Brief communication: Increasing shortwave absorption over the sea ice 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, absorption of solar shortwave radiation in the polar oceans poleward of 60° latitude is increasing at both poles. The observations show that apart from retreating sea-ice, additional effects such as
10 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 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, Pfaffling et al. 2008) and younger (Maslanik, Fowler et al. 2007) coupled
15 with a decline in its extent (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). 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, 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
20 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). 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
25 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), 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.

5   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

10   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 beginning in 1982 (Key, Wang et al. 2016). Its great advantage is that the dataset inherently takes into account changes in cloud cover

15   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)

20   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). 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

25   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). Details on the retrieval of the variables can be found in the respective Climate   Algorithm   Theoretical   Basis   Document

30   (http://www1.ncdc.noaa.gov/pub/data/sds/cdr/CDRs/AVHRR_Extended_Polar_Pathfinder/AlgorithmDescription.pdf   (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.

5   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 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%.

20 **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 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). 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 0.34 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 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.

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) 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 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 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, 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 2.3 ($\pm$0.6) · 10^{25} J/yr . In the Southern Hemisphere energy absorption by the ice-ocean system south of 60°S also increased but, due to the large interannual variability, only at a statistically insignificant rate of 1.8 ($\pm$1.9) · 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 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 $4.1(\pm2.3) \cdot 10^{25}$ 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. 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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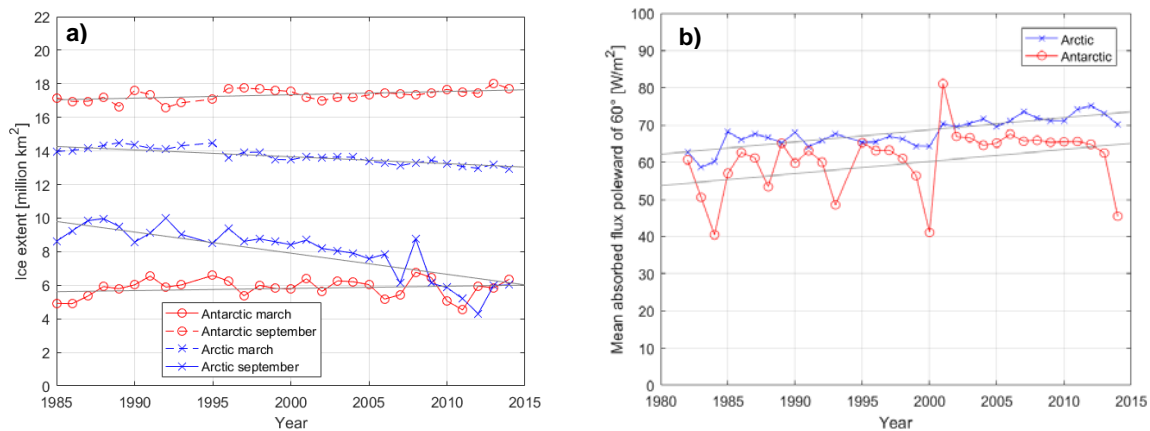
Figures

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 60° latitude in the Arctic (crosses) and Antarctic (circles).
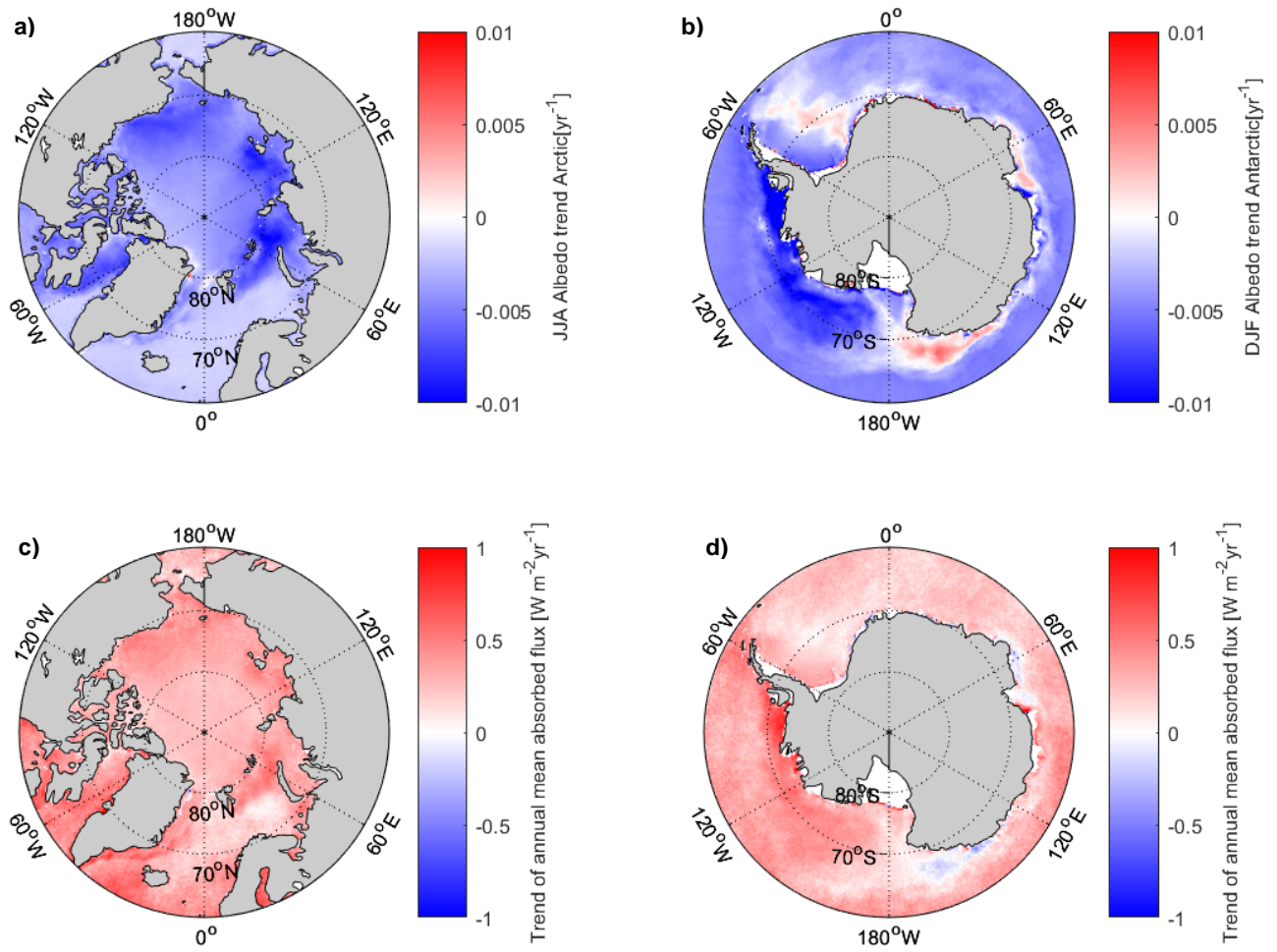
Figure 2: Spatial distribution of trends in sea ice albedo and overall energy deposition into the polar oceans: Trends [yr⁻¹] of mean daytime summer sea-ice albedo in the Arctic (a) and Antarctic (b) and trends [W/m²yr] of shortwave energy flux (c,d) absorbed by the ice-ocean system. The latter inherently includes both changes in albedo and cloud cover due to the nature of the APP-x dataset.
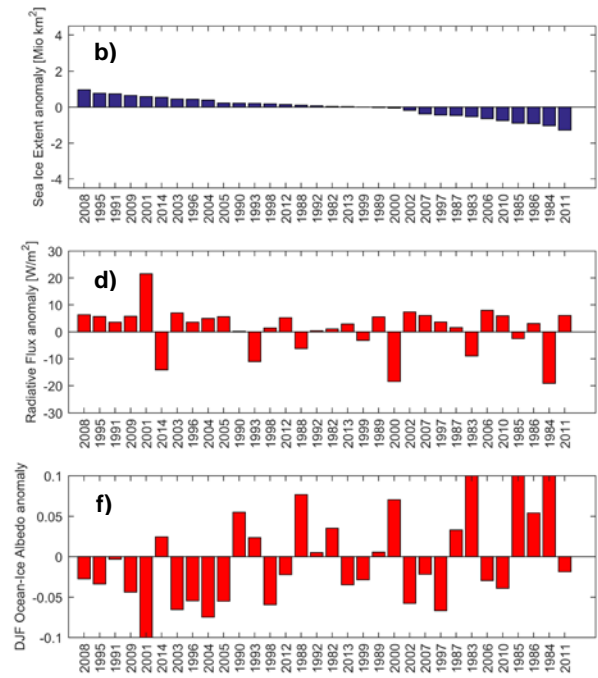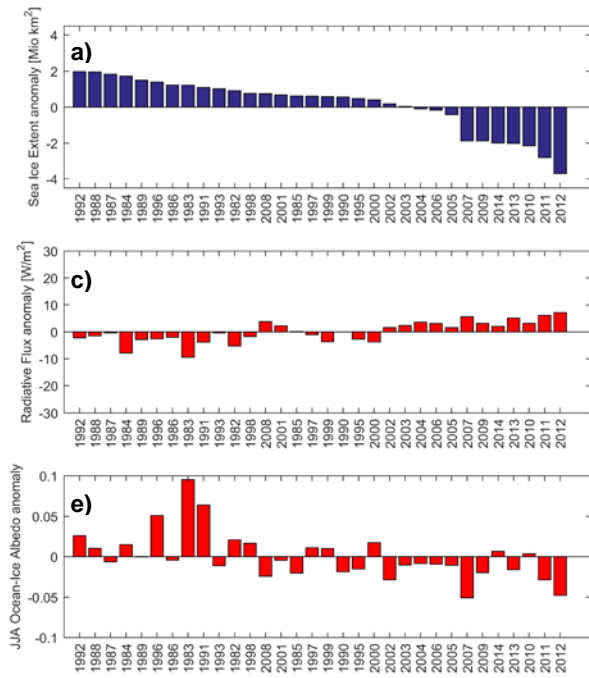
Figure 3: Anomaly of mean, absorbed shortwave flux and sea-ice albedo sorted from positive to negative sea-ice extent anomaly: Arctic (left) and Antarctic (right) sea ice extent anomaly (a,b), annual anomaly of shortwave flux absorbed by the ice ocean system polewards of 60° (c,d) and summer albedo anomaly (e,f).