Thank you to the three reviewers of this manuscript. I really appreciate your thoughtful and useful comments. Your reviews have helped improve the manuscript.

Interactive comment on "Sunlight, Clouds, Sea Ice and Albedo: The Umbrella Versus the Blanket" by Donald K. Perovich

Anonymous Referee #1

Received and published: 3 April 2018

Review of the manuscript entitled 'Sunlight, Clouds, Sea Ice and Albedo: The Umbrella Versus the Blanket' by Donald K. Perovich

This is a well-written and concise manuscript that in a very simple and straightforward manner investigates the coupled effects of cloud radiative feedback and ice-albedo feedback on the Arctic Ocean surface radiation budget. Its strength is precisely the simplification that are made that help promote an understanding of the coupled sea ice - atmosphere system, and stimulates ideas for further research. However, these simplifications might result in a fundamental flaw in the interpretation of the results, and it is not clear how to directly translate these results into real-world situations which are dominated by variability. I think the basic problem is that conditions are considered constant, and averaged, over a 24h period, while in fact there are significant diurnal variations, especially in the incoming shortwave radiation (see Fig. 2A), but also cloudiness.

The interpretation of the 24h-averages is that sunny skies cause less melting of sea ice surfaces than cloudy skies. However, during a clear sky 24h period, the shortwave radiation would promote positive net radiation balance (surface warming/melting) during daytime, and a negative balance (cooling/refreezing) during nighttime. Such day and night differences would have repercussion on what the actual break-even and zero-net albedos would be. The largest melting would appear to occur during situations when the daytime was clear sky and the nighttime was cloud covered. I don't think it would be so much more work to expand this discussion to include a basic consideration of diurnal effects, and it looks to me that the used dataset would support such analysis without too much added complexity.

I did perform an hourly calculation of break-even albedo. It was only in September that the sun actually set, but in all cases there were variations in incident sunlight, and break-even albedo from solar midnight to solar noon. For example, in June the break-even albedo ranged from 0.09 at solar midnight to 0.70 at solar noon. I have hourly results for all the cases, but I believe that the daily averages are the most meaningful and so that is what I used.

Furthermore, and I do not think it is necessarily needed to illustrate the point of the manuscript, is to expand it towards a more rigorous statistical analysis by incorporating more surface radiation balance datasets from various locations and time periods. There are quite a few such datasets.

I don't think there are many complete datasets in the Arctic ice pack. SHEBA included an entire year with detailed data for clouds, radiative fluxes, albedos, and ice mass balance - a rare combination. I do look forward to analyzing data from the upcoming MOSAiC field campaign.

Some specific comments:

Title: I would suggest including 'radiative budget' in some way in the title.
I added Radiative Budget to the title.

Abstract: This is a very short and 'stoic' abstract. If allowed by the journal, some more information and explanation could be included to make the abstract more selfexplanatory.
I agree that the abstract is short, but there is a maximum word count of 200.

page 1, line 25. In addition to cloud and albedo, there are also effects from the solar zenith angle. See e.g. Minnett (1999, doi:10.1175/1520-0442-12.1.147), which could be included as a citations in the manuscript.
I added this comment and the reference.

Table 1. Instead of 'na', consider including the positive or negative 'net zero albedo' values.
I followed Reviewer 3's suggestion and changed "na" to "None" and explained the meaning of "None" in the caption.

page 5, line 15. 'Net radiative cooling'. It would be good to clarify here and elsewhere that this is for a daily average.
I added daily average.

page 6, line 9. 'Five monthly pairs' is a very small dataset to justify Arctic wide conclusions.
I agree that it is important to be careful about extrapolating. The main point of the

page 6, line 22. From 'On the aggregate scale: : :' to the end of results: Consider moving this into the Discussion section.
Good idea. I moved this into the Discussion section.

page 7, line 3: 'Thus, sunny skies can delay the onset of melt in May and facilitate the onset of freezeup in September.' This general statement might need re-evaluation of diurnal effects are considered.
The general statement is still true when averaged over a day. It is also true for most hours of the day.

Interactive comment on “Sunlight, Clouds, Sea Ice and Albedo: The Umbrella Versus the Blanket” by Donald K. Perovich

Anonymous Referee #2

Received and published: 4 April 2018

This manuscript describes a set of calculations carried out to assess the magnitudes of surface radiative forcing for a sea ice cover during summer. The calculations present relative differences between cloudy and clear conditions for the 5 months typically spanning melt season in the Arctic. The data employed are taken from the SHEBA project.

The topic is interesting and relevant for TC readership. The presentation is clear, original, and insightful. I agree that sweeping simplifications were made, but for the purpose of illustrating how these concepts apply to the real world Arctic, they seem justified and appropriate. This is a simple, yet clear, illustration of how radiative forcing responds to clouds and surface albedo for a sea ice cover. It is true that the analysis is done exclusively for individual “snapshot” samples in time, but the conclusions are informative and instructional.

Minor comments: Abstract line 6: First sentence should state the domain you are consideringâ˘A˘ T“The surface radiation budget of the Arctic Ocean plays: : :”
Added “of the Arctic Ocean” to the sentence.

Abstract line 12: “other four months” is not clear, could say “other four months of the melt season” or explicitly spell them out “For May, June, August, and September, the net: : :”
Spelled out the four months as suggested.

p. 1 Line 18: Just improving prediction of ice extent? What about also improving prediction of ice thickness (specifically surface melt)?
Added “thickness, and surface melt” as suggested.

p. 3 line 10: “First,” p. 3 line 16: “to check” p.3 line 25: : “: : :defined as the albedo that, for a given radiative forcing, results: : :” p.3 line 27: “fall” p. 3 line 30: “: : :is greater than outgoing: : :”
I made all of these changes.

Fig. 2: The legends would be easier to decode if they were more consistent with the terminology used in the text. I recommend using “sunny” and “cloudy” for the color legend (it’s totally clear in the text which date is which condition, but it’s not intuitive in the figure and someone looking at the figure won’t really care what the date is, they just care about the sky conditions). Also, the line type legend would be clearer if stated as “incoming” and “outgoing”, as used in the caption and the text.
I changed the figure as suggested.

p. 6 line 15- 16: This sentence is a bit unclear. Does it mean “Under cloudy skies the net radiative flux is always less than for clear skies for leads and almost always less for ponds.”?
I changed this to “is usually less”

p. 8 line 18: can’t tell if the end of this sentence is a copy and paste accident or whether there are commas missing, but it needs to be rewritten
I did a little rewritting and fixed the punctuation.

p. 8 line 19: “: : :freezing in August, greatly reducing the pond fraction, and young ice: : :”
Rewrote this portion to improve clarity.

p. 10 line 15 - 16: Does this mean that one should expect to see significant differences in surface melt between cloudy and sunny conditions? This may merit a reference to Perovich et al. 2003, where this idea was posed.
I added a sentence and the Perovich et al., 2003 reference as suggested.

p. 10 line 17: Not sure what “favoring” means here? How about “For M, J, A, and S, the : : : albedo is greater than the break-even albedo, suggesting that sunny skies promote less surface melt”?
Changed the text as suggested.

And, finally, a question: Does this analysis suggest that a cloudy period is required (or even just hugely beneficial) to the initiation of melt in the early summer? If so, this might be a nice conclusion.
This is an interesting point. There is some speculation at this time that melt onset might be triggered by rain or fog. However, nothing definitive has been determined yet.

Interactive comment on "Sunlight, Clouds, Sea Ice and Albedo: The Umbrella Versus the Blanket" by Donald K. Perovich

Anonymous Referee #3

Received and published: 16 April 2018

The manuscript presents an insightful analysis on the role of sunny and cloudy skies in the surface radiation budget as the albedo seasonally evolves. The effect of changing sea ice conditions on the net radiative flux was investigated by comparing sea ice conditions in the Beaufort Sea in 1998 and 2007. The main findings demonstrate that sunny skies had a lower net radiation flux in May and September, while cloudy skies had a lower net radiative flux in June-August in 1998. For 2007, cloudy conditions had a smaller net radiative flux than sunny conditions in June-September due to increased melt pond and open water coverage. The results are informative to the sea ice and broader communities, and hint at the changing sensitivity of the sea ice cover to atmospheric conditions and its feedback on the surface radiation budget in a changing Arctic system.

The manuscript is well-organized, the methodology and assumptions clearly described and justified, and the conclusions well-supported by the results. Please find suggestions below that I hope the author will find useful:

Pg. 1, Abstract: Similar to the comment for the conclusion, it would be helpful to include 1-2 sentences describing how the results relate to the broader picture of sea ice-atmosphere interactions in a changing Arctic.
I added a paragraph to the Conclusions expanding on the implications

Pg. 1, Line 12: Which four months?
Spelled out the four months as suggested.

Pg. 1, Line 25: Typo here and throughout the text for "Intrieri."
I apologize for the misspelling. I corrected the spelling throughout the text.

Pg. 3, Lines 8-9: "It was challenging..." How sensitive are the zero net and break-even albedo values to 24 hours of slightly vs. highly variable conditions?

Pg. 3, Lines 10-16: It would be useful to include the cloud cover and type if that information is available.
There is detailed information from the cloud lidar and radar. However, there is a not a description that is suitable for this paper.

Pg. 3, Line 16: Typo "to check."
Typo corrected

Pg. 3, Line 19: Please enumerate all equations.
Question to the editor: Should all equations be numbered, or just those that are specifically mentioned.

Pg. 3, Line 27: Typo in "fall."
Typo corrected

Pg. 4, Table 1: Although it's already described in the text, it would be helpful to include a brief sentence in the table caption explaining "na."
I changed na to "None" and added a sentence to the table caption explaining the meaning of "None."

Pg. 8, Line 17-18: Please clarify "In 2007,... bare ice."
Clarified the sentence by minor editing.

Pg. 10, Conclusions: It would be helpful to expand on the implications of the results here. How do they relate to the big picture? What was learned by comparing the 1998 and 2007 sea ice conditions?
I added a paragraph to the Conclusions expanding on the implications

Sunlight, Clouds, Sea Ice~~, and~~ Albedo and the Radiative Budget: The Umbrella Versus the Blanket

Donald K. Perovich

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Abstract. The surface radiation budget of the Arctic Oceanplays a central role in summer ice melt and is governed by clouds and surface albedo. I calculated the net radiation flux for a range of albedos under sunny and cloudy skies and determined the break-even value, where the net radiation is the same for cloudy and sunny skies. Break-even albedos range from 0.30 in September to 0.58 in July. For snow covered or bare ice, sunny skies always result in less radiative heat input. In contrast, leads always have, and ponds usually have, more radiative input under sunny skies than cloudy skies. Snow covered ice has a net radiation flux that is negative or near zero under sunny skies, resulting in radiative cooling. Areally averaged albedos for sea ice in July result in a smaller net radiation flux under cloudy skies. For ~~the other four months~~May, June, August and September, the net radiation is smaller under sunny skies.

1. Introduction

The Arctic sea ice cover has undergone a major decline in recent decades. There has been a reduction in ice extent (Meier et al., 2014; Parkinson and DiGirolamo, 2016), ice thickness (Kwok and Rothrock, 2009; Laxon et al., 2013; Lindsay and Schweiger, 2015), and a shift towards younger ice (Maslanik et al., 2011). This younger, thinner ice cover is more vulnerable to forcing from the atmosphere and ocean. Understanding the feedbacks and forcing driving these changes is critical to improving predictions of ice extent, thickness, and surface melt.

Longwave and shortwave radiation are primary drivers in the surface heat budget during summer melt (Persson et al., 2002). The surface radiative balance consists of contributions from incoming shortwave radiation, reflected shortwave radiation, incoming longwave radiation, and outgoing longwave radiation. Clouds have a major impact on both the incoming longwave and shortwave radiative fluxes. In the winter, the impact is straightforward: clouds warm the surface. The situation in the summer is more complex with clouds playing two opposing roles. They act as an umbrella, cooling the surface by reducing the incoming shortwave radiation. They also act as a blanket, warming the surface by increasing the incoming longwave radiation. Which effect dominates depends on the type of clouds, the solar incidence angle (Minnett, 1999) and the albedo of the surface. Previous work by ~~Interieri~~Intrieri et al. (2002) used data from the Surface Heat Budget of the Arctic Ocean (SHEBA) field campaign (Perovich et al., 1999; Uttal et al., 2002) to show that for most of the year clouds acted to warm the surface, but there was a period in summer when clouds cooled the surface.

Here we further explore the impact of clouds on the radiative balance from the perspective of ice surface conditions and albedo during SHEBA. As the melt season progresses from May through September, the ice surface conditions and the albedo change, influencing the net radiation balance. Figure 1 shows the evolution of the ice cover and the albedo from May through September including pre-melt, the melt season, and fall freezeup. Prior to melt the surface is a mix of snow covered ice and open water. During melt, it is a complex, evolving matrix of bare ice, melt ponds, and open water. The albedos of these surfaces range from 0.07 for open water (Pegau and Paulson, 2001) to 0.85 for snow covered ice (Perovich et al., 2002a). Significant temporal evolution of the albedo occurs during this period, along with a great increase in spatial variability. We will explore the impact of these changes in surface albedo on the net radiative forcing for sunny and cloudy sky conditions.

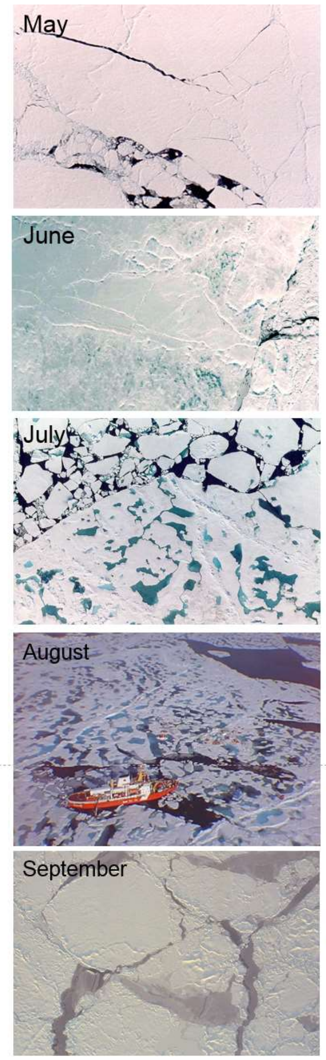

Figure 1. Aerial photographs showing the evolution of ice conditions from pre-melt in May through melt in June, July, and August, and freezeup in September.

2. Methods

I used data from the SHEBA field campaign (Uttal et al., 2002) to compare the net radiative forcing for sunny and cloudy skies for different surface conditions and albedos. The SHEBA dataset contains a complete observational record of the radiative fluxes (Persson et al., 2002), cloud conditions (~~Interieri~~Intrieri et al., 2002), and ice conditions and albedo (Perovich et al., 2002a, b). The focus of the prior work and this study, was on radiative fluxes and the relatively small turbulent fluxes were not considered (Persson et al., 2002; ~~Interieri~~Intrieri et al., 2002). Using these datasets, I selected pairs of 24-hour-long periods of sunny and cloudy conditions for each month from May through September, with the pairs as close together in time as possible. It was challenging to get a 24 hour, complete solar cycle of uniform sky conditions, particularly for sunny skies in July and August when clouds are pervasive.

The selection of cloudy and sunny pairs from the complete summer SHEBA database was a three-step process. First~~,~~ values of the incoming longwave and shortwave radiation (Persson et al., 2002) were examined. Periods of relatively small incoming shortwave and large incoming longwave were identified as potential cloudy periods, while large incoming shortwave and small incoming longwave were possible sunny periods. The cloud properties of these periods were then examined using the SHEBA cloud data browser of the NOAA Earth Systems Research Laboratory (https://www.esrl.noaa.gov/psd/arctic/sheba/browser/index.html). This database has a complete record of radiometer and lidar cloud retrievals from SHEBA. The final step was to check the qualitative description of sky conditions recorded in logs by observers in the field during the experiment. Table 1 lists the selected periods.

For each of the selected cases the net radiation flux was calculated using

$$F_{net} = (1-\alpha)S + L^{\downarrow} - L^{\uparrow} \quad , \qquad (1)$$

where S is the incoming shortwave radiation, $L^{\downarrow}$ is the incoming longwave radiation, $L^{\uparrow}$ is the outgoing longwave radiation, and α is the albedo of the surface. The sign convention is positive to the surface (incoming). Values observed during the SHEBA experiment (Uttal et al., 2002) provide the radiation fluxes (Persson et al., 2002) and the albedos (Perovich et al., 2002a).

To explore the impact of albedo we calculated a zero net albedo (α_o) and a break-even albedo (α_e). The zero net albedo is defined as the albedo that for a given radiative forcing results in a value of $F_{net} = 0$.

$$\propto_o = \frac{\left[S + L^{\downarrow} - L^{\uparrow}\right]}{S}$$

For albedos greater than α_o, there is net radiative cooling. There are radiative forcings where α_o does not fall~~s~~ within the allowable albedo range of 0 to 1. For example, in early spring, the incoming shortwave is small, skies are often sunny and the outgoing longwave is larger than the incoming longwave, giving a negative value of α_o. This means the net radiation is negative regardless of albedo. In contrast, if the incoming longwave is greater tha~~t~~n outgoing, then α_o will always be greater than one and the net radiation will always be positive regardless of the albedo.

Table 1. Summary of monthly sunny / cloudy pairs including longwave and shortwave fluxes (W m^{-2}), break-even albedos, and zero net albedos. $L^{\downarrow}$ and $L^{\uparrow}$ are the incoming and outgoing longwave radiation, and S is the incoming shortwave. A value of none for zero net albedo means that there is no physically realistic albedo (between 0 and 1) that gives a radiative balance of zero.

Start	End	Sky conditions	Break-even albedo	Zero net albedo	$L^{\downarrow}$	$L^{\uparrow}$	S
May			0.40				
5/24/98 0:00	5/24/98 24:00	Clear		0.80	205	275	345
5/29/98 0:00	5/29/98 24:00	Cloudy		~~na~~None	320	314	219
June			0.54				
6/15/98 0:00	6/15/98 24:00	Clear		0.82	231	301	389
6/16/98 16:00	6/17/98 16:00	Cloudy		~~na~~None	315	308	218
July			0.58				
7/25/98 13:00	7/26/98 13:00	Clear		0.83	265	313	284
7/22/98 0:00	7/22/98 24:00	Cloudy		~~na~~None	320	316	161
August			0.38				
8/27/98 10:00	8/28/9810:00	Clear		0.73	258	294	132
8/26/98 3:00	8/27/98 3:00	Cloudy		0.95	303	308	81
September			0.30				
9/4/98 20:00	9/5/98 20:00	Clear		0.63	267	293	71
9/2/98 10:00	9/3/98 10:00	Cloudy		0.81	294	303	47

The break-even albedo is the albedo where the net radiation for cloudy skies (subscript *c*) is the same as sunny skies (subscript *s*).

$$F_{netc} = F_{nets}$$

$$(1 - \propto_e)S_s + L_s^{\downarrow} - L_s^{\uparrow} = (1 - \propto_e)S_c + L_c^{\downarrow} - L_c^{\uparrow}$$

Solving for α_e gives

$$\alpha_e = 1 - \left[\frac{L_c^{\downarrow} - L_s^{\downarrow} - L_c^{\uparrow} + L_s^{\uparrow}}{S_s - S_c}\right]$$

For albedos greater than the break-even albedo, sunny skies have a smaller net radiation than cloudy skies. If the albedo is less than the break-even value, the net radiation is smaller for cloudy skies.

3. Results

Figure 2 shows one of the sunny (June 15) and cloudy (June 17) sky data pairs. There is very little difference in the outgoing longwave as the surface was near 0°C in both cases. The incoming longwave is smaller at all times for the sunny skies, with a sunny sky daily average of 230 Wm^{-2} compared to 315 Wm^{-2} for cloudy skies. The sunny sky incoming shortwave radiation is 1.5 to 2 times the cloudy sky values during the day, with a daily average incoming shortwave of 388 Wm^{-2} for sunny skies and 218 Wm^{-2} for cloudy skies.

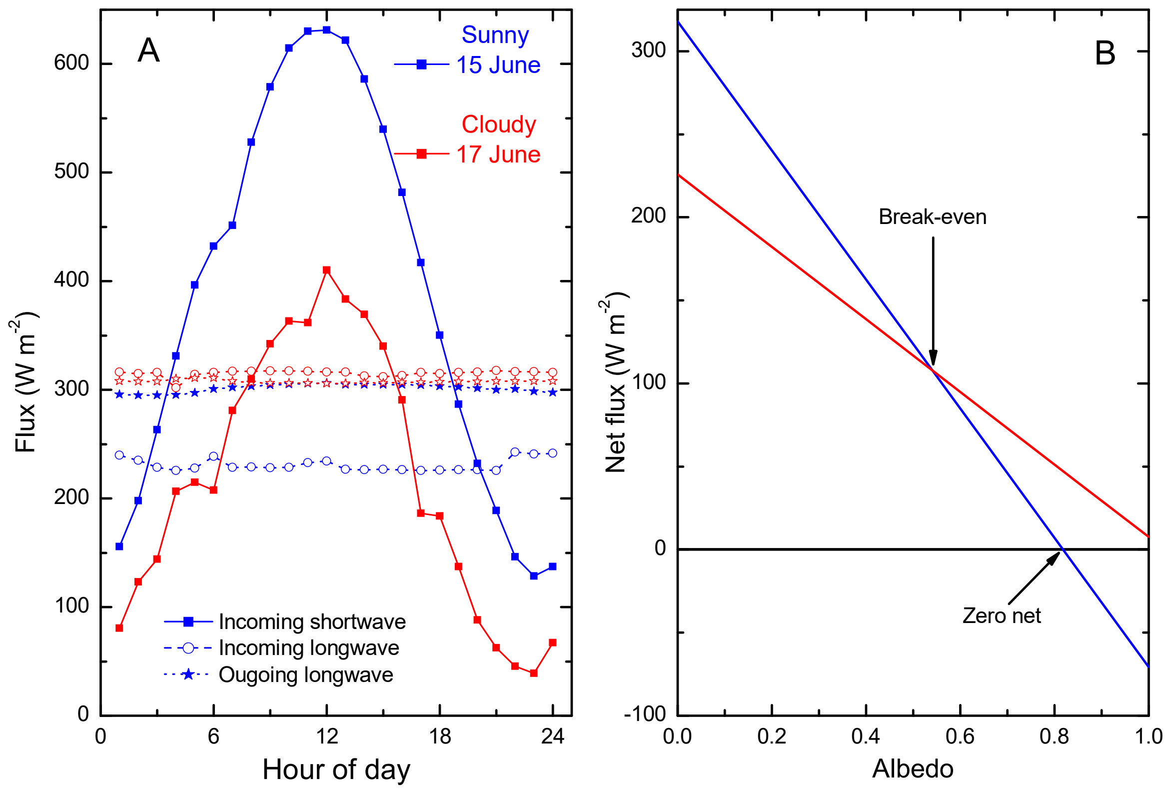

Figure 2. Results from sunny (15 June) and cloudy (17 June) skies: A) Hourly values of incoming longwave and shortwave radiation and outgoing longwave. B) The net radiation as a function of albedo with the break-even and zero net albedos indicated.

The net radiation flux as a function of albedo (Equation 1) is plotted in the Figure 2B. The slope of the sunny sky line is steeper than the cloudy sky line because the incoming shortwave is larger. The sunny and cloudy lines intersect at a break-even albedo of 0.54. For albedos larger than 0.54 the net radiation flux is smaller for sunny skies than cloudy skies. For sunny skies, the zero net albedo is 0.82 and larger albedos result in a daily average net radiative cooling of the surface. This implies that dry snow, with an albedo of about 0.85, would experience radiative cooling under the sunny sky conditions. For cloudy skies, the net radiation flux is always positive, regardless of the albedo.

Table 1 summarizes results for the sunny/cloudy pairs selected for each month from May through September. The dates, sky conditions, daily averaged shortwave and longwave radiation, and zero net albedos are reported for each day, along with the break-even albedo for each month. Break-even albedos range from a low of 0.30 in September, when the incoming shortwave is small, to a peak value of 0.58 in July. Under sunny skies, there is a physically possible zero net albedo for every month. In May, June, and July values are 0.80 to 0.83 implying that snow covered ice could experience a slight radiative cooling. In August and September, when the incoming shortwave radiation is smaller, the sunny sky zero net albedos are 0.73 and 0.63 respectively. For cloudy skies, only September has a physically possible value (0.81) for the zero net albedo.

The sunny / cloudy sky impact on different ice types is examined in Figure 3. The sunny minus cloudy average daily net radiation for the five monthly pairs is plotted as a function of albedo. The slope of the line depends primarily on the difference between the sunny and cloudy incoming shortwave radiation. The steepest slope is in June when the incoming shortwave is the largest and the shallowest is in September when the incoming shortwave radiation is smallest. Also plotted are the lines denoting typical albedos (Pegau and Paulson, 2001; Perovich et al., 2002a) for leads (α_w= 0.07), bare ice (α_i = 0.65), and snow (α_s = 0.85) plus a shaded box showing the range of pond albedos (α_p = 0.15 to 0.40). Under cloudy skies, the net radiative flux is always less for leads and is usually ~~almost always~~ less for ponds. For light blue ponds in May, August, and September there is little difference in net radiation between cloudy and sunny skies. In contrast, the net radiative flux is always less under sunny skies for bare ice and snow and is substantially less in May and June.

Break-even albedos for the five monthly pairs are plotted in the insert. Values increase from May to June, reach a maximum in July, and then decrease in August and September. The July maximum in break-even albedo is largely due to a reduced contrast between sunny and cloudy incoming longwave radiation compared to June values.

3. Discussion

On the aggregate scale the ice cover is an ensemble of surface conditions including snow covered ice, bare ice, ponds, and leads, with significant spatial variability and temporal evolution. The impact of sunny and cloudy skies on the net radiation flux for the aggregate scale ice cover depends on the aggregate scale albedo α_g, which is a function of the composition of the ice cover:

$$\propto_g = \propto_{si} A_{si} + \propto_y A_y + \propto_p A_p + \propto_w A_w$$

The area fractions of snow covered and bare ice (A_{si}), ponded ice (A_p), leads (A_w), and young ice (A_y) (Table 2) were determined from aerial photographs from May through September during the SHEBA experiment (Perovich et al., 2002b) The albedos of these surface types were measured throughout the summer (Perovich et al., 2002a).

Aggregate scale albedos for SHEBA range from a minimum of 0.50 in July to a maximum of 0.82 in May. The net radiation flux on the aggregate scale is smaller for sunny skies than cloudy skies in May, June, August, and September. Only July has a net radiation flux greater for sunny skies than cloudy. The 10% higher net radiation for sunny skies is due to the small value of the aggregate-scale albedo and to the reduced difference between sunny and cloudy sky incoming longwave radiation. July is also the period of the largest net radiative flux for both sunny and cloudy skies. The net radiative flux is always positive for cloudy skies. For the May and September cases, the aggregate scale net radiative flux is negative under sunny skies. Thus, sunny skies can delay the onset of melt in May and facilitate the onset of freezeup in September.

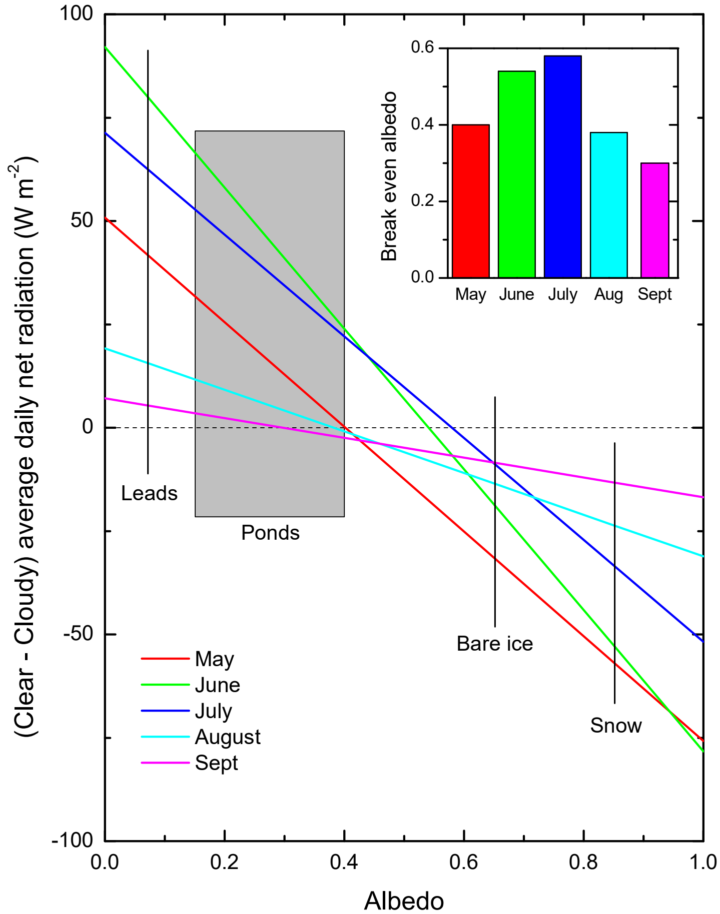

Figure 3. Sunny minus cloudy average daily net radiation as a function of albedo. The albedos of leads, ponds, bare ice, and snow are plotted for reference. The insert shows the break-even albedo for each monthly sunny/cloudy pair.

~~3. Discussion~~

These results indicate that for the aggregate scale ice cover during SHEBA, the net radiation flux is smaller under sunny skies compared to cloudy for every summer month except July. These results are for the ice around a ship in the Beaufort Sea drifting northward from 76º N in May 1998 to 79º N in September 1998. The advantage of using this case is that there are extensive data on the state of the ice cover, cloud conditions, and radiative fluxes. It is possible, with some simplifying assumptions, to extrapolate the results of this study. For example, assuming the cloud properties remain the same and changing the latitude would change the incoming shortwave radiation and change the break-even albedo. Moving to higher latitudes decreases both, making sunny skies more beneficial to maintaining the ice cover. Changes in the timing of the onset dates of melt and freezeup, as well as changes in the age of the ice, also influence the evolution of albedo and consequently the sunny / cloudy sky balance. Net radiation is less under sunny skies for changes that result in more snow covered or bare ice. Changes increasing ponds and leads favor cloudy skies for smaller net radiation.

We can explore the potential impact of changing ice conditions on the aggregate scale by comparing SHEBA in 1998 to the same region in 2007, which had a record summer minimum ice extent, with significant ice loss in the Beaufort Sea. The 2007 ice concentration (NSIDC-5001) and pond fraction (Rosel et al., 2012) were determined from satellite data at the same locations as the 1998 SHEBA cases in Table 1. The area fractions and areally averaged albedos for the two years are summarized in Table 2 and plotted in Figure 4.

Table 2. Monthly aggregate-scale ice cover composition and albedo from May through September in 1998 and in 2007.

	Net radiative flux (W m-2)											
Date	Sunny	Cloudy	Areally averaged albedo	Break even albedo	Snow / ice fraction	Snow / ice albedo	Lead fraction	Lead albedo	Pond fraction	Pond albedo	Young ice fraction	Young ice albedo
1998												
May	-7.1	45.6	0.82	0.40	0.97	0.84	0.03	0.07	0		0	
June	48.6	74.6	0.69	0.54	0.93	0.73	0.03	0.07	0.04	0.35	0	
July	93.9	84.2	0.50	0.58	0.73	0.63	0.05	0.07	0.22	0.17	0	
August	17.9	28.6	0.59	0.38	0.80	0.72	0.18	0.07	0.02	0.40	0	
September	-0.6	7.8	0.65	0.30	0.72	0.84	0.13	0.07	0		0.15	0.20
2007												
May	-15.0	40.5	0.84	0.40	1.00	0.84	0.00	0.07	0.00		0	
June	131.7	121.3	0.48	0.54	0.50	0.73	0.21	0.07	0.29	0.35	0	
July	133.9	106.9	0.36	0.58	0.48	0.63	0.31	0.07	0.21	0.17	0	
August	54.0	50.9	0.32	0.38	0.31	0.72	0.54	0.07	0.15	0.40	0	
September	28.6	27.2	0.24	0.30	0.14	0.84	0.80	0.07	0.05		0	0.20

To focus on the impact of changing ice conditions, the observed radiative fluxes from SHEBA were used in the 2007 analysis. This means that the break-even albedo is the same in 2007 as in 1998. The 1998 observed albedos for snow, bare ice, ponds, and leads were also used in 2007. The focus is on the impact of changes in the state of the ice cover. Ice conditions in the SHEBA region were markedly different in 2007 compared to 1998. In 2007, there was much more open water from June through September ~~were much smaller~~ and much less ~~bare~~ ice. Pond fractions were much larger in June and August of 2007 (Figure 4, Table 2). In 1998, ponds were freezing in August greatly reducing the pond fraction. By September 1998 ~~and~~ young ice was forming in ~~September~~leads. In contrast, ~~F~~freezeup was later in 2007;~~,~~ ponds were not freezing in August and there was no young ice ~~was not forming~~formation in leads in early September.

Aggregate scale albedos in May for the two years are comparable (0.82 and 0.84). However, from June through September aggregate scale albedos were substantially smaller in 2007 than in 1998 (Table 2). More leads and more melt ponds in 2007 resulted in a smaller aggregate scale albedo and a considerable increase in the net radiative balance. The decrease in albedo also changed the sunny / cloudy dynamic. For the ice conditions observed in 2007, with more ponds and leads, the albedo was less than the break-even albedo in every month except May. Thus, cloudy skies were more favorable to maintaining the ice cover from June through September.

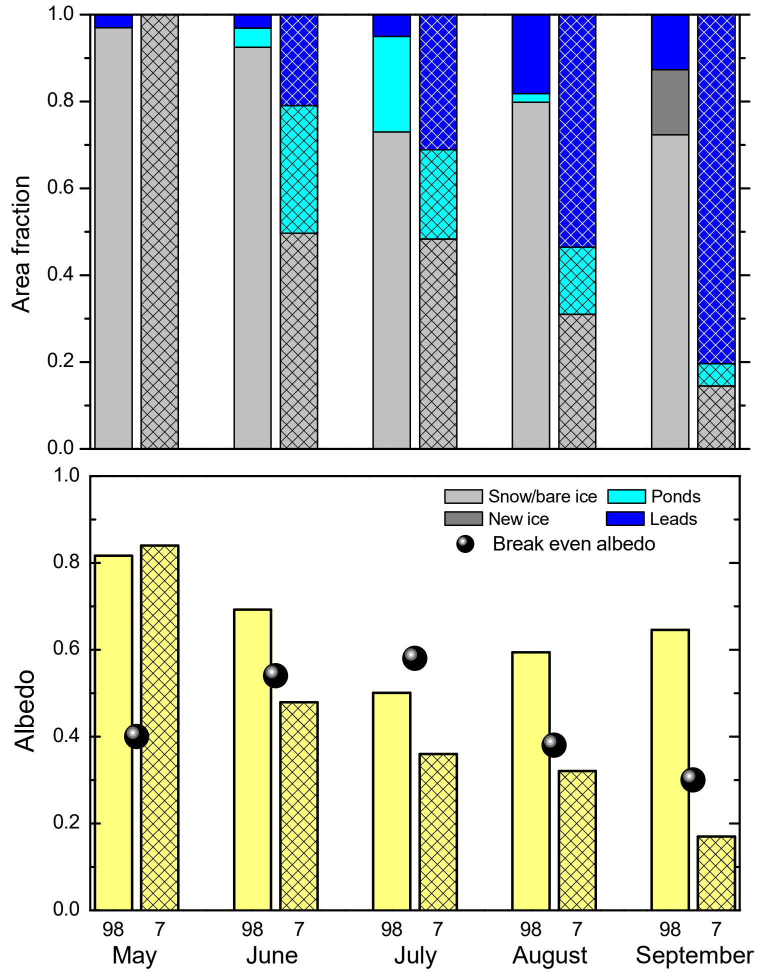

Figure 4. Top panel: Area fractions of snow/bare ice, ponds, leads, and new ice in 1998 and 2007. Bottom panel: Aggegate scale albedos for 1998 and 2007 along with break-even albedos. Solid bars show 1998 results and hatched bars show 2007.

Ice conditions will continue to dictate whether sunny or cloudy skies result in smaller net radiative fluxes. Observed changes to the summer ice cover in recent decades show less ice, younger ice, and early melt onset all reduce the aggregate scale albedo, increasing the radiative flux under both sunny and cloudy skies. However, the increase is greater under sunny skies. The SHEBA data showed that sunny skies in 1998 often provided a modest respite from surface melt. This may not be true in the future.

4. Conclusions

Using field observations from the SHEBA program, I selected pairs of sunny and cloudy days for each month from May through September and calculated the net radiation flux for various surface conditions and albedos. To explore the impact of albedo, I calculated a break-even albedo, for which the net radiation for cloudy skies is the same as for sunny skies. For albedos larger than the break-even value, the net radiation flux is smaller under sunny skies than cloudy skies. Break-even albedos range from 0.30 in September to 0.58 in July. For snow covered or bare ice, sunny skies always result in less radiative heat input. In contrast, leads always have, and ponds usually have, more radiative heat input under sunny skies than cloudy skies. Under sunny skies, snow covered ice has a net radiation flux that is negative or near zero, resulting in radiative cooling.

Aggregate scale albedos calculated using results from SHEBA show that sunny skies usually result in reduced radiative heat input. For May, June, August, and September, the areally averaged albedo is greater than the break-even albedo, ~~favoring~~ suggest that sunny skies promote less surface melt. This is consistent with surface melt observations made during SHEBA (Perovich et al., 2003). For the May and September cases, the areally averaged net radiation flux is even negative under sunny skies. It is only for the July case that the areally averaged albedo of 0.50 is less than the break-even albedo, resulting in a smaller net radiation flux under cloudy skies than under sunny skies.

Future impacts on net radiative balances will depend on both ice and cloud conditions. As the sea ice cover evolves towards more first year ice, greater melt pond coverage, and more open water, the area-averaged albedo will be less than the break-even albedo for much of the summer. This implies less melting under cloudy conditions than sunny. However, the net radiative balance will still likely be less under sunny skies at the beginning of the melt season in May and early June.

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