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Observed changes in the albedo of the Arctic sea ice zone between 1982-2009

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The surface albedo of the Arctic sea ice zone is a crucial component in the energy budget of the Arctic region [1, 2]. The treatment of sea ice albedo has been identified as a main source of variability in the future sea ice mass loss forecasts in coupled climate models [3]. There is a clear need to establish datasets of Arctic sea ice albedo to study the changes based on observational data, and to aid future modeling efforts. Here we present an analysis of observed changes in the mean albedo of the Arctic sea ice zone based on such a dataset [4], consisting of 28 years (1982-2009) of homogenized satellite data. Along with the albedo effect of the well-known loss of late-summer sea ice cover [5, 6], we show that the mean albedo of the remaining late-summer Arctic sea ice zone is decreasing. The change per decade in the mean August sea ice zone albedo is -0.029 ± 0.011. With the exception of May mean sea ice zone albedo, all trends are significant with a 99% confidence interval. Variations in sea ice zone albedo can be explained using sea ice concentration surface air temperature, and elapsed time from onset of melt as drivers.

Our goal in this paper is to present and analyze the evolution of the Arctic sea ice black-sky albedo during the last three decades, as observed by the CLARA-A1-SAL (CM SAF cLouds, Albedo and RAdiation - AVHRR 1st release - Surface ALbedo) dataset. Here, we define "albedo" as the total solar flux reflectivity of Earth's surface when all atmospheric absorption and scattering effects have been corrected for (i.e. broadband shortwave directional-hemispherical reflectance). We focus on the melting season of the sea ice (May-August), which offers sufficient solar illumination at high enough solar elevation angles to permit robust surface albedo retrievals. We examine the albedo evolution through the monthly mean products of CLARA-A1-SAL; Figure 1 shows the August monthly mean albedo of the Arctic from four years in the dataset. In August, worsening illumination conditions combined with high cloud fractions often create an area around the North Pole where albedo is not retrievable with the CLARA-A1-SAL algorithm.

Our focus is on large-scale changes and trends in the mean surface albedo of

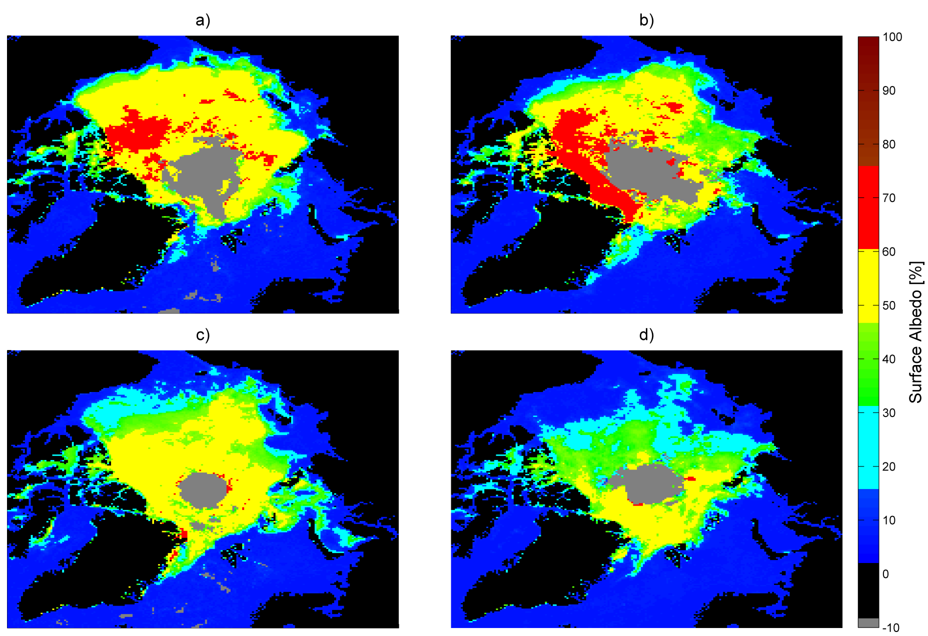

Figure 1: The August monthly mean land-masked surface albedo of the Arctic from a) 1985, b) 1997, c) 1999, and d) 2008. Years selected to illustrate the maxima and minima of Arctic sea ice albedo in the dataset. Grey color indicates grid cells with less than 30 valid retrievals during the month.

the Arctic Ocean and its sea ice. To extract this information, we carry out two masking operations. First we mask all land areas (as in Figure 1), averaging the remaining grid cells. The result is the mean open water-sea ice composite albedo of the Arctic (henceforth composite albedo), containing the effects of variations in the ice-covered area. The area that we define as the Arctic Ocean is the area shown in Figure 1. To extract solely the albedo of the sea ice zone, we further mask all grid cells outside the ice concentration threshold (15%), and average the remaining cells. The result of this second operation is the mean sea ice zone albedo of the Arctic. These temporal evolution of these two quantities may then be studied separately, as shown in Figure 2. To ensure that annual variations in the size of this no-data area do not affect the August albedo trends, we implemented a spatiotemporal gap-filling of the August data [7]. We analyze both the original and gap-filled dataset.

We find that the monthly means of both composite and sea ice zone albedo show a significant (at 99% confidence level) negative linear trend throughout the time series (Figure 2), with the exception of May sea ice zone albedo. The trend slopes and correlation coefficients are listed in Table 1. The lack of a significant negative trend in the May sea ice zone albedo is not surprising. Field study results indicate that the sea ice and its snow cover recover each winter so that the sea ice zone in May consists mainly of cold snow on top of thickened ice, having a stable albedo of 0.7-0.8 [8]. However, years of severe ice loss precondition the sea ice to a lower extent the following spring, leading to the observed negative trend in the composite May albedo in Figure 2a.

The presence of negative trends in both the composite and sea ice zone albedo is also supported by other evidence. A recent study by Markus et al. [9] showed that melt onset occurs, on average, 2-3 days earlier per decade over the central Arctic Ocean. The effects of this earlier melt are combined with the documented disappearance of old multi-year ice [10] and the related thinning of the Arctic sea ice cover as a whole [11]. Thus, open water leads will appear sooner, the snow cover on top of younger, thinner ice will be wetter and melt ponding will start earlier and be more intensive. All this leads to a continuous decrease in both the composite albedo and the albedo of the ice cover, as is readily seen in the June-July data of Figure 2.

During August, the snow and ice melt have reached their peak and Arctic Ocean albedo is at a minimum. The observed negative albedo trend is strongest during August; gap-filled data have slightly larger negative trends relative to original data. The composite albedo trend is quite robust, but the trend strength of sea ice albedo (of August and also in general) is much weaker. This is explained by the facts that a) the slope of the negative trend is slight, and b) annual variation in the intensity and phase of August precipitation over the Arctic can have a significant impact on the sea ice albedo, increasing variance in the time series. This makes it harder to identify a dominant trend in the data. In an attempt to better resolve the underlying trend in the sea ice albedo, we performed a wavelet denoising of the August timeseries. The denoised data shows a much more robust linear trend (Table 1). While we have also calculated second-degree polynomial fits for illustrative purposes, they are not shown here to be physically the correct choice. Supplementary Figure 2 shows the wavelet-denoised data and fits. While a rapid decline in late-summer sea ice albedo is line with recent CMIP5 climate model projections [12], other recent studies have proposed possible Arctic climate feedback mechanisms that could act to stabilize albedo [13].

Month	linear trend slope (units/decade)	R^2
May, composite	-0.019 ± 0.006	0.62
May, sea ice	-0.007 ± 0.005	0.21
June, composite	-0.027 ± 0.009	0.61
June, sea ice	-0.019 ± 0.010	0.35
July, composite	-0.029 ± 0.008	0.66
July, sea ice	-0.020 ± 0.009	0.44
August, composite	-0.030 ± 0.008	0.70
August, sea ice	-0.029 ± 0.011	0.50
August gap-filled, composite	-0.035 ± 0.009	0.70
August gap-filled, sea ice	-0.032 ± 0.012	0.54
August gap-filled & denoised, sea ice	-0.032 ± 0.006	0.82
Month	**2nd degree polynomial (x=year)**	**R^2**
August gap-filled, sea ice	$-0.0002x^2 + 0.0015x + 0.461$	0.61
August gap-filled & denoised, sea ice	$-0.0002x^2 + 0.0020x + 0.458$	0.95

Table 1: Observed trends in monthly mean albedos through least-squares fitting
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Based on our dataset, are there indications that the decline of the late-summer sea ice zone albedo could be accelerating? Previously, Laine [14] analyzed Arctic sea ice albedo from the Arctic Polar Pathfinder dataset [15] covering 1982-1998, and found only weak or nonexistent trends. To compare results, we also calculated the August albedo trend for this period from the CLARA-A1-SAL dataset. The trend (-0.01 units/decade) agreed with the results of Laine within the error limits, being also substantially weaker than the August albedo trend of the full dataset. While an acceleration in late-summer albedo decrease from the mid-1990s over the sea ice zone would be consistent with dominantly positive near surface temperature anomalies in climate simulations and reanalysis datasets [16], there is considerable year-to-year variability in the August mean sea ice zone albedo which prevents us from drawing conclusions on this question.

In other studies, observed sea ice retreat appears to have followed a linear trend [6] at least to the 2000s, although some studies also suggest that the ice cover decline is accelerating [17, 5]. There is also considerable disagreement among the CMIP3 climate models on the timespan required for predominantly ice-free late summer conditions in the Arctic [3], with some studies suggesting a future slowing of ice loss [18]. We find that the decline of late-summer Arctic Ocean composite and sea ice albedo appear to be equally rapid up to 2009. The albedo of the Arctic Ocean is not only affected by the retreating ice cover, but

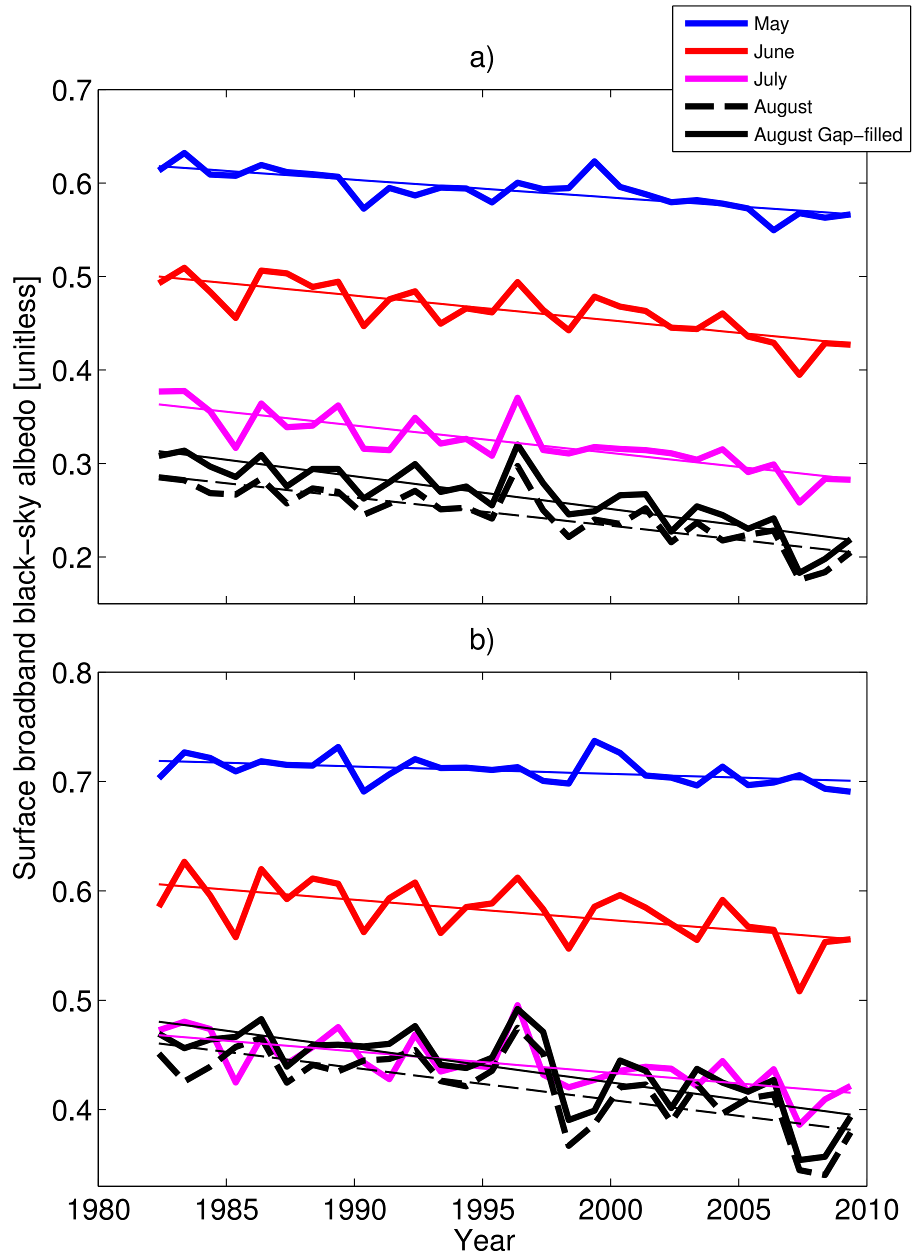

Figure 2: a) The evolution of the monthly mean open water-sea ice composite albedo of the Arctic, and b) The evolution of the monthly mean sea ice albedo of the Arctic. Thin lines indicate best-fit linear trends.

also by changes in the mean surface conditions of the ice-covered area itself.

But which factors contribute most to the changes in Arctic sea ice zone albedo? For the areally averaged albedo of the sea ice zone, changes in ice concentration are a strong driver because of the large contrast between the albedos of ice and open water [19]. Melting and freezing events in the optically accessible snow and ice layers are another main source of albedo changes, and Perovich et al. [19] also identify the timing of melt onset as an important control on the cumulative solar energy absorbed by the ice and open water, implying that melt onset timing changes should also cause albedo changes in the sea ice zone.

Following this theory, we should be able to explain the majority of our observed changes through the following variables: a) ice concentration, b) surface air temperature (SAT), and c) time since melt onset. We also expect that all these variables should be linearly related with surface albedo. We extracted ice concentration data from the the NSIDC NASA Team passive microwave sea ice concentrations product [20], SAT data from the NCEP-DOE AMIP-II reanalysis [21], and melt onset dates from the dataset by Markus et al. [9]. The products were spatially averaged over the ice-covered Arctic Ocean to conform with the CLARA-A1-SAL averages for sea ice. To correctly handle melt onset, SAT data was converted to Celsius degrees. We then carried out a linear regression against the CLARA-A1-SAL (non-gapfilled) average sea ice albedo, attempting to constrain the coefficients to physical limits. The resulting best-fit parameterization of sea ice zone albedo is

$$\alpha_{SI} = 0.6387 * C - 0.0065 * SAT_{65-90N} - 0.0011 * (DOY - MOD) + 0.0676 \quad (1)$$

where C is the average sea ice concentration over the Arctic, SAT_{65-90N} is the average SAT of all regions north of 65N, DOY is the average day of year of each monthly mean (15th day of month), and MOD is the average day on which onset of melt occurred over the Arctic. The constant term was forced as 0.0676 to ensure that the parameterization agrees well with open water albedo when C is zero (at a Sun Zenith Angle of 60 degrees).

The parameterized albedo is shown against CLARA-A1-SAL in Figure 3. The achieved fit is quite good, with RMSE of 0.015 or 0.016 for each month. Interestingly, it turned out that using the average SAT of all areas north of 65 degrees latitude produces somewhat better parameterization results for August than using the average SAT of the sea ice zone (RMSE of 0.0154 versus 0.0186). The parameterization of eq. 1 reproduces a realistic estimate of approximately 0.71 for sea ice albedo when ice concentration is equal to one (when the other two terms reduce to zero, i.e. at melting point temperatures at the onset of melt season). It needs to be kept in mind that the scope of the parameterization is limited; it only considers averaged variables over the entire Arctic sea ice zone, its temporal validity is limited to the melting season, and being empirical in nature, has limits on the validity range on SAT. Passive microwave-based ice concentrations are generally biased low during the melt season [22], also contributing to the uncertainty of the parameterization. Still, the parameterization seems capable of explaining observed changes in ice albedo data in accordance with previous studies and physical constraints, reinforcing the plausibility of the trends seen in CLARA-A1-SAL.

The results of this study form a cohesive picture with previous studies on the properties and change in Arctic sea ice. The retreating and thinning sea ice zone is clearly also growing darker. This decreasing albedo is both a cause and effect of change in the sea ice. Of course, past change is not a guarantee of future change, but the various ongoing changes in the Arctic sea ice suggest that its albedo is not about to find a new equilibrium state soon. While the data hints at a possibility of an accelerated albedo decrease since the mid-1990s, there is too much year-to-year variability in the dataset to draw conclusions on that point. It is notable that early summer albedo changes have the greatest effect on the energy budget because the insolation is typically larger than during late summer [19]. For detailed (shortwave) energy budget studies, one should also consider the spatiotemporal variations in cloudiness and insolation, as well as the cloudiness effect on snow and ice albedo, along the lines of Hudson [23].

Methods

The analyzed dataset, called CM SAF cLouds, Albedo and RAdiation - AVHRR 1st release - Surface ALbedo (CLARA-A1-SAL), is constructed on Advanced Very High Resolution Radiometer (AVHRR) optical imager data between 1982-2009. The dataset has been developed in the Satellite Application Facility on Climate Monitoring (CM SAF), a project of EUMETSAT. Similar AVHRR-based surface albedo datasets have been created before (e.g. [15, 24]), but this dataset is the first to be built upon a homogenized data record of measured AVHRR radiances [25]. This homogenization removes much of the inter-satellite calibration differences in the imagery, making the retrievable albedo dataset internally more consistent. The CLARA-SAL algorithm and validation results have been described in detail by [4]. Generally speaking, the retrieval accuracy for snow and ice is determined to be 5-15% (relative).

The CLARA-A1-SAL albedo dataset is created based on a homogenized Fundamental Climate Data Record (FCDR) of AVHRR radiances (following [25]). The algorithm follows a sequential processing approach, where the main processing steps are 1) cloud masking to determine clear-sky pixels, 2) topography correction of geolocation and radiometry where local mean terrain slopes exceed 5 degrees, 3) atmospheric correction to compensate for absorption and scattering effects in the solar flux, 4) anisotropy correction for surface reflectances of land (non-snow) surfaces, 5a) conversion of surface reflectances into spectral albedos for land (non-snow) surfaces, and 5b) conversion of spectral albedos into a broadband albedo (snow/ice albedo retrieved through hemispherical averaging of bidirectional broadband snow/ice reflectances). The retrieved albedo is defined over a waveband of 0.25-2.5 μm (0.35-2.8 μm for snow). Full algorithm description is available in the dataset Algorithm Theoretical Basis Document (ATBD) available from the CM SAF website, or in [4].

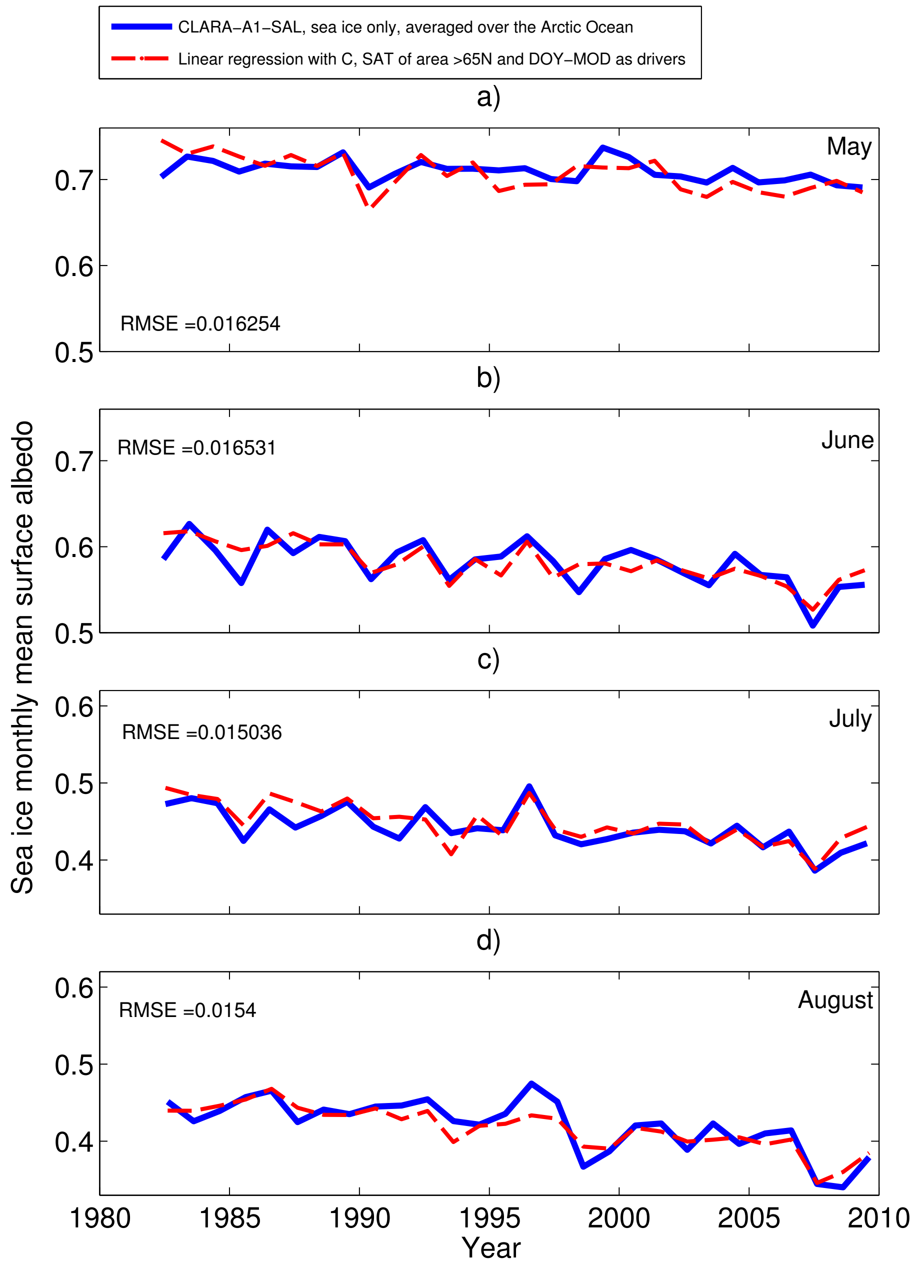

Figure 3: CLARA-A1-SAL average sea ice albedo over the Arctic per month (solid blue line), and the parameterized sea ice albedo from eq. (1) using ice concentration, SAT, and time difference from onset of melt season as drivers (dashed red line).

The data used in this study is from the Arctic subset of CLARA-A1-SAL. This subset was formed by projecting the satellite retrievals on a 25 kilometer resolution equal-area polar grid. The use of an equal-area projection means that no weighting was required for analysis of large-scale albedo means and trends. As a quality assurance procedure, we have excluded all grid cells whose monthly mean albedo is composed of fewer than 60 successful GAC-resolution retrievals. The amount of excluded grid cells is on average less than 1% of the entire grid for May-July, and 3.5% for August.

We did the land-masking of the CLARA-SAL dataset using the Global Self-Consistent Hierarchical High-Resolution Shoreline (GSHHS) low resolution data [26]. The open water masking was done using the National Snow and Ice Data Center monthly mean sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS passive microwave data [20]. We constrain our definition of sea ice cover to be larger or equal than 15% ice concentration. We performed the gap-filling of the August albedo maps using the algorithm by Garcia [7]. The gap-filling used the monthly mean albedos of June and July as input along with the data from August itself.

We evaluated the statistical significance of all trends using a two-tailed Student's t-test. We define a significant trend to have a 99% confidence interval, and a statistically significant trend to have a 95% confidence interval.

We implemented the wavelet filtering of the August mean albedo timeseries using the Stanford Wavelab software (version 850). The wavelet chosen was the Daubechies number 4.

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