Replies to Review comments:

We thank you very much for your efforts in evaluating our work. Please find our replies in blue font under your comments.

Editor's comments:

I have now received two reviews of the revised version of your manuscript, see attached. You will find that both reviewers agree on a crucial point, namely that your numbers suggest an insignificant increase in Antarctic SW absorption. They hence find that the current title and abstract of the manuscript are misleading.

We agree that the title may be slightly misleading. However, this title was a result of the previous review round and a direct suggestion of the reviewers. We returned to a title close to our initial submission: "Increasing shortwave absorption over the Arctic Ocean is not balanced by trends in the Antarctic". We still consider this a very important result that has not been previously shown in the literature. We have reformulated the text to stress the main finding of similar trends in direction and magnitude in both hemispheres. The Antarctic trend is just masked in a larger interannual variability leading to statistical insignificance at 95% level (it would be significant at 90% level).

The reviewers also agree that the general result for the Arctic is certainly not surprising, which poses some doubts regarding the amount of truly novel information contained in this manuscript.

As indicated in our manuscript, this is the first study to make a quantitative comparison on a consistent bi-hemispheric observational dataset. Furthermore, these concerns are only raised by referee #1 (Sebastian Bathiany), while referee #3 (Ian Eisenman, report #2) does not mention these concerns, but rather states "The manuscript is clearly written, and I find it well suited for publication in this journal" and evaluates "accepted subject to minor revisions" not encompassing further analysis.

I tend to agree with the view of reviewer 1 that the overall scientific content of this manuscript must be increased for it to become publishable in *The Cryosphere*. This is also reflected by the concerns of reviewer 2 who finds the result for the Arctic somewhat trivial and the significance of the result for the Antarctic unclear. Reviewer 1 poses some suggestions to improve the significance of your study, which I hope you will find helpful for revising this manuscript.

As mentioned above, referee #3 (Ian Eisenman, report #2) only mentions that the results for the Arctic are not surprising. However, there is no indication by him that the Arctic results are the main part of the manuscript. He explicitly states "The manuscript is clearly written, and I find it well suited for publication in this journal."

All reviewers agreed on the format of a brief communication in *The Cryosphere* (Ian Eisenman in this review round: "… well suited for publication in this journal" and Sebastian Bathiany during the first round of reviews: "I consider the format of a brief communication and the journal as a suitable choice to publish these results."). We are firm on our decision not to further extend the analysis but to use this study to stimulate further scientific work. The tasks necessary to add additional analysis go well beyond the scope of a "Brief communication" and resources for such an analysis are lacking.

For such revised version, I in particular ask that you more explicitly specify the scientific advance of your manuscript for the scientific audience of The Cryosphere.

We tried to reformulate some passages to make this clearer. We wrote this paper because there is so far no scientific literature covering the combined effects of Arctic and Antarctic shortwave energy balance, which we consider an important topic. Changes in the two polar regions have not always been in the same direction, e.g., dramatic decreases in Arctic sea ice extent countered by increases in the Antarctic sea ice cover. But what do these often opposite changes mean in terms of the surface energy budget? We consider it important to provide scientific evidence to questions that are raised by society and to stress the importance of a global view on sea ice process related studies.

Comments by Referee #3 (Ian Eisenman)

This Brief Communication assesses the change in surface shortwave absorption in both Polar Regions during 1982-2014. The authors find an increase in the Arctic, which is unsurprising given the rapid sea ice retreat, but they also report an increase in the Antarctic despite the observed sea ice expansion in that hemisphere. The manuscript is clearly written, and I find it well suited for publication in this journal, although I think the points raised below should first be addressed.

We thank you very much for your positive evaluation of our work! Indeed, the increase in the Arctic is not surprising, as apparent also from the many citations given in the text. What is important here is how the increase in the Arctic compares to the trend in absorption in the Antarctic, particularly given the different trends in sea ice. We are happy that you positively evaluate our main finding that the slight increase in Antarctic shortwave absorption (or a statistically significant non-decrease) does not compensate for Arctic increases.

Major comment:

I am a bit confused regarding the significance of the Southern Hemisphere result. The authors write that in the Southern Hemisphere "energy absorption by the ice-ocean system south of 60S also increased but, due to the large interannual variability, only at a statistically insignificant rate" (page 4 lines 23-25). But despite this, the text says "both hemispheres show a distinct increase in energy deposition" (page 4 line 25) and "positive energy absorption trends in both hemispheres" (page 5 line 1), the title states that shortwave absorption is increasing "at both poles", and the abstract says it is "increasing at both poles". Am I missing something here? If the results do not show a significant increase in shortwave absorption in the Southern Hemisphere, then I think the title, abstract, and main text should be revised to reflect this point.

We thank you very much for highlighting this inconsistency. This title was suggested by the other reviewer during the first round of revisions. We agree with your concerns and returned to a title (as well as some text formulations) closer to our initial submission. Also, the lack of clarity may have come from the fact that the shortwave absorption trends are actually very similar in magnitude, but the large interannual variability in the Antarctic renders the southern trend statistically insignificant. We however still find this an important result and we reformulated this for clarity.

Minor comments:

page 4 line 22-23: I found the choice of units of the increase in absorbed shortwave to be somewhat unclear. It seems most intuitive to present this in terms of how much the absorbed energy in W/m^2 (averaged over the relevant polar region) increases each year. This is instead presented here in units of J/yr, which I find somewhat confusing. Furthermore, I am confused by the values. The rate of increase reported here for the region 60N-90N is 2.3 x 10^25 J/yr (page 4 line 22-23). But unless I'm mistaken, this is more than the total TOA solar energy incident on the earth, which is 5.5 x 10^24 J/yr (calculated as 1340 W/m^2 * surface area of earth/4).

As the areal distribution of the sea ice zone is significantly different at both poles, and we wanted to provide a measure that allows us to easily compare the budget of both hemispheres, we chose J/yr. We agree that the presented numbers were too high. We found an error in our calculations and now the numbers are 5 orders of magnitude lower. The correction of this error however does not have an effect on our main conclusion. Thank you very much for catching this mistake!

page 3 line 25: The 1982-2004 sea ice trends reported in this paragraph, averaged between September and March, have a magnitude in the Arctic that is 5.2x larger than in the Antarctic. This is fairly similar to the 1979-2012 annual values reported in the IPCC AR5, which have a magnitude in the Arctic that is 2.9x larger than in the Antarctic. I think it would be more accurate to revise how this is described from Arctic losses being "thus roughly one order of magnitude stronger" than Antarctic increases to "thus five times larger in magnitude" (or something similar).

We thank you very much for your suggestion and adopted your suggested formulation.

page 3 line 21: When error bars are given for trends, are these 68% confidence intervals (as are often used), or are they 95% confidence intervals (as implied on page 3 line 19)? It would be helpful if this were specified.

Indeed, these are 95% confidence intervals. We added the following statement to the preceding paragraph: "Given error intervals for trends are 95% confidence intervals."

page 1 line 19: The argument being made here may be supported by our own finding that there is a large uncertainty in the 1979-2012 Antarctic sea ice extent trend due to intercalibration across sensor changes (Eisenman et al. 2014, The Cryosphere 8 1289-1296). I don't mean to angle for a self-citation here, and I certainly leave this to the authors' discretions, but I just figured I'd mention this in case the authors find that it strengthens their case.

We agree with you on this point! This work was referenced in an earlier version of the manuscript but removed due to the comments during editorial review. We have added it again, as it is an important example showing inconsistencies in the datasets.

page 2 lines 21-29: (typo) ice extent trends should be in units of km^2/yr, not km/yr.

Maybe there was some error with the PDF display? We double checked that the appropriate units are used.

page 2 lines 26-27: (typo) "as a climate data record variables" should presumably be "as climate data record variables".

Corrected

page 3 line 22: (typo) "in the Antarctic in the Southern Hemisphere" should presumably be "in the Southern Hemisphere".

Corrected

Comments by referee #1 (Sebastian Bathiany)

General comments
In my opinion, the manuscript has improved in readability compared to the previous submission. The authors have made some statements clearer and have corrected shortcomings in their analysis.

We thank you for the positive evaluation of our revised version.

I still have some concerns regarding the relatively small amount of robust and novel conclusions in this paper. In the paper, and even more so in the discussion, the authors mention the interest of the media as well as claims by so-called climate sceptics as a motivation for their study. However, a research paper is primarily meant to address other researchers.

It is a valid objective of a scientific publication to raise questions and to stimulate scientific discussion based on findings in a novel observational data record, especially since we chose the format of a Brief Communication and not a full-length paper. We would not have submitted this paper if the information presented was covered in existing scientific literature. Also, science may very well be driven by the curiosity of society, so we think that if questions arise from society in public discussion, they actually should be appropriately addressed in the scientific literature.

The main statement that the short-wave absorption is increasing should hence be complemented with an analysis of the causes. In my opinion the article could therefore elaborate a bit more on the potential scientific merits of its approach, and explore the main statements in some more analytical detail.
Specifically, the conclusions about the role of sea-ice albedo and clouds could be supported with some more evidence. From the analysis of sea ice distribution, surface albedo and absorbed short-wave radiation, the authors conclude that changes in cloud properties and ice albedo are responsible for the observed changes in short-wave absorption, but these properties are not shown directly. It would be ideal if the authors could somehow quantify the individual contributions of changes in sea-ice albedo and cloud coverage in order to support their statements. For example, how has the downwelling short-wave flux changed? As several cloud properties are also included in APP-x (for example cloud radiative forcings), it might not be out of proportion for this brief communication to test whether changes in these properties are in line with the author's claims that are based on some other variables of the same dataset.

We thank you for your suggestions in which directions the research could be extended. However, doing so is beyond the scope of this Brief Communication, thus we did not add further analyses. We will pursue these excellent suggestions in the future.

In the conclusions, the authors repeat their statement that the short-wave absorption is increasing. I would also expect some statements about the scientific relevance of this finding, e.g. implications about our understanding of the polar climate, and how future research should address the questions that have to remain open.

We thank you for this suggestion. We added some text as suggested.

Specific comments

- p. 2, l. 14: It is stated here and also at other places (e.g. p. 4, l. 13/14) that the dataset "takes into account" changes in cloud cover, albedo changes, etc. This seems to relate to the statement that "the energy balance is kept closed" (p. 2, l. 22/23) which seems to involve some kind of model. I suggest to explain this in more detail. Why is it an advantage to use this approach instead of independent observations of different variables? For readers not familiar with the available data, it could be explained in more detail which properties are observed and which are inferred by the authors involving additional assumptions.

The processing is described in the methods section "APP-x contains twice-daily data of many surface, cloud, and radiative properties retrieved at high sun and low sun times … from satellite data using a suite of algorithms and a radiative transfer model (Key, Wang et al. 2016)." This presents the appropriate reference, where retrieval details can be found. We do not think that it would be beneficial to include more detailed information about what exact models are used into our text, as this is not central to our conclusions. Nevertheless, we agree that the statement may be unclear, so it has been revised.

- p. 3, l. 8: "accounts for true cloud cover". How? And what is "true"?

We removed the ambiguous word "true".

- Fig. 1: Why is the short-wave absorption much more variable in the Southern hemisphere? Given these fluctuations, is the trend significant at all? If not, it should not be claimed that the solar absorption has been increasing, and the conclusions might be better based on the correlations between variables instead of the trends.

The Southern Hemisphere absorption is much more variable, because it is very sensitive to the large annual cycle of sea ice cover in the southern ocean. Significance of the trend is discussed in the text, while the main important point is that there is no significant opposed trend.

- Fig. 2: I am puzzled by the fact that the sign of the trends is spatially so uniform, even in places where there is no sea ice. How can this be the case? Could there be a bias?

Shortwave absorption trends outside the sea ice zone are caused by changes in cloud cover and atmospheric composition, which are more uniformly distributed than sea-ice. Of course, satellite products can contain biases, however due to the validation of the APP-X albedo and shortwave fluxes we do not think this is the case here.

Minor comments

Main text

- What is new about the APP-x dataset, i.e. what makes it a “novel tool”? Hasn’t AVHRR data been available for a long time?

This is described in p2. L.13 “It provides surface radiative properties and fluxes consistently derived twice daily (high and low sun) for both polar regions beginning in 1982”. You are absolutely correct that AVHRR has been around for a long time. However it is new in APP-x, that the derived variables are based on methods developed specifically for the polar regions.

- p. 2, l. 12: remove “large”

removed

- p. 3, l. 11: “slightly larger numbers” – how much larger approximately?

Details of the comparison to passive Microwave data were included in our replies to the last review round: http://www.the-cryosphere-discuss.net/tc-2016-279/tc-2016-279-AC3-supplement.pdf

- p. 4, l. 3: rephrase to make clearer: “seasonal Arctic sea ice..., the dataset shows a decrease..., while in the Antarctic, albedo trends show regional differences ... ice concentration.”
Rephrased accordingly

- p. 4, l. 11: remove “relatively”
Removed

- p. 4, l. 15: “The mean annual shortwave energy flux....”
Edited accordingly

- p. 4, l. 18/19: Why is the absorption more spatially uniform in the Arctic?
Added “due to uniform sea ice changes”

- p. 4, l. 24: I suggest to cite the source of this result, or explain how this test was done.
A trend, where the 95% confidence interval encompasses zero is not significant at 95% confidence level.

- p. 4, l. 26/27: “energy absorption” – isn’t it only the short-wave absorption and not the full energy balance what the authors address here?
Changed to “shortwave energy absorption”

- p. 4, l. 30: “does not show a pattern” – I don’t understand what is meant here.
We reworded for clarity

- p. 5, l. 11: “Increases in Antarctic sea ice only occur during the Southern Hemisphere winter”. Fig. 1a seems to contradict this statement. Anyways, I do not consider this aspect important enough for the conclusions section. Instead, I would prefer to see a discussion of the implications of the main results (see above).

We added the word “Significant increases…” for clarification. We also added some of your suggestions to the conclusion.

Fig. 1
- Fig. 1: The caption refers to minimal and maximal seasonal extent, but within Fig. 1a it is referred to March and September (by the way, months are written with a capital letter).

This is the correct labelling, as minimal extent occurs in different months in both hemispheres.

Fig. 2
- Caption: trends in “sea ice albedo”. Is this really what the figure is showing? As far as I understand it shows the surface albedo change.

Corrected accordingly

- I suggest to use a different colour bar that gives less weight to very small changes and more weight to large changes.

Thank you for the suggestion, the figure is now clearer.

- a) and b) “Arctic” and “Antarctic” are unnecessary details in the variable name because one can see what region it is on the map anyways.

Corrected accordingly

Fig. 3
- This figure is not discussed in the text. I suggest to embed it in the line of argument more explicitly.

The figure is discussed in p.4,ll. 30-34

- “albedo anomaly”. Surface albedo, I guess?!

Corrected accordingly

Brief communication: Increasing shortwave absorption over the ~~sea ice area at both poles~~Arctic Ocean is not balanced by trends in the Antarctic

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Abstract ~~Here we show on~~On the basis of ~~the~~a new, consistent, long-term observational satellite dataset ~~APP-x~~we show that despite the observed increase of sea ice extent in the Antarctic, absorption of solar shortwave radiation in the ~~polar oceans~~southern ocean poleward of 60° latitude is ~~increasing at both poles~~not decreasing. The observations show that apart from retreating sea-ice, additional effects such as changes in cloud cover and surface albedo lead to a total increase of solar shortwave energy deposited into the polar oceans~~ despite of the marginal increase~~, as trends in Antarctic ~~winter~~ sea ice ~~extent.~~cover cannot offset the retreat of Arctic sea ice.

1 Introduction

Changes in the Arctic and Antarctic cryosphere have been continuously monitored by different satellite programs since the 1970's. Arctic sea ice is becoming thinner ~~(Haas, Pfaffling et al. 2008)~~(Haas, Pfaffling et al. 2008) and younger ~~(Maslanik, Fowler et al. 2007)~~(Maslanik, Fowler et al. 2007) coupled with a decline in its extent ~~(Serreze, Holland et al. 2007, Stroeve, Serreze et al. 2012)~~(Serreze, Holland et al. 2007, Stroeve, Serreze et al. 2012). This leads to a decrease in area-average sunlight reflection, and thus to higher energy absorption in the Arctic Ocean ~~(Perovich, Jones et al. 2011, Nicolaus, Katlein et al. 2012)~~(Perovich, Jones et al. 2011, Nicolaus, Katlein et al. 2012). While some areas in Antarctica have also experienced a reduction of the sea ice cover, a modest overall gain of sea ice ~~extent~~area has been recorded in the Southern Hemisphere (Cavalieri, Gloersen et al. 1997~~, Stammerjohn, Massom et al. 2012)~~, Stammerjohn, Massom et al. 2012). How these opposing trends relate to each other on a global scale is governed by a multitude of factors, such as the different latitudinal position of the ice cover and constraints by land masses, significant differences in the physical properties of the ice surface, and different forcing mechanisms from lower latitudes ~~(Meehl, Arblaster et al. 2016)~~(Meehl, Arblaster et al. 2016)~~. This difference in hemispherical sea ice extent trends is a point frequently raised in the public debate, but its impact is poorly studied. A particular problem is the lack of a long-term consistent observational dataset covering both poles.~~

. A particular problem in relating Arctic and Antarctic trends and their global impacts is the lack of a long-term consistent observational dataset covering both poles (Eisenman, Meier et al. 2014).

The increased absorption of sunlight due to the loss of sea ice results in ocean warming, more ice loss, a decrease in albedo, and a further increase in absorbed sunlight. This is known as the ice-albedo feedback (Curry, Schramm et al. 1995), a critical process in the global shortwave energy budget. Most of this added heat will be lost due to increased longwave emission during winter and will not be carried on into the next year. Especially in the Arctic, a longer sea ice melt season ~~(Markus, Stroeve et al. 2009)~~(Markus, Stroeve et al. 2009), thinner ice ~~(Haas, Pfaffling et al. 2008)~~(Haas, Pfaffling et al. 2008), and increased melt-pond coverage ~~(Rösel and Kaleschke 2012)~~(Rösel and Kaleschke 2012) lead to increasing solar shortwave energy deposition in the ice-ocean system ~~(Nicolaus, Katlein et al. 2012)~~(Nicolaus, Katlein et al. 2012), adding to the increase in absorption due to decreasing sea ice extent ~~(Pistone, Eisenman et al. 2014)~~(Pistone, Eisenman et al. 2014). However, surface characteristics of Antarctic sea ice are less affected by global climate change (Allison, Brandt et al. 1993, Brandt, Warren et al. 2005~~, Laine 2008)~~, Laine 2008). Antarctic sea ice is mainly melting from below as the ice drifts away from the continent into warmer circumpolar waters, ~~which is opposite~~in contrast to the surface melting induced by melt ponding on Artic sea ice. Therefore, sea-ice extent losses in the Arctic are most pronounced during the Northern Hemisphere summer. In the Antarctic, the increasing extent of Antarctic sea ice is observed during the Southern Hemisphere winter, when the impact of sea ice cover on the shortwave energy balance is weaker.

Here we evaluate observations of the combined effect of different radiative processes in both hemispheres on the shortwave energy budget of the polar oceans. Our goal is to determine to what extent the increased absorption of solar shortwave energy caused by losses and other changes in Arctic summer sea ice ~~can compensate for the~~are offset by potentially decreased absorption ~~caused by modest~~due to observed increases of sea ice extent in the Antarctic. The recently published Advanced Very High Resolution (AVHRR) Polar Pathfinder - Extended (APP-x) dataset provides a novel tool to investigate this question on the ~~large~~ global scale. It provides surface radiative properties and fluxes consistently derived twice daily (high and low sun) for both polar regions beginning in 1982 ~~(Key, Wang et al. 2016)~~(Key, Wang et al. 2016). Its great advantage compared to earlier, individual products based on AVHRR data is that the integrated dataset inherently takes into account changes in cloud cover and albedo changes of various sources, allowing us to evaluate the actual shortwave energy deposition changes in the oceans poleward of 60° latitude. We calculated monthly averaged shortwave radiative fluxes into the ice-ocean system to estimate the partitioning of absorbed shortwave energy between sea ice and the unfrozen ocean surface.

Methods

The results presented here are based on version 1.0 of the Extended AVHRR (Advanced Very High Resolution Radiometer) Polar Pathfinder (APP-x) data. APP-x contains twice-daily data of many surface, cloud, and radiative properties retrieved at high sun and low sun times (04:00 and 14:00 local solar time for the Arctic; 02:00 and 14:00 for the Antarctic) from satellite data using a suite of algorithms and a radiative transfer model ~~(Key, Wang et al. 2016)~~(Key, Wang et al. 2016). ~~During~~All variables are derived from the ~~retrievals the energy balance is kept closed~~same set of satellite radiances, allowing ~~our~~an integrated view on the effects of sea-ice changes. We use the variables ice thickness, surface albedo, cloud cover and downwelling shortwave radiation at the surface. The APP-x record begins in 1982 and continues to the present day, though version 1.0 used in this study covers the period 1982-2014. Through validation studies, the APP-x variables used here have been determined to be of sufficient accuracy to be considered as a climate data record variables. APP-x shortwave fluxes have been validated against observations from the SHEBA ice camp and the CERES satellite product (Riihelä et.al, JGR 2017, in press).(Riihelä, Key et al. 2017). Details on the retrieval of the variables can be found in the respective Climate Algorithm Theoretical Basis Document (http://www1.ncdc.noaa.gov/pub/data/sds/cdr/CDRs/AVHRR_Extended_Polar_Pathfinder/AlgorithmDescription.pdf (Key and Wang 2015)(Key and Wang 2015)). APP-x utilizes the Near-real-time Ice and Snow Extent (NISE) product from the National Snow and Ice Data Center (Boulder, Colorado, USA) for surface type identification.

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The energy flux absorbed by the surface was calculated as

$$E = E_{down} \cdot (1 - \alpha) \,, \qquad (1)$$

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and multiplied by 12 hours and the grid cell size to obtain the total amount of absorbed energy, where E_{down} inherently accounts for the true cloud cover. All grid cells with ice thickness greater than 0 were considered as ice covered. The APP-x data product does not contain a separate field for ice-concentration, but ice thickness is only calculated for cells with an ice concentration >15% in the NISE product. Sea ice extent was calculated as the number of ice-covered grid cells multiplied by the cell size (25x25 km). This yields slightly larger numbers than comparable analyses on the direct basis of passive microwave sea-ice concentration products with higher resolution, but the magnitude of changes proved to be unaffected.

Shortwave energy fluxes were calculated for the twice-daily data and averaged over each month to reduce the influence of retrieval errors and intermittent gaps in the data. For the calculation of total absorbed energy, twice daily data was summed up to monthly values. For grid cells with invalid retrievals due to low light during winter, shortwave fluxes were set to zero and the albedo was set to one. Monthly data of average energy flux and total absorbed energy were then used for annual and long-term averages as well as for time series analysis. Data for the year 1994 were excluded from time series analysis due to a significant gap in the observations. Trends were calculated through linear regression using the Matlab curve-fitting toolbox. All trends presented as significant have confidence levels above 95%. Given error intervals for trends are 95% confidence intervals.

Results

An analysis of the dataset revealed a decrease of September sea-ice extent of -0.126 (± 0.03) million km²/year for the Northern Hemisphere and an insignificant increase of 0.012 (± 0.02) million km²/year in the ~~Antarctic in the~~ Southern Hemisphere summer in March (Figure 1a). Antarctic sea-ice extent increased 0.020 (± 0.01) million km²/year in September during Southern Hemisphere winter, while winter sea ice loss in the Arctic is weaker in March with a loss of -0.041 (± 0.01) million km²/year. Arctic sea-ice extent losses are thus ~~roughly one order of~~five times larger in magnitude~~ stronger~~ than the small increases in ice area in the Antarctic, leading to a combined total sea ice loss of -0.106 million (± 0.03) km²/year in September and -0.028 (± 0.025) million km²/year in March. This reproduces the known global net loss of sea-ice covered area during the last few decades ~~(Stammerjohn and Smith 1997, Stammerjohn, Massom et al. 2012, Stroeve, Serreze et al. 2012)~~(Stammerjohn and Smith 1997, Stammerjohn, Massom et al. 2012, Stroeve, Serreze et al. 2012). Thus, the loss of sea ice extent in the Arctic does not compensate for the slight gains in the Antarctic area-wise. Given the differences in the latitudinal distribution of Arctic and Antarctic sea ice, however, the impact of these changes on the absorption of solar radiation warrants further investigation.

The summer mean daytime albedo for ice-covered areas in the APP-x dataset was 0.34 for the Arctic (June/July/August) and 0.41 for the Antarctic (December/January/February) which compares well to earlier studies (Allison, Brandt et al. 1993). The higher albedo of Antarctic sea ice may be caused mainly by a thicker snow cover with little surface melt and consequently the lack of melt water pond formation. In accordance with the observed trend towards younger, predominantly seasonal Arctic sea ice~~ cover~~ with larger melt pond coverage, the APP-x dataset shows a decrease of the mean Arctic summer sea ice albedo, while in the Antarctic albedo trends show regional differences driven by the changes in ice concentration ~~in the Antarctic~~ (Figure 2). In this analysis of albedo trends, we only consider summer daytime albedos, as the albedos retrieved during wintertime are questionable due to low light levels and observation gaps. ~~However, this~~This does not significantly affect our analysis of energy fluxes, as the largest uncertainty in the albedo occurs with low fluxes subsequently leading to a low energy flux uncertainty.

Antarctic sea ice exists mainly in the latitude zone between 55 and 77°S. In contrast, Arctic sea ice occupies the region between approximately 70 and 90°N. Due to its generally higher snow cover ~~(Massom, Eicken et al. 2001)~~(Massom, Eicken et al. 2001) and the 20% higher albedo as well as its location at lower latitudes with higher shortwave insolation, the presence of sea ice does have a ~~relatively~~ stronger impact on the local shortwave energy balance in the Antarctic. Mean annual shortwave energy uptake by the ice-ocean system polewards of 60° latitude was calculated twice daily from APP-x surface albedo and incoming solar radiation at the surface and averaged for each month. The use of these APP-x quantities inherently accounts for trends in cloud cover and surface albedo changes.

~~Mean~~The mean annual shortwave energy flux into the ice-ocean system poleward of 60° accounts for 68 W/m^2 in the Arctic, and 60 W/m² in the Antarctic (Figure 1b). Average Southern Hemisphere absorption shows high interannual variability throughout the satellite record, while the absorbed flux of the ice-ocean system in the Arctic clearly increased by

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0.48 W/m^2 per year. While the trend in the absorption of solar shortwave energy is fairlymore uniform across the Arctic Ocean due to uniform sea ice changes, there are large regional differences in the Antarctic (Figure 2c,d). More solar energy is absorbed in the Bellingshausen and Amundsen Seas, with smaller areas of decreasing energy absorption.

Combining the effects of cloud cover induced insolation changes, reduced sea ice extent and a lower surface albedo, the total annual shortwave energy absorbed by the ice-ocean system north of 60°N increased at a rate of 2.31.7 ($\pm$0.65) $\cdot$ $10^{25}$$10^{20}$J/yr . In the Southern Hemisphere energy absorption by the ice-ocean system south of 60°S also increased at a very similar rate of 1.8 ($\pm$1.9) $\cdot$ 10^{20} J/yr but, due to the large interannual variability, only at a the trend is not statistically insignificant rate of 1.8 ($\pm$1.9) $\cdot$ 10^{25} J/yrsignificant. Despite the increasing winter sea ice extent in the south, both hemispheres show a distinct increase in energy deposition in the ice-ocean system leading to ice melt and ocean warming. Increased ice extent in the Antarctic therefore does not decrease annual mean energy absorption as might be expected. An analysis of anomalies in sea ice extent, albedo and shortwave energy deposition in the ice-ocean system shows that energy deposition is not directly correlated with the ice extent and albedo anomalies in general but can be offset by changes in cloud cover leading to increasing shortwave energy absorption in spite of albedo increases (Figure 3).

In the Antarctic, the energy flux anomaly does not show a pattern except forrelation to ice extent but rather to interannual variability, while in the Arctic anomalies in albedo and heat input into the ice-ocean system are much more closely related to the sea ice extent anomaly. Thus, in the context of the surface shortwave radiation balance, losses in Arctic sea ice and the resulting increase in solar energy absorption are not balanced by the moderate gains in sea ice extent in the Antarctic. On the global scale, changes in the shortwave energy partitioning in the polar oceans poleward of 60° latitude lead to a combined increased energy deposition of 4.13.5($\pm$2.31) $\cdot$ $10^{25}$$10^{20}$ J/yr comprised of positive energy absorption trends in both hemispheres despite moderate increases in Antarctic sea ice extent.

When extending our analysis from the oceans to all land and ocean areas poleward of 60° latitude, the result is similar with an increasing flux of 0.3 W/m^2 per year absorbed by the planet's surface poleward of 60°. This trend is somewhat weaker than over the ocean alone, as changes in land cover properties are not as pronounced as changes in ice extent and properties. Still, changing snow cover and prolonged melting seasons cause more absorption of sunlight and further heating of the climate system.

Conclusion

In conclusion, a consistent long-term observational, satellite-based time series shows that changes in the shortwave energy budget caused by a decreasing Arctic sea ice cover are not balanced by the slight increases observed in Antarctic sea ice extent. IncreasesSignificant increases in Antarctic sea ice only occur during the Southern Hemisphere winter and thus have only a minor impact on the energy balance, while Arctic sea ice changes are accompanied by a spatially uniform decrease of sea-ice albedo during the summer, further increasing the energy input to the northern polar ocean and thereby strengthening the ice-albedo feedback. This demonstrates the different roles that partitioning of solar shortwave radiation plays in the two very different sea ice zones of our planet. It is necessary to better understand the influence of the changes in different processes such as sea ice distribution, sea ice albedo and cloud properties on the shortwave radiation budget in these two very different polar regions.

Author Contributions

CK performed the calculations, prepared the figures and wrote the text, SH had the initial idea for this study and contributed to the setup of the study, JK contributed the APP-x data and provided insight into its use. All authors were involved in the writing of the manuscript. The authors declare that they have no conflict of interest.

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References

Allison, I., R. E. Brandt and S. G. Warren (1993). "East Antarctic sea ice: Albedo, thickness distribution, and snow cover." Journal of Geophysical Research: Oceans **98**(C7): 12417-12429.

Brandt, R. E., S. G. Warren, A. P. Worby and T. C. Grenfell (2005). "Surface Albedo of the Antarctic Sea Ice Zone." Journal of Climate **18**(17): 3606-3622.

Cavalieri, D. J., P. Gloersen, C. L. Parkinson, J. C. Comiso and H. J. Zwally (1997). "Observed Hemispheric Asymmetry in Global Sea Ice Changes." Science **278**(5340): 1104-1106.

Curry, J. A., J. L. Schramm and E. E. Ebert (1995). "Sea Ice-Albedo Climate Feedback Mechanism." Journal of Climate **8**(2): 240-247.

Eisenman, I., W. N. Meier and J. R. Norris (2014). "A spurious jump in the satellite record: has Antarctic sea ice expansion been overestimated?" The Cryosphere **8**(4): 1289-1296.

Haas, C., A. Pfaffling, S. Hendricks, L. Rabenstein, J.-L. Etienne and I. Rigor (2008). "Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat." Geophysical Research Letters **35**(17): L17501.

Key, J. and X. Wang (2015). Climate Algorithm Theoretical Basis Document, Extended AVHRR Polar Pathfinder (APP-x), NOAA/NESDIS Center for Satellite Applications and Research and the National Climatic Data Center**:** 85 pp.

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Key, J., X. Wang, Y. Liu, R. Dworak and A. Letterly (2016). "The AVHRR Polar Pathfinder Climate Data Records." Remote Sensing **8**(3).

Laine, V. (2008). "Antarctic ice sheet and sea ice regional albedo and temperature change, 1981–2000, from AVHRR Polar Pathfinder data." Remote Sensing of Environment **112**(3): 646-667.

Markus, T., J. C. Stroeve and J. Miller (2009). "Recent changes in Arctic sea ice melt onset, freezeup, and melt season length." Journal of Geophysical Research-Oceans **114**.

Maslanik, J. A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi and W. Emery (2007). "A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss." Geophysical Research Letters **34**(24): L24501.

Massom, R. A., H. Eicken, C. Hass, M. O. Jeffries, M. R. Drinkwater, M. Sturm, A. P. Worby, X. Wu, V. I. Lytle, S. Ushio, K. Morris, P. A. Reid, S. G. Warren and I. Allison (2001). "Snow on Antarctic sea ice." Reviews of Geophysics **39**(3): 413-445.

Meehl, G. A., J. M. Arblaster, C. M. Bitz, C. T. Y. Chung and H. Teng (2016). "Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability." Nature Geosci **advance online publication**.

Nicolaus, M., C. Katlein, J. Maslanik and S. Hendricks (2012). "Changes in Arctic sea ice result in increasing light transmittance and absorption." Geophysical Research Letters **39**: L24501.

Perovich, D. K., K. F. Jones, B. Light, H. Eicken, T. Markus, J. Stroeve and R. Lindsay (2011). "Solar partitioning in a changing Arctic sea-ice cover." Annals of Glaciology **52**(57): 192-196.

Pistone, K., I. Eisenman and V. Ramanathan (2014). "Observational determination of albedo decrease caused by vanishing Arctic sea ice." Proceedings of the National Academy of Sciences of the United States of America **111**(9): 3322-3326.

Riihelä, A., J. R. Key, J. F. Meirink, P. Kuipers Munneke, T. Palo and K.-G. Karlsson (2017). "An intercomparison and validation of satellite-based surface radiative energy flux estimates over the Arctic." Journal of Geophysical Research: Atmospheres **122**(9): 4829-4848.

Rösel, A. and L. Kaleschke (2012). "Exceptional melt pond occurrence in the years 2007 and 2011 on the Arctic sea ice revealed from MODIS satellite data." J. Geophys. Res. **117**(C5): C05018.

Serreze, M. C., M. M. Holland and J. Stroeve (2007). "Perspectives on the Arctic's Shrinking Sea-Ice Cover." Science **315**(5818): 1533-1536.

Stammerjohn, S., R. Massom, D. Rind and D. Martinson (2012). "Regions of rapid sea ice change: An inter-hemispheric seasonal comparison." Geophysical Research Letters **39**(6): n/a-n/a.

Stammerjohn, S. E. and R. C. Smith (1997). "Opposing Southern Ocean Climate Patterns as Revealed by Trends in Regional Sea Ice Coverage." Climatic Change **37**(4): 617-639.

Stroeve, J. C., M. C. Serreze, M. M. Holland, J. E. Kay, J. Malanik and A. P. Barrett (2012). "The Arctic's rapidly shrinking sea ice cover: a research synthesis." Climatic Change **110**(3-4): 1005-1027.

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Figures

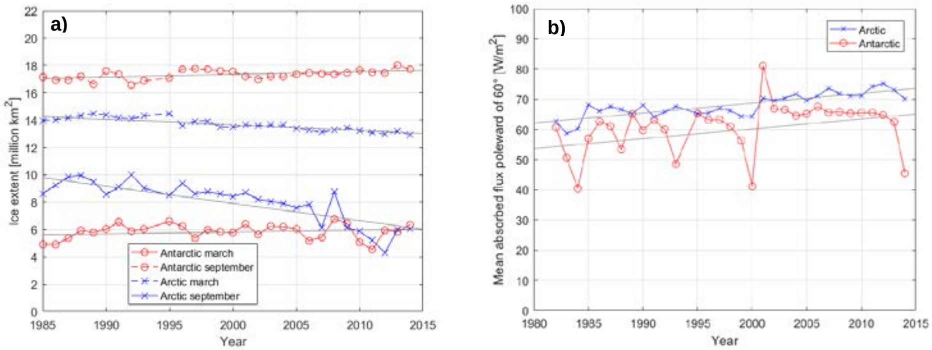
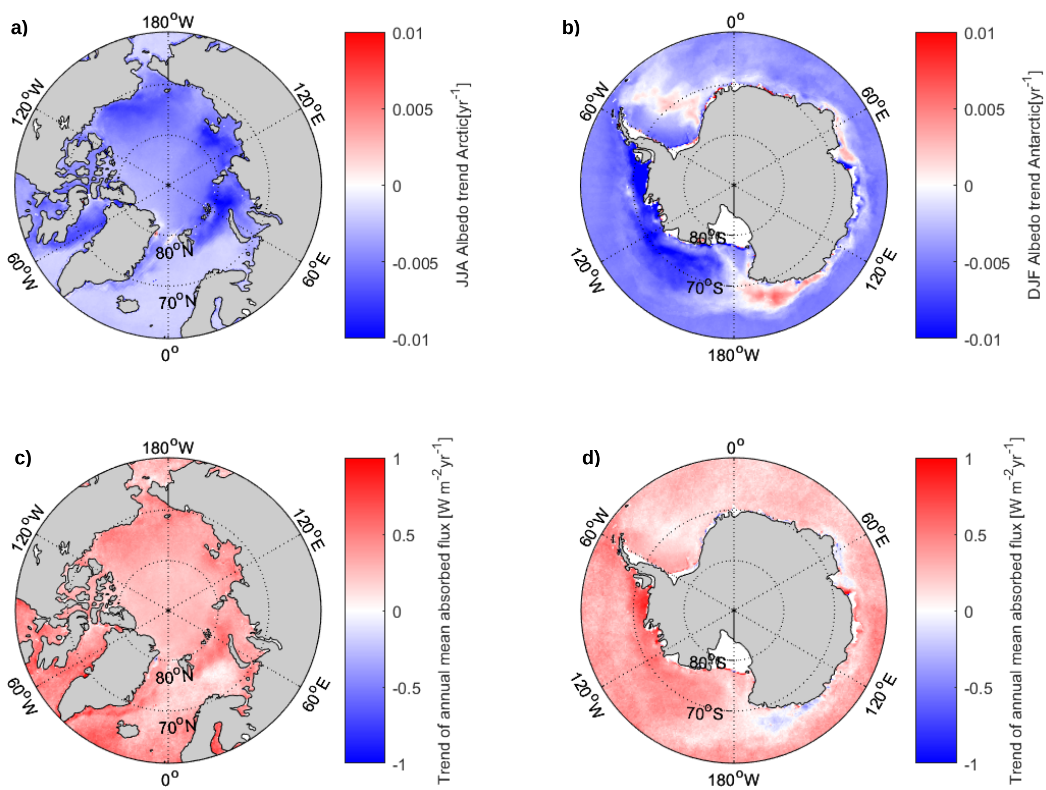


Figure 1: a) Long-term trends of sea ice extent: Temporal evolution of sea ice extent in Antarctica (red) and the Arctic (blue) for minimal (solid line) and maximal (dashed line) seasonal extent as derived from APP-x data. Grey lines indicate fitted linear trends. b) Annual mean flux into ice ocean system: Shortwave radiative flux absorbed by the ice-ocean system poleward of 60° latitude in the Arctic (crosses) and Antarctic (circles).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JJA Albedo trend Arctic[yr^{-1}]
b)
0°
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60°E
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120°E
80°S
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DJF Albedo trend Antarctic[yr^{-1}]
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Trend of annual mean absorbed flux [W m^{-2}yr^{-1}]
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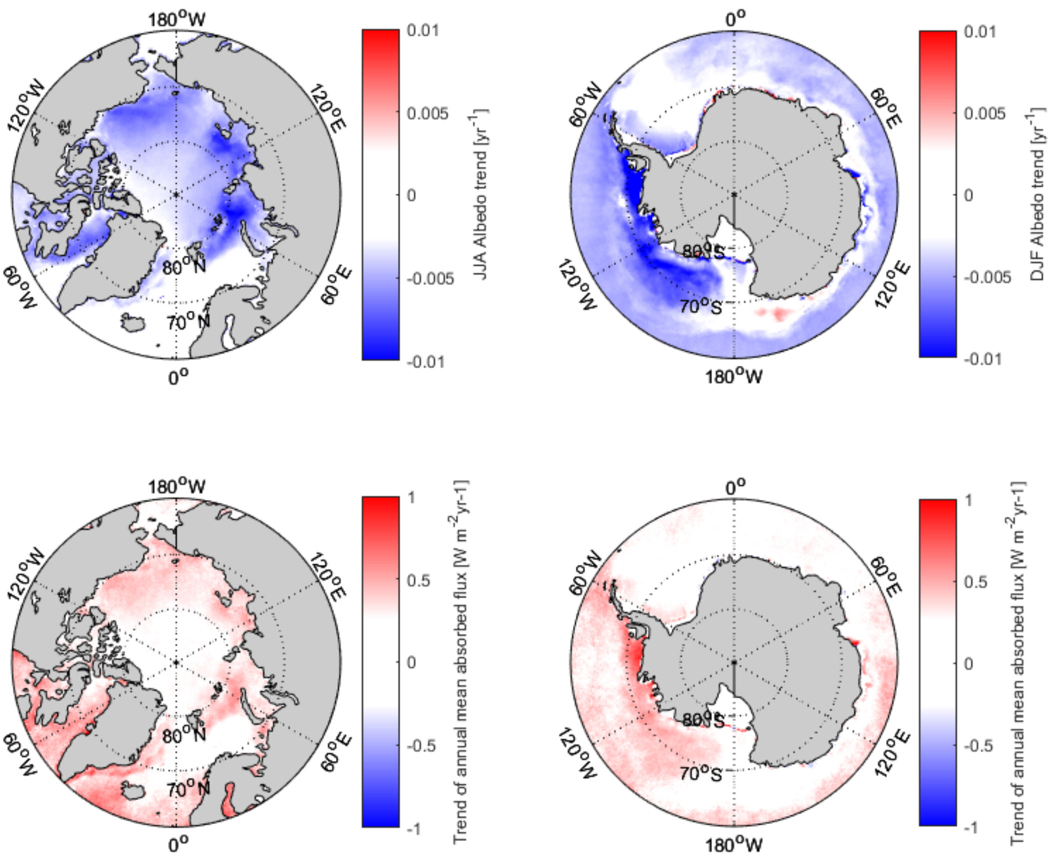

Figure 2: Spatial distribution of trends in ~~sea ice~~surface albedo and overall energy deposition into the polar oceans: Trends [yr^{-1}] of mean daytime summer sea-ice albedo in the Arctic (a) and Antarctic (b) and trends [W/m²yr] of shortwave energy flux (c,d) absorbed by the ice-ocean system. The latter inherently includes both changes in albedo and cloud cover due to the nature of the APP-x dataset.

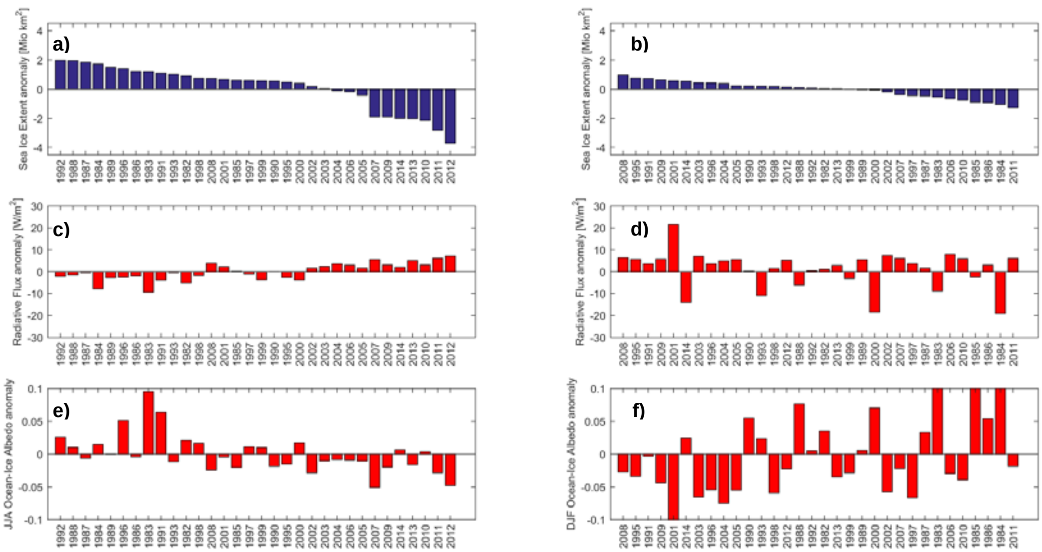

Figure 3: Anomaly of mean, absorbed shortwave flux and ~~sea-ice~~surface albedo sorted from positive to negative sea-ice extent anomaly: Arctic (left) and Antarctic (right) sea ice extent anomaly (a,b), annual anomaly of shortwave flux absorbed by the ice ocean system polewards of 60° (c,d) and summer albedo anomaly (e,f).