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Summer Sea Ice Albedo in the Arctic in CMIP5 models

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Abstract

Spatial and temporal variations of summer sea ice albedo over the Arctic are analyzed using an ensemble of historical CMIP5 model simulations. The results are compared to the CLARA-SAL product that is based on long-term satellite observations. The summer sea ice albedo varies substantially among CMIP5 models and many models show large biases compared to the CLARA-SAL product. Single summer months show an extreme spread of ice albedo among models; July-values vary between 0.3 and 0.7 for individual models. The CMIP5 ensemble mean, however, agrees relatively well in the Central Arctic but shows too high ice albedo near the ice edges and coasts. In most models, the ice albedo is spatially too uniformly distributed. The summer to summer variations seem to be underestimated in many global models and almost no model is able to fully reproduce the temporal evolution of ice albedo throughout the summer. While the satellite observations indicate the lowest ice albedos during August, the models show minimum values in July and substantially higher values in August. Instead, the June values are often lower in the models than in the satellite observations. This is probably due to too high surface temperatures in June, leading to an early start of the melt season and too cold temperatures in August causing an earlier refreezing in the models. The summer sea ice albedo in the CMIP5 models is strongly governed by surface temperature and snow conditions, particularly during the period of melt onset in early summer and refreezing in late summer.

The summer surface net solar radiation of the ice covered Arctic areas is highly related to the ice albedo in the CMIP5 models. However, the impact of the ice albedo on the sea ice conditions in the CMIP5 models is not clearly visible. This indicates the importance of other Arctic and large scale processes for the sea ice conditions.

1 Introduction

Arctic climate has strongly changed in the last decades (ACIA, 2005). The observed warming in the Arctic regions is about twice the rate of the global mean warming (ACIA, 2005; IPCC, 2007; Richter-Menge and Jeffries, 2011). The warming is concurrent with an extension of melting season (Markus et al., 2009) and a rapid decline of Arctic sea ice extent in the last decades (Comiso et al., 2008; Stroeve et al., 2012) with a recent extreme September minimum in 2012 (Devasthale et al., 2013; Guemas et al., 2013). Future projections indicate a continuous climate change in the Arctic in the next decades (Vavrus et al., 2012; Koenigk et al., 2013).

The observed Arctic temperature amplification compared to lower latitudes has led to an intensive discussion on the role of the surface albedo. Riihelä et al. (2013) showed in a recent study that the observed surface albedo of the remaining Arctic ice area has decreased significantly since 1982. Besides the ice-albedo feedback, the importance of enhanced meridional energy transport (Graversen et al., 2008), changes in clouds and water vapour (Graversen and Wang, 2009; Liu et al., 2008), the weak vertical mixing in the Arctic winter inversion (Bintanja et al., 2011) and enhanced ocean heat transport into the Arctic (Spielhagen et al., 2011; Koenigk and Brodeau, 2013) have been discussed as possible sources for Arctic temperature amplification. However, it seems to be beyond question that the ice albedo feedback is an important contributor to Arctic temperature amplification and changes in sea ice conditions (Serreze et al., 2009; Winton, 2006).

The surface albedo is strongly affecting the radiation budget of the Earth and global climate models react very sensitive to changes in the surface albedo (Li et al., 2006). This is particularly true for the Arctic since temporal and spatial variations of surface albedo are extremely high in the Arctic; values can vary between around 0.8 for snow covered ice and around 0.5 for melting ice and are even substantially lower if melt ponds are formed on the ice or if the ice becomes very thin and totally melts (Laine, 2004). Refreezing or snow falls can lead to rapid albedo increases. These temporal and spatial variations on small scales make modeling the albedo of the Arctic ice/snow system challenging. Hodson et al. (2013) showed that the cross model variations of ice albedo contribute to the large uncertainties in the Arctic climate as simulated by global climate models. Liu et al. (2007) analyzed the albedo in the Arctic by using SHEBA-data as input for 4 global climate model albedo schemes and compared the results to the observed SHEBA-albedo. The values varied substantially from model to model indicating substantial differences in the model albedo parameterizations.

In a recent study, Karlsson and Svensson (2013) showed that Arctic mean surface albedo varies strongly among CMIP5 models with large consequences for the radiation balance. This, among other reasons, further warrants detailed evaluation of the spatio-temporal variability of surface albedo over the Arctic. The recently released surface albedo product from the Satellite Application Facility on Climate Monitoring (CM-SAF) clouds, albedo and radiation dataset (CLARA-SAL, Riihelä et al., 2012; Karlsson et al., 2013) and sea ice concentration from the Ocean and Sea Ice Satellite Application Facility (OSI-SAF) data set (Eastwood et al., 2011) allow such detailed evaluation of CMIP5 models. This is the main focus of the present study. Furthermore, we discuss the main sources for the cross model variations and possible implications for the Arctic climate.

2 Model simulations and data

2.1 Model data

Historical simulations from 21 CMIP5-models are analyzed. One ensemble member from each model has been used and all models were selected from the CMIP5 data base where all relevant variables were available (http://esgf-data.dkrz.de/esgf-web-fe/).

The surface albedo in the models was calculated from monthly mean values of the downward and upward surface solar radiation (as done in Karlsson and Svensson, 2013). Monthly mean sea ice concentration was used to extract the sea ice albedo for the ice covered part of each grid box:

$$\alpha_{\text{surf}} = \alpha_{\text{ice}} \cdot A_{\text{ice}} + \alpha_{\text{water}} \cdot (1 - A_{\text{ice}})$$

with α_{surf} = surface albedo, α_{ice} = albedo of the ice covered part, α_{water} = albedo of the ice-free part, A_{ice} = ice covered area.

Hereby, we assumed a constant surface albedo of the ice free part of 0.07. We only considered sea ice albedo for grid points exceeding 15 % ice concentration in order to be consistent with the results from the satellite product (Sect. 2.2).

We used ice concentration, ice thickness, snow depth on ice and surface temperature from the models to further analyze ice albedo variations. Note, that snow depth was only available for 16 out of the 21 global models.

The period 1982–2005 was used for comparison with satellite data of the same period.

2.2 Observations and data

We used the surface albedo product from the Satellite Application Facility on Climate Monitoring (CM-SAF) clouds, albedo and radiation dataset (CLARA-SAL, Riihelä et al., 2012; Karlsson et al., 2013) and sea ice concentration from the Ocean and Sea Ice Satellite Application Facility (OSI-SAF) data set (Eastwood et al., 2011) as comparison for the model data. Both data sets are available on a 0.25° grid. The surface albedo is available for 1982–2009 and ice concentration from 1979–2009. The CLARA-SAL surface albedo is defined as the inherent surface reflectance and presents the mean albedo in each grid box, averaging over the ice and ocean parts of the box. Figure 1 shows an example for the CLARA-SAL surface albedo and the CMIP5 ensemble mean. While the large scale patterns look similar, the satellite data provides much more detailed information and resolves finer transition from open ocean to sea ice.

To extract the sea ice albedo from the CLARA-SAL data we used the ice concentration from the OSI-SAF product and split the albedo in the ice-covered part and the ice-free part, assuming a constant albedo of 0.07 as for the model simulations. We will refer to this ice albedo based on CLARA-SAL surface albedo and OSI-SAF ice concentration as CLARA-SAL ice albedo.

The uncertainties of sea ice concentrations are largest in summer when it is difficult to distinguish between open water and water on ice. This is particular the case for areas with low ice concentrations; therefore we excluded all grid points with an ice concentration below 15 % from the analysis.

The CLARA-SAL surface albedo has been validated by Riihelä et al. (2010) using observed values from the Tara-experiment. Time-average products show an accuracy of 5–10 %.

No comprehensive observational data sets exist for surface temperature, snow depth and ice thickness in the Arctic Ocean area. We thus used surface temperature from the ERA-interim reanalysis (Dee et al., 2011) as comparison for the model results. Note, that the reanalysis also has relatively large uncertainties since the Arctic is a data sparse region. Ice thickness and snow depth are compared to results from the literature.

3 Results

3.1 Sea ice conditions in the CMIP5 models

The Arctic surface albedo in the CMIP5 climate models might depend strongly on the distribution of sea ice concentration and thickness in the models. Thus, this section presents the spatial distributions of the Arctic ice conditions in the global models before discussing the albedo in the following sections.

The sea ice extent in the Arctic in the CMIP5 model ensemble shows a very large spread although some improvements are observed compared to the CMIP3-ensemble (Stroeve et al., 2012; Massonnet et al., 2012). Figure 2 shows the spatial distribution of September sea ice concentration in the 21 CMIP5 models used in this study and in the satellite observations. The ice edge is relatively well simulated in the CMIP5 model ensemble mean. However, ice concentration is too small in the Central Arctic and ice extends slightly too far to the coasts, particularly in the Kara Sea. Variations among models are very large showing both strongly underestimated and overestimated Arctic ice areas. Also the distribution of ice concentration varies strongly among models. Even models with realistic ice extents do not necessarily show a realistic ice distribution. A number of models tend to simulate highest ice concentrations in the middle of the Arctic Basin and not along the north coasts of Greenland and the Canadian Archipelago as observed by satellites.

There is no single model that outperforms the sea ice concentration distribution of the ensemble mean.

The large spread of ice conditions among models is also obvious in the ice thickness distribution (Fig. 3). The Central Arctic ice thickness varies between about 1 m and 4 m in the end of the 20th century. A few models simulate a secondary maximum of ice thickness near the Siberian coast. Although, the distribution of ice thickness is not well observed, observational based estimates suggest an ice thickness distribution (Belchansky et al., 2008; Rothrock et al., 2003; Kwok and Cunningham, 2008), which compares relatively well with the CMIP5 ensemble mean.

The reasons for the large spread in sea ice conditions among models are probably wide and include varying oceanic and atmospheric heat transports into the Arctic, varying Arctic atmospheric and oceanic circulations, differences in Arctic cloud and radiation processes and different parameterizations in the sea ice models. Due to a number of positive feedbacks, active in the Arctic, Arctic climate reacts very sensitive to small differences in these parameters.

3.2 Surface albedo

Figure 4 shows the summer mean (mean over June, July, and August) surface albedo in CLARA-SAL and the CMIP5 models. Since the surface albedo is an average over the entire gridbox it is showing a mixture of ice albedo and water albedo. This means, the differences in ice concentrations in the CMIP5 models shown in Sect. 3.1 might partly explain the cross model spread in summer surface albedos and deviations from the satellite observations.

Highest summer surface albedo in CLARA-SAL occurs between the North Pole and the coasts of northern Greenland and the Canadian Archipelago with values of up to 0.65. Towards the ice edges and the coasts of Alaska and Siberia, surface albedo is reduced and falls below 0.5, partly due to more open water in these areas.

The ensemble mean of the CMIP5 models simulates the observed distribution relatively well. However, surface albedo varies strongly among models. The majority of models show summer-values between 0.55 and 0.7 in the Central Arctic but a few outliers simulate substantially lower or higher albedo values.

The spatial pattern of the observed surface albedo is relatively well simulated in most models with highest albedos in the area between North Pole and northern Greenland/Canadian Archipelago. However, in a few models the maximum is moved away from the Greenland coast into the interior of the Central Arctic. These are those models, where also the sea ice concentration is highest in the interior of the Arctic away from Greenland's north coast. Generally, the distribution of sea ice concentration in each individual model strongly determines the distribution of the surface albedo. However, there is no clear relation between ice concentration and surface albedo across models.

A number of models underestimate the observed gradient of albedo in the Arctic and show a too uniform surface albedo over large parts of the Central Arctic.

The differences among models and between models and CLARA-SAL are substantially larger for single months than for the summer average (not shown). In June, surface albedo is already strongly reduced in a few models due to earlier onset of snow and ice melt and warmer surface temperatures while the Arctic is still snow-covered in others, leading to a much higher albedo. CLARA-SAL shows still high albedo values in the Central Arctic and north of Greenland and the Canadian Archipelago; here values exceed 0.7 but the albedo is substantially reduced towards the coasts. Only a few models are able to reproduce this strong gradient towards lower Arctic latitudes. In July, the satellite observations show maximum values of slightly above 0.6 near the North Pole but much smaller values near the ice edges and coasts. Most models simulate surface albedos between 0.54 and 0.58 in the Central Arctic and slightly below 0.4 near the ice edges but a few models have substantially too high or too low albedos. Again, models tend to simulate spatially too uniformly distributed surface albedo compared to CLARA-SAL.

In August, the satellite product produces values between 0.5 and 0.6 over most of the ice covered part of the Arctic and thus smaller spatial variations as in June and July. Also, most of the models show relatively uniform albedo patterns but variations among models are huge, between about 0.3 in GISS-E2-R and 0.75 in MIROC5. A part of this spread can be explained by much more open water areas in the models with lower surface albedo (Fig. 2). In addition, freeze up starts already in August in a number of models, leading to increased albedo compared to CLARA-SAL.

3.3 Sea ice albedo

As already discussed, the surface albedo might depend substantially on the sea ice concentration and does not allow for a proper comparison between models and between models and observations since a number of processes affect the ice conditions. Thus, in the following, we focus on the albedo of the ice covered part of each grid box.

The mean summer ice albedo in CLARA-SAL reaches up to 0.7 between the North Pole and the north coasts of Greenland and Ellesmere Island (Fig. 5). It drops first slightly towards lower latitudes and then rapidly near the ice edges and coasts. Here, ice albedo reaches average summer values below 0.4. The ensemble mean of the CMIP5 models compares well to the satellite data in the Central Arctic. It reproduces both the area of maximum albedo as well as the slight reduction towards lower latitudes. However, the ensemble mean misses the rapid reduction of ice albedo near the ice edges and coastlines; values are between 0.58 and 0.62.

Individual models simulate a large range of summer sea ice albedos although the range is slightly reduced compared to the surface albedo (Fig. 4). Nine out of the 21 models are able to simulate an ice albedo distribution in the Arctic, which is similar to the observed one; however, the strong reduction near the ice edge often misses. The other models simulate spatially very uniform ice albedo fields.

In June (not shown), most models – except for four – still show relatively high albedos with values between 0.6 along the ice edges and 0.8 in the interior of the Arctic. This compares to CLARA-SAL values between 0.5 and 0.8. In July, CLARA-SAL data show a strong ice albedo reduction in the entire Arctic Basin but the large gradient from the North Pole/Greenland region towards the ice edges still exists. The CMIP5 ensemble mean shows slightly lower values in the Central Arctic but higher ice albedos near the ice edges compared to CLARA-SAL and is thus, as in June, strongly underestimating the spatial gradient in the Arctic. In August, CLARA-SAL ice albedo reaches its minimum while it starts to increase again in the CMIP5 ensemble mean.

The standard deviation of summer mean ice albedo for the period 1982–2005 is shown in Fig. 6. CLARA-SAL shows smallest summer to summer variations north of the Canadian Archipelago and largest variations along the ice edges and coastlines where values up to 0.1 are reached. As shown above, spatial variations of ice albedo are largest near the ice edge and the strongly varying position of the ice edge between summers can explain the large standard deviation here. Results from Perovich and Polashenski (2012), analyzing four years of albedo observations near Barrow, further indicate that the year to year variations are largest in the melt period. Thus, a longer melt period near the ice edge and coastlines compared to the Central Arctic, might contribute to large summer albedo variations in these regions.

The model ensemble mean produces a similar distribution of the standard deviation than CLARA-SAL but shows generally smaller variations, particularly near the ice margins and coasts. The standard deviation of the ice albedo varies strongly among individual models; models with spatially uniformly distributed ice albedo tend to simulate smaller summer-to-summer variations. This might either indicate that the albedo

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formulations in these models react less sensitive to variations in the driving parameters or that the temporal and spatial variability of the forcing fields is smaller.

The summer ice albedo trend in CLARA-SAL is relatively small in the interior of the Arctic (Fig. 7 and Table 1) but strongly negative along the ice edges, particularly in the Pacific sector of the Arctic, in the period 1982–2005. This goes along with a slight northward movement of the ice edge in this period. Between 2005 and 2009 when summer ice reduction accelerated (not shown), CLARA-SAL shows an increased ice albedo reduction, even in the Central Arctic. These results agree well to findings by Laine (2004) – showing almost no trend in the Central Arctic but slightly negative trends in the surrounding seas for 1982–1997 – and recent results by Riihelä et al. (2013), indicating an enhanced surface albedo reduction since the mid 1990s. The trend in the CMIP5 models is small compared to the observed one; however, a few models show similar to the satellite data, a negative trend in larger areas of the Arctic Ocean with ice albedo reductions of 0.1 in the 24 yr period.

3.4 Ice albedo in the Central Arctic

To avoid comparing effects that are related to different simulations of the ice edge, we focus in the following on the Central Arctic Ocean. The ocean area between 80° N and 90° N shows a relatively high ice concentration in all CMIP5 models during the summer (JJA) and allows for a direct comparison between ice albedo and related variables in this area.

Figure 8 shows the summer averaged sea ice albedo, surface temperature and snow depth, averaged over the ocean points between 80° N and 90° N between 1982 and 2005. The ice albedo in CLARA-SAL varies substantially from summer to summer and reaches values between 0.62 and 0.69. The CMIP5 ensemble mean agrees relatively well but individual models simulate a large range of ice albedos. Most of the models underestimate the temporal variations as expected from Fig. 6.

The trend in the Central Arctic (Table 1) is negative both in the satellite data and all models except for two. The CMIP5 ensemble mean shows a significant negative trend in all summer months with the largest reductions in June and July. In contrast, the satellite data indicate almost no trend in June but a substantial – although not significant at the 95 % level – reduction during August. Most individual models show a negative trend in all three summer months but with the smallest trend in August. Note that the time series are short to identify clear trends and that trends are only in a few models statistically significant.

In most albedo schemes, surface temperature and snow depth (and cover) play a leading role for the albedo of the ice/snow system. Depending on the degree of sophistication of the albedo scheme, other variables like e.g. ice thickness, snow age, melt ponds or flooding play an important role as well. Here, we concentrate on the impact of surface temperature and snow depth on ice albedo in the Central Arctic. We chose snow depth instead of snow cover since more CMIP5 models provide snow depth on ice than snow cover. However, for those models providing both depth and cover, they are highly correlated during summer.

Surface temperature is negatively correlated to the ice albedo in the summer. This is particularly the case if surface temperature is near freezing and melting points and a small change in surface temperature strongly affects the physical properties of the ice/snow system. The highest correlation between surface temperature and ice albedo is found in June and almost all models show a high negative correlation (Table 2). In July and August, the correlations are negative in most models but a few show low or even positive correlations, which mostly are not statistically significant. In May, surface temperature is still much below freezing temperature in many models, which leads to a smaller correlation between temperature and ice albedo in a number of models and also in the ensemble mean.

The CLARA-SAL ice albedo is significantly positively correlated with ERA-interim surface temperature in May and negatively correlated in June, July and August (not significant at 95 %-level in July and August). Similar to the models, the highest negative correlation is found in June but correlations are smaller than in most models. However, since ERA-interim surface temperatures are not observed temperatures and

ERA-interim and CLARA-SAL not from a consistent data set as the model variables are, a lower correlation does not necessarily mean that models generally overestimate the relation between surface temperature and ice albedo.

Snow depth plays an important role in all summer months. All models show a highly positive correlation between snow depth and ice albedo in June and August (Table 3). Correlations in May and July are substantially lower in many models but still positive and often statistically significant.

The summer evolution of ice albedo, surface temperature and snow depth in the Central Arctic, averaged over the 24 yr period is shown in Fig. 9. The spread in sea ice albedo among models is relatively small in May, with values around 0.8 in almost all models except for two showing a substantial lower albedo. CLARA-SAL indicates an ice albedo of slightly below 0.8 in May. All models show an albedo reduction in June and July with an increasing spread among models; the ensemble mean is lower than in CLARA-SAL in June but agrees well in July. In August, almost all models simulate an increasing ice albedo, which is in contrast to CLARA-SAL, showing a further ice albedo reduction.

The surface temperature in the Central Arctic shows the largest spread among models in May. In June and particularly July, spread is strongly reduced and all models simulate surface temperatures slightly below 0 °C. In August, temperature starts to fall and the spread among models increases again. The model ensemble mean is slightly warmer (colder) than ERA-interim in June (August), which might explain the different development of ice albedo in models and CLARA-SAL. This assumes however, that ERA-interim provides a more realistic temperature evolution throughout the summer than the models.

The snow depth is varying between 20 cm and 40 cm in most models in May, is strongly reduced in June and only very little snow is left in July and August. This is in relatively good agreement with the snow depth climatology from Warren et al. (1999), who proposed a slightly larger snow depth of about 35 cm in May, 30 cm in June, 10 cm in July and 5 cm in August. However, Warrens results based on data from the period 1954–1991.

4 Discussing the impact of ice albedo spread among models

The large spread among simulated ice albedos in the CMIP5 models is one important contributor to the large uncertainties in model simulations of both present day climate and future climate conditions in the Arctic. Different ice albedos have a direct effect on the absorption of solar radiation at the ice surface. Given the same downward solar radiation at the surface, a smaller ice albedo will reduce the reflection and thus increase the net surface solar radiation. As a consequence, more ice is reduced, which further reduces the surface albedo. This relation between ice albedo and net solar surface radiation is clearly reflected in the CMIP5 models (Fig. 10). Net solar surface radiation is highly correlated with the ice albedo in the Central Arctic. The downward solar radiation is of course also influenced by absorption and reflection processes in the atmosphere. Thus, the downward solar surface radiation differs among models; summer (MJJA) average values vary between roughly 150 $\mathrm{W\,m^{-2}}$ and 205 $\mathrm{W\,m^{-2}}$. However, no clear relation exists between ice albedo and downward solar radiation.

Karlsson and Svensson (2013) argued that the ice albedo strongly affects the surface cloud radiative effect and thus not only the shortwave but also the longwave radiation. They stated that “models with a high sea-ice albedo have a smaller cloud albedo effect than those models having less reflective sea-ice surface”. This has also implications for the behavior of the models in a changing climate and the large spread in simulated ice albedos affects the response of the energy budget to climate change.

The strong impact of the albedo on the surface energy budget should affect sea ice conditions and indeed Karlsson and Svensson (2013) could show that the annual amplitude of average Arctic sea ice concentration is higher in models with low summer ice albedos than in models with high summer ice albedo. However, they did not find any significant relation between ice albedo and trends and absolute values of the ice concentration. We extended this analysis to ice thickness in the Arctic but we did not find any significant relation between September Arctic ice volume and summer sea ice albedo either. However, models with extremely low and high ice albedo tend to simulate thick and thin ice, respectively. This can also be seen comparing Figs. 3 and 5. Hodson et al. (2013) divided the CMIP3-model ensemble into two groups of models with high and low ice albedo and showed that the simulated mean Arctic ice volumes differed significantly between these two groups.

5 Summary and conclusions

This study focused on evaluating spatial and temporal variations of Arctic summer ice albedo in the CMIP5 models using satellite observations (CLARA-SAL) of surface albedo for the period 1982–2005.

The summer sea ice concentration and thickness distributions in the Arctic are strongly varying among the CMIP5 models. Even some of those models showing a realistic September Arctic ice extent do not necessarily simulate realistic spatial ice distributions. This leaves doubts about the reliability of sea ice development in future projections and indicates the importance of analyzing spatial fields in addition to integrative time series.

We extracted the ice albedo from the surface albedo by taking the ice concentration into account and assuming a constant surface albedo for the ice-free part. The summer sea ice albedo varies substantially among CMIP5 models and many models show large biases compared to the CLARA-SAL product. The CMIP5 ensemble mean, however, agrees relatively well to the satellite data.

The ice albedo is too uniformly distributed in most models and overestimated at the ice edge. This is very likely a deficiency in the parameterization of the albedo of the ice/snow system. In contrast to the ice albedo, the spatial pattern of the surface temperature shows an increase near the ice edge in most CMIP5 models. However, the response of the sea ice albedo to this increase is obviously not sufficient to simulate the observed large ice albedo decrease. Although, we did not analyze the albedo parameterizations of the individual models, many models seem to have a minimum ice albedo, which is too high compared to the ice albedo found by satellites and direct measurements (Perovich and Polashenski, 2012), and do not have at all or only simplistic melt pond parameterizations. Thus, only few models are able to simulate ice albedos below about 0.5. The overestimated albedo near the ice edge might lead to reduced summer ice melt in the models compared to reality due to an underestimated ice albedo feedback. This might contribute to the problem that many global models are not reproducing the observed rapid sea ice reduction in the last decade (Stroeve et al., 2007, 2012; Massonnet et al., 2012).

In addition, the CMIP5 models are not fully able to reproduce the albedo-evolution throughout the summer. The ice albedo is smaller in most CMIP5 models in June compared to CLARA-SAL. On the other hand, it starts to increase in the models already in August when it reaches its minimum in CLARA-SAL. To which degree the ice albedo parameterizations themselves are responsible for this shift in annual cycle remains unclear. We found that also surface temperature shows the same shift compared to ERA-interim, which might indicate that larger scale climatic conditions are responsible but it cannot be ruled out that too low (high) albedo in June (August) in the models contribute to the too warm (cold) conditions.

The summer sea ice albedo in CMIP5 models is governed by surface temperature and snow conditions, particularly during the period of melt onset in early summer and refreezing in late summer.

The summer surface solar radiation absorption of the ice covered Arctic areas is strongly affected by the ice albedo and strongly varying among CMIP5 models. The impact of the ice albedo on the sea ice conditions in the CMIP5 models is not clearly visible indicating the importance of other processes like e.g. large scale atmospheric and oceanic circulation patterns for the sea ice conditions. Furthermore, this relation might be masked by the fact that sea ice albedo is often used as tuning parameter to overcome other model shortcomings in the Arctic.

The results from this study do not necessarily indicate which model has the most realistic albedo scheme since the albedo is governed by parameters like surface temperature and snow conditions, which are affected by large scale model climate conditions. If a model is generally too cold (too warm) in the Arctic, we would expect a too high (too low) surface albedo in this model, which leads to positive feedbacks with even colder (warmer) conditions. The Arctic climate system can thus not correctly be simulated (others then with compensating errors) if the large scale atmospheric and oceanic circulation determining the input of mass, heat and momentum into the Arctic is not correctly simulated. Strong tuning of the albedo in order to achieve realistic Arctic ice and climate conditions in 20th century simulations might lead to unrealistic amplification rates in future simulations.

To further improve albedo parameterization, comprehensive observational data sets are needed to force the albedo scheme, test improvements and to evaluate the results.

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Table 1. Ice albedo trend for the period 1982–2005, averaged over 80–90° N. Trends that are significant at the 95 %-significance level are marked bold.

Trend per 24 yr	Jun	Jul	Aug	JJA
ACCESS1-3	−0.003	0.008	0.017	0.007
CanCM4	−0.010	−0.037	−0.018	−0.022
CanESM2	**−0.053**	**−0.102**	0	**−0.050**
CMCC-CESM	−0.030	−0.004	−0.008	−0.014
CNRM-CM5	−0.016	−0.001	0.009	−0.003
CSIRO-Mk3-6-0	**−0.018**	−0.007	−0.010	**−0.012**
EC-Earth	−0.052	−0.012	−0.013	−0.025
FGOALS-g2	**−0.027**	**−0.081**	**−0.079**	**−0.062**
GFDL-ESM2M	−0.024	−0.002	−0.012	−0.012
GFDL-ESM2M	−0.024	−0.002	−0.011	−0.012
GISS-E2-R	0	−0.003	0.034	0.01
HadCM3	0.003	0.005	0.004	0.004
HadGEM2-ES	−0.017	0.001	0.014	−0.001
INMCM4	−0.008	−0.011	−0.011	−0.010
IPSL-CM5A-LR	−0.026	−0.012	0.007	−0.010
MIROC5	−0.022	−0.009	**−0.022**	**−0.019**
MIROC-ESM	0.003	0.001	−0.011	−0.002
MPI-ESM-LR	0.002	−0.021	0.003	−0.005
MPI-ESM-MR	−0.010	−0.022	−0.010	−0.014
MRI-CGCM3	−0.065	**−0.103**	−0.069	**−0.078**
NorESM1-M	−0.006	−0.025	**−0.053**	**−0.028**
CMIP5 mean	**−0.019**	**−0.021**	**−0.012**	**−0.017**
CLARA-SAL	−0.008	−0.014	−0.038	−0.019

Table 2. Correlation between ice albedo and surface temperature, averaged over 80–90° N. Correlations that are significant at the 95 %-significance level are marked bold.

Correlation coeff.	May	Jun	Jul	Aug	JJA
ACCESS1-3	**–0.57**	**–0.79**	–0.21	–0.32	**–0.40**
CanCM4	**0.71**	**–0.44**	**–0.75**	**–0.77**	**–0.77**
CanESM2	**0.62**	**–0.75**	**–0.80**	**–0.72**	**–0.68**
CMCC-CESM	**–0.54**	**–0.89**	**–0.41**	**–0.74**	**–0.70**
CNRM-CM5	–0.34	**–0.68**	–0.10	–0.31	–0.13
CSIRO-Mk3-6-0	**–0.47**	**–0.88**	**–0.69**	**–0.76**	**–0.82**
EC-Earth	–0.35	**–0.92**	**–0.69**	**–0.63**	**–0.85**
FGOALS-g2	0.09	**–0.78**	**–0.83**	**–0.73**	**–0.85**
GFDL-CM3	**–0.68**	**–0.94**	–0.24	**–0.88**	**–0.89**
GFDL-ESM2M	**–0.60**	**–0.92**	**–0.62**	**–0.53**	**–0.82**
GISS-E2-R	**–0.72**	–0.26	0.12	**0.40**	0.15
HadCM3	**–0.95**	–0.27	0.16	–0.04	–0.02
HadGEM2-ES	**–0.64**	**–0.87**	**–0.75**	**–0.44**	**–0.66**
INMCM4	**–0.94**	**–0.55**	–0.33	0.26	0.07
IPSL-CM5A-LR	**–0.81**	**–0.94**	**–0.63**	**–0.81**	**–0.91**
MIROC5	0.02	**–0.98**	**–0.88**	**–0.94**	**–0.95**
MIROC-ESM	–0.33	**–0.95**	–0.01	**–0.93**	**–0.82**
MPI-ESM-LR	–0.01	**–0.66**	–0.11	–0.10	**–0.46**
MPI-ESM-MR	–0.27	**–0.51**	**–0.40**	–0.24	**–0.61**
MRI-CGCM3	**–0.72**	**–0.87**	**–0.78**	**–0.79**	**–0.91**
NorESM1-M	**0.52**	**–0.64**	**–0.58**	**–0.63**	**–0.77**
CMIP5 mean	–0.33	**–0.74**	**–0.45**	**–0.51**	**–0.61**
CLARA-SAL/ERAint	**0.53**	**–0.43**	–0.23	–0.38	**–0.61**

Table 3. Correlation between ice albedo and snow depth, averaged over 80–90° N. Correlations that are significant at the 95 %-significance level are marked bold.

Correlation coeff.	May	Jun	Jul	Aug	JJA
ACCESS1-3	0.14	**0.91**	−0.35	0.39	**0.48**
CanESM2	**0.43**	**0.72**	**0.88**	**0.73**	**0.82**
CNRM-CM5	0.37	**0.83**	−0.25	**0.61**	**0.47**
CSIRO-Mk3-6-0	**0.43**	**0.87**	−0.09	**0.60**	**0.72**
EC-Earth	−0.07	**0.78**	**0.87**	**0.73**	**0.85**
FGOALS-g2	**0.59**	**0.76**	**0.92**	**0.93**	**0.94**
GFDL-CM3	**0.47**	**0.87**	**0.63**	**0.71**	**0.88**
GFDL-ESM2M	**0.48**	**0.94**	0.28	**0.73**	**0.90**
HadGEM2-ES	0.30	**0.93**	**0.49**	**0.63**	**0.58**
INMCM4	**0.46**	0.05	−0.30	0.21	−0.04
MIROC5	0.18	**0.66**	**0.77**	**0.84**	**0.78**
MIROC-ESM	0.06	**0.77**	−0.17	**0.57**	**0.49**
MPI-ESM-LR	**0.43**	**0.69**	**0.84**	**0.86**	**0.82**
MPI-ESM-MR	−0.05	**0.62**	**0.94**	**0.88**	**0.90**
MRI-CGCM3	**0.40**	**0.84**	**0.93**	**0.96**	**0.93**
NorESM1-M	0.26	**0.52**	**0.78**	**0.80**	**0.71**
CMIP5 mean	0.31	**0.74**	**0.45**	**0.70**	**0.70**

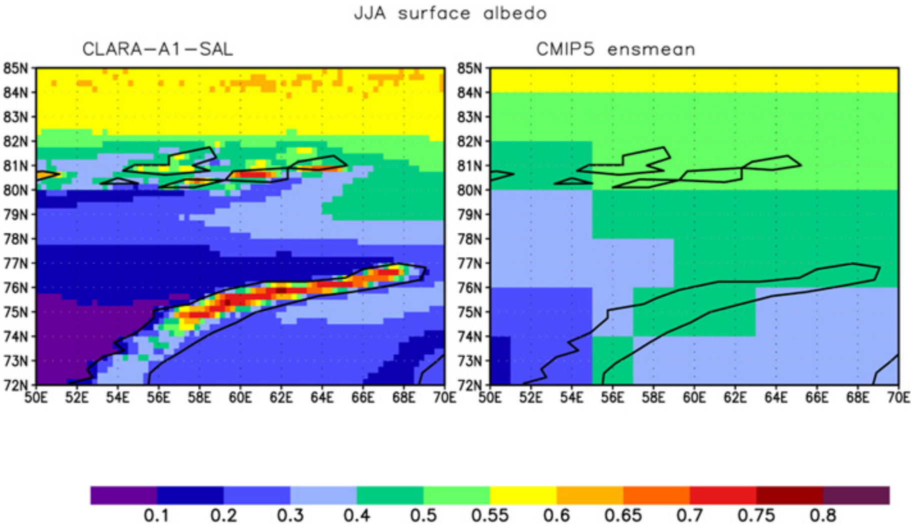

Fig. 1. Summer (JJA-average) surface albedo in the north eastern Barents Sea region, averaged over 1982–2005, in CLARA-SAL on a 0.25° × 0.25° grid and in the CMIP5 ensemble mean interpolated on a 2° × 2° grid.

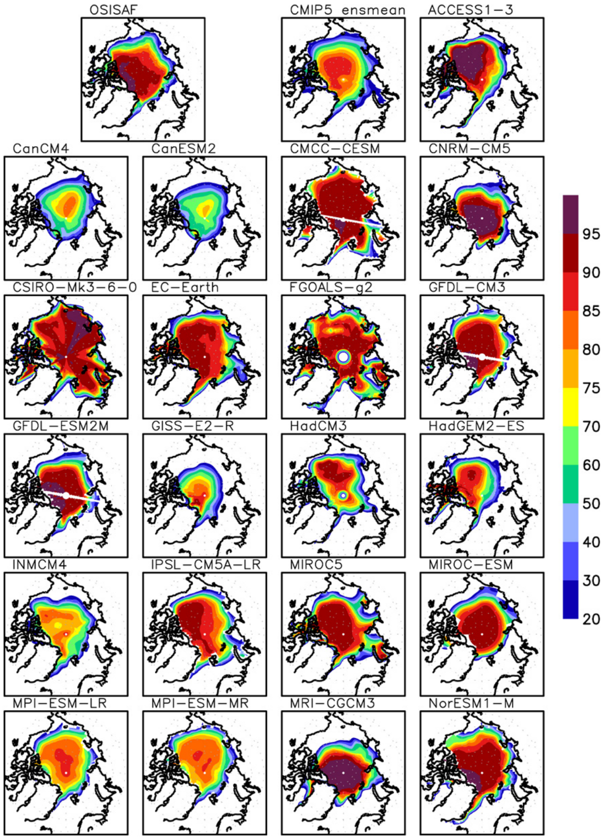

Fig. 2. September sea ice concentration in the OSISAF-satellite product, CMIP5 ensemble mean and individual CMIP5-models, averaged over the period 1982–2005.

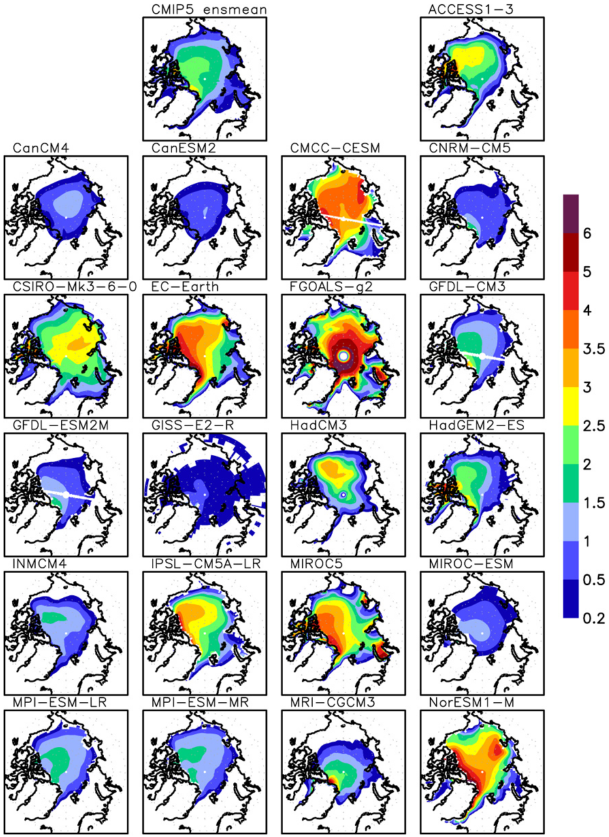

Fig. 3. September sea ice thickness in m in the CMIP5 ensemble mean and individual CMIP5-models, averaged over the period 1982–2005.

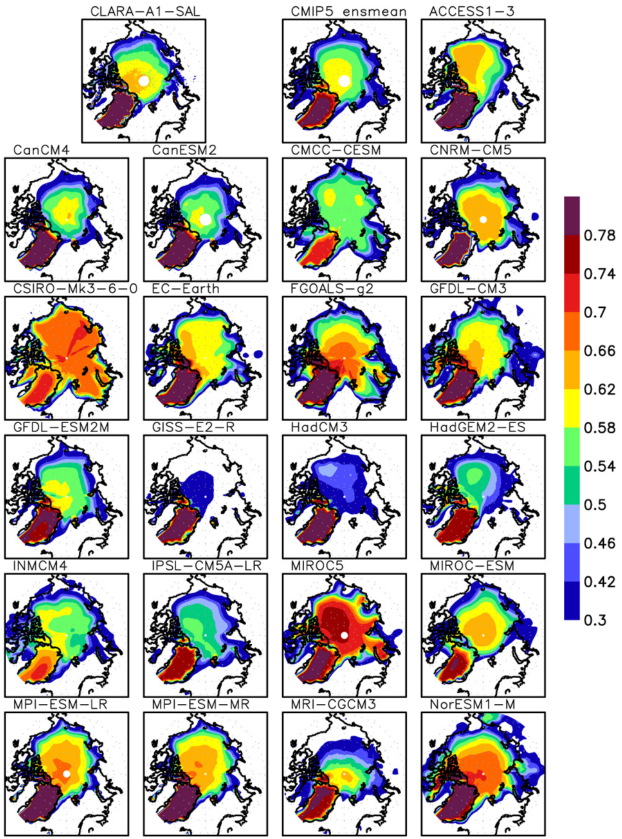

Fig. 4. Summer-averaged (JJA) surface albedo in CLARA-SAL, the CMIP5 ensemble mean and the individual CMIP5 models. Shown is the time average over the period 1982–2005.

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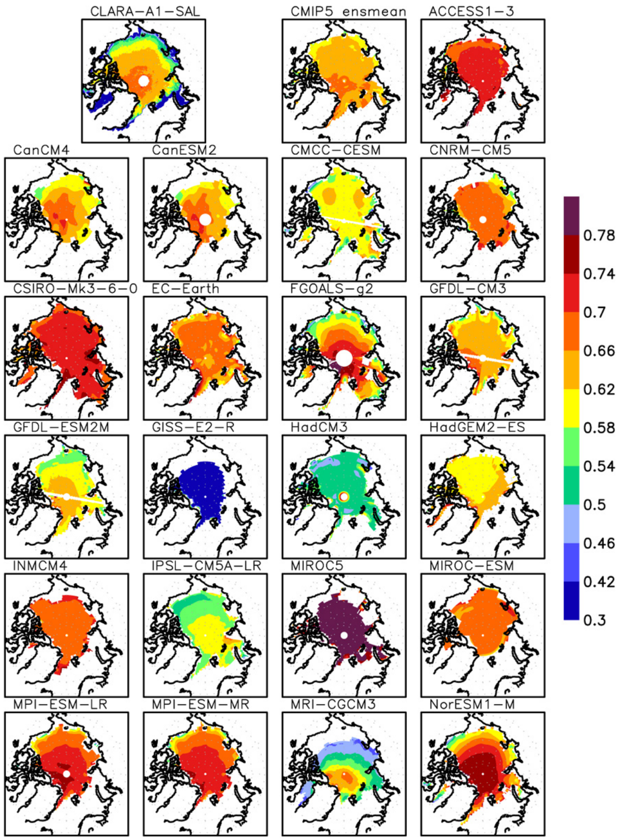

Fig. 5. Summer averaged (JJA) sea ice albedo, as derived from the satellite data and the CMIP5-model ensemble. Shown is the time average over 1982–2005.

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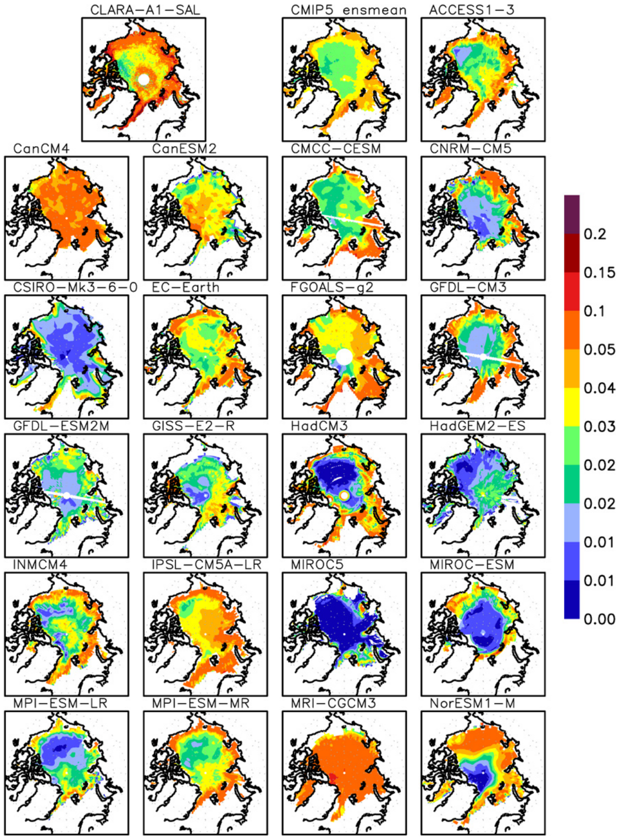

Fig. 6. Standard deviation of summer averaged (JJA) sea ice albedo in CLARA-SAL, the CMIP5 ensemble mean and the individual CMIP5 models. Shown is the time average over 1982–2005.

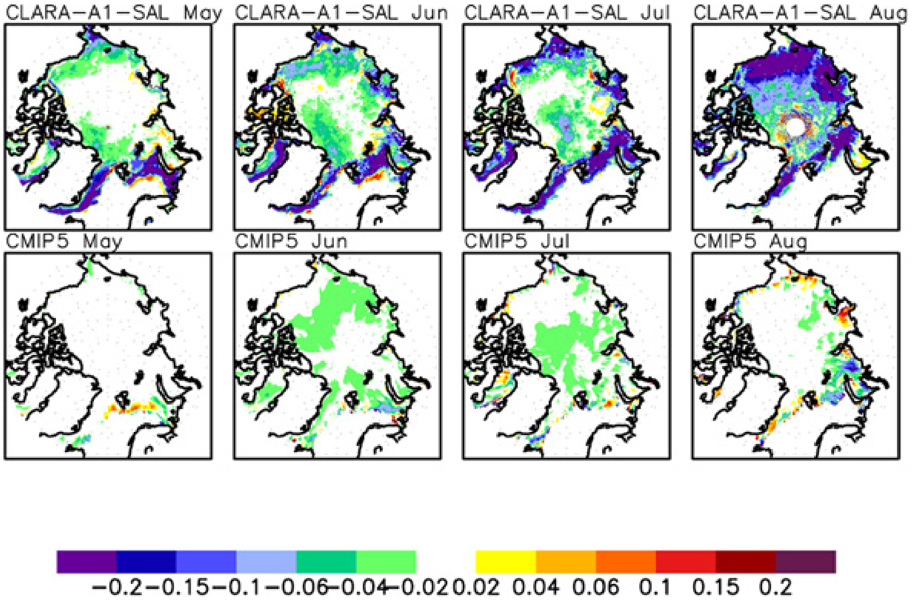

Fig. 7. Sea ice albedo trend for May, June, July and August in CLARA-SAL and the CMIP5 ensemble mean. Shown is the trend per 24 yr (1982–2005).

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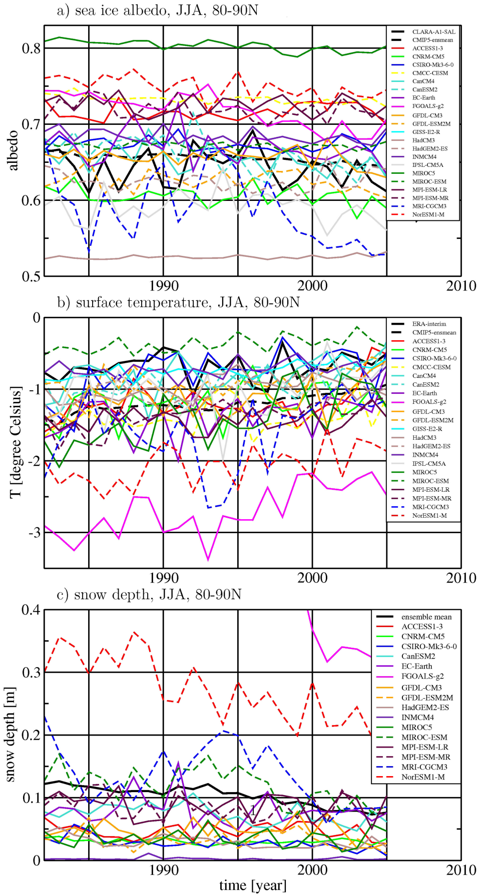

Fig. 8. (a): Summer averaged (JJA) ice albedo in the Central Arctic, averaged over 80–90° N for 1982–2005. **(b)** The same as **(a)** but for surface temperature. **(c)** The same as **(a)** but for snow depth on ice

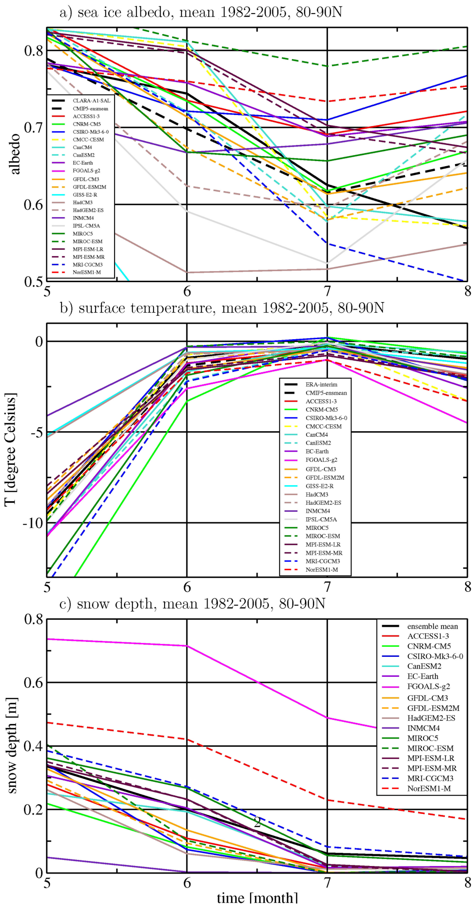

Fig. 9. (a) Time evolution of sea ice albedo through May to August, averaged over 80–90° N and 1982–2005. **(b)** The same as **(a)** for surface temperature. **(c)** The same as **(a)** for snow depth.

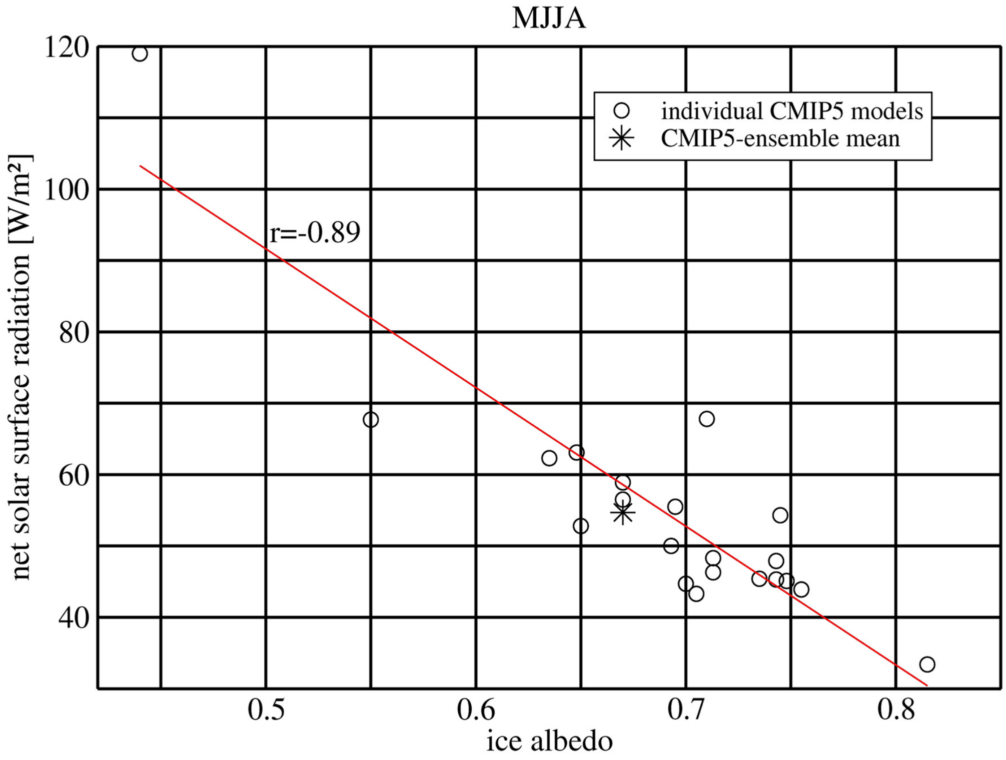

Fig. 10. Relation between summer (MJJA) mean sea ice albedo and net solar surface radiation of the ice covered area averaged over 80–90° N.