Factors affecting projected Arctic surface shortwave heating and albedo change in coupled climate models

Marika M. Holland and Laura Landrum

National Center for Atmospheric Research, Boulder, CO, USA

We use a large ensemble of simulations from the Community Earth System Model to quantify simulated changes in the twentieth and twenty-first century Arctic surface shortwave heating associated with changing incoming solar radiation and changing ice conditions. For increases in shortwave absorption associated with albedo reductions, the relative influence of changing sea ice surface properties and changing sea ice areal coverage is assessed. Changes in the surface sea ice properties are associated with an earlier melt season onset, a longer snow-free season and enhanced surface ponding. Because many of these changes occur during peak solar insolation, they have a considerable influence on Arctic surface shortwave heating that is comparable to the influence of ice area loss in the early twenty-first century. As ice area loss continues through the twenty-first century, it overwhelms the influence of changes in the sea ice surface state, and is responsible for a majority of the net shortwave increases by the mid-twenty-first century. A comparison with the Arctic surface albedo and shortwave heating in CMIP5 models indicates a large spread in projected twenty-first century change. This is in part related to different ice loss rates among the models and different representations of the late twentieth century ice albedo and associated sea ice surface state.

1. Introduction

Arctic sea ice has undergone dramatic reductions over the satellite era starting in 1979. These reductions have been largest in September, reaching a linear loss rate of approximately 12% per decade by 2011 [1]. In concert with the ice cover loss, the Arctic sea ice pack has thinned (e.g. [2]), become younger (e.g. [3]) and had an earlier
Figure 1. The zonal averaged warming amplification factor, defined as the change in zonal average temperature relative to the global mean temperature change, for a number of different models participating in CMIP5 (table 1). The change is computed as the average for 2080–2100 minus the average for 2006–2016. Results are shown for simulations run with the RCP8.5 forcing scenario for the twenty-first century. The asterisks on the right-hand side show the 70–90 N Arctic amplification factor for the different models, which range from 1.8 to 3.5. (Online version in colour.)

melt onset [4]. Climate models project these changes to continue as greenhouse gas concentrations rise, with the likelihood for ice-free Septembers occurring within this century (e.g. [5,6]). Changing sea ice conditions have implications for ice–ocean and ice–atmosphere heat and moisture exchange and as such have the potential to modify large-scale climate conditions.

Perhaps the most obvious of these implications is the influence that ice loss has on the surface shortwave energy budget. The resulting positive surface albedo feedback enhances Arctic warming relative to the global mean [7], which is a nearly universal feature of the projected climate response to rising greenhouse gas concentrations ([8]; figure 1). Why the range in polar amplification factors between coupled models is so great remains unclear. For the recent ice retreat, Perovich et al. [9] determined that considerable increases in surface shortwave absorption within the Arctic basin have occurred in response to sea ice area loss. This has been confirmed in a recent study [10], which indicates that, in addition to ice area loss, changes in the onset of surface melting and sea ice surface properties have contributed to a decrease in Arctic surface albedo and increase in net solar heating.

Ice cover decline has been most rapid in September and, consequently, the largest reductions in surface albedo occur after the peak in incoming shortwave radiation. While September conditions are indicative of the integrated melting over the season, the direct effect of September ice loss contributes little to enhanced Arctic shortwave absorption. Instead, smaller surface albedo reductions in June and July are likely to play an important role in enhanced net solar heating of the surface, because they occur at a time of higher solar radiation. The surface albedo reductions during these months include contributions from changes in both ice area and the surface state of the sea ice. The surface albedo of the ice undergoes large seasonal variations (e.g. [11]) as it transitions from a bright snow-covered surface to a ponded state. The timings of these transitions are related to the onset of surface melting, disappearance of the snowpack and initiation of pond formation. Changes in when these transitions occur have implications for the net surface shortwave budgets and general Arctic change.

These considerations argue for a better understanding of the changing surface albedo, and how this interacts with the time-varying solar insolation to modify the net surface shortwave budgets. The relative importance of different factors for determining changes in the net solar energy budget will probably change as the Arctic transitions from a perennial to a seasonal ice cover as predicted by many climate models for this century (e.g. [5,6]). As such, the evolution of relative factors over time is required in order to understand and quantify the strength of the surface albedo feedback.
Table 1. CMIP5 models used in analysis. Only a subset of the models is used to assess snow cover on sea ice as shown.

<table>
<thead>
<tr>
<th>model</th>
<th>institute ID</th>
<th>modelling centre/group</th>
<th>snow data</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCESS1–0</td>
<td>CSIRO-BOM</td>
<td>Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia</td>
<td>yes</td>
</tr>
<tr>
<td>ACCESS1–3</td>
<td></td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>BCC-CSM1.1</td>
<td>BCC</td>
<td>Beijing Climate Center, China Meteorological Administration</td>
<td>yes</td>
</tr>
<tr>
<td>BNU-ESM</td>
<td>GCESS</td>
<td>College of Global Change and Earth System Science, Beijing Normal University</td>
<td>yes</td>
</tr>
<tr>
<td>CanESM2</td>
<td>CCCMA</td>
<td>Canadian Centre for Climate Modelling and Analysis</td>
<td>yes</td>
</tr>
<tr>
<td>CCSM4</td>
<td>NCAR</td>
<td>National Center for Atmospheric Research</td>
<td>yes</td>
</tr>
<tr>
<td>CESM1-CAM5</td>
<td>NSF-DOE-NCAR</td>
<td>Community Earth System Model contributors</td>
<td>yes</td>
</tr>
<tr>
<td>CESM1-WACCM</td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>CNRM-CM5</td>
<td>CNRM-CERFACS</td>
<td>Centre National de Recherches Meteorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique</td>
<td>yes</td>
</tr>
<tr>
<td>CSIRO-Mk3–6–0</td>
<td>CSIRO-QCCCE</td>
<td>Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence</td>
<td>yes</td>
</tr>
<tr>
<td>GFDL-CM3</td>
<td>NOAA-GFDL</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory</td>
<td>yes</td>
</tr>
<tr>
<td>GFDL-ESM2M</td>
<td></td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>GFDL-ESM2G</td>
<td></td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>GISS-E2-H</td>
<td>NASA GISS</td>
<td>NASA Goddard Institute for Space Studies</td>
<td>no</td>
</tr>
<tr>
<td>GISS-E2-R</td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>HadGEM2-CC</td>
<td>MOHC</td>
<td>Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)</td>
<td>yes</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td></td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>INM-CM4</td>
<td>INM</td>
<td>Institute for Numerical Mathematics</td>
<td>yes</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>IPSL</td>
<td>Institut Pierre-Simon Laplace</td>
<td>no</td>
</tr>
<tr>
<td>IPSL-CM5A-MR</td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>IPSL-CM5B-LR</td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>MIROC5</td>
<td>MIROC</td>
<td>Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine–Earth Science and Technology</td>
<td>yes</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>MIROC</td>
<td>Japan Agency for Marine–Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo) and National Institute for Environmental Studies</td>
<td>yes</td>
</tr>
<tr>
<td>MIROC-ESM-CHEM</td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>MPI-M</td>
<td>Max Planck Institut für Meteorologie</td>
<td>yes</td>
</tr>
<tr>
<td>MPI-ESM-MR</td>
<td></td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>MRI</td>
<td>Meteorological Research Institute</td>
<td>yes</td>
</tr>
<tr>
<td>NorESM1-M</td>
<td>NCC</td>
<td>Norwegian Climate Centre</td>
<td>yes</td>
</tr>
</tbody>
</table>
Here, we examine these issues using a large ensemble of simulations from a state-of-the-art climate model, the Community Earth System Model 1 (CESM-CAM5), for the pre-industrial, twentieth and twenty-first century climate. The model and simulations are described in §2. Analysis methods to quantify changing sea ice seasonality and shortwave budgets are discussed in §3. Results on the timing of seasonal triggers, relationships to the surface albedo variations, and time-varying changes in the albedo and net shortwave budgets are described in §4. Comparisons of albedo projections from other climate models from the Coupled Model Intercomparison Project 5 (CMIP5; table 1) are presented in §5. A conclusion and discussion are provided in §6.

2. Climate model experiments

(a) CESM-CAM5 large ensemble

We make use of a large ensemble of simulations from the Community Earth System Model with the Community Atmosphere Model v. 5 (CESM-CAM5; [12]). This includes 30 ensembles that run from 1920 to 2080. For the twenty-first century, the RCP8.5 scenario forcing is used [13,14]. Results that quantify the timing of seasonal triggers rely on daily simulation output, which is available from these integrations.

The CESM is described in [15] and the large ensemble simulations are discussed in [12]. The model uses the CAM5 with a resolution of $0.9^\circ \times 1.25^\circ$ and 26 vertical levels. As discussed by Kay et al. [16], CAM5 has a better representation of Arctic cloud properties than earlier model versions. The ocean component [17] is based on the Parallel Ocean Program 2 (POP2; [18]). It uses a nominal $1^\circ$ resolution displaced-pole grid with 60 vertical levels. The land component, the Community Land Model 4 (CLM4; [19]), is run on the same grid as the atmospheric model. The sea ice model component is the Los Alamos National Laboratory Community Ice Code (CICE4; [20]) with some updates. In particular, it includes an improved shortwave radiative treatment. This includes multiple scattering radiative transfer that depends on inherent optical properties of the sea ice system [21], the deposition and cycling of black carbon and dust, and parametrized surface melt ponds [22]. These new model capabilities influence the surface albedo feedback [22] and have implications for the role of changing sea ice surface conditions on the net shortwave energy budgets as discussed here.

Previous work has indicated that CESM simulations (albeit with an earlier version of the atmosphere model, CAM4) show a good representation of the late twentieth century Arctic sea ice [23]. This includes a reasonable spatial distribution and basin average of ice concentration, ice thickness and timing of melt onset and freeze-up. The CESM-CAM5 Arctic sea ice extent annual cycle is also well simulated in the late twentieth century (figure 2a), and September ice extent trends from the large ensemble simulations bracket the observed ice loss over the satellite record (figure 2b). September sea ice undergoes significant loss in projections of the twenty-first century (figure 2b), reaching near ice-free conditions in September in the middle of the twenty-first century with the RCP8.5 forcing scenario. Significant internal variability is superimposed on this long-term ice loss with periods of decadal ice gains possible even during the twenty-first century (see also [25,26]).

(b) CMIP5 models

Simulations from the CMIP5 [27] are discussed in §5. This includes analysis of historical simulations for the late twentieth and twenty-first century projections with the RCP8.5 forcing scenario. Given that different models submitted different numbers of ensemble members, only single ensemble members are used in this analysis. Table 1 shows the CMIP5 models that are used in this study. The models used were selected based on their availability at the time that the analysis was performed. Note that one of the CMIP5 models shown in these results is the CESM-CAM5, which was also used for the large ensemble simulations.
3. Analysis methods

(a) Sea ice seasonality

As discussed by Perovich et al. [11], the Arctic sea ice albedo undergoes a large annual cycle with a number of distinct phases, including dry snow, melting snow, pond formation, pond evolution and autumn freeze-up. ‘Seasonal triggers’, such as the timing of melt onset, initiate the transition between these phases. The timing of these triggers and the length of the subsequent phase strongly affect the surface albedo evolution.

We assess changes in the seasonality of the sea ice by diagnosing a number of changes in the timing and length of these different phases as follows. We specifically focus on seasonality metrics, including snow melt onset and the length of the snow-free season, that can modify the net shortwave budgets by influencing the surface albedo during a time of high solar insolation. The length of the snow-free season is defined as the number of days within a calendar year that...
the snow on sea ice for a gridcell is less than 0.005 m in thickness. To establish snowmelt onset in the CESM-CAM5, we define the day of onset for each grid cell as the earliest day within the calendar year for which the change in daily snow thickness is negative (e.g. the snow is thinning). This is assessed from daily averaged snow thickness information that is smoothed with a 15 day running mean. Other definitions of melt season onset (for example, based on temperature criteria) are possible. Several possible definitions were considered here and found to give qualitatively similar results.

(b) Shortwave budgets

Models generally simulate increases in Arctic surface radiative heating during summer in future projections (e.g. [28,29]). This is largely due to enhanced surface shortwave absorption as a consequence of the albedo feedback (e.g. [7,30]). Here, we assess simulated changes in the Arctic surface shortwave budgets, including the relative importance of the changing sea ice areal coverage versus the changing albedo of the sea ice itself.

The net surface shortwave budget is equal to

$$\text{SW}_{\text{net}} = (1 - \alpha)\text{SW}_{\text{dn}}$$

(3.1)

where $\text{SW}_{\text{dn}}$ is the incoming shortwave and $\alpha$ is the surface albedo, which equals

$$\alpha = f_{\text{ice}}\alpha_{\text{ice}} + (1 - f_{\text{ice}})\alpha_{\text{ocn}},$$

(3.2)

for ice-covered seas. Here, $f_{\text{ice}}$ is the fractional ice area, $\alpha_{\text{ice}}$ is the albedo of sea ice and $\alpha_{\text{ocn}}$ is the ocean albedo. Following the method of Qu & Hall [31] for surface albedo changes, we separate changes in the net SW budget ($\Delta \text{SW}_{\text{net}}$) into contributions from changing surface albedo ($\Delta \text{SW}_{\text{net,\alpha}}$) and changing incoming shortwave ($\Delta \text{SW}_{\text{net,DN}}$):

$$\Delta \text{SW}_{\text{net}} = \Delta \text{SW}_{\text{net,\alpha}} + \Delta \text{SW}_{\text{net,DN}},$$

(3.3)

where

$$\Delta \text{SW}_{\text{net,DN}} = (\text{SW}_{\text{dn}}^n - \text{SW}_{\text{dn}}^0) \left(1 - \frac{\alpha^n + \alpha^0}{2}\right).$$

(3.4)

and

$$\Delta \text{SW}_{\text{net,\alpha}} = -\left(\frac{\text{SW}_{\text{dn}}^n + \text{SW}_{\text{dn}}^0}{2}\right) (\alpha^n - \alpha^0).$$

(3.5)

Equations are diagnosed at time $n$ relative to time 0, which is defined as the 1920–1950 average. For the CESM-CAM5 Large Ensemble, we focus on three time periods for comparing shortwave budgets: the late twentieth century (1990–2009 average), the mid-twenty-first century (2040–2059 average) and the late twenty-first century (2060–2079 average).

We further separate the changes in net shortwave associated with the surface albedo ($\Delta \text{SW}_{\text{net,\alpha}}$) into a component due to a changing ice albedo ($\Delta \text{SW}_{\text{net,\alpha_{\text{ice}}}}$),

$$\Delta \text{SW}_{\text{net,\alpha_{\text{ice}}}} = -\alpha'_{\text{ice}} \frac{\text{SW}_{\text{dn}}^n + \text{SW}_{\text{dn}}^0}{2},$$

(3.6)

and a component due to a changing ice fractional coverage ($\Delta \text{SW}_{\text{net,\alpha_f}}$),

$$\Delta \text{SW}_{\text{net,\alpha_f}} = -\alpha'_{\text{f}} \frac{\text{SW}_{\text{dn}}^n + \text{SW}_{\text{dn}}^0}{2},$$

(3.7)

where (following [31] for the albedo of snow-covered surfaces)

$$\alpha'_{\text{ice}} = f_{\text{ice}}'\alpha_{\text{ice}} + \frac{f_{\text{ice}}^0}{2} (\alpha_{\text{ice}}^n - \alpha_{\text{ice}}^0).$$

(3.8)
and

\[
\alpha_f' = \left( f_{\text{ice}}^n - f_{\text{ice}}^0 \right) \left( \frac{\alpha_{\text{ice}}^n + \alpha_{\text{ice}}^0}{2} - \alpha_{\text{ocn}} \right). \tag{3.9}
\]

We assume that the ocean albedo remains constant over time. Note that, for the CMIP5 analysis, we are not able to diagnose the shortwave heating contributions due to the ice albedo and ice area changes separately because ice albedo information is not generally available and cannot be accurately derived from the monthly average surface albedo and ice concentration values provided. Instead only the changes associated with the net albedo changes (equation (3.5)) and incoming shortwave changes (equation (3.4)) are diagnosed.

4. Results from the CESM-CAM5 large ensemble

(a) Changing sea ice seasonality

Within CESM-CAM5, the sea ice albedo is computed based on the inherent optical properties of snow, ice and ponds [21]. These specified optical properties coupled with the evolving sea ice state conditions give rise to the time-evolving prognostic albedo. The resulting albedo values show reasonable agreement with observations. For example, as shown in figure 3a for a location in the Beaufort Sea (in the vicinity of the Surface Heat Budget of the Arctic (SHEBA) drifting field campaign), the albedo undergoes a similar evolution to that discussed by Perovich et al. [11]. This includes a dry snow regime, with an albedo of about 0.84, a melting snow phase with a June averaged albedo of 0.71, a pond formation and evolution period with average July and August albedos of about 0.5 and a autumn freeze-up in which the albedos increase back to the dry snow values. These regimes arise from the simulated timing of transitions between different surface states and the specified optical properties associated with various surface conditions.

The model exhibits considerable interannual variability, particularly in the albedos during the ponded and freeze-up phases (figure 3b). The variations during the ponded phase are particularly important for the net shortwave heating, because they occur at a time of high solar insolation. Model biases influence the albedo simulation. In particular, as in an earlier version of CESM (the CCSM4 model), the simulations discussed here suffer from the incidence of ‘frozen summers’ in which the melt season never fully evolves [32]. This results in about 5% of the simulated years from 2005 to 2015 in the 30 ensemble members never dropping below an average July albedo of 0.6 for the point shown in figure 3. Other locations further north have a higher incidence of these ‘frozen summers’. The reasons for this are discussed further by Light et al. [32] and are related to ephemeral summer snowfall events. As in CCSM4, the sea ice albedo simulation here exhibits lower (and generally more realistic) summertime values when these ‘frozen summers’ are excluded from the analysis.

The timing of the transition between different phases of the surface ice state evolution and the length of those phases will strongly affect the sea ice surface albedo. Snow melt onset exhibits large interannual variability but becomes progressively earlier throughout the twentieth and twenty-first centuries within the CESM-CAM5 Large Ensemble simulations (figure 4a). For the observational period, from 1980 to 2010, the linear trend in the Arctic melt onset is about 2 days earlier per decade. While a direct comparison with satellite data is problematic because of different onset definitions (e.g. [23]), this is quite similar to the results of Markus et al. [4] that indicate a 2.5 days per decade earlier melt onset for the Central Arctic. Additionally, the satellite-derived onset trends are well within the scatter of the trends across the different large ensemble members, which range from an almost negligible 0.1 days per decade to a very sizable 4.2 days per decade earlier onset for the 1980–2010 period. The large range across simulated trends suggests an important role for internal variability over the observed period. On a longer period, over the twenty-first century, an ensemble mean trend of just over 2 days per decade earlier onset is simulated over an Arctic domain and the spread across ensemble members is considerably smaller with a range of trends from −1.6 to −2.4 days per decade.
The simulated earlier onset causes an earlier decline in the sea ice albedo transition from dry to melting snow conditions. It also contributes to a lengthened snow-free season for the Arctic sea ice, with a trend of over 20 days per decade over the twenty-first century (figure 4b). The earlier onset influences ponding on the sea ice and increased pond concentrations are simulated for the twenty-first century (figure 5). Note that these increases start from a reasonable late twentieth century state, and the CESM-CAM5 simulated pond concentrations are consistent with satellite-derived values [33] and with values from stand-alone sea ice models forced with observationally based atmospheric data (e.g. [34,35]) that use more sophisticated melt pond schemes (e.g. [35,36]) than that contained within CESM-CAM5.

(b) Changing Arctic shortwave budgets

The simulated changes in the seasonality of Arctic sea ice conditions and the ice areal coverage influence the net shortwave heating in the Arctic. While the sea ice surface changes generally result in a smaller albedo reduction than that associated with ice area loss, they occur at a time
Figure 4. Changing sea ice seasonality metrics averaged over an Arctic domain from 1920 to 2080 for the CESM-CAMS Large Ensemble. (a) The timing of melt onset in calendar days and (b) the length in days of the snow-free season. The white lines show the ensemble mean, whereas black lines show results from the different ensemble members.

Figure 5. The simulated Arctic regional average pond areal coverage concentration in per cent for June (lower line) and July (upper line) for 1920–2080 from the CESM-CAMS Large Ensemble. The solid lines indicate the ensemble mean and the dashed lines are one standard deviation from the mean. The values are for pond concentrations on ice between 0.65 and 1.39 m in thickness (the second sea ice category within the ice thickness distribution).
**Figure 6.** The simulated 30 year running trends in surface albedo versus net surface shortwave heating for 1920–2080 from the CESM-CAMS Large Ensemble. Values are averaged from 70 to 90 N. Each point shows a different value from the 30 ensemble members and 30 year trend realizations. The solid lines show the relevant regression. Different colours represent values for different months as indicated. (Online version in colour.)

of maximum solar insolation. As such, trends in the surface albedo during May and June have a larger effect on the absorbed shortwave radiation than the larger albedo changes that result from ice loss in September (figure 6). Based on a linear regression of the net shortwave radiation trends on the surface albedo trends, a 1% per decade reduction in the surface albedo is associated with an increase in net shortwave radiation of 2.7 W m\(^{-2}\) in June but only 0.5 W m\(^{-2}\) in September, consistent with the annual cycle of incoming solar radiation. To understand changing Arctic heating and the role of the surface albedo feedback, changes in the shortwave budget terms throughout the summer, including various seasonal factors that contribute to albedo reductions, are needed.

Changes in the surface heat budget for 70–90 N for the 2060–2079 average relative to 1920–1950 are shown in **figure 7**. As in many other coupled climate models (e.g. [28,29]), projected

**Figure 7.** Changes in the 70–90 N surface heat budget in the CESM-CAMS Large Ensemble for 2060–2079 relative to 1920–1950. Positive values indicate enhanced surface heating. White indicates net shortwave, black indicates net longwave and grey indicates net turbulent (latent + sensible) flux changes.
increases in summer shortwave heating occur, which act to warm the ocean and melt sea ice. These are in part compensated by a flux of heat from the surface to the atmosphere in the autumn and winter months, in the form of turbulent fluxes and net longwave radiation. This seasonality of surface heating changes contributes to an Arctic amplification signal, which has the largest surface air temperature increases during the autumn and winter months (e.g. [8,37]).

Figure 8 shows the changes in the surface shortwave budget terms for three different time periods. These are averages computed over the sea ice zone, which is defined here as the region in the 1920–1950 mean where Northern Hemisphere September ice concentration exceeds 10% areal coverage. Some consistent factors arise for all time periods. The net solar heating increases, as enhanced absorption associated with lower albedos (equations (3.5)–(3.7)) overwhelms reductions in surface incoming solar radiation (equation (3.4)). For the 1990–2009 average changes, the uncertainty associated with internal climate variability as diagnosed by the standard deviation across ensemble members is considerable, reaching about 40% of the ensemble mean monthly net shortwave increase for June to September. For the later time period changes, the greenhouse gas forced signal is more evident and the standard deviation of the net solar heat increase across ensemble members is less than 10% of the ensemble mean for the months of June to September.

The incoming radiation decreases for all months (figure 8), with particularly large reductions in July and August. The standard deviation in this decrease across ensemble members is about 15% of the ensemble mean for the 1990–2009 period and about 5–10% of the mean change for the later periods. The ensemble mean reductions are quite large during the later and warmer time periods, reaching about 29 W m\(^{-2}\) in July for the 2060–2079 ensemble average. Declining incoming solar radiation is consistent with increasing cloud optical depth in the warming climate (e.g. [38]) and reduced multiple scattering between the reflective surface and the cloud cover as the surface albedo declines (e.g. [39]).

The albedo-related shortwave budget changes typically increase through the late twentieth and twenty-first centuries (figure 8). For the 1990–2009 period, the net albedo-related increase varies considerably across ensemble members, with an across-member standard deviation of about 25–30% of the monthly ensemble mean change for June to September. For the later period changes, the across-member standard deviation becomes a considerably smaller 2–7% fraction of the mean. The changes associated with the albedo of sea ice (equation (3.8)) are larger earlier in the summer (June/July), due to changes in melt onset timing and snow cover and pond conditions. The maximum changes associated with reduced ice concentration (equation (3.9)) generally occur later (July and August). The relative importance of the various albedo terms changes considerably over the twentieth and twenty-first centuries. In the late twentieth/early twenty-first century (figure 8a), the changes in the albedo of the ice itself are responsible for over half of the increased shortwave absorption in June and July. The influence of the ice albedo change steadily decreases over the twenty-first century, with changes in the fractional coverage of the sea ice becoming increasingly important. By the 2060–2079 time period (figure 8c), when substantial ice area reductions occur throughout the summer months, the surface albedo reductions associated with ice concentration loss contribute over a 100 W m\(^{-2}\) increase in surface heating in July. By this time, changes in shortwave absorption associated with the ice albedo only remain important during June, but for that month still account for over 30 W m\(^{-2}\) of increased surface heating.

While the direct influence of ice albedo reductions on net shortwave budgets declines over the twenty-first century, they continue to influence early melt season conditions and are linked to ice area loss (and related surface albedo reductions) over the summer. For example, locations that exhibit large increases in shortwave heating due to ice albedo reductions in June are associated with the locations that show large reductions in ice concentration later in the season. This suggests that processes driving reductions in the albedo of the sea ice at the beginning of the melt season contribute to enhanced melting through the season and resulting late-summer reductions in ice concentration.
Figure 8. Monthly changes in the surface shortwave heat budgets in the CESM-CAM5 Large Ensemble for three different average periods, including (a) 1990–2009, (b) 2040–2059 and (c) 2060–2079. Differences are relative to the 1920–1950 mean. Changes in the net shortwave are shown by the black lines. These comprise changes in the net shortwave associated with ice area-related albedo changes (white), sea ice albedo changes (grey) and incoming radiation changes (black). To isolate the Arctic ice-covered region, the values are averaged over the area where the 1920–1950 averaged September ice concentration is greater than 0.1.

5. Results from other climate models

As shown above, simulations from the CESM-CAM5 Large Ensemble suggest that variations in the albedo of sea ice associated with changing snow and melt pond conditions have an important
Figure 9. Projected change in the annual average 70–90°N surface net shortwave radiation in W m$^{-2}$ relative to the 1980–2000 mean from a number of CMIP5 models. The values are smoothed with a 20 year running mean to reduce the influence of internal variability. The grey shading shows results from the CESM-CAM5 large ensemble simulations for reference. (Online version in colour.)

influence on changing polar surface heat budgets. Other climate models also project declines in the Arctic surface albedo and enhanced shortwave absorption. However, the magnitude of change varies considerably across models (figure 9), with some showing almost no net shortwave increase over the twenty-first century and others reaching almost 20 W m$^{-2}$ increased shortwave absorption annually. The CMIP5 multi-model scatter in the 2080–2099 averaged 70–90°N net shortwave increase is significantly correlated with the Arctic amplification factor (figure 1) at $R = 0.6$. Notably, the CESM-CAM5 Large Ensemble simulations are on the upper end of the projected shortwave heating increases, as shown by the grey shading in figure 9. CESM-CAM5 also has a relatively high Arctic amplification factor of 2.7.

The annual cycle of the change in net shortwave budget terms for a mid-twenty-first century (2045–2055) average is shown in figure 10. As in the CESM-CAM5 simulations, the CMIP5 models exhibit reductions in the net shortwave heating associated with solar insolation (figure 10c) that are generally overwhelmed by enhanced absorption associated with the surface albedo changes (figure 10b; note that surface albedo changes for CMIP5 models were not separated into changes due to ice area and changes due to ice albedo because sea ice albedo output was not available from all CMIP5 models). The CESM-CAM5 Large Ensemble simulations exhibit the largest net shortwave increase among the CMIP5 integrations due to large albedo-related changes with only modest compensation by the decreased incoming radiation. In general, the compensation between the albedo and incoming radiation terms differs among the models and can lead to different net shortwave changes. A dominant factor in the across-model scatter in projected Arctic net shortwave change is the different projections of surface albedo change. Indeed, for changes in the mid-twenty-first century, the across-model scatter in annual net shortwave change is correlated to the surface albedo-associated net shortwave term (equation (3.5), $\Delta S W_{\text{net, o}}$) at 0.9. This surface albedo term is in turn strongly related to different ice loss rates among the models (at $R = -0.7$ for July values at 2050). However, even for the same ice loss amount, the heating change can vary by a factor of more than 3 (figure 11).

Another important determinant of the multi-model scatter in albedo-related solar heating is the albedo simulated in the late twentieth century. Models with a higher late twentieth century Arctic surface albedo tend to simulate larger increases in albedo-related net solar heating for the same ice loss amount (figure 12). The late twentieth century Arctic albedo is strongly related to the albedo of the ice-covered surface and is indicative of the ice–ocean albedo contrast. It is not surprising that models with a larger contrast (and hence a large albedo change per loss of ice) exhibit larger warming for the same amount of sea ice loss. However, this has implications for the strength of the albedo feedback within models and projected Arctic change. Note that the
Figure 10. Changes in 70–90 N averaged net surface shortwave budget terms averaged for the mid-twenty-first century (2045–2055) relative to the 1980–2000 mean for a number of CMIP5 models. Shown are changes in (a) the net surface shortwave flux ($\Delta SW_{\text{net}}$), (b) the net shortwave flux associated with surface albedo changes ($\Delta SW_{\text{net,} \alpha}$) and (c) the net shortwave flux associated with incoming shortwave radiation ($\Delta SW_{\text{net, DN}}$). Results showing the range across the CESM–CAM5 Large Ensemble simulations are indicated by the thick vertical bars. (Online version in colour.)

CESM-CAM5 Large Ensemble (and CESM-CAM5 CMIP5) simulations are somewhat of an outlier in the relationship shown in figure 12. In particular, CESM-CAM5 late twentieth century surface albedos are well within the CMIP5 range (although at the higher end) but the July albedo-related shortwave increases are considerably higher than other CMIP5 models. The reasons for this are
unclear as there are many differences among the models. However the enhanced CESM-CAM5 response might in part be due to the presence of explicit and time-varying melt pond properties in CESM-CAM5 that are not included in most other CMIP5 models.

There are a number of reasons why models exhibit spread in late twentieth century Arctic surface albedo. These include differences in the surface albedo parametrizations themselves (and the possibility of tuning within those parametrizations) and differences in the simulated surface conditions, such as the timing of melt onset, snow conditions and melt pond properties. The albedo parametrizations do vary considerably across the models. For example, few CMIP5
models (e.g. [22,40,41]) include prognostic equations for melt pond volume within their simulations. Note that these parametrizations are simpler than newer pond model schemes that have been developed but not yet included and/or released from fully coupled model simulations (e.g. [35,42]). Both [43] and [44] have analysed variations in summer Arctic sea ice albedo for the late twentieth century within a number of CMIP5 models and find large scatter across the models. This is consistent with the different subset of CMIP5 models analysed here (figure 13a).

Similar to [44], we find that snow conditions on sea ice play an important role in the multi-model scatter of late twentieth century surface albedo (figure 13). These snow conditions differ substantially across the models ([45]; figure 13b), with some models retaining appreciable snow
during the summer months in contrast to observations (e.g. [46]). The scatter in snow thickness across the models is significantly correlated to their simulation of surface albedo for all months with correlations reaching 0.68 for June (figure 13c). This indicates that not only the albedo parametrizations themselves, but also the simulated climate properties (such as snow conditions) that are inputs to those parametrizations are important for the multi-model scatter. Improving these aspects of the simulated Arctic climate is important in order to narrow the uncertainty in the surface albedo feedback strength and its influence on projected change. This suggests that improvements in atmospheric processes and precipitation may be as important as sea ice model improvements for narrowing the scatter in future surface albedo change.

6. Conclusion

Analysis of the surface shortwave budget in the Arctic in the CESM Large Ensemble [12] gives insight into the seasonal influences of changes in surface solar insolation, ice area and ice albedo on the surface shortwave budget. Solar heating increases throughout the twenty-first century as decreased albedos lead to increased absorption despite decreases in solar insolation. The largest reductions in solar insolation occur in July and August, reaching an approximately 30 W m$^{-2}$ deficit in July for the 2060–2079 average. This amounts to over 40% of the total net surface shortwave increase.

Albedo-related shortwave budget changes counteract the reduced solar insolation. These are associated with both changing sea ice albedo and changing ice area. As the Arctic climate warms, the melt season starts earlier, leading to reductions in ice albedo as the ice surface becomes snow-free for a longer time period and enhanced melt ponding occurs. Changes in the sea ice albedo have a larger influence on the shortwave budget in early summer (June/July) and in the late twentieth/early twenty-first centuries, when over half of the increased June and July shortwave absorption is due to changes in sea ice albedo. Changes associated with reduced ice concentration, on the other hand, occur later in the summer (July and August) and increase in relative importance throughout the twenty-first century. By 2060–2079, the surface albedo reductions associated with ice concentration loss contribute about a 100 W m$^{-2}$ increase in surface heating in July. However, even for this later time period, changes in the ice albedo itself play an important role in enhanced heating at the beginning of the melt season in June. This helps to bring about the melt season and enhance the sea ice melt out and ice-area-related albedo reductions.

From an analysis of additional CMIP5 models, it is clear that large discrepancies exist in the evolution of Arctic surface albedo changes and net solar heating across the various models. This is, in part, associated with the well-documented scatter in the simulated ice area loss within these models (e.g. [5,6]). However, this is only part of the story. The models also differ considerably in the relative compensation between incoming shortwave reductions and albedo-related absorption increases, suggesting clouds and other factors play a role. They also differ in the late twentieth century simulated ice albedo and hence the ice to open water albedo contrast. This impacts both the relative importance of ice area loss for albedo change and how the albedo of the sea ice itself can evolve in the projected climate. Both of these factors contribute to the large scatter in projected net Arctic surface heat budgets.

These results have implications for the modelling and observational requirements needed to assess changing shortwave heat budgets and the surface albedo feedback in the Arctic. The inclusion within models of physically based treatments of melt pond evolution and snow metamorphosis effects on sea ice will allow for a better representation of the evolving sea ice albedo and its influence on associated feedbacks. Improved melt pond parametrizations (e.g. [35,42]) have recently been incorporated into sea ice model components and are likely to be used within the next phase of CMIP models. Arguably of equal importance to the sea ice representation are biases in the atmospheric forcing of sea ice, such as the phase and amount of precipitation, which affect the sea ice surface state and its future evolution. Model development efforts should target related atmospheric processes in order to improve model accuracy in projected Arctic climate change.
Regarding the observational record, our work suggests that previous studies that have estimated changing surface shortwave absorption in the Arctic based on the changing ice concentration alone are likely to provide an underestimate of the actual changes that have occurred. Work aimed at quantifying observed changes in the albedo of the ice-covered Arctic (e.g. \[10,47\]) is important to better understand the changing Arctic system.

**Acknowledgements.** We thank the CESM1(CAM5) Large Ensemble Community Project and supercomputing resources provided by NSF/CISL/Yellowstone for the simulation of and access to the large ensemble integrations. We acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups (listed in table 1) for producing and making available their model output. For CMIP the US Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. Finally, we would like to thank two anonymous reviewers who provided constructive input that led to improvements in this manuscript.

**Funding statement.** We acknowledge grants from the National Science Foundation (NSF OPP-0902068 and OPP-0902065).

**References**


47. Perovich D, Nghiem S, Markus T, Schweiger A. 2007 Seasonal evolution and interannual variability of the local solar energy absorbed by the Arctic sea ice-ocean system. J. Geophys. Res. 112, C03005.