Replies to Reviewer Comments:

Please find our replies to the reviewer's comments in blue print.

Reviewer 1 (W. Eschenbach):

The values given in Figure 1 (b) are not correct. According to the CERES satellite data, from 2001-2014 the amount of sunlight absorbed into the arctic oceans is between 50 and 55 W/m2. Antarctic oceans varied between 55 and 58 W/m2 over the period.

The authors give values from 150 to 180 W/m2 for the Arctic and from 180 to 245 W/m2 for the Antarctic.

The Kiehl-Trenberth global energy budget gives a global average value of 167 W/m2 fro absorption, and the CERES data gives a global average of 162 W/m2 ... the authors' claim is larger than the K/T global average.

We thank you very much for bringing up this point. Indeed there was a mistake in our calculations. Cells with invalid retrievals – generally due to fluxes very close to zero - are labelled as NaN (not-a-number) in the APP-x product. NaN cells were ignored during averaging, resulting in numbers that were too large in our manuscript. We fixed this by assigning zero fluxes to NaN values, as incorrect retrievals originate from too little sunlight in winter. Consequently we set NaN albedos to 1. Our numbers lie now in the range that you report, considering the recently identified underestimation of absorbed fluxes in the CERES data over the Arctic (Riihelä 2017, JGR, in press).

However, you unfortunately did not provide any sources or calculation details for your numbers. Your plots are rather inconsistent regarding latitude limits. In these calculations the threshold latitude is of significant importance. While you label all your plots as "absorption poleward of 50°", your second plot clearly only shows data starting from 60°. Also the dotted lines in your plot (~66°) probably present what your plotting routines define as "Arctic" and "Antarctic". We can just assume that your first plot also just shows data poleward of 66°, as even your black "global average" line is around 54 W/m² despite the fact that you claim above a global average of ~165 W/m²

Of course lower latitude contributions to the mean value are crucial due to their relatively large areas and larger fluxes. For a more poleward latitudinal threshold smaller numbers result as average values.

This boils down to a central question for this study: What is the right cut-off latitude? The latitudinal extent of sea-ice differs dramatically both between the hemispheres and also within the different regions of the hemispheres themselves. Our initial approach was to encompass all sea-ice for our calculations. However, we see that this might be confusing as it differs from generally used classifications. Also this leads to a high number of processes other than sea-ice retreat influencing the results.

We thus recalculated for a latitudinal threshold of poleward of 60°. While this still encompasses some of the generally ice-free oceans, it covers most of the sea-ice extent throughout all seasons. We do not want to reduce this limit further to 66° as this would exclude a significant portion of the area seasonally covered by sea ice and areas that have experienced large changes in sea ice cover in recent decades.

The APP-x shortwave fluxes have been successfully validated e.g. against observations from SHEBA, a drifting observation ice camp, as well as again CERES fluxes (Riihelä 2017, JGR in press). We are thus confident in the calculated fluxes.

There is a separate issue. The CERES data shows a clear peak in Arctic oceanic absorption during the 2012 low in sea ice. There is no indication of this in the APP-x data.

This is also visible in the APP-x data after correcting the calculations. A new version of Figure 1b is included in the revised manuscript.

Best regards,

w.

Reviewer 2 (S. Bathiany)

General comments

In their brief communication, the authors focus on the surface short-wave balance in high latitudes. They use a new observational dataset (APP-x) to analyse trends over the recent decades and analyse the reasons behind these trends. I consider the format of a brief communication and the journal as a suitable choice to publish these results. Also, in the light of the large ongoing changes in the Arctic, the topic is of high relevance for science and the public. The general outline of the analysis is clear, and the relevant steps are explained.

We thank you very much for the positive evaluation of our work. We are happy that you also consider a brief communication in "The Cryosphere" as the right outlet for this research.

However, I also see two major issues that in my opinion should be addressed before the paper can be published:

1. General motivation for this paper

I had some problems to understand the motivation behind this analysis. This is related to the fact that the authors aim to compare the hemispheres to each other. I am wondering why exactly the comparison of the hemispheres is useful or relevant. Is there anything we can learn about how the energy balance works? Or are there implications for predictions or other practical aspects? The analysis of trends in sea-ice albedo, seaice area (or extent) and cloud cover, and their combined effect on the short-wave (SW) absorption at the heart of this study. This is done individually for both hemispheres, and important differences are mentioned. The authors make the interesting point that SW absorption increases in the Southern Ocean, despite the slight increase in sea-ice area. To my taste, this could be communicated as the main result (if it is new) in title and abstract because it is much more straightforward than comparing hemispheres. Although the authors do not add energy balance terms from both hemispheres together, their wording sometimes suggests this. I suggest to not say that solar absorption in one hemishere "does not compensate" what is going on in the other hemisphere. I find this formulation confusing. I expect different effects at a certain location to be able to compensate each other, but not in two very remote regions that do not communicate directly.

Indeed our motivation for this study is mainly coming from requests from the public (and media) that we frequently get. We agree that the concept of putting both hemispheres in one pot is somewhat far-fetched in a scientific way of thinking alone. However, this comparison is frequently made by "climate sceptics", where increases in Antarctic sea ice cover are used as an argument to counter the decreasing trend in Arctic sea ice. We feel the urgent need to address this through an analysis of not just the changes in sea ice in the two polar regions, but also the impact of those changes on the surface shortwave radiation budget, which in turn impacts sea ice. Furthermore, the discussion paper has received significant attention in the community (article metrics) and related media requests show that the comparison of both hemispheres is a relevant topic. Having said that, the reviewer makes a good point that the finding of increased absorbed solar radiation in the Antarctic is interesting and important. We emphasize this point in the revised manuscript.

Another problem with the title is that it even suggests a comparison of two unrelated processes or units. This is of course not true but confronting “sea ice gain” in one hemisphere with “increased solar absorption” in the other hemisphere is unfortunate in my opinion. Alternatives for the title could be “Increasing short-wave absorption in southern high latitudes despite increasing sea ice area” or “Short-wave absorption is increasing over both of Earth’s poles” or something similar. In general, the implications of this finding could be made clearer.

We agree with your view that the title is comparing apples and oranges somewhat, so we suggest an alternative title combining your suggestions “Increasing shortwave absorption over the sea ice area at both poles”

2. There seems to be a problem with the numbers, at least in Fig. 1b and the associated text. As pointed out in the interactive comment by W. Eschenbach, the short-wave absorption values are not in agreement with other datasets. Some error might have been made in the calculations? The authors should correct it and check if their claims still hold.

Indeed there was a mistake in our calculations. Cells with incorrect retrievals are labelled with NaN in the App-X product. Unfortunately NaN cells were ignored during averaging, leading to way too high numbers in our manuscript. We fixed this by attributing zero fluxes to NaN values, as incorrect retrievals originate from too little sunlight in winter. Consequently we set NaN albedos to 1. Our numbers lie now in the range cited by W. Eschenbach, considering the known underestimation of absorbed fluxes by CERES data (Riihelä 2017, JGR, in press). However, our conclusions are unaffected by this calculation error.

Specific comments

1. Abstract: I think that it can be written more clearly (also see main comment 1).

We reformulated the abstract in the revised version.

2. Fig. 1: Also as pointed out by W. Eschenbach, the temporal evolution of the fluxes in Fig. 1b is surprising. I understand from Fig. 3 that despite the low sea ice in specific years, we cannot automatically assume a large peak in SW absorption in these years, mainly because of confounding effects of cloud cover fluctuations? However, I am also wondering about the peculiar oscillation-like pattern in the Arctic time series, with a rapid increase every 5 years, followed by an accelerating decrease. This pattern is repeated several times with increasing magnitude. The authors may want to check if this behaviour is real.

We thank you for pointing out the oscillation-like pattern with jumps. It is related to changes in the satellites used in APP-x, as NOAA’s polar-orbiting satellites experience “orbital drift” in their equator crossing times. After accounting for NaN retrievals and changing the cut-off latitude, this pattern was largely eliminated. Additionally, the APP-x shortwave fluxes are adjusted to the target times (04:00/02:00 and 14:00), thereby reducing the effect of orbital drift.

3. Fig. 3: The peaks in Fig. 3c seem to not coincide with those in Fig. 1b, or are at least shifted in time. For example, in Fig. 1b, 2000 is a year with low absorption in the Arctic and 2001 is a year with high absorption. But in Fig. 3c, both years have negative anomalies, whereas 2002 has a positive anomaly. Also, year 1994 is missing. I understand from the text why it is missing in the southern hemisphere, but it could be included in the analysis of the northern hemisphere.

This was due to a bad handling of the missing year 1994, which disturbed the order. Actually the data outage also affects the northern Hemisphere in 1994, so we removed it from all plots.

4. What is the reason for the increased downwelling SW radiation over the Southern Ocean? The authors could elaborate a bit on the role of cloud cover. Is this signal expected in the light of anthropogenic climate change, or is it random (internal variability)? So, what could be expected for the future?

We added some discussion on the reasons for the increased downwelling SW radiation. This seems to be caused by cloud cover. However one would rather expect an increasing cloud cover with retreating ice, thus we speculate that this is driven by local effects and interannual variability.

5. Methods: Why is it necessary to first calculate the cumulative absorbed energy in the whole region over one year and then convert it into fluxes again for the figures? The dataset already seems to contain fluxes. The potential calculation error mentioned above may be related to this.

Of course flux averages are calculated directly on the fluxes given by the dataset. We clarify this in the revised version.

Is there any good reason why the sea ice extent is defined differently than in other studies?

We added some explanations as to why we used this threshold of ice-thickness larger than zero. APP-x does not contain an ice-concentration field, though it does use NSIDC ice concentration >15% internally during the retrieval to determine whether a pixel is ice-covered. Thus all pixels with sea ice concentration > 15% have a valid ice-thickness and pixels below the threshold don't. So we are indeed using the same definition as in other studies. Differences to other studies just result from the rather course resolution of APP-x.

Reviewer 3 (Anonymous Referee #2)

The Brief Communication uses a new dataset, APP-x, to examine trends in the annual mean absorbed flux of shortwave radiation in the polar regions from 1985-2014. It addresses relevant scientific questions within the scope of the journal. The conclusions are appropriate for a Brief Communication. The article is clearly written and easy to read. However I have some criticisms.

We thank you very much for the constructive evaluation of our work!

I felt the authors could improve the description of the motivation for the study. For example, why consider only shortwave radiation and not include the emitted longwave radiation? The stated goal is "to determine to what extent the increased absorption of solar shortwave energy caused by losses in Arctic summer sea ice can compensate for the decreased absorption caused by modest increases of sea ice extent in the Antarctic." But why? I assume the reason for doing this is to assess the contribution to the overall global energy balance? If so, please comment on how you think how longwave radiation would contribute to the story?

Indeed our motivation for this study is mainly coming from requests from the public (and media) that we frequently get. We agree that the concept of putting both hemispheres in one pot is somewhat far-fetched in a scientific way of thinking alone. However this comparison is frequently made by "climate sceptics", so we feel the urgent need to counter this with a reasonable scientific answer. Furthermore, the discussion paper has received significant attention in the community (article metrics) and related media requests show that the comparison of both hemispheres is a relevant topic.

We added some discussion on longwave radiation. However we want to keep the manuscript focused on shortwave and do not attempt to describe the full energy balance of the polar regions as this would be too large for a brief communication. We focus on only shortwave because besides its major role in sea ice melt (solar heating & melting) it also impacts many other aspects of the sea ice system, such as biological production.

Commas are placed in unusual places and sometimes seem to be missing; eg p. 1, line 9 insert comma after "sea-ice". Please check throughout the document.

We will check the manuscript for typographic errors throughout the text.

p. 1, Line 19: Please give a reference for the debate.

We reformulated for clarity, as this is not really a debate.

p. 2: I think that the AAP-x data set calculates ice thickness using a 1D OTIS model with satellite-derived input variables. Is there any validation of these AVHRR ice thicknesses in the Southern Hemisphere?

We agree, that ice thickness is hardly validated due to a lack of reference data. However ice thickness was only used for ice detection, so it does not impact our calculations.

As an aside, the one-dimensional thermodynamic ice model (OTIM) is described in Wang, X., J. Key, and Y. Liu, 2010, A thermodynamic model for estimating sea and lake ice thickness with optical satellite data, J. Geophys. Res.-Oceans, 115, C12035, doi:10.1029/2009JC005857.)

p. 2, Line 22: More snow on Antarctic sea ice is also likely to give a higher albedo in the Southern Ocean.

Yes, but snow on sea-ice is not separately accounted for in the APP-x dataset. We added another mention of the effect of snow on albedo in the revised version

p. 3: It is excellent that the authors compare sea ice concentration derived from the APP-x data with passive microwave concentration data. But I would like to have seen some sort of quantitative comparison. This would increase the reader's confidence in the new dataset.

As the ice thickness retrieval is thresholded internally by the NSIDC ice concentration, our APP-x ice extent is effectively a regridded NSIDC ice extent. Thus we do not see the need for a further comparison. For your reference, we provide a version of figure 1A with passive microwave ice extent from the University of Bremen at the end of this document.

p. 3, Lines 10-15: I would like to have seen some estimate of the error in the quoted measurements.

We added confidence intervals as determined during the trend-fitting to all numbers.

p. 3, Line 26-27: I did not understand this sentence. Do you mean "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 uncertainty in the time-averaged energy flux."?

Yes, we rephrased accordingly to make it clearer

p. 3, Line 29: ahha – here snow cover is mentioned. Please support with a reference.

We added a reference.

p. 4, line 1-2: Is the APP-x surface albedo not used to obtain ice thickness through the OTIM model? How does the lack of independence of surface albedo and ice thickness affect the calculation of shortwave energy flux?

We agree, but as we did not split solar energy deposition into ice and ocean compartments all that counts is albedo. Albedo retrieval is independent of the ice-thickness retrieval, while the modelled ice-thickness is of course dependent on the retrieved albedo.

p. 4, Line 3-4: Do you really know the annual shortwave energy flux to 0.1 in 200 Wm-2? Please make it clear that you have considered the accuracy of your results.

Thank you for pointing out this inconsistency. While these results are numerically correct according to the APP-x product, the accuracy of the entire measurement is of course less. We thus rounded these numbers to the significant digits in the revised version.

p. 4, Line 6-7 states that “Average Southern Hemisphere absorption remained relatively constant throughout the satellite record” while on line 13 it states “In the Southern Ocean energy absorbed by the ice-ocean system south of 50oS also increased…” I am confused by this apparent contradiction and I suspect that I have missed a subtlety.

We reformulated for clarity.

p. 4, Line 12-13: I think you say the total annual shortwave energy in the northern hemisphere increases at a significant rate, while in the Southern hemisphere it did not. Yet the numbers seem similar (8.77 X 1025 Jyr-1 compared with 6.14 X 1025 Jyr-1). Please justify. Again I may have missed a subtlety but, if so, perhaps you could make this clearer.

We reformulated this for clarity in the revised version.

Fig 1a): Confidence would be increased in the dataset if the slope from another reliable source (eg NSIDC) was added to the figure.

As explained above, the data is derived using a widely accepted NSIDC product, so we do not see the need for further comparison. Adding further lines into the figure would confuse it. For your reference we just provide a version of the figure with black dotted / dash-dotted lines representing the according ice extent data from the University of Bremen below. As mentioned in the text, the magnitude is affected due to the different resolution, but the trends are very similar.

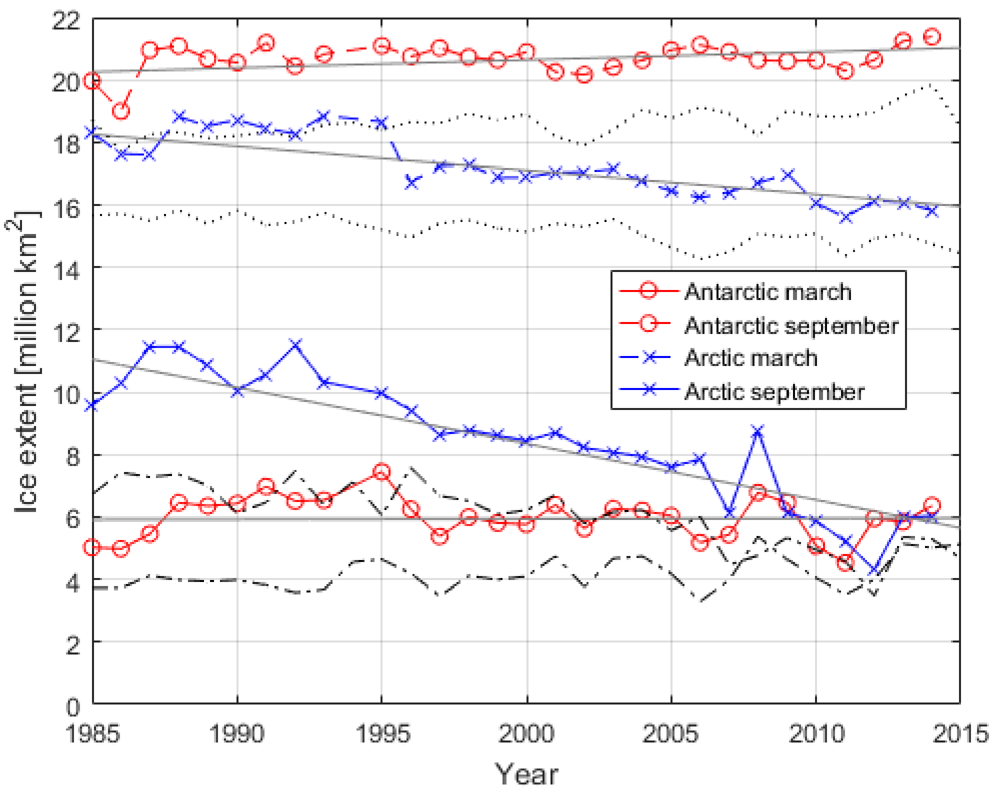

Fig 1b): What are the intriguing jumps in the data?

We thank you for pointing out these jumps. As this stayed visible also after accounting for NaN retrievals and changing the cut-off latitude, we hypothesized that these patterns are related to drifting equator crossing times during the lifetime of individual satellites. However we reconfirmed, that these patterns do not appear in the variables themselves. Thus we are convinced, that these are not artefacts, but real variation in the data.

Fig 2: The trend should be in Wm-2yr-1. Remove comma after "both"

Corrected accordingly

Fig 3: Caption and figure do not agree.

Corrected accordingly

Brief communication: ~~Antarctic sea ice gain does not compensate for increased solar~~Increasing shortwave absorption ~~from Arctic~~over the sea ice ~~loss~~area at both poles

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Abstract Here we show on the basis of the new consistent long-term observational satellite dataset APP-x~~,~~ that despite the observed increase of sea ice extent in the Antarctic~~ cannot compensate for the loss~~, absorption of ~~Arctic sea ice in terms of the~~solar shortwave radiation ~~budget~~ in the polar oceans poleward of ~~50~~60° latitude~~.~~ is increasing at both poles. The observations show~~,~~ that apart from retreating sea-ice, additional effects ~~like albedo~~such as changes ~~and especially changing~~ in cloud ~~coverage~~cover and surface albedo lead to a total increase of solar shortwave energy deposited into the polar oceans despite of the marginal increase in Antarctic winter sea ice extent.

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 et al., 2008)~~(Haas, Pfaffling et al. 2008) and younger ~~(Maslanik et al., 2007)~~(Maslanik, Fowler et al. 2007) coupled with a decline in its extent ~~(Serreze et al., 2007;Stroeve 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 ~~(Nicolaus et al., 2012;Perovich et al., 2011)~~(Perovich, Jones et al. 2011, Nicolaus, Katlein et al. 2012). While some areas in Antarctica have also experienced a reduction of sea ice cover, a modest overall gain of sea ice extent has been recorded in the Southern Hemisphere (Cavalieri, Gloersen et al~~.,~~. 1997~~;Stammerjohn et al., 2012)~~, Stammerjohn, Massom et al. 2012). How these opposing trends relate to each other on a global scale is ~~debated due to~~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 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.

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 et al., 1995), a critical~~

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Formatiert: Einzug: Erste Zeile: 1,27 cm process in the global shortwave energy budget. Most of this added heat will again be lost due to increased longwave emission during winter and not be carried on into the next year. Especially in the Arctic, a longer sea ice melt season (Markus et al., 2009), thinner ice (Haas et al., 2008), and increased melt pond coverage (Rösel and Kaleschke, 2012) lead to increasing solar shortwave energy deposition in the ice-ocean system (Nicolaus et al., 2012), adding to the increase in absorption due to decreasing sea ice extent (Pistone et al., 2014). However, surface characteristics of Antarctic sea ice are less affected by global climate change (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), thinner ice (Haas, Pfaffling et al. 2008), and increased melt-pond coverage (Rösel and Kaleschke 2012) lead to increasing solar shortwave energy deposition in the ice-ocean system (Nicolaus, Katlein et al. 2012), adding to the increase in absorption due to decreasing sea ice extent (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). Antarctic sea ice is mainly melting from below as the ice drifts away from the continent into warmer circumpolar waters, which is opposite 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 in Arctic summer sea ice can compensate for the decreased absorption caused by modest 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 over the time periodbeginning in 1982 to 2014 (Key et al., 2016)(Key, Wang et al. 2016). Its great advantage is that the 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 changing polar oceans poleward of 5060° 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 et al., 2016). During retrieval,(Key, Wang et al. 2016).

During the retrievals the energy balance is kept closed, allowing our 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 ~~used~~ APP-x variables used here have been determined to be of sufficient accuracy to be considered as a climate data record ~~variable.~~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). 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.

The energy flux absorbed by the surface was calculated as

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

and multiplied by 12 hours and the grid cell size to ~~retrieve~~obtain the total amount of absorbed energy, where E_{down} ~~already~~inherently accounts for the true cloud cover ~~moderated insolation.~~. All grid cells with ice thickness greater than 0 were considered as ice covered ~~and the sea~~. 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-~~time~~term averages as well as for time series analysis. ~~Antarctic data~~Data for the year 1994 were excluded from time series analysis due to a significant gap in the observations ~~during the summer period.~~. Trends were calculated ~~as~~through linear regression using the Matlab curve-fitting toolbox. All trends presented as significant ~~are significant at a~~have confidence ~~level~~levels above 95%.

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Results

An analysis of the dataset revealed a decrease of September sea-ice extent of -0.~~168~~126 (± 0.03) million km²/year for the Northern Hemisphere and an insignificant increase of 0.~~005~~012 (± 0.02) million km²/year in the Antarctic in the Southern Hemisphere summer in March (Figure 1a). Antarctic sea-ice extent increased 0.~~028~~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.~~071~~041 (± 0.01) million km²/year. Arctic sea-ice extent losses are thus roughly one order of magnitude stronger than the small increases in ice area in the Antarctic, leading to a combined total sea ice loss of -0.~~140~~106 million (± 0.03) km²/year in September and -0.~~066~~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 ~~(Stroeve et al., 2012;Stammerjohn et al., 2012;Stammerjohn and Smith, 1997)~~(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.

The summer mean daytime albedo for ice-covered areas in the APP-x dataset was 0.~~30~~34 for the Arctic (June/July/August) and 0.~~36~~41 for the Antarctic (December/January/February) which compares well to earlier studies ~~(Allison et al., 1993). The higher albedo of Antarctic sea ice may be caused mainly by~~(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 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 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.

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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 ~~and the 17~~(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 ~~50~~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 annual shortwave energy flux into the ice-ocean system poleward of ~~50~~60° accounts for ~~166.6~~68 W/m^2 in the Arctic, and ~~208.6~~60 W/m² in the Antarctic (Figure 1b). ~~The Antarctic ice-ocean system absorbs on annual average more shortwave energy per unit area of ocean basin, as sea ice quickly retreats to areas close to the continent and the ocean basin itself is located at lower latitudes compared to the Arctic, where landmasses cover the mid latitudes.~~ Average Southern Hemisphere absorption ~~remained relatively constant~~shows high interannual variability throughout the satellite record, butwhile the absorbed flux of the ice-ocean system in the Arctic clearly increased by 0.48 W/m^2 per year. While the trend in the absorption of solar shortwave energy is fairly uniform across the Arctic Ocean, there are large regional differences in the Antarctic (Figure 2c,d). More solar energy is absorbed in the Bellingshausen and Amundsen Seas, but a decrease inwith smaller areas of decreasing energy absorption occurs in the Weddell Sea and most other regions.

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 5060°N increased at a rate of $8.77 \cdot 10^{25}$ $2.3\ (\pm 0.6) \cdot 10^{25}$ J/yr . In the Southern Hemisphere energy absorption by the ice-ocean system south of 5060°S also increased, with but, due to the large interannual variability, only at a statistically insignificant rate of $6.14 \cdot 10^{25}$ $1.8\ (\pm 1.9) \cdot 10^{25}$ J/yr. 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 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 for 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 Antarctica.the Antarctic. On the global scale, changes in the shortwave energy partitioning in the polar oceans poleward of 5060° latitude lead to a combined increased energy deposition of $4.1.49 \cdot 10^{26}$ $(\pm 2.3) \cdot 10^{25}$ J/yr composed fromcomprised of positive energy inputabsorption trends in both hemispheres despite moderate increases in Antarctic sea ice extent.

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When extending our analysis from the oceans to all land and ocean areas poleward of 5060° latitude, the result is similar with an increasing flux of 0.413 W/m^2 per year absorbed by the planet's surface poleward of 5060°. 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 bipolar shortwave energy budget caused by a decreasing Arctic sea ice cover are not balanced by the slight increases observed in Antarctic sea ice extent. 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.

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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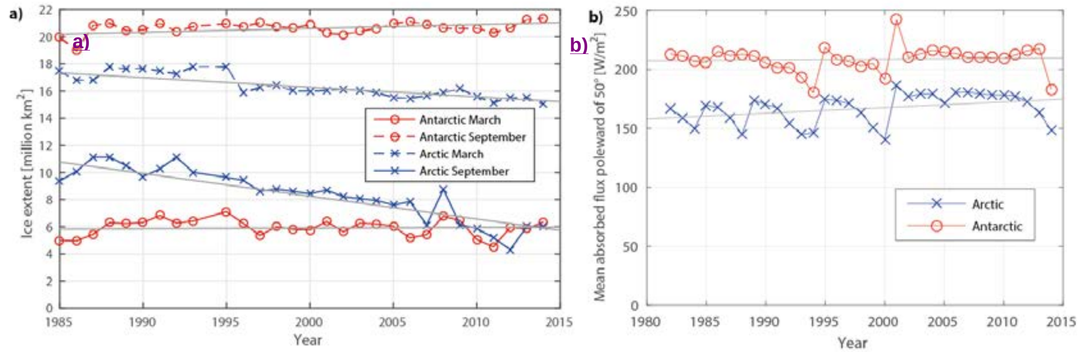
Figures



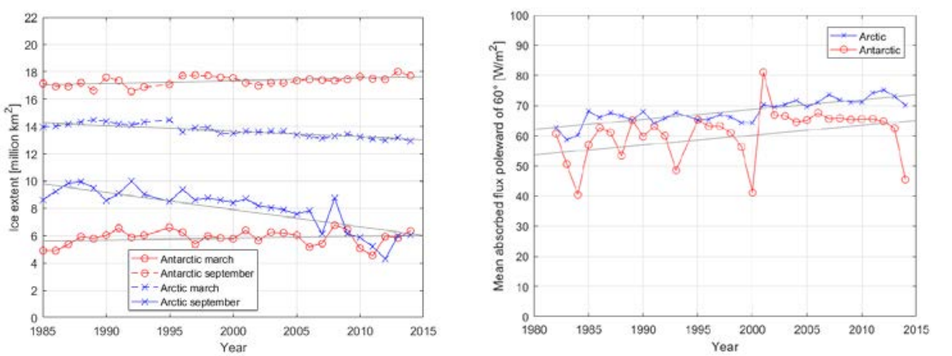
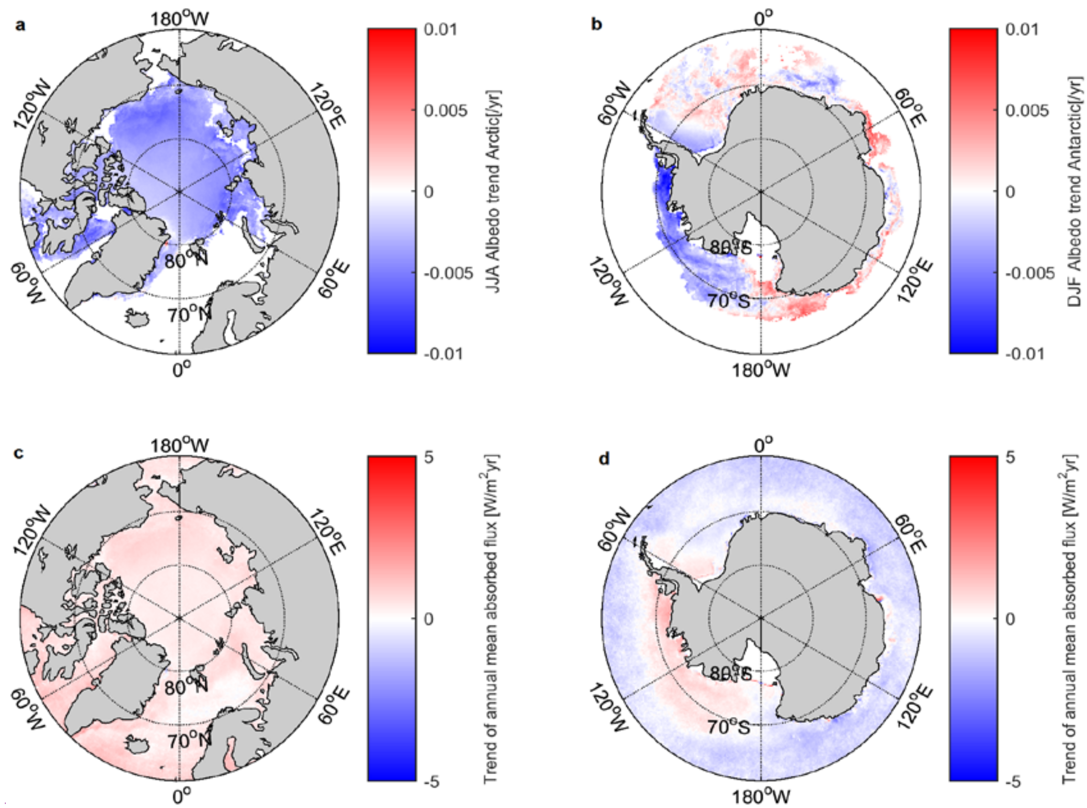


Figure 1: a) Long-term trends of sea ice extent: Temporal evolution of sea ice extent in Antarctica (red) and the Arctic (blue) for minimal (solid line) and maximal (dashed line) seasonal extent as derived from APP-x data. Grey lines indicate fitted linear trends. b) Annual mean flux into ice ocean system: Shortwave radiative flux absorbed by the ice-ocean system poleward of ~~50~~60° latitude in the Arctic (crosses) and Antarctic (circles).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JJA Albedo trend Arctic[/yr]
b
0°
60°W
60°E
120°W
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d

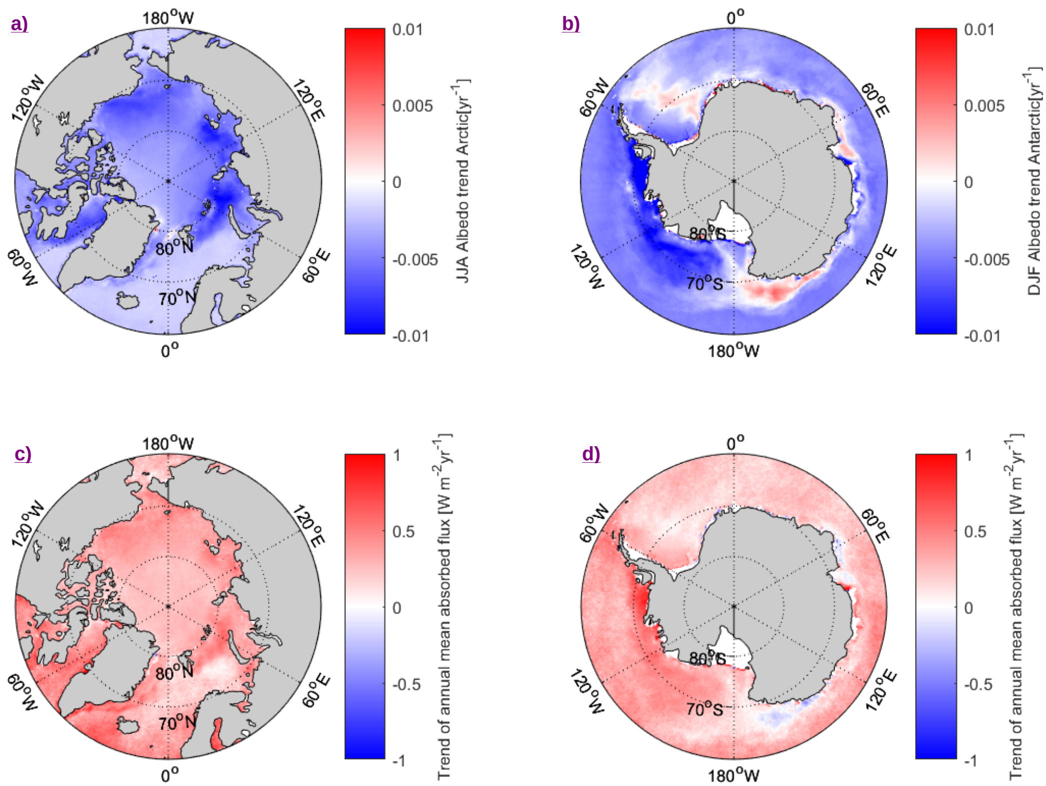
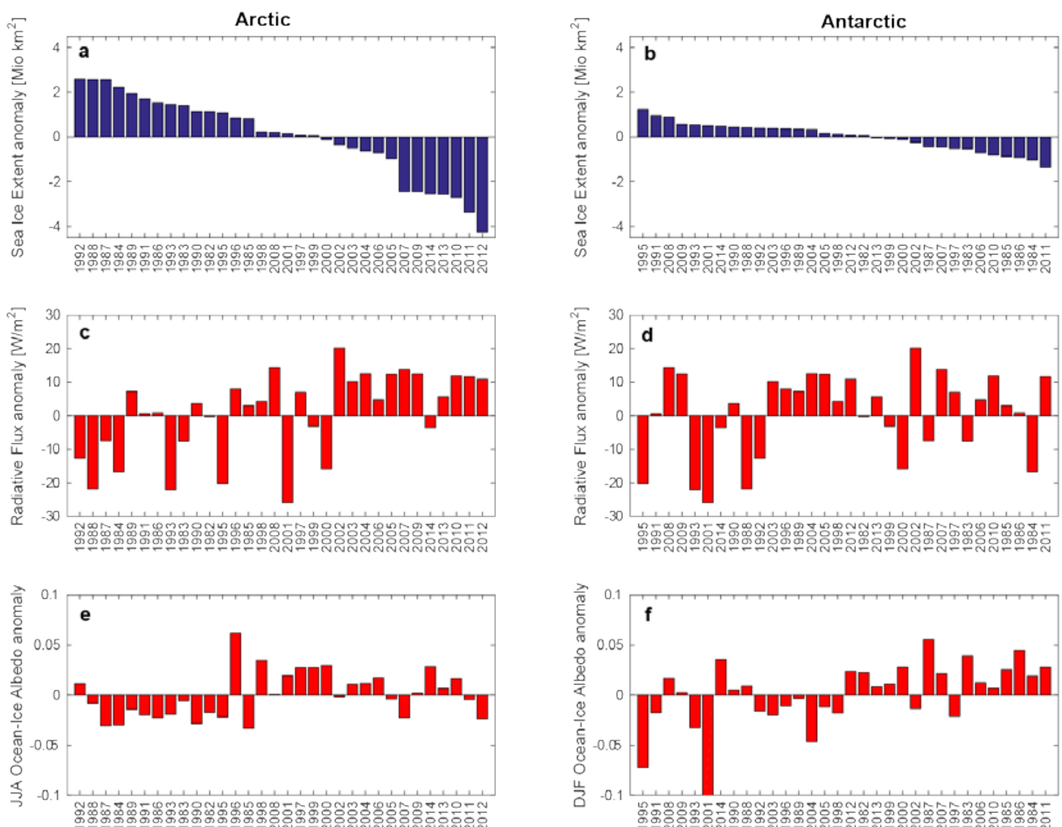


Figure 2: Spatial distribution of trends in sea ice albedo and overall energy deposition into the polar oceans: Trends [yr^{-1}] of mean daytime summer sea-ice albedo in the Arctic (a) and Antarctic (b) and trends [W/m²yr] of shortwave energy flux (c,d) absorbed by the ice-ocean system. The latter inherently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


Arctic
Antarctic
a
b
c
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Sea Ice Extent anomaly [Mio km^2]
Radiative Flux anomaly [W/m^2]
JJA Ocean-Ice Albedo anomaly
DJF Ocean-Ice Albedo anomaly

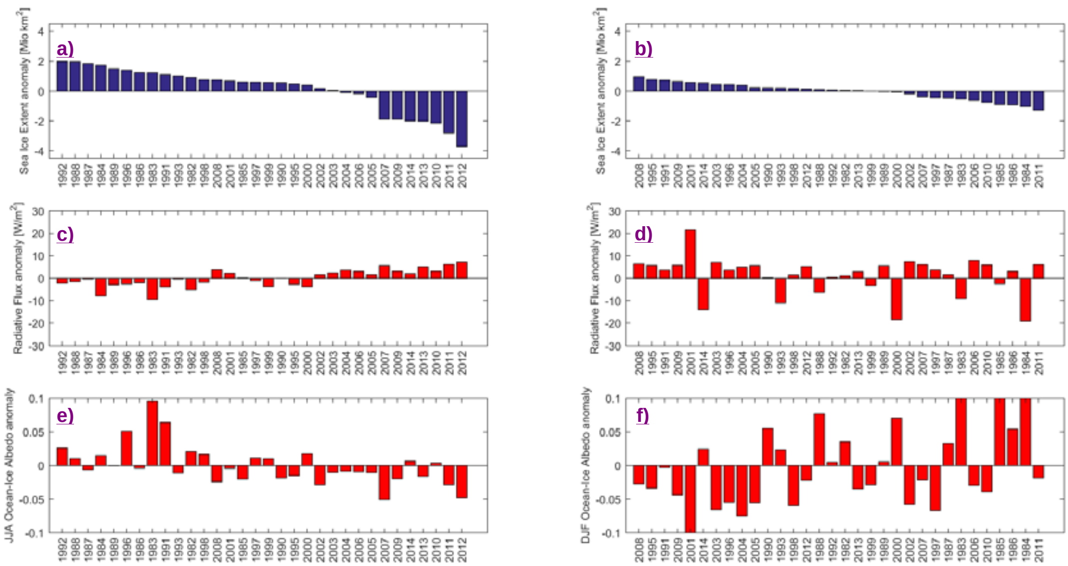

Figure 3: Anomaly of mean, absorbed shortwave flux and sea-ice albedo sorted ~~by~~from positive to negative sea-ice extent anomaly: Arctic (left) and Antarctic (right) sea ice extent anomaly (a,b), ~~summer albedo anomaly (c,d) and~~ annual anomaly of shortwave flux absorbed by the ice ocean system polewards of ~~50°~~ (60° (c,d) and summer albedo anomaly (e,f~~) sorted from positive to negative sea ice extent anomaly.~~).