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Brief communication: Antarctic sea ice gain does not compensate for increased solar absorption from Arctic ice loss

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Abstract Here we show on the basis of the new consistent long-term observational dataset APP-x, that the observed increase of sea ice extent in the Antarctic cannot compensate for the loss of Arctic sea ice in terms of the shortwave radiation budget in the polar oceans poleward of 50° latitude. The observations show, that apart from retreating sea-ice additional effects like albedo changes and especially changing cloud coverage 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) and younger (Maslanik et al., 2007) coupled with a decline in its extent (Serreze et al., 2007;Stroeve 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). 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 et al., 1997;Stammerjohn et al., 2012). How these opposing trends relate to each other on a global scale is debated due to 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). 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 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 (Allison et al., 1993;Brandt 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 period 1982 to 2014 (Key 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 50° 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, 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. Through validation studies, the used APP-x variables have been determined to be of sufficient accuracy to be considered as a climate data record variable. 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)) .

The energy flux absorbed by the surface was calculated as

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

and multiplied by 12 hours and the grid cell size to retrieve the total amount of absorbed energy, where E_{down} already accounts for true cloud cover moderated insolation. All grid cells with ice thickness greater than 0 were considered as ice covered and the sea ice extent was calculated as the number of ice-covered grid cells multiplied by the cell size (25x25 km).

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This yields slightly larger numbers than comparable analyses on the 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. Monthly data were then used for annual and long-time averages as well as time series analysis. Antarctic 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 linear regression using the Matlab curve-fitting toolbox. All trends presented as significant are significant at a confidence level above 95%.

Results

An analysis of the dataset revealed a decrease of September sea-ice extent of -0.168 million km²/year for the Northern Hemisphere and an insignificant increase of 0.005 million km²/year in the Antarctic in the Southern Hemisphere summer in March (Figure 1a). Antarctic sea-ice extent increased 0.028 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 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 million km²/year in September and -0.066 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). 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 for the Arctic (June/July/August) and 0.36 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 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 and the 17% 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 energy uptake by the ice-ocean system polewards of 50°

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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° accounts for 166.6 W/m^2 in the Arctic, and 208.6 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 throughout the satellite record, but the absorbed flux of the ice-ocean system in the Arctic 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 in 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 50°N increased at a rate of $8.77 \cdot 10^{25}$ J/yr . In the Southern Hemisphere energy absorption by the ice-ocean system south of 50°S also increased, with a rate of $6.14 \cdot 10^{25}$ 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. 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 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. On the global scale, changes in the shortwave energy partitioning in the polar oceans poleward of 50° latitude lead to a combined increased energy deposition of $1.49 \cdot 10^{26}$ J/yr composed from positive energy input 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 50° latitude, the result is similar with an increasing flux of 0.41 W/m^2 per year absorbed by the planet's surface poleward of 50°. 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

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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, 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. 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

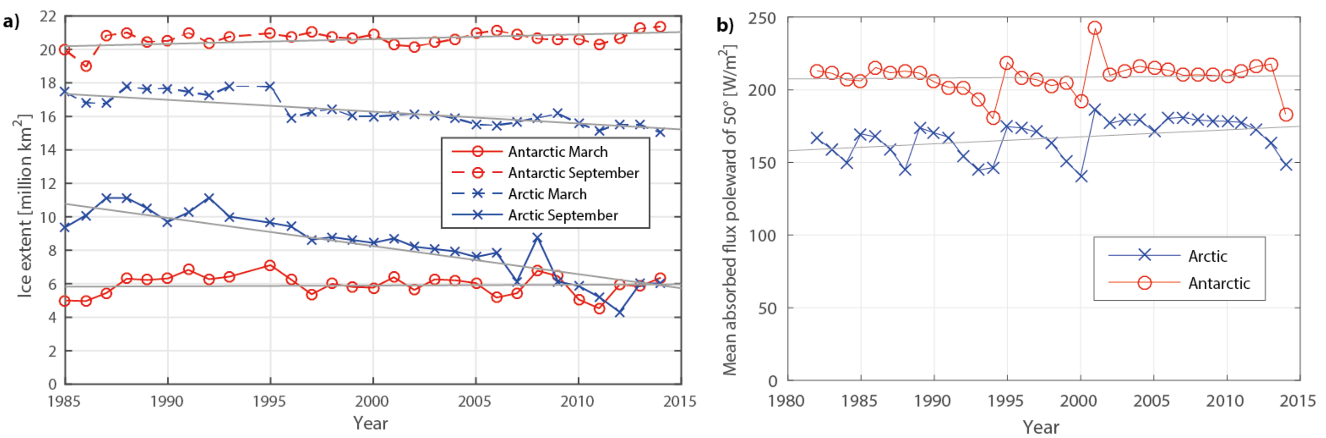

Figure 1: a) Long-term trends of sea ice extent: Temporal evolution of sea ice extent in Antarctica (red) and the Arctic (blue) for minimal (solid line) and maximal (dashed line) seasonal extent as derived from APP-x data. Grey lines indicate fitted linear trends. b) Annual mean flux into ice ocean system: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

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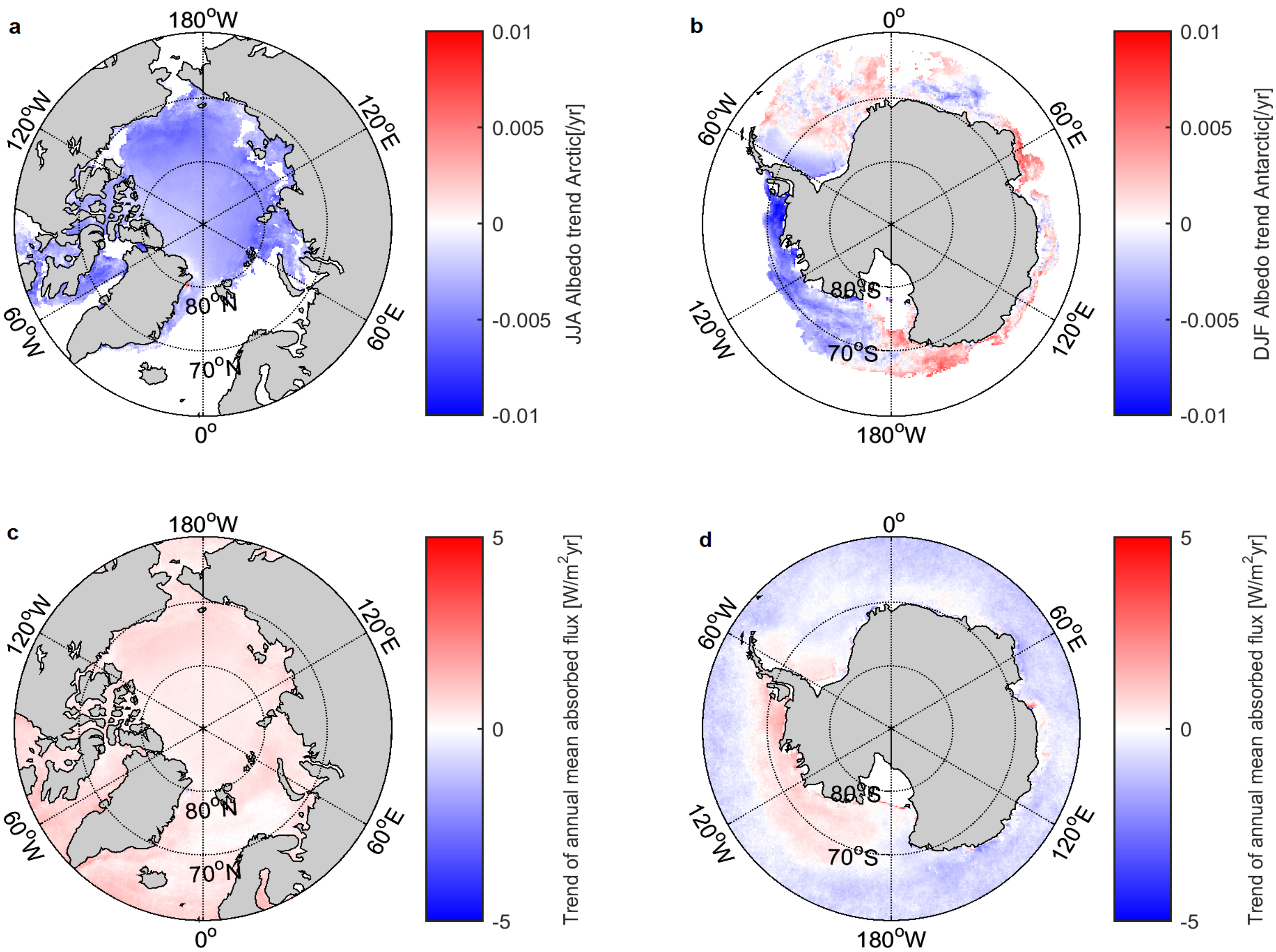

Figure 2: Spatial distribution of trends in sea ice albedo and overall energy deposition into the polar oceans: Trends [yr^{-1}] of mean daytime summer sea-ice albedo in the Arctic (a) and Antarctic (b) and trends [W/m^2yr] of shortwave energy flux (c,d) absorbed by the ice-ocean system. The latter inherently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

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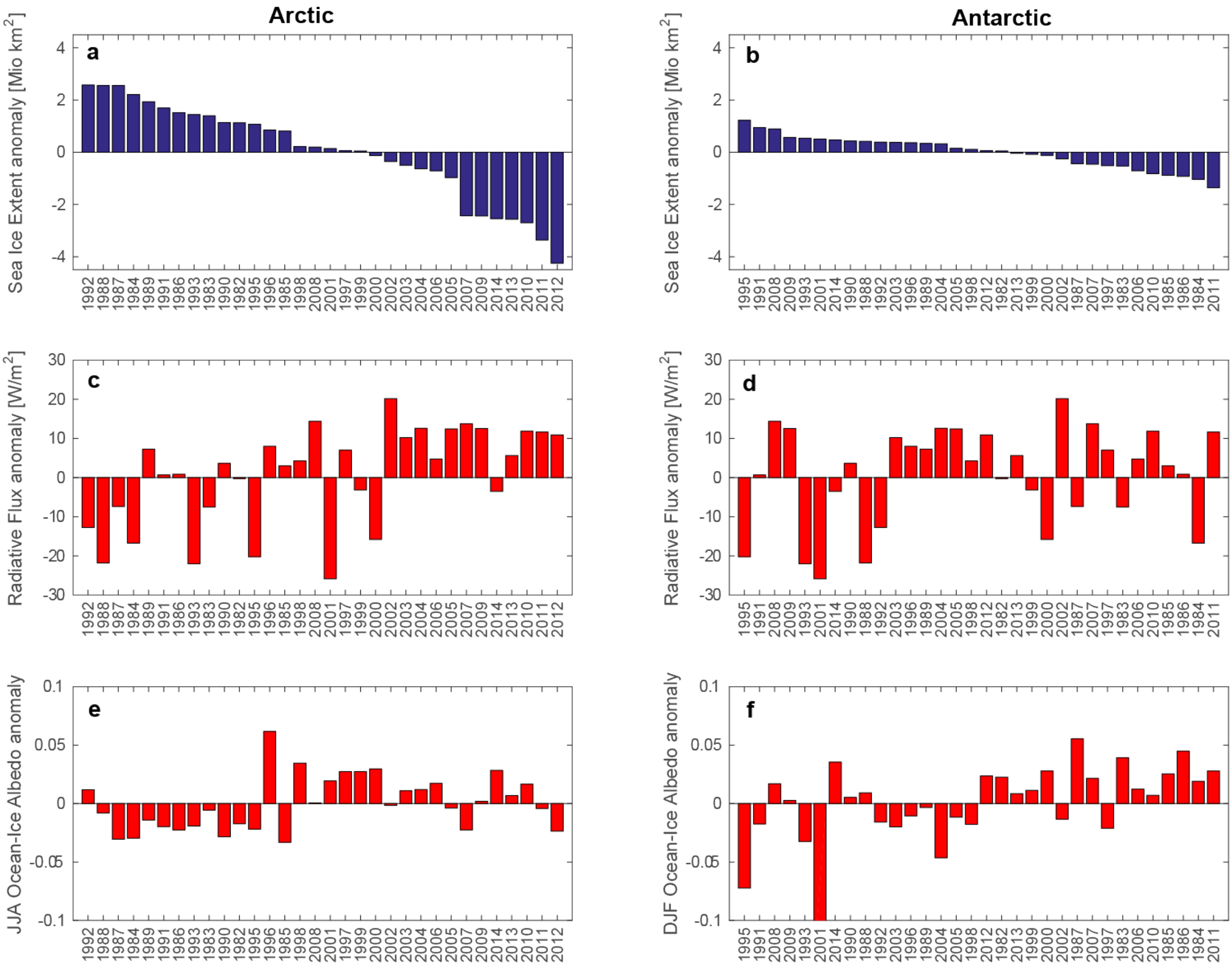

Figure 3: Anomaly of mean, absorbed shortwave flux and sea-ice albedo sorted by sea-ice extent anomaly: Arctic (left) and Antarctic (right) sea ice extent anomaly (a,b), summer albedo anomaly (c,d) and annual anomaly of shortwave flux absorbed by the ice ocean system polewards of 50° (e,f) sorted from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