) is much too simplistic and misleading, since it implies that seasonal evolution and inter annual trends are driven entirely by changes in ice thickness. However, prior to the onset of melt the differences in snow albedo on different ice classes (with the exception of very thin ice) are likely insignificant. Much more important in this context are development, areal fraction, and optical properties of ponds on sea ice. It is here that major contrasts between different ice age (MY vs. FY ice) and ice thickness are expressed. Moreover, these processes are dominant for the months of June and July, such that the discussion of Fig. 2 (June) in terms of ice thickness classes is not really appropriate. Here, a more rigorous discussion of the observed trends in terms of the seasonal cycle of ponds on sea ice (Perovich and Polashenski, 2012; Polashenski et al., 2012; Rösel and Kaleschke, 2012a) is needed. In particular, the work by Rösel and Kaleschke (2012a,b) is highly relevant because it discusses the role of spatio-temporal variations in ponding on sea ice in the context of sea ice concentration and extent anomalies based on remote sensing data. A closer examination of their findings may help explain some of the spatial patterns seen in Fig. 2 and the inter annual variations shown in Fig. 1. It is also relevant in the discussion of reductions in albedo in the month of June (p. 4, l. 18) which is as much or more a function of ponding as of reduction in ice concentration.

Thank you for the insightful comment. While we believe that changes in mean Arctic ice thickness have some effect on annual trends, we have added a number of sentences to the analysis and discussion of absorption trends which include the process of melt pond formation and its effect on sea ice albedo (see manuscript page 5, lines 16-24). In the revised manuscript, we attribute the changes in absorption over ocean (especially in summer) to changes in sea ice area/extent as well as to the occurrence of melt ponds on the increased amount of first-year ice. Both Rösel references have been added.

(2) The authors attribute changes in albedo over land to changes in snow cover duration during the snow-covered period, and to changes in vegetation and cloudiness after loss of snow cover. This may be too simplistic and requires further analysis. First, while the albedo contrasts between clouds and snow cover may not be as large as those between land surface and clouds, they cannot be ruled out as important without further analysis. For example, the spatially coherent trend for the month of April towards reduction in absorption of shortwave energy in NW Siberia may well be due to changes in cloudiness rather than duration of snow cover (which persists well beyond April). Without specific references to the published literature or some additional analysis of a particular subregion in a case study it is difficult to accept the explanation offered by the authors wholesale.

We have added a significant analysis describing the potential effects of cloud cover on surface absorption over the study period (see manuscript page 6, lines 17-34). We examined the trend of increased absorption over NW Siberia and found that cloud cover decreased ~1% from 1982-2015 in that region which corresponds to an increase in shortwave absorption at the surface. The figures inserted below show the trends described. While the changes in cloudiness over Northwestern Siberia may have impacted the overall trend, we see that the decrease in surface absorption due to clouds was outweighed by changes in surface absorption due to other factors, possibly increased snow cover. We hope that the analysis of potential cloud effects added to the manuscript offers enough explanation that the reader can accept that changes in the snow/ice surface is the main driver of these changes.


APR Cloud Trend, Land Pixels

APR

Reviewer 1, Comment 2 Figure: Changes in April cloud trends (left) and changes in April surface shortwave absorption (right) 1982-2015. Data shows a decrease in cloud cover over NW Siberia which corresponds to an increase in absorbed shortwave radiation.

(2b) Second, some of the discussion of snow and ice albedo variations needs to be reviewed and potentially revised. For example, on p. 4, l, 11ff a difference between snow albedo over sea ice (0.6) and land (0.7) is seen as being important. Where do these estimates come from? The paper by Sturm et al. cited here only discusses tundra snow. Both values are low if they refer to dry early spring snow before the onset of melt. Moreover, I am not aware of data showing that the albedo of snow covered sea ice is that much lower than that of tundra snow. This needs to be either corrected or further substantiated.

These estimates originally came from the cited Sturm et al. paper. We have updated the values to 0.8 dry, snow-covered sea ice (Rösel et al., 2010) and 0.85 (Greenfell and Perovich, 2004). These references have been included. The key is the difference between open land and open water. The albedo difference between open water and sea ice is and will continue to be more impactful than the albedo difference between snow-covered land and bare land.

(3) The discussion of the spatial patterns of trends could be expanded a bit, ideally by referencing either published work or at least a slightly more in depth analysis for a subregion.

We have added detail to this section. Particularly, we highlight the changes in absorption over the marginal Arctic Seas compared to those over high-latitude land masses (see manuscript page 5, lines

27-28). We note that our absorption trend results match the spatial patterns and (relative) magnitudes of changes in radiative forcing over land and ocean seen by Flanner et al. (2011).

(3) It is asserted that spatially coherent trends such as that in Greenland or Siberia are driven by trends in cloudiness. This appears plausible, but would benefit from some more detail. However, this raises the question as to what spatially heterogeneous trends are driven by (e.g., April over much of the landmass, or June in much of North America). Are the trends for individual grid cells or small aggregations of grid cells significant if they are neighboring on grid cells with opposite sign in the trend?

We have added text expanding the effects of cloud trends. In the above responses to comments, we include an image that shows the trend in April cloud cover from APP-x data over land. The spatial patterns in the surface absorption trends, then, are likely driven by the changes in cloud trends, which fit the description you give above. While not as obvious as heterogeneity depicted in April and June over North America, we point to Figure 3 in the manuscript, which shows that many cells with adjacent, oppositely-signed absorption trends during September correspond well with changes in clouds (i.e., south of the Laptev Sea in coastal and interior Siberia).

(4) The previous comment relates to a significant shortcoming in the manuscript that should be easily remedied. Specifically, the discussion of the methods employed in deriving the different data sets and their analysis is currently much too superficial. First, it would be preferable to separate the description of the datasets used and the analysis methods employed from the reporting of results. Specifically, l. 24 on p. 3 would be a natural break. Then, while reference to the paper by Key et al. (2016) to describe the data product is fine, the current paper needs to provide more information on how the data sets were generated in particular as relevant to the specific variables (albedo and absorbed shortwave energy, for example) discussed here. For example, how has broadband albedo been derived from spectral radiances and what are the associated errors and uncertainties associated with such a derivation? With the ocean regions located at higher latitudes than the land areas, does this introduce a potential bias because of lower solar zenith angles relative to sensor zenith angles? With a lack of bireflectance distribution function (BRDF) data over melting sea ice as opposed to snow cover over land this may introduce significant uncertainties as well. Further details for the MERRA reanalysis products should also be provided in a restructured methods and data section.

We have redesigned and improved the section explaining the APP-x dataset (manuscript page 3, lines 20-31) and have separated the explanation of the data from the analysis of results. There is now a paragraph that details how albedo and downwelling shortwave radiation were determined within the APP-x dataset as well as their uncertainties and limitations. To answer your specific questions: Key et al. (2001) states that while the anisotropic reflectance correction is not perfect, it does account for potential viewing and illumination biases. More detail on the MERRA2 analysis, including results and input variables, has been added.

Specific edits: - p. 1, l. 4: For clarity throughout it may be better to refer to sea ice albedo feedback and snow albedo feedback (or at least clarify at the start that ice albedo feedback only refers to sea ice)

Done.

- p. 1, l. 12: reads a bit awkward, maybe change to something like “the timing of the seasonal transition from high to low albedo . . . shifting towards greater insolation associated with summer solstice”

Re-worded, thank you for the suggestion.

- p. 3, l. 27: change to “confidence of the trends is calculated”

Changed.

- p. 4, l. 2: Not sure how Perovich et al. 2002 is relevant here since this paper does not discuss land or terrestrial snow albedos but multiyear sea ice.

This reference was removed.

- p. 4, l. 3: These two references only touch on the radiation budget obliquely; citation of a paper with actual analysis such as Pistone et al. 2014 or Perovich et al., 2007 that provide actual attribution would be more appropriate.

The Serreze et al. reference was removed and the Pistone et al. reference has been added.

- p. 6, l. 7: change to “Figure 2. However,”

Edited.

- p. 6, l. 12ff: The way this metric is described here and in the figure caption is confusing. Are you plotting the time period during which albedo falls into the interval {0.25,0.4}? Or are you plotting the days for which the albedo first drops below 0.4 and 0.25? Please clarify.

The latter. We are plotting the days for which the albedo first drops below 0.4 and then below 0.25. This has been clarified in the text.

- p. 11, l. 25 & 26: these papers are out of alphabetical order

Fixed.

- Fig. 5: Units on vertical axis should be MJ/day

Changed. Thank you for the insight and close reading, with all of your comments.

Arctic Climate: Changes in Sea Ice Extent Outweigh Changes in Snow Cover

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Abstract. Recent declines in Arctic sea ice and snow extent have led to an increase in the absorption of solar energy at the surface, resulting in additional surface heating and a further decline in snow and ice. Using 34 years of satellite data, 1982 - 2015, we found that the positive trend of solar absorption over the Arctic Ocean is more than double that over Arctic land, and the magnitude of the ice-albedo feedback is four times that of the snow-albedo feedback in summer. The ~~time of the high-to-low albedo transition~~timing of the high to low albedo transition ~~each year is moving toward~~has shifted closer to the ~~high sun~~greater insolation of the summer solstice over ocean, but ~~moving~~ further away from the summer solstice over land. Therefore, decreasing sea ice cover, not changes in terrestrial snow cover, ~~have~~ has been the dominant radiative feedback mechanism over the last few decades~~ and may play an even larger role in future Arctic climate change.~~.

1 Introduction

Over the last few decades satellites have observed an unprecedented reduction in Arctic sea ice extent (Pistone et al., 2014; Parkinson et al., 1999; Stroeve et al., 2012). Sea ice extent has decreased dramatically~~ since 2007~~, with the ten lowest minimum Arctic sea ice extents after 2007. The Arctic-wide melt season has become longer from 1979 to 2013 with a rate of 5 days per decade (Stroeve et al., 2014). September sea ice extent decreased by 45% ~~in September~~ from 1979 to 2016, and if current trends continue, some Arctic shelf seas are forecasted to be ice-free during summer in the 2020s (Onarheim et al., 2018). Over Northern Hemispheric land, snow cover extent has been decreasing in all seasons (Hori et al., 2017). Shrinking sea ice cover and terrestrial snow cover decrease the reflectivity (albedo) of the surface, resulting in more absorption of solar (shortwave) radiation, more surface heating, and further reductions in snow and ice. These processes are known as the sea ice-albedo feedback over ocean and the snow-albedo feedback over land. Here we examine how changes in surface albedo over the ocean and land areas of the Arctic have affected shortwave absorption differently, and how this interplay between albedo and shortwave absorption may change in the future. Results are presented for the majority of the satellite record, from 1982 to 2015, and for the pan-Arctic from 60°N latitude to the pole.

Between 1979 and 2011, the Arctic top-of-atmosphere (planetary) albedo decreased from 0.52 to 0.48~~ (Pistone et al., 2014)~~, and subsequent years with record or near-record low sea ice extent have further increased the amount of heat absorbed in the Arctic (Pistone et al., 2014). As the multi-year ice concentration decreases and is replaced by open water in the summer and thin, first-year ice in the winter, the darker surfaces reflect less sunlight and absorb more energy. The total absorbed solar radiation for the Arctic Ocean has therefore increased. Pinker et al. (2014) and Kashiwase et al. (2017) examined shortwave absorption in the upper Arctic ocean, with the latter finding that increases in open water may have led to a 50% increase in absorption since 1979.

The recent decreases in Arctic albedo are not entirely due to reduced sea ice cover, but also due to changes in the terrestrial snow cover (Robinson & Frei, 2000). Snow extent has decreased over Eurasia and North America since the late 1980s (Robinson & Frei, 2000*;* Kato et al., 2006) and is expected to continue decreasing by 3.7% (±1.1%) per decade during the spring ~~(Thackeray et al., 2016) ~~over the 21st century (Thackeray et al., 2016). Hemispheric snow extent may strongly influence early spring temperatures through a strong positive feedback between spring snow cover and the radiative balance over mid- and high-latitude land in the Northern Hemisphere (Groisman et al., 1994), in which retreating snow cover has led to a lower polar albedo and increased radiative absorption in April and May over the satellite record (Robinson & Frei, 2000; Robinson et al., 2005). Since 2007, the decrease in Northern Hemisphere snow cover has accelerated during the late spring and summer due to warmer spring air temperatures augmenting surface net radiation (Hernández-Henríquez et al., 2015).

Though the radiative effects of reduced snow and ice cover are straightforward, changing surface types in the Arctic may initiate albedo interactions that are complex. More open water in the Arctic Ocean has also led to an increase in cloud cover (Liu et al., 2012), which could offset the decreases in summer albedo caused by melting ice (Kato et al., 2006) and the replacement of multiyear ice with thinner, first-year ice (Nghiem et al., 2007). In ~~the ~~winter, when clouds inhibit radiative cooling of ice and open water, large anomalies in cloud cover may enhance or deter refreezing. This preconditioning of sea ice in the winter can influence t~~he albedo~~the initial ice conditions for the spring melt and ~~into the~~affect sea ice concentration (and therefore the Arctic albedo) through the melting season and into the fall of the following year (Letterly et al., 2016; Liu & Key, 2014).~~,~~ ~~illustrating how changes in cloud cover during different seasons may affect the planetary albedo (Letterly et al., 2016; Liu & Key, 2014).~~

The radiative feedbacks of changing snow cover and sea ice in the Northern Hemisphere have been studied (Perovich & Light, 2015; Fernandes et al., 2009; Flanner et al., 2011; Perovich et al., 2007). Perovich et al. (2007) analyzed the changes in solar energy during the melting period in the Arctic, but only over the period 1998-2004. Flanner et al. used top-of-atmosphere (TOA) fluxes to determine that the total impact of the cryosphere on radiative forcing between ~~1972 ~~1979 and 2008 was -4.6 to -2.2 Wm^{-2}. Their results included changes in snow and ice over the entire Northern Hemisphere, but applied a fixed annual albedo cycle over sea ice.

With satellite-derived surface radiative flux data now available from the early 1980s, it is now possible to study the relative effects of changing snow cover and sea ice on the Arctic surface energy budget. Does the increasingly early arrival of snow melt in the spring reduce the Arctic surface albedo more than the decrease in sea ice during the summer? Have the climatological changes associated with a warming Arctic affected the absorption of solar radiation more over land or over sea? Will trends in Arctic land and ocean surface albedo result in similar trends in solar radiation absorption in the near future? In this study, we use satellite-derived surface radiative fluxes from 1982 to 2015 to examine the inter-annual changes in surface albedo and the absorption of solar energy caused by the timing of the melt onset, and to estimate the major albedo feedbacks from the ocean and land. This study focuses on the effects of snow and ice cover changes on the surface shortwave radiation budget of the Arctic - defined as the area poleward of 60°N - not the remote effects of mid-latitudes on the Arctic.

2 Arctic Shortwave Absorption Trends over Snow and Sea Ice

The primary dataset for this study is the Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder Extended (APP-x) (Key et al., 2016). APP-x consists of twice-daily, 25 km composites at two local solar times in the Arctic (04:00 and 14:00) and Antarctic (02:00 and 14:00) starting in 1982. Data from 1982 through 2015 at 14:00 local solar time (high sun) are employed. APP-x includes surface temperature, surface broadband albedo, sea ice thickness, cloud properties (coverage, optical depth, effective particle size, thermodynamic phase, and top pressure), and radiative fluxes at the surface and TOA. ~~Algorithms are described in Key et al. (2016) and references therein.~~

In APP-x, the retrieval of surface albedo involves four steps. First, the reflectances of the two shortwave channels are converted to a broadband reflectance. Then, the TOA broadband reflectance is corrected for anisotropy and atmospheric attenuation, and converted from TOA broadband albedo to a surface broadband albedo. Finally, the surface clear sky brodaband albedo is adjusted for the effects of cloud cover in cloudy pixels over snow and ice (Key et al., 2001). The reflectance is also corrected for dependencies on sun-satellite-surface viewing geometry. Uncertainties in the retrieval of surface albedo are larger in cloudy sky conditions than in clear sky conditions. Downwelling fluxes at the surface are computed with a neural network, called FluxNet, which is trained to simulate a radiative transfer model (Key and Schweiger, 1998). The neural network uses derived geophysical variables as input (Key, 2015). To determine the absorbed shortwave energy at the surface, the downwelling shortwave flux was multiplied by the surface absorption (1-albedo) for each pixel. More details of the algorithms are described in Key et al. (2016) and references therein.

The study areas are land and non-land between 60-90°N latitude, where land is typically snow-covered and ocean is ice-covered during the winter, except for parts of the North Atlantic Ocean. Land includes Greenland. "Non-land" is almost exclusively ocean, but does include some inland lakes. For simplicity, we use "ocean" to mean "non-land" throughout the rest of this paper. Over this domain, the land and ocean areas contain a similar number of equal-area pixels, with land areas consisting of 26,682 25 km pixels and ocean areas consisting of 27,674 pixels, a difference in area of ~~only~~ 3.58%.

APP-x data show that annual mean absorbed solar radiation at the Arctic surface has increased over the 1982-2015 period (Figure 1).

The magnitude of absorption and the rate of increase, however, were~~as~~ different for land and ocean. Trends in surface albedo, surface temperature, cloud cover, and shortwave radiation are calculated using ~~monthly mean~~annual mean values with a linear least square fit regression over the thirty-four-year period, and confidence of the trends ~~are~~ is calculated using 2-tail student's t test. Over land, the average increase in absorption was 0.21 W m^{-2} year^{-1}, significant at the 90% confidence level; Over ocean, the average increase was 0.43 W m^{-2} year^{-1}, significant at the 99.9% confidence level. The shortwave absorption increase over ocean was, therefore, approximately two times ~~larger~~ as large as~~than~~ the increase over land. Absorption over the ocean increased by 0.3% of the annual mean ocean absorption per year, resulting in an approximate 10% increase over 34 years. Over land, the increase was 0.09% of the annual mean per year, or about 2.7% over the study period. The increased absorption over land can be attributed to the decreasing snow cover and hence decreasing albedo, especially in spring (Robinson & Frei, 2000; Déry & Brown, 2007~~; Perovich et al., 2002~~). The increased solar absorption over ocean can be attributed to the shrinking sea ice cover (~~Serreze et al., 2007~~Pistone et al., 2014; Polyakov et al., 2012). Including or omitting Greenland in the calculations for land has a relatively small impact on the results. If Greenland is excluded, the average annual mean shortwave absorption over land increases by about 18 Wm^{-2}~~, but the~~ but the strength of the absorption trend ~~decreases slightly~~is slightly weaker. Greenland's high albedo results in less shortwave absorption than other Arctic land areas, but the decrease in this albedo over time, especially over Greenland's coastal areas, contributed to a stronger absorption trend. Excluding Greenland decreases the absorption trend over land from 0.09% of the annual mean to 0.06%.

The larger trend over ocean than land results from the larger albedo difference between dry, snow-covered sea ice (greater than 0.~~6~~8) and open water (0.1) (Rösel et al., 2012) than between snow-covered land (0.~~7~~85) (Greenfell and Perovich, 2004) and land during the melting season (0.2-0.4) (Sturm et al., 2005). Though the change in shortwave absorption over ocean areas outpaces that of land, the greater magnitude of absorption over land, i.e., the actual amount of energy absorbed, is due to greater insolation at lower latitudes. The radiative feedbacks associated with these changes in absorption over both land and ocean are discussed later.

Figure 2 shows the spatial pattern of shortwave absorption trends over the Arctic for April, May, June, and September. These months were chosen because they illustrate the changes during the annual transition from high-to-low snow cover over land (April and May), high-to-low sea ice cover over ocean (June), and the annual sea ice minimum (September). Over Arctic land, the strong increase in absorption due to decreasing springtime snow cover (Robinson & Frei, 2000; Stone et al., 2002) is seen in May. Absorption trends in northern Europe, central Siberia, and the Alaskan Interior are particularly affected by this loss in snow, and this spatial pattern of radiative forcing was also seen by Flanner et al. (2011). Land areas show the greatest absorption increase from March through May, with average May absorption increasing by 1 W m^{-2} per year. Some of the increasing absorption trends in the early spring may be caused by changes in vegetation. Land with more exposed shrub experiences albedo decreases earlier in the year than where there is less shrub or no vegetation at all (Sturm et al., 2011). Once temperatures are above freezing, sensible heat flux overtakes solar heating and the impact from vegetation causing lower albedo values is reduced (Loranty et al., 2011; Sturm et al., 2005). This means that changes in absorption over land during the summer months are primarily driven by changes snow cover, not vegetation. Chapin et al. (2005) determine that on cloud-free summer days, broadband albedo over the Alaskan North Slope has been reduced by 0.0002 per year due to changes in vegetation from 1982-1999. ~~By June, the majority of terrestrial snow has melted, so the changes in absorption trends over land during the summer months are smaller than their spring values. Furthermore, since terrestrial snow cover has mostly melted by June, the main drivers of absorption trends over land during the summer may be changes in cloud cover or vegetation (Chapin et al., 2005; Loranty et al., 2011).~~

In contrast, most of the sea ice lasts through early summer, but changes in sea ice thickness and the formation of melt ponds still allow for changes in absorption (Perovich & Polashenski, 2012). Sea ice albedo typically decreases with thickness (Lindsay, 2001), and an increase in melt pond fraction (open water) further reduces surface albedo. As higher temperatures cause the surface of the sea ice (0.8 albedo) to begin melting, the thin layer of water atop the ice (0.6 albedo) can reduce the absolute albedo by 20%. Liquid water more readily absorbs radiation than the surrounding ice and causes more water to pool and create melt ponds, further reducing the ice concentration and albedo of an ice-covered surface (Rösel et al., 2012). Melt ponds that appear early in the melting season allow for greatly increased absorption over sea ice, and may even drive regional-scale sea ice changes in extreme cases (Rösel and Kaleschke, 2012). By late February or early March, sea ice concentration and extent reach their annual maximum under weak sunlight, so absorption trends over the Arctic Ocean are very small. From June to October, however, the multi-decadal changes to ~~sea ice~~the extent, thickness, and the surface albedo of summer sea ice ~~(as well as thickness)~~ caused the absorption rate to increase faster than absorption over land, particularly in the Beaufort and Chukchi Seas. Flanner et al. (2011) also noted that increases in radiative forcing from 1978-2008 over lower-latitude Arctic seas were greater than those over land during June-October. Sea ice extent and concentration have decreased over the last few decades, and thick, multiyear sea ice that was prevalent in the 1980s and 1990s has lost as much as 50% of its thickness (Kwok & Rothrock, 2009), if not vanished altogether (Serreze et al., 2007). First year ice is more susceptible to the formation of melt ponds, which can cause precipitous decreases in albedo (Rösel et al., 2012). The increase in surface absorption over the Arctic Ocean, then, is due to a combination of the replacement of multiyear sea ice with first year ice and open water over the study period.

While the decrease in the absorption of shortwave radiation is largely due to reductions in sea ice and snow cover extents, the linear correlations between snow cover anomalies or sea ice extent anomalies and shortwave absorption anomalies are both approximately -0.6 (not shown). Regional and seasonal changes in cloud cover explain some of the variance in these relationships. The 34-year trends in cloud cover were explored using APP-x data from 1982-2015. Over land, an increase (decrease) in highly reflective cloud cover is associated with decreases (increases) in surface absorption. For example, Arctic land areas that have experienced an increase in cloud cover (Alaska, western Russia, and northcentral Siberia) show decreasing trends in shortwave absorption. The spatial variability of the surface shortwave absorption over land in Figure 2 can be explained, in part, by trends in cloud cover. Figure 3 provides an example for September, where both positive and negative trends in cloud cover over eastern Siberia show a strong relationship with trends in absorbed solar radiation. While portions of the Arctic Ocean have also experienced changes in cloud cover, their effect on trends in shortwave absorption are much less, primarily because most of the ocean is still ice-covered and the reflectivities of ice and cloud are similar. We found that the trends in absorbed shortwave radiation over land are more affected by changes in cloud cover than over the ocean, and that trends in cloud cover can result in radiative absorption increases or decreases over land during the period of study, as shown in Figure 3.

While it can be seen qualitatively that the regional effect of clouds can be large, quantitatively determining their overall influence on the trend in absorbed shortwave radiation, i.e., to separate the influence of changes in cloud cover from changes in sea ice and snow cover, is not possible with the data available. Instead, we ~~In order to~~ quantify the contribution of clouds ~~on the shortwave flux at the surface, the authors performed a calculation that~~ by determining ~~determines~~ their maximum possible effect ~~of clouds~~ on downwelling shortwave radiation at the surface ~~between 1982-2015~~over the study period. This ~~calculation~~is done by using ~~uses~~ the 34-year average downwelling shortwave surface flux for each of the sunlit months (March-September) ~~-~~and the 34-year average cloud cover trend (fractional cloud cover) ~~(from March-September) for each point~~ to determine the changes in instantaneous surface shortwave flux. At each grid point in each month, the 34-year average downwelling flux is multiplied by the cloud cover trend. A positive cloud cover trend will result in a decrease in the downwelling and vice versa. For t~~T~~his calculation it is assumed~~s~~ that all clouds ~~changes take place in the form of~~are optically thick (~~or~~ “black”) ~~clouds which have very low transmissivity~~and reflect almost all incident sunlight, as optically thick clouds would have the maximum effect on downwelling shortwave radiation. This~~e~~ assumption ~~of all clouds being optically thick~~ is valid based on ~~the study by~~ Wang and Key (1995), which finds that visible~~overall Arctic~~ ~~cloud~~optical depths for Arctic clouds are ~~between~~in the range of 5-6, corresponding to a transmittance of near zero (0.2-0.6~~-0.2%~~%). ~~The high spatial variability in cloud cover trends reduces their net effect on the surface energy budget.~~ The average cloud cover trend over land and ocean are -0.265% and -0.392%, respectively, or 10% and 4% of the change in shortwave absorption.

For March-September, changes in cloud cover from 1982-2015 resulted in an increase of surface absorption by 1.94 Wm^{-2} over land and 2.19 Wm^{-2} over ocean. These cloud-based changes in surface absorption account for only a 0.5% increase in ~~incoming shortwave~~surface insolation over the ocean and a 0.4% increase over land.

Even though September experienced the greatest decrease in sea ice extent, the smaller incoming solar flux at this time of year result in smaller absorption increases than those of early summer. The early spring, late fall, and winter months exhibit far weaker trends in shortwave absorption over ocean than land due to lower variability in the sea ice cover and smaller solar fluxes - decreasing to zero in the winter - at the high latitudes.

Surface radiation and cloud cover data from the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications 2 (MERRA2) reanalysis (Rienecker et al., 2011) are employed to provide verification of the results from APP-x. This study used MERRA2 version 1.3 and determined the absorbed shortwave radiation trends at the surface from the surface incoming shortwave flux (SWGDN) surface albedo (ALBEDO) variables.

Performing the same analysis as ~~above~~before on MERRA2 data produced similar results. The trends in absorbed radiation for the month of June from APP-x and MERRA2 show similar patterns, though with larger magnitudes in APP-x (~~not shown~~Figure 4). The reanalysis data show an increase in absorption over ocean during June and mixed trends over land, which correspond spatially to APP-x trends~~s~~. The results were consistent with APP-x, with increasing, uniform ocean heating during high summer, and changes over land influenced by factors other than surface albedo. The most obvious differences between the reanalysis data and APP-x occur over the central Arctic Ocean, where MERRA2 absorption trends are weaker than those in APP-x. The cause of this difference is due to the fixed albedo value that MERRA2 assigns to sea ice, which does not take sea ice thickness or melt ponds into account. As seen in the APP-x results, thinner ice and irregularities in the ice surfaces increase the absorbed surface radiation.

3 Timing of Transition from High to Low Albedo

The trends in solar energy absorption at the surface are both a result of, and a forcing for, changes in surface albedo. As increasing solar absorption over the Arctic continues to affect land and ocean differently, we now explore how the timing of the low albedo portion of the year has changed over time, and how the timing relates to the available solar energy. Markus et al. (2009) determined that between 1979 and 2007, nearly all regions of the Arctic showed a trend towards earlier annual melting and later refreezing, which self-enhances as sea ice thickness decreases. Results presented here are consistent with their analysis and expand upon the surface energy implications.

Using APP-x data, we are able to track the changes of land and ocean albedo throughout the study period. The impacts on the surface energy budget are apparent in Figure 2.~~,~~ H~~h~~owever, the absolute timing of the low albedo period as well as the shift in timing of this period over the last few decades require further examination. ~~-~~One approach to analyzing these changes in the land and ocean albedo is to determine the day-of-year (DOY) in which the average albedo over land and over ocean reached their minima for each year. However, due to late freezing and thawing events and dynamically-driven changes in the sea ice edge, changes in the albedo minimum DOY do not accurately explain trends in absorbed solar energy over the last 34 years. We find that using the DOY range from when the Arctic transitioned from a relatively low albedo (the day that albedo first went below 0.4) to a very-low albedo (the day that albedo went below 0.25) state provides a better metric for comparing the changes in albedo over land and ocean (Figure ~~4~~5). Figure 5 shows that the majority of the snow cover over land melts earlier in the year than sea ice, which is due to higher sun and temperatures at a lower latitude. Terrestrial snow cover also melts earlier because the snow-free land adjacent to snow-covered land warms faster than the unfrozen ocean around the sea ice.

~~The intention here is to show that the~~An examination of Figure 5 shows that Arctic has reached a lower albedo state increasingly early in the calendar year over both land and ocean since 1982. A linear fit of the midpoint between the days of year at which the 0.4 and 0.25 albedo levels were reached shows a decrease of 0.64 days per year over ocean and 0.62 days per year over land over the last 34 years. Both of these trends are significant at the 99.9% confidence level. Furthermore, the rate at which the albedo is decreasing from 0.4 to 0.25 has accelerated. Over ocean, a linear fit of the length of the interval showed that it took over 16 days for the average ocean albedo to decay to 0.25 from 0.4 in the initial years of the study. By the end of the record, this albedo decrease took just 8 days (significant at the 99.9% confidence level). Over land, the change in rate of albedo decrease showed a prominent decrease from 17 days to 9 days over 34 years, although the statistical confidence level is less than 90%.

The regression in time of the low-albedo period towards earlier in the year over both land and ocean may have important radiative implications in the future. Over ocean, the low-albedo period was reached two weeks closer to the summer solstice (DOY 172) in 2015 than in 1982-1985, with the low-albedo range midpoint going from DOY 188 to DOY 167. Over land, the low-albedo range midpoint regressed nearly 20 days away from the summer solstice, closer to DOY 152. Though both land and sea experienced lower albedos migrating closer to the beginning of the year, the low-albedo period over land now occurs before the summer solstice, while the low-albedo period over the ocean occurs closer to the solstice and therefore at a time with much greater solar insolation. Even though the insolation during the low-albedo period is greater today than it was in the early portion of the study, the midpoint of the low-albedo interval has regressed past the summer solstice in the last few years (Figure 5). This implies that current trends in sea ice changes may cause the albedo transition to occur even further towards the beginning of the year, thereby experiencing weaker insolation, similar to the regression of the low-albedo period over land. As such, the differences between land and ocean absorbed shortwave trends may grow smaller as their albedo transition occurs earlier in the year.

The magnitude of insolation on any given day at the peak solar time is greater at lower latitudes. Therefore, even small changes in albedo in the lower Arctic can have large effects on the amount of energy absorbed at the surface. Conversely, large changes in albedo at higher latitudes are required to significantly affect shortwave absorption due to the weaker instantaneous insolation at higher latitudes. For instance, in 1982, the average albedo of all ocean pixels at 75°N was 0.345 on July 1. By 2015, the average ocean albedo on that date had decreased to 0.234, a change of over 11% (absolute). The corresponding change in average absorbed shortwave energy at 75°N on July 1 between 1982 and 2015 was 14.3 W m^{-2}. In contrast, the average land albedo at 65°N on July 1 decreased only 1.6% (absolute) between 1982 and 2015, yet the change in absorbed energy over land (4.8 W m^{-2}) was 34% of the change that occurred over ocean. At 75°N, albedo must decrease three times as much as it does at 65°N for the same increase in absorption in July, based on differences in the magnitude of insolation.

However, the magnitude of the flux accumulated over the entire day around the summer solstice is larger at higher latitudes. Figure 6 provides a simple illustration of the changes in the ~~TOA~~ accumulated, top-of-atmosphere, incoming shortwave flux at 65°N and at 75°N. For an equivalent change in albedo, the accumulated absorbed TOA shortwave flux is larger at higher latitudes because, even though the sun is lower, there are more hours of sunlight. The change in TOA absorbed accumulated flux at 65°N is 96% of the change in accumulated flux at 75°N. This relationship is also true at the surface. The accumulated flux on July 1 was calculated for the average ocean and land surface at 65°N and 75°N using albedos from the years 1982 and 2015. Results showed that at both latitudes, the accumulated flux on July 1 increased more over ocean between 1982 and 2015 than over land. Accumulated flux increases over ocean at 75°N (4.73 MJ) were more than twice as high as the changes at 65°N (2.05 MJ). Accumulated flux changes over land at 75°N (3.11 MJ) were also much higher than at 65°N (0.16 MJ). The greater changes in accumulated flux are related to larger albedo decreases at higher latitudes, where snow cover and sea ice may have changed more drastically than at 65°N. Therefore, at both latitudes over the last 34 years, the average ocean pixel has experienced a greater change than the average land pixel.~~The change in TOA absorbed accumulated flux at 65°N was 96% of the change in accumulated flux at 75°N.~~

Figure 6 also shows the changes that occur due to a low-albedo regression towards earlier times of the year. Over ocean, the shift in the timing of lower albedos to earlier in the year means that more sunlight was absorbed over the ocean in 2015 than in 1982, all else being equal (e.g., cloud cover). Over land, the regression of low albedo towards earlier in the year still results in an increase in absorbed energy, but it can only increase modestly due to decreasing sunlight further from the summer solstice. This relationship is valid for both the peak solar time and the accumulated absorbed fluxes.

~~Figure 5 provides a simple illustration of the changes in top-of-atmosphere insolation that occur due to a low-albedo regression towards earlier times of the year. Over ocean, the shift in the timing of lower albedos to earlier in the year means that more sunlight was absorbed over the ocean in 2015 than in 1982, all else being equal (e.g., cloud cover). Over land, the regression of low albedo towards earlier in the year still results in an increase in absorbed energy, but it can only increase modestly due to decreasing sunlight further from the summer solstice.~~

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4 Stronger Snow-Albedo and Ice-Albedo Feedbacks

The increased solar absorption due to the temporal regression of the low-albedo period results in a positive surface albedo feedback. One way to define the ~~The~~ strength of the albedo feedback ~~can be quantified as~~is the change in net incoming shortwave radiation with respect to surface temperature due to changes in surface albedo ~~as~~ (Cess and Potter, 1988; Qu and Hall, 2007; Fernandes et al., 2009):

$$\frac{\partial Q}{\partial T} = -I\frac{\partial \alpha_p}{\partial \alpha_s}\frac{d\alpha_s}{dT}$$

where *Q* is the net (absorbed) shortwave radiation at the top of the atmosphere (W m^{-2}), *I* is incoming solar radiation at the TOA surface (W m^{-2}), *T* is temperature (K or C), ζ_p is the planetary albedo at TOA, and ζ_s is the surface albedo. The term *I* is calculated as the montly mean incoming solar radiation at the APP-x grid level. The term $\partial\langle_p/\partial\langle_s$ over land and over ocean is calculated using an analytical model developed by Qu and Hall (2007) and surface albedo for all-sky and clear-sky only, albedo at TOA for all-sky and clear-sky only, cloud amount, and cloud optical thickness monthly means from APP-x 1982 to 2015 at the APP-x grid level. Coefficients required in this analytical model, ε_1 and ε_2 in each month, are derived following Eq.10 in Qu and Hall (2007) with collocated monthly means of planetary albedo at TOA for all-sky and clear-sky, cloud amount, cloud optical depth, and surface albedo at the APP-x grid level as a regression sample; another parameter (coefficient) required in this model is T_a^{cr}, effective clear-sky atmospheric transmissivity, which is derived monthly following Eq.5 in Qu and Hall (2007), using each collocated planetary albedo at TOA for clear-sky and surface albedo as a regression sample. The term $I\ \partial\langle_p/\partial\langle_s$ over land and over ocean is calculated following Eq. 12 in Qu and Hall (2007) at the APP-x grid level and then averaged. The term $d\langle_s/dT$ over land and over ocean is calculated as the averaged ratio of the monthly surface albedo trend to the monthly surface temperature trend at the APP-x grid level following Fernandes et al. (2009). All procedures follow Qu and Hall (2007) and Fernandes et al. (2009).

For a unit temperature change, the net solar radiation absorbed by the earth system over ocean is less than that over land in April, but about four times as large as that over land in June and July (Figure 7). The feedback strengths in June are 16.3 W m^{-2} K^{-1} over ocean and 3.8 W m^{-2} K^{-1} over land. The stronger surface albedo feedback over the ocean at the high-sun time of the year will amplify the warming effect, allowing for even more solar radiation to be absorbed by the earth system in the future, pushing the low-albedo threshold back even earlier in the year, and leading to a further decline in the Arctic sea ice cover.

~~The increased solar absorption due to the temporal regression of the low-albedo period results in a positive surface albedo feedback. The strength of the albedo feedback can be quantified as the change in net incoming shortwave radiation with respect to surface temperature due to changes in surface albedo as (Cess and Potter, 1988; Qu and Hall, 2007; Fernandes et al., 2009):~~

~~where~~ Q ~~is the net (absorbed) shortwave radiation at the top of the atmosphere (W~~ m^{-2}~~),~~ I ~~is incoming solar radiation at the top of the atmosphere (TOA) surface (W~~ m^{-2}~~),~~ T ~~is temperature (K or C),~~ $\langle_p$ ~~is the planetary albedo at TOA, and~~ $\langle_s$ ~~is the surface albedo. The term~~ $\partial\langle_p/\partial\langle_s$ ~~over land and over ocean is calculated using an analytical model developed by Qu and Hall (2007), and surface albedo for all-sky and clear-sky only, albedo at TOA for all-sky and clear-sky only, cloud amount, and cloud optical thickness monthly means from APP-x. The term~~ $d\langle_s/dT$ ~~over land and over ocean is calculated as the ratio of the surface albedo trend to the surface temperature trend. Each term is calculated at every 25 km cell and averaged over ocean and land weighted by the absolute magnitude of the temperature trend (Fernandes et al., 2009).~~

~~For a unit temperature change, the solar radiation absorbed by the earth system over ocean is less than that over land in April, but about four times as large as that over land in June and July (Figure 6). The feedback strengths in June are 16.3 W~~ m^{-2} K^{-1} ~~over ocean and 3.8 W~~ m^{-2} K^{-1} ~~over land. The stronger surface albedo feedback over the ocean at the high-sun time of~~

~~the year will amplify the warming effect, allowing for even more solar radiation to be absorbed by the earth system in the future, pushing the low-albedo threshold back even earlier in the year, and leading to a further decline in the Arctic sea ice cover.~~

5 Conclusion

The surface radiation budget of the Arctic is strongly influenced by changes in albedo, cloud cover, moisture, and heat advection. This study examined multi-decadal changes in the amount of solar radiation absorbed at the surface of Arctic land and ocean, together and separately, as a result of changes in albedo due to decreasing sea ice and snow cover. Analyses of the ~~AVHRR Polar Pathfinder Extended (~~APP-x~~)~~ satellite dataset and the NASA MERRA2 reanalysis over the 34-year period 1982-2015 determined that the magnitude of shortwave absorption is greater over land than the ocean, and that changes in snow and sea ice cover have led to an increase in absorbed shortwave radiation of 10% over ocean and 2.7% over land. ~~However,~~I ~~i~~t was found that the rate of change in absorption over the Arctic Ocean is more than double the rate over Arctic land, and that the magnitude of the ice-albedo feedback is four times that of the snow-albedo feedback in summer. However, the difference in the trend in shortwave absorption between land and ocean may decrease as the low-albedo period occurs further away from the summer solstice.

The timing of the annual low-albedo period has changed~~,~~ and has changed differently for land and ocean. While similar studies assume a consistent ~~annual~~ albedo cycle when determining the cryosphere's contribution to the global energy budget (Flanner et al., 2011), here we find that the inclusion of inter-annual changes to surface albedo result in a significant change to the surface shortwave energy budget of the Arctic between 1982 and 2015. Since 2010, for example, average ocean albedo in the study area during late June has been as low as mid-September albedo in 1982-1985. Similarly, Arctic land is losing its snow cover earlier in the year. If these trends continue, the temporal regression of the low-albedo period over land and ocean will have different effects on absorbed solar radiation in the future because the low-albedo period ~~is moving~~has moved further~~away~~ from the high-sun/maximum insolation time of year over land, but ~~moving~~ has moved closer to~~toward~~ the high-sun time over ocean. ~~This can be expected to intensify the ice-albedo feedback more than the snow-albedo feedback~~This has resulted in an intensification of the ice-albedo feedback more than the snow-albedo feedback, which may decrease as snow and ice melt earlier in the year. The absorption changes ~~described here~~ illustrate the relative importance of the snow-albedo feedback and the ice-albedo feedback~~,~~ and point toward the decreasing sea ice cover, not changes in terrestrial snow cover, as the foremost radiative ~~Arctic~~ feedback mechanism affecting recent and likely near-future Arctic climate change.

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Author Contribution

All authors contributed to the writing of this paper. Aaron Letterly performed much of the data analysis and drafted the manuscript. Yinghui Liu led the snow-albedo and ice-albedo feedback section. Jeffrey Key formulated the research idea and goals, and performed some calculations.

Competing Interests

The authors declare that they have no conflict of interest.

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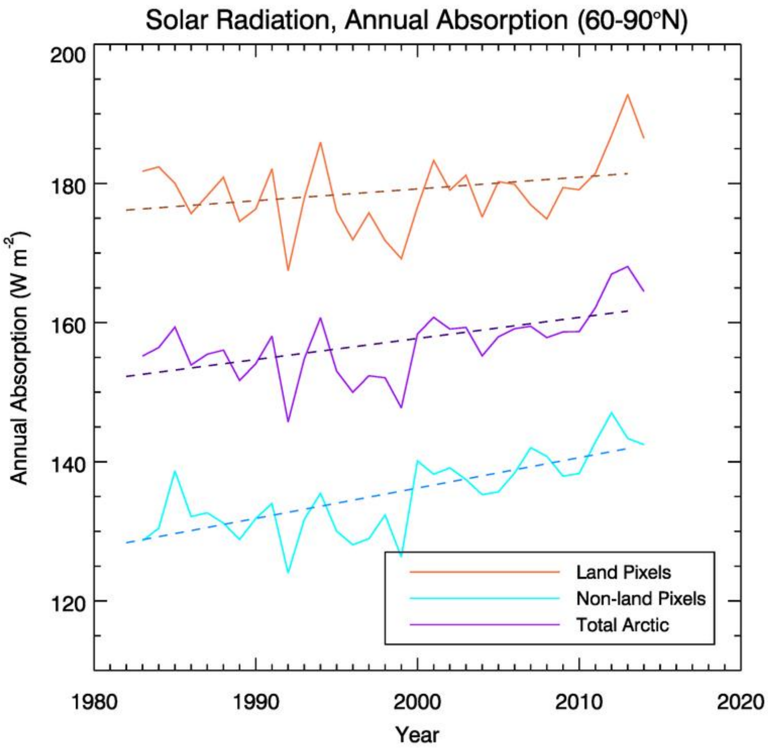

Figure 1: Average ~~monthly~~ annual surface shortwave absorption ~~per year~~ (W m^{-2}) from 60-90°N for the combined land and ocean area (purple), land only (orange), and ocean only (cyan). Dotted lines are linear trends.

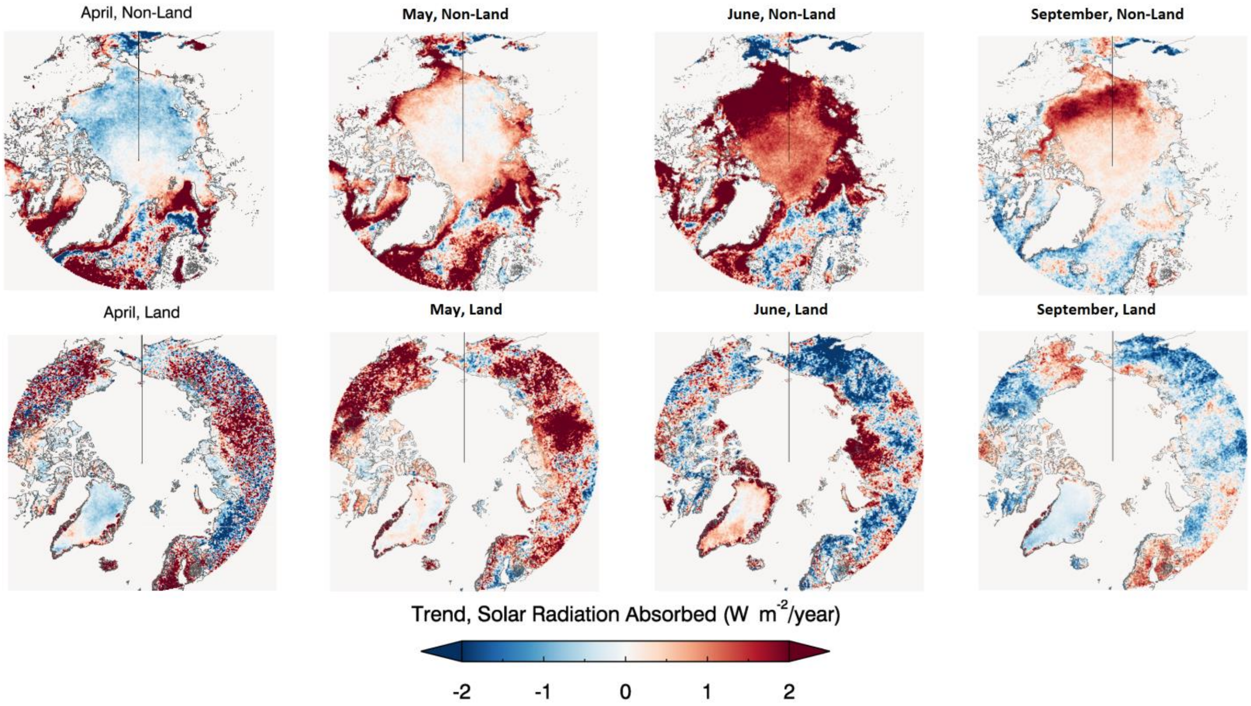

Figure 2: Trends in absorbed radiation for selected months over ocean (top row) and land (bottom row).

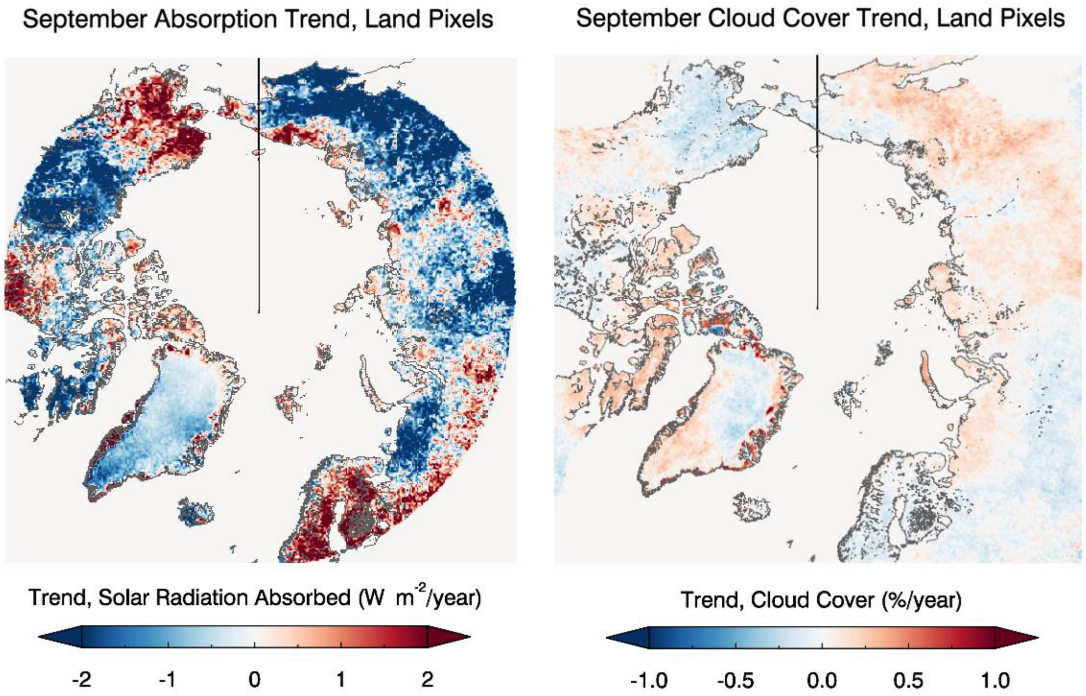

Figure 3: Trends in absorbed shortwave radiation over land (left) and cloud cover trends over land (right) during September.

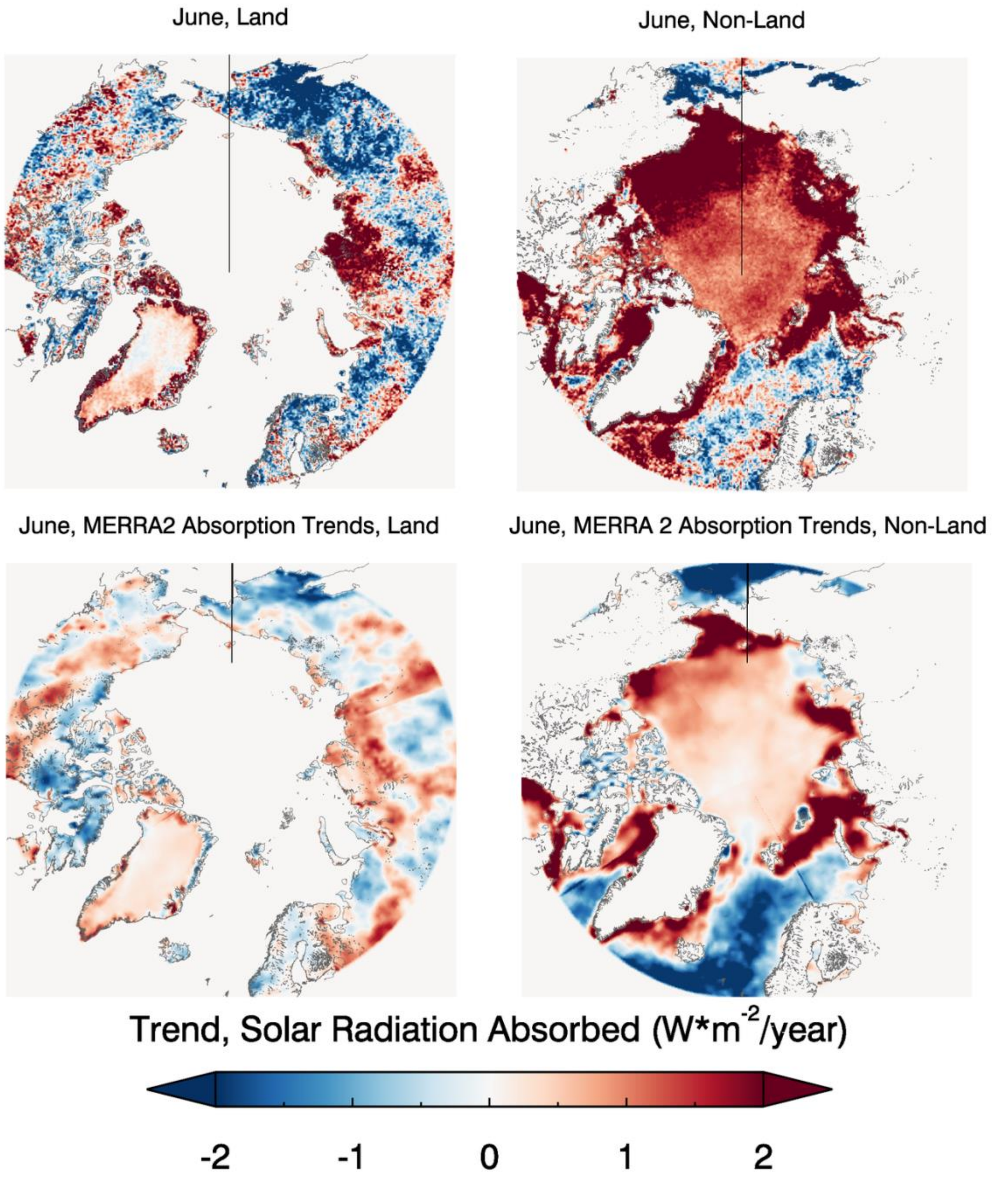

Figure 4: Trends in absorbed radiation from APP-x over land (top left) and ocean (top right) compared to trends from MERRA2 over land (bottom left) and ocean (bottom right) during June.

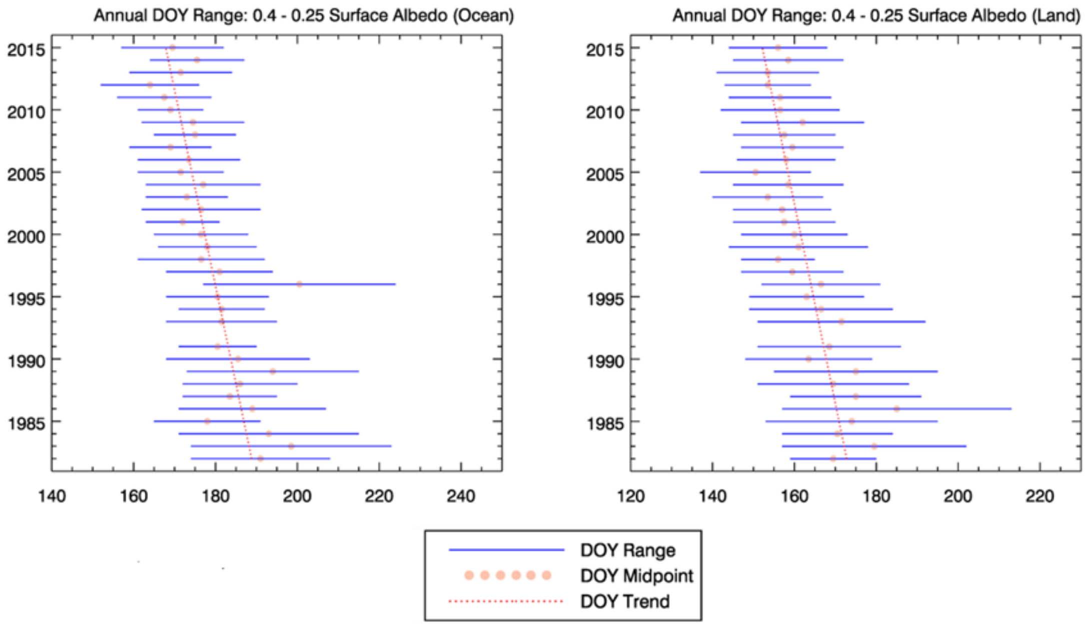

Figure ~~4~~5: Day of year range between 0.4 and 0.25 albedo over ocean and land (blue) from 1982 to 2015. The dotted trend line (red) shows the regression of the DOY midpoint (pink) over the time period.

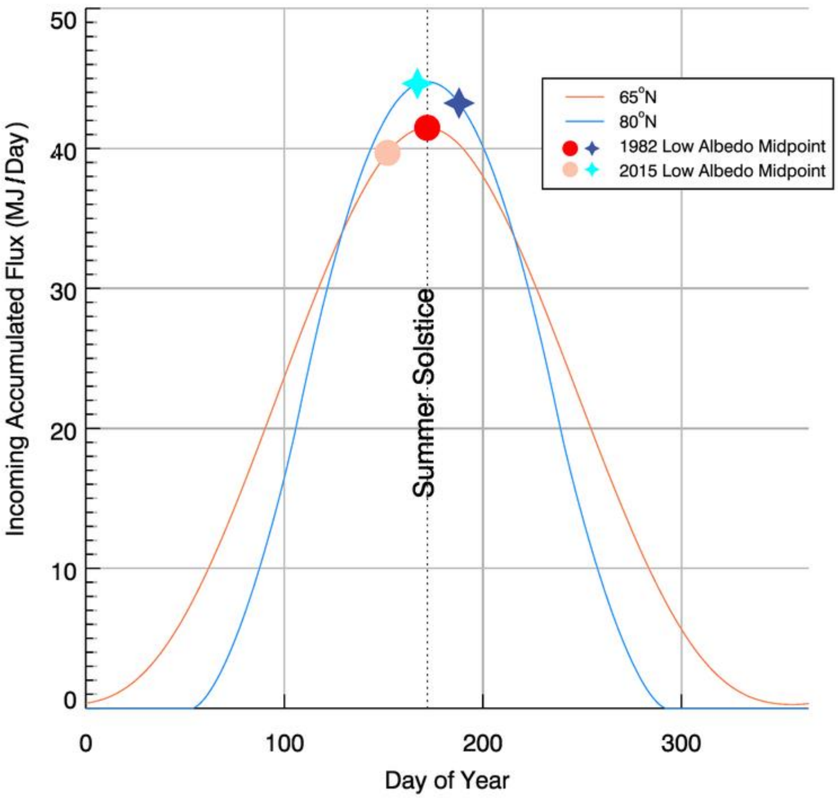

Figure ~~5~~6: Accumulated top-of-atmosphere incoming shortwave flux for each day and for the 65°N (orange) and 80°N (blue) latitudinal bands, roughly representing the Arctic Ocean and Arctic land, respectively. Darker symbols represent the day of year that the midpoint trend of the low-albedo period (Figure 3) was reached over land (circle) and ocean (star) in 1982, while lighter symbols show the day of year of the 2015 low-albedo period midpoint trend. Arrows clarify the direction in time for the change in the low-albedo period midpoints.

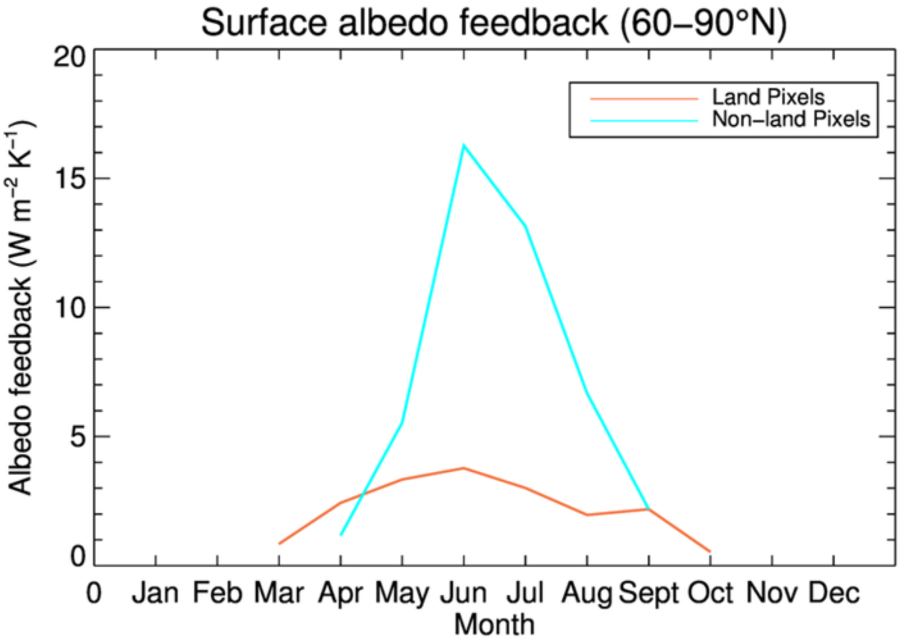

Figure ~~6~~7: The snow-albedo and ice-albedo feedbacks (equation 1) for Arctic land (orange) and ocean (cyan) for the period 1982-2015.