Please find below the referees comments (in black) and our answers (in blue).

Anonymous Referee #1

The article presents a feedback atmospheric process following the decrease in sea ice concentration. The feedback begins with the change in sea ice concentration, followed by the surface energy balance change that changes cloud condition, then back to the surface energy balance. The feedback process presented in this paper roughly halves the direct consequence of the sea ice reduction, through cloud radiative effect. The article is an important contribution for evaluating the consequence of the on-going sea ice reduction, in a more realistic way than so far published works.

We thank the reviewer for her (his) positive comments.

For improving the realiability of presented numericals and also for easier readability by the workers in other fields however, minor alterations are suggested as listed below:
Scientific aspect:

1) The recgnition of clouds is a key point of this work. It is necessary to present how the CERES evaluation recognises the clouds. There are manuals stating this process, but a brief summary of the process in one paragraph will help readers.

Additional discussion and references to the cloud retrieval techniques are provided in Section 2.1.

2) Surface fluxes, whether through satellites or model computations, are subject to errors that are often large. The quoted papers in the reference list do not satisfy this test. This reviewer recommends the authors to make a point-by-ponit comparison with the first-class ground observations. The sites, Ny-Alesund, Barrow, Alert and Resolute have long-standing observations of high quality irradiances for the Arctic. Similarly, Neumeyer, Syowa and South-Pole offers high quality irradiances with additional cloud information. The data are available at BSRN Centre at AWI, Bremerhafen.

Thank you for this comment. We also agree that the determination of radiative surface fluxes using satellite data is a challenge prospect. The CERES science team has spent much of the last 20 years analysing and refining these data. The requested comparisons have been undertaken and published by the CERES Science Team (e.g., Kato et al. 2018). Kato et al. (2018) compared the CERES surface EBAF Ed 4 monthly mean surface radiative fluxes with 46 buoys and 36 land sites, including the high-quality sites in the Arctic (e.g, Ny-Alesund, Barrow, Alert, and Resolute). The uncertainty estimates for individual surface radiative flux terms in the Arctic range from 12-16 W m^{-2} (1σ) at the monthly mean 1^{o}x^{o}1 gridded scale. Moreover, previous studies have stated that the CERES SFC EBAF fluxes are as a key benchmark for evaluating the Arctic surface radiation budget (Boeke et al. 2016; Christensen et al. 2016; Duncan et al. 2020). This discussion is now included in the text.

References:

Kato, S. and coauthors, 2018: Surface Irradiances of Edition 4.0 Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Data Product. *J. Climate*, **31**, 4501-4527, doi: 10.1175/JCLI-D-17-0523.1.

Boeke, R. C. and P. C. Taylor, 2016: Evaluation of the Arctic surface radiation budget in CMIP5 models. *J. Geophys. Res.,* **121**, 8525-8548, doi: 10.1002/2016JD025099.

Christensen, M., A. Behrangi, T. L'Ecuyer, N. Wood, M. Lebsock, and G. Stephens (2016), Arctic observation and reanalysis integrated system: A new data product for validation and climate study, Bull. Am. Meteorol. Soc., doi:10.1175/BAMS-D-14-00273.1.

Duncan, B. N., Ott, L. E., Abshire, J. B., Brucker, L., Carroll, M. L., Carton, J. and coauthors, 2020: Space-based observations for understanding changes in the arctic-boreal zone. *Reviews of Geophysics*, 58, e2019RG000652. https://doi.org/10.1029/2019RG000652

Presentation and minor typological comments: P2, L 63 and elsewhere: It is necessary to provide the full names of ACRONYMs at their first appearences, e.g., CMIP on this page and P3 L 75 EBAF. P 3,
OK, done see lines 72-74 and 85.

Figure 1: To be consistent with the text, Swcre and Lwcre should read SWcre and LWcre.
OK, done see Figure 1.

P4, L 98: The quoted publication, Kato et al. (2013) barely offers the information on the accuracy of irradiances, nor any of the authors are experienced with radiation science.

Additional references describing and analysing the CERES SFC EBAF data have been added to the manuscript along with a more detailed description of the surface radiative flux uncertainty, also see previous response. The reviewer should also know that the author list includes a member of the CERES Science Team experienced with radiation science. See section 2.1.

P6, L 149: This sentence appears incomplete, or some words may have gone lost.
P12, L223-224: This sentence is difficult to understand.
P14, L 310: "half if induced by" may read "half is induced by".
P15, L 317: "should aim to reduce" may read better when "should aim at reducing".
P18, L 390: Too many authors presented. This paper was written by four authors only.
Ok, done. Thanks

These are, however a minor comments, and this reviewer hopes that the authors will work for the quickest publication of this interesting work.
We thank the reviewer for his constructive comments that allows us to improve he manuscript.

Please find below the referee comments (in black) and our answers (in blue).

Anonymous Referee #2

The study investigates the correlation and covariation between cloud radiative effect (CRE) and sea ice in the Arctic and Antarctic using satellite and climate model data. It is found that clouds play a significant role in damping the net change in radiation absorbed at the surface as a result of sea ice changes.
It is an interesting study, but I have issues with the interpretation and the manuscript is not particularly well written. There are language issues that need to be worked on

and the methodology and logical steps need to be explained better. The results are interesting and potentially of some importance for our interpretation of the ensemble spread in polar climate responses in the CMIP-archives. While I do not think many new analyses are needed, I do fear that some of the interpretations are to bold and need to be moderated. Therefore, I cannot advise to accept without major revisions of the manuscript.

Major points

You write in the abstract that "years with less sea ice and a larger net surface radiative flux are also those that show an increase in sunlight reflected back to space by clouds." I am not convinced that this is, in fact, what you find. I would rather say that they are the years with a larger CRE. This is not the same, since as you point out when discussing mechanism (I) in L157 onwards: Even if cloud properties are held constant, the CRE can change due to the changes in clear-sky radiation induced by changes in sea ice decline and surface albedo. When surface albedo is lowered, more of the sunlight passing through the atmosphere is absorbed at the surface resulting in greater SW_total. But SW_clear increases even more since the lower albedo allows a larger fraction of the extra downwelling SW at the surface to be absorbed. This means that the quantity SW_cre = SW_total – SW_clear is decreased even in the absence of cloud changes – a purely surface-related effect.

I believe the above quoted statement ignores this; a point which is reflected in the next sentence: "An increase in absorbed solar radiation when sea ice retreats (surface albedo change) explains 66 ± 2% of the observed signal". As I understand your analyses, these 66% are exactly this surface-only effect. So the "observed signal" referred to in this sentence is the signal in CRE and not in "sunlight reflected back to space by clouds" as the previous sentence suggests.

We strongly agree with the reviewer. As noted by the reviewer, we state in the manuscript that surface albedo changes can drive substantial change in the cloud radiative effect and that such a change can occur in the absence of a change in cloud properties. Through the initial writing of the manuscript we went great lengths to try to unsure that this interpretation was clear. However, it is clear that we have missed a few statements. This point is extremely important, as it can change our interpretation, yet nuanced at the same time. We have gone through the manuscript to correct all instances of this. As she (he) suggested, we replaced "an increase in sunlight reflected back to space by clouds" by "larger cloud radiative effect" see line 25.

I believe this is not just a matter of wording. I think it really is an important part of how the results are interpreted and served to the reader. I will therefore give more examples where this distinction is not made clearly enough throughout the manuscript:

L187: "We estimate that the cloud changes in the Antarctic system are damping by 56% . . .". Here, "cloud changes" should be replaced by "the existence of clouds and the changes therein" or something to that effect, since as I understand it, the existence accounts for two thirds of the effect and the changes for only one third. Right?

We agree that this is an important point and does change the interpretation of the results as well as the implications of the manuscript. We have tried to make this point clear by rewriting the abstract as to highlight this point.

From lines 28-32: "Thus, present-day cloud properties significantly reduce the net radiative impact of sea ice loss on the Arctic and Antarctic surface radiation budgets. As a result, climate models must accurately represent present-day polar cloud properties in order to capture the surface radiation budget impact of polar sea ice loss and thus the surface albedo feedback."

In addition, the text in lines 263-265 specifically calls out "Thus, the observed negative correlation between SWcre and SWsfc over the polar seas results from the larger effects of process (I) than (II)." Also, as suggested by the reviewer "cloud changes" is replaced by "the existence of clouds and their property variations" (see line 277).

L223: "polar sea ice and cloud covarying in a way that substantially reduces the overall impact of the sea ice loss". Again, as far as I can see, only a third of the effect is due to the covariance. Two thirds is just due to clouds being present.

Ok, done. This sentence is replaced by "the results suggest clouds substantially reduce the impact of sea ice loss on the surface radiation budget and thus the observed sea the sea ice albedo feedback" see lines 314-315.

L245:" We argue that the strong increase of SWcre under decreased sea ice observed during summer is induced by larger values of cloud optical depth (Fig. 7a)". Again, what about process (I)?

Ok, done "SWcre" is replaced by "SWcreCloud", see line 339.

L309 (conclusion): "Satellite data indicates that the increased cloud cover/thickness correlates with sea ice melting, reducing by half the potential increase of net radiation at the surface". I think your results show that, only 33% of the by-half-reduction is due to changed clouds, while the remaining 66% is due to the mere presence of clouds.

In the new version of the manuscript, the words "Cloud cover/thickness" are replaced by "cloud radiative effect". See line 408.

Minor points

L37 Introduction: You should look into the results of Qu and Hall (2006, JClimate) who in their figure 6a illustrate that across a climate model ensemble, planetary albedo variations resulting from surface albedo variations are muted by half. While this study focused on terrestrial albedo variations due to snow changes, the point is the same: The mere existence of clouds damp the TOA effect of surface albedo variations. This is similar enough to your findings that they ought to be discussed in the context of your results. Either in the intro, discussion or conclusions.

This reference is included in the in the new version of the manuscript in the discussion when discussing the TOA dampening effect (see lines 317-319). During the review of this manuscript, we became aware of a recent paper by Sledd and L'Ecuyer (2019). This paper uses reanalysis output to quantify the "masking" or damping effect of clouds on the radiative effect of surface albedo variability. There result corroborates our result arguing that clouds damp the effect of surface albedo variability on top-of-atmosphere albedo (reflected shortwave flux) by half. This reference has also been added to the manuscript (see lines 319-321).

Reference:

Sledd and L'Ecuyer, 2019: How Much Do Clouds Mask the Impacts of Arctic Sea Ice and Snow Cover Variations? Different Perspectives from Observations and Reanalyses. https://www.mdpi.com/2073-4433/10/1/12/htm#B28-atmosphere-10-00012

Figure 1: In the equations below panel b, I believe you have ordered the terms on the RHS wrong: Shouldn't it be SWtotal-SWclear, and LWtotal-LWclear?

Ok, done see new figure 1.

L72 "Methods and data": As this section is currently, you talk a lot about the data but not really about the methods you will use. Then you go directly to the "Results and discussions" section which is difficult to read because the entire methodology is left in the supplement. I believe your statistical methods and your plots are so non-standard, and not least completely central to your analyses and conclusions, that they should be lifted from the supplement and into the "Methods and data" section.
Ok, methods are moved from supplementary to Methods and data (see section 2.7 and 2.8).

L78-80: You need to explain the sign convention of the fluxes explicitly. I assume all fluxes are taken positive downwards, but it does not say so anywhere and while Figure 1 does say, for instance, LWclear at the end of a red arrow, this does not explain the sign convention. If anything, it is a bit confusing since this makes it look as if the LW's are taken positive upward.
Ok, done (see lines 81 and 106-107).

Figure 3: How are the models ordered? Not alphabetically, it seems.
The models are ordered alphabetically in the new version of the manuscript (see actual figure 4).

L157: Mechanism (I) is really important to the paper (as discussed above). Given this major importance, the explanation of the mechanism is not clear enough, so that all readers understand it. It becomes too easy for the reader to misunderstand it and think that is actually has something to do with the clouds when it really is a surface-only phenomenon. Please restructure the paragraph explaining mechanisms I and II such that you give yourself room enough to do it properly. Also, you have made the nice schematic in Figure 1. Use this and point to it in your explanations.
Ok done, see lines 242-252.

L164-166: This sentence assumes the reader is familiar with how to read Fig 4, something we are not until we have read the supplement. Lifting this into Section 2 would help a lot – but at least be clear and tell the reader that the supplement is, in fact, a prerequisite for understanding the entire paper.
In the new version of the manuscript we moved the method section from the supplement to the Method and data section 2.7. We also referred to this section in lines 255, 293, 305 and 363.

L183-184: Units on the equations?
Ok done, see lines 271-272.

L190-191: Here you just add the errors but I am unsure whether you shouldn't, in fact, be adding them in quadrature. This, of course, depends on whether you believe the

errors to be correlated or not. Please consider this carefully.
Ok, done, see line 280.

Figure 7: Is the data (or the methodology behind it) in this figure taken directly from Taylor et al? If so, please say so. Otherwise, the reader searches this paper for details in vain.
Ok done see lines 96-100 and 363, data from CERES and method as described in section 2.7.

L294/Figure 8gh: You do not discuss the red cross in Figure 8 gh. Why then show it? If you have a point with this information, you need to discuss it in the text. Otherwise, remove it from the figure.
New sentence "We also note that from the 32 models tested, only few show consistent trends in both SWdown and SIC over 2001-2016 (Figure 9gh)" is included in the new version of the manuscript (see lines 392-393).

L296: "This analysis suggests that the models showing a larger trend in cloud cover also show larger decreases in sea-ice extent and clearly demonstrate the strong coupling of these two variables.": Yes, but do you propose anything in terms of causality between the two? If not, you should be clear about this. Otherwise, the reader may try and read between the lines here.
Ok, the sentence "However, the direction of causality between the two variables is unclear" is included in the new version of the manuscript. See lines 391-392.

L316: "that show smaller trends in surface". Shouldn't this be larger trends? That is, at least, what I get out of L295.
We agree, larger is the correct word. Thus, smaller is replaced by larger in the new version of the manuscript. See line 414.

Figure 8: The time series are anomalies, but with respect to which period?
The anomalies in respect to the whole period. This is clearly stated in the new version of the manuscript. See line 434.

Suppl. L54: optical depth.
This is moved to the main text, see line 195.

Suppl. L73: What are M and N? You do not seem to say so.
Ok done see lines 149 and 155.

Suppl L78: A_i is the total area of all grid cells with a particular SIC change, right? Please explain this better.
To avoid a misunderstanding between i of year yi with the one used in equations, we replaced i in the equations by j.
$\sum_{j=1}^{N} A_j$ is the total area of all grid cells with a particular SIC change. In case of 60% SIC change with an increment of 10%, for example, $\sum_{j=1}^{N} A_j = A_1 + A_2 + A_3 + A_4 + A_5$

A_1 is the total area of all grid cells with SIC change from 60% to 0% in two consecutive years.

A_2 is the total area of all grid cells with SIC change from 70% to 10% .

A_3 is the total area of all grid cells with SIC change from 80% to 20%.

$A_4$is the total area of all grid cells with SIC change from 90% to 30%.

$A_1$is the total area of all grid cells with SIC change from 100% to 40%.

Actual figure 2 and line 158 explains this in better way than the old version.

Suppl L90: What is SX_p?
As mentioned in previous lines 85-89 actual lines 169-174 "S" is the slope while Xp is the relative change in sea ice concentration.

Language:
There are many examples of language that is not quite at an acceptable level. I cannot list them all, but I urge you to have a native English-speaker go carefully through the manuscript. Examples are
L 20: clouds ->cloud
L21: responding
L23: "manner of the" sounds weird. Please rephrase.
L45: determines
L58: Alternatively -> On the other hand

Ok, done. Thanks. Experienced scholarly writer P. C. Taylor who is *native English-speakers* have edited this new version of the manuscript.

We thank the reviewer for the constructive comments that helped us to improve the manuscript.

Clouds damp the radiative impacts of Polar sea ice loss

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Patrick C. Taylor (patrick.c.taylor@nasa.gov)

Abstract

Clouds ~~plays~~play an important role ~~on~~in the climate system ~~through two main contrasting effects~~: (1) cooling the Earth by reflecting incoming sunlight to space ~~part of incoming solar radiation;~~ and (2) warming the ~~surface~~Earth by ~~reducing the Earth's loss of~~ reducting thermal energy loss to space. ~~Recently, scientists have paid more attention to the warming role of clouds because of the acceleration of Arctic sea ice melting and because of recent studies that did not find any response of cloud cover fraction to reduced sea ice in summer. On the contrary, with this work based on satellite~~Cloud radiative effects are especially important in polar regions and have the potential to significantly alter the impact of sea ice decline on the surface radiation budget. Using CERES data and 32 CMIP5 climate models, we ~~reveal that~~ quantify the influence of polar clouds on the ~~cooling role of clouds is dominant. Indeed, cloud dynamic occurring in combination with sea ice melting plays an important~~ radiative impact of polar sea ice variability. Our results show that the cloud shortwave cooling effect ~~by altering~~strongly influences the impact of sea ice variability on the surface ~~energy~~radiation budget and does so in ~~an apparently contradicting way~~a counter-intuitive manner over the polar seas: years with less sea ice ~~are also those that show an increase of the radiative energy reflected back to space by clouds. An increase in absorbed solar radiation when sea ice retreats (surface albedo change) explains~~ and a larger net surface radiative flux show a more negative cloud radiative effect. Our results indicate that 66 ± 2% of ~~the observed signal. The remaining 34 ± 1% are~~ this change in the net cloud radiative effect is due to the ~~increase~~reduction in ~~cloud cover/thickness when sea ice retreat and associated reflection to space. This interplay~~

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~~between clouds and sea ice reduces by half the increase of net radiation at the surface that follows~~ surface albedo and the ~~sea ice retreat, therefore~~remaining 34 ± 1% is due to an increase in cloud cover/optical thickness. The overall cloud radiative damping ~~the impact of polar~~ effect is 56 ± 2% over the Antarctic and 47 ± 3% over the Arctic. Thus, present-day cloud properties significantly reduce the net radiative impact of sea ice loss~~. We further highlight how this process is mis-represented in some~~ on the Arctic and Antarctic surface radiation budgets. As a result, climate models must accurately represent present-day polar cloud properties in order to capture the surface radiation budget impact of polar sea ice loss and thus the surface albedo feedback.

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~~Radiation from the sun is the primary energy source to the Earth system, responsible for the energy driving motions in the atmosphere and ocean, for the energy behind water phase changes, and for the energy stored in fossil fuels. Only a fraction(Loeb et al., 2018)~~Solar radiation is the primary energy source for the Earth system and provides the energy driving motions in the atmosphere and ocean, the energy behind water phase changes, and for the energy stored in fossil fuels. Only a fraction (Loeb et al., 2018) of the solar energy arriving to the top of the Earth atmosphere (shortwave radiation, SW) is absorbed at the surface. Some of it is reflected back to space by clouds and by the surface, while some is absorbed by the atmosphere. In parallel, the Earth's surface and ~~the~~ atmosphere emit thermal energy back to space, called outgoing longwave (LW) radiation~~ (LW),~~, resulting in a loss of energy (Fig. 1). The balance between these energy exchanges ~~determine~~ determines Earth's present and future ~~Earth's~~ climate. ~~Such land-atmosphere interactions are~~The change in this balance is particularly important over the Arctic where summer sea ice is retreating at an accelerated rate (Comiso et al., 2008), surface albedo is rapidly declining, and surface temperatures are rising at a rate double that of the global average (Cohen et al., 2014; Graversen et al., 2008), ~~possibly~~ impacting sub-polar ecosystems (Cheung et al., 2009; Post et al., 2013) and possibly mid-latitude climate (Cohen et al., 2014; Cohen et al. 2019).

~~Clouds play a considerable role in modifying the radiative energy flows, thereby affecting the Earth's climate. This is done both by increasing the amount of SW reflected back to space and by reducing the LW energy loss to space (Fig 1). These cloud effects on Earth's radiation budget can be gauged by the Cloud Radiative Effect (CRE), defined as the difference between the actual atmosphere and the same atmosphere minus the clouds (Charlock and Ramanathan, 1985). The different spectral components of this effect can be estimated from satellite observations: the global average shortwave cloud radiative effect (SWcre) is negative since clouds reduce the surface incoming solar radiation with a resulting cooling effect. On the contrary, the longwave cloud radiative effect (LWcre) is positive since clouds absorb then reemit up and down according to the cloud top and base temperatures generating a warming effect (Harrison et al., 1990; Loeb et al., 2018; Ramanathan et al., 1989).~~

Cloud properties and their radiative effects exhibits significant uncertainty in the polar regions (e.g., Curry et al. 1996; Kay and Gettelman 2009; Boeke and Taylor 2016; Kato et al. 2018). For instance, climate models struggle to accurately simulate cloud cover, optical depth, and cloud phase (Cesana et al., 2012; Komurcu et al., 2014; Kay et al. 2016). An accurate representation of polar clouds is necessary because they strongly modulate radiative energy fluxes at the surface, in the atmosphere, and at the TOA influencing the evolution of the polar climate systems. In addition, polar cloud properties interact with other properties of the polar climate systems (e.g., sea ice) and influence how variability in these properties affects the surface energy budget (Qu and Hall 2006; Kay and L'Ecuyer 2013; Sledd and L'Ecuyer 2019). Morevoer, Loeb et al. (2019) documented severe limitations in the representation of surface albedo variations and their impact on the observed radiation budget variability in reanalysis products, motivating the evaluation of radiation budget variability over the polar seas in climate models. In this study, we use the Clouds and the Earth's Radiant Energy System (CERES) top-of-atmosphere (TOA) and surface (SFC) radiative flux datasets and 32 Coupled Model Intercomparison Project (CMIP5) climate models to estimate the relationship between the CRE and the surface radiation budget in polar regions to improve our understanding of how clouds modulate the surface radiation budget.

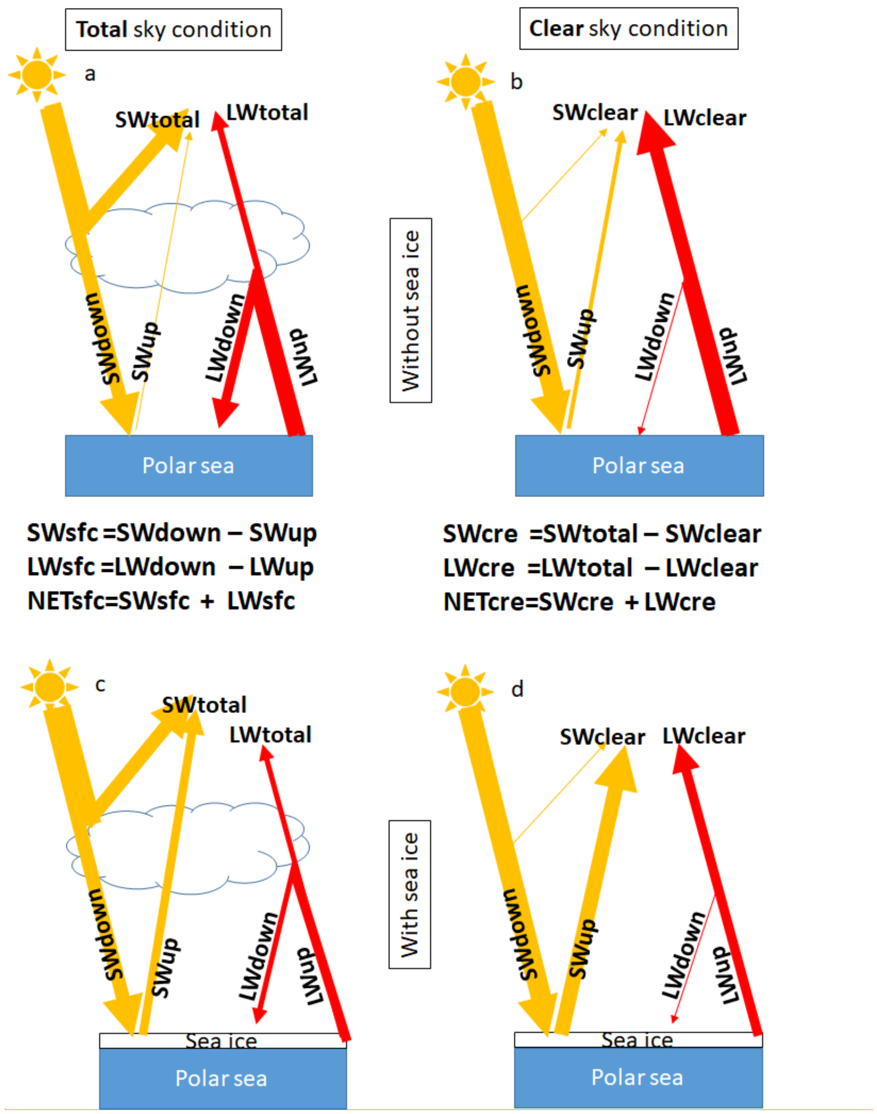

Figure 1 Schematic representation of radiative energy flows in the polar seas under total sky conditions (a, c) and clear sky conditions (b, d) for two contrasting surface conditions: without sea ice (a, b) and with sea ice (c, d). All fluxes are taken positive downwards.

2. Methods and data

~~**2.1 Cloud Radiative Effect:** CRE is used as a metric to assess the radiative impact of clouds on the climate system, which is defined as the difference in net irradiance at the top of atmosphere TOA between total sky conditions and in the absence of clouds. Using the CERES EBAF Ed4.0 (Loeb et al., 2018) flux measurements and CMIP5 modeled flux, the cloud radiative forcing is calculated by taking the difference between clear sky and total sky net irradiance flux at the TOA.~~

In addition to radiative fluxes, cloud cover fraction (CCF) and cloud optical depth (COD) data available from CERES EBAF data are used. Monthly mean CCF and COD data are derived from instantaneous cloud retrievals using the Moderate-resolution Imaging Spectroradiometer (MODIS) radiances (Trepte et al. 2019). Instantaneous retrievals are then are spatially and temporally averaged onto the 1°x1° monthly mean grid consistent with CERES EBAF.

2.2 Cloud Radiative Effect: CRE is used as a metric to assess the radiative impact of clouds on the climate system, defined as the difference in net irradiance at TOA between total-sky and clear-sky conditions. Using the CERES Energy Balanced And Filled (EBAF) Ed4.0 (Loeb et al., 2018) flux measurements and CMIP5 simulated fluxes, CRE is calculated by taking the difference between clear-sky and total-sky net irradiance flux at the TOA. All fluxes are taken as positive downwards.

$$\mathbf{SW_{cre}=SW_{total}-SW_{clear}} \quad (1)$$

$$\mathbf{LW_{cre}=LW_{total}-LW_{clear}} \quad (2)$$

$$\mathbf{NET_{cre}=SW_{cre}+LW_{cre}} \quad (3)$$

~~**2.2 Earth's surface radiative budget:** The net SWsfc (LWsfc) at the surface is calculated as the difference between incoming **SW**$_{down}$ **(LWdown)** and outgoing **SWup (LWup)** as shown in equations 4 (5).~~

$$\mathbf{SW_{sfc}=SW_{down}-SW_{up}} \quad (4)$$

$$\mathbf{LW_{sfc}=LW_{down}-LW_{up}} \quad (5)$$

$$\mathbf{NET_{sfc}=SW_{sfc}+LW_{sfc}} \quad (6)$$

2.5 Polar seas: We ~~defined~~define the polar seas as ~~the seas~~ocean regions where ~~we observed~~the monthly ~~sea ice concentration~~SIC is larger than 10% at least one month during 2001-2016 period. Polar seas extent is shown in Figure S1.

2.6 CMIP5 Models To reconstruct the historical CRE and surface energy ~~balance~~budget and ~~predict~~project their future changes, we used an ensemble of simulations conducted with 32 ~~earth system~~climate models (~~names of the used~~ models used are shown in Figure 3 and S3) contributing to the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). These model experiments provided: historical runs (1850-2005) in which all external forcings ~~comes from~~are consistent with observations and future runs (2006-2100) ~~under~~using the RCP8.5 emission scenarios (Taylor et al., 2012). The comparison with the satellite data is made over 2001-2016~~. To do that, we merged~~ by merging historical runs 2001-2005 with ~~rcp8~~RCP8.5 2006-2016.

2.7 Estimation of the local variations in radiative flux, cloud cover, and cloud optical depth concurrent with changes in sea ice concentration

This study employs a novel method for quantifying the variations in radiative fluxes and cloud properties with SIC. This methodology leverages inter-annual variability of sea ice cover to assess these relationships. Figure 2 schematically shows the methodology based on the following steps. We use SW as an example and apply the approach in the same way to other variables.

1) ΔSW_j values are summarized in a schematized plot (Figure 2a) where each cell j in such plot shows the average ΔSW_m observed for all possible combinations of SIC at a grid box between two consecutive observation years (year yi and yi+1 from time period 2001-2016) displayed on the X and Y axes, respectively. For the sake of clarity in Figure 2 the X and Y axes report SIC in intervals of 10%, while in Figure 5, 6, 7, S5 and S6 the axes are discretized with 2% bins.

2) Because of the regular latitude/longitude grid used in the analysis, the area of the grid cells (a_m) varies with the latitude. The energy signal (ΔSW_j) is therefore computed as an area weighted average (Equation 7) where M is the number of grid cells that are used to compute cell j in the schematised plot Fig 2a. Figure 2b shows the total area of all these grid cells as described by Equation 8.

$$\Delta SW_j = \frac{\sum_{m=1}^{M} a_m \Delta SW_m}{\sum_{m=1}^{M} a_m} \qquad (7)$$

$$A_j = \sum_{m=1}^{M} a_m \qquad (8)$$

3) Calculation of the area weighted average (ΔSW_p) of the energy signal of all N cells with the same fraction X of a change in SIC (shown with the same colour in Figure 2a) Equation 9.

$$\Delta SW_p = \frac{\sum_{j=1}^{N} A_j \Delta SW_j}{\sum_{j=1}^{N} A_j} \qquad (9)$$

$\sum_{j=1}^{N} A_j$ is the total area of all grid cells with a particular SIC change.

ΔSW_p is the energy weighted average of all grid cells with a particular SIC change.

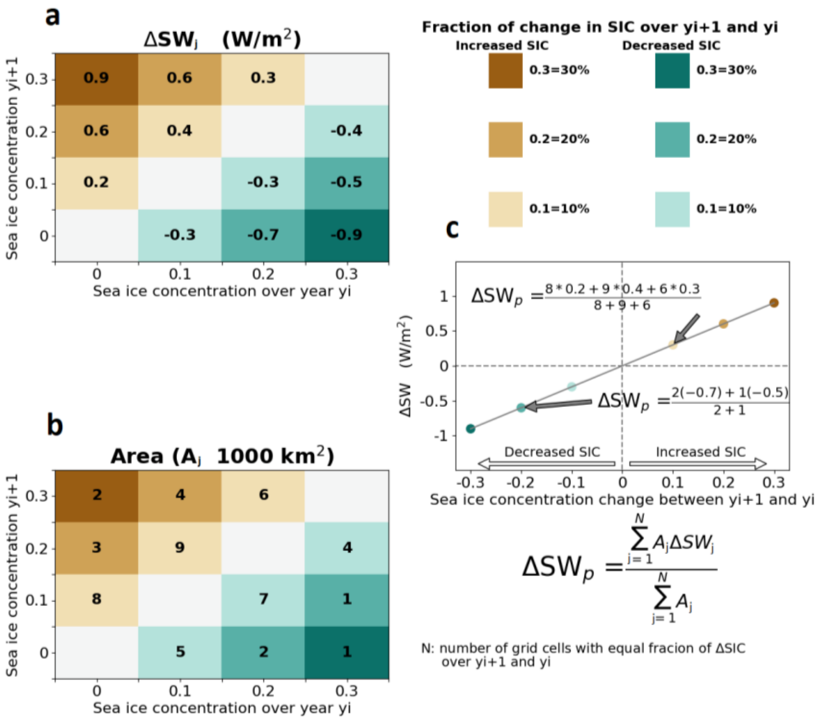

Figure 2 Schematic representation of the methodology used to quantify the energy flux sensitivity to changes in sea ice concentration as a linear regression between the percentage of sea ice concentration and the variation in energy flux (right panel) using SW energy flux data and sea ice concentration defined in the left panels.

The average energy signals (ΔSW_p) per class of sea ice concentration change are reported in a scatterplot (Fig. 2 right panel) and used to estimate a regression line with zero intercept.

The slope S of this linear regression represents the local SW energy signal generated by the complete sea ice melting of a 1° grid cell. The weighted root mean square error (WRMSE) of the slope is estimated by Equation 10, where p represents one of the NP points in the scatterplot (Fig. 2 right panel) and X_p is the relative change in sea ice concentration in the range ±1 (equivalent to ±100% of sea ice cover change).

$$WRMSE = \sqrt{\frac{\sum_{p=1}^{NP} A_p \left(\Delta SW_p - S\, X_p\right)^2}{\sum_{p=1}^{NP} A_p}}, \quad \text{where} \quad A_p = \sum_{j=1}^{N} A_j \qquad (10)$$

2.8 Diagnosis of contributions to SWcre

SWcre at the surface for the year yi (Eq. 11) and year yi+1 (Eq. 12) is function of surface albedo α, SWdown under clear sky conditions ($SW\downarrow_{clr}$) and SWdown under total sky conditions ($SW\downarrow_{tot}$).

$$SWcre_{yi} = (1-\alpha_{yi})(SW\downarrow_{tot,yi} - SW\downarrow_{clr,yi}) \qquad (11)$$

$$SWcre_{yi+1} = (1-\alpha_{yi+1})(SW\downarrow_{tot,yi+1} - SW\downarrow_{clr,yi+1}) \qquad (12)$$

Using the first-order Taylor series expansion to (11) yields

$$\Delta SWcre_{yi+1-yi} = (-\Delta\alpha_{yi+1-yi})(SW\downarrow_{tot,yi} - SW\downarrow_{clr,yi}) + (1-\alpha_{yi})\Delta_{yi+1-yi}(SW\downarrow_{tot} - SW\downarrow_{clr}) \qquad (13)$$

Where

$$\Delta_{yi+1-yi}(SW\downarrow_{tot} - SW\downarrow_{clr}) = (SW\downarrow_{tot,yi+1} - SW\downarrow_{clr,yi+1}) - (SW\downarrow_{tot,yi} - SW\downarrow_{clr,yi}) \ (14)$$

Separating the terms yields,

$$\Delta SWcre_{ALB} = (-\Delta\alpha_{yi+1-yi})(SW\downarrow_{tot,yi} - SW\downarrow_{clr,yi}) \ (15)$$

Where $\Delta SWcre_{ALB}$ is the part of SWcre change that is induced by the change in surface albedo.

$$\Delta SWcre_{cloud} = (1-\alpha_{yi})\Delta_{yi+1-yi}(SW\downarrow_{tot} - SW\downarrow_{clr}) \qquad (16)$$

Where $\Delta SWcre_{cloud}$ is the part of SWcre change that is induced by the change in cloud cover and cloud optical depth.

$$\Delta SWcre_{yi+1-yi} = \Delta SWcre_{ALB} + \Delta SWcre_{cloud} \ (17).$$

The above equations are used in figure 7 and S5.

3. Results and discussions

3.1 Negative correlation patterns between cloud radiative effect and surface radiation on polar seas

Given the known cloud influence on the surface radiative budget, a positive correlation between ~~Top Of Atmosphere (~~TOA~~)~~ CRE and surface radiative budget is expected (the amount of absorbed radiation at the surface decreases with a more negative SWcre and a less positive LWcre) [illegible] a positive correlation between the [illegible] annual [illegible] NETcre [illegible] NETsfc [illegible] over much of the [illegible] globe using the CERES TOA flux data from 2001-2016. However, our analysis reveals the opposite pattern over the polar seas (defined in section 2.5) where the correlation is negative over the Antarctic and partly negative over the Arctic (Bering Strait, Hudson Bay, Barents Sea and the Canadian Archipelago, Fig. [illegible] the [illegible] SWcre and LWcre [illegible] for the SW (Fig. ~~2cd~~3cd) shows a similar ~~patterns~~pattern of correlation as ~~before~~the NETcre (Fig. ~~2ab~~3ab) but with a stronger magnitude, while LWcre generally ~~experience~~shows the opposite correlations (Fig. ~~2ef~~3ef). This suggests that ~~SW radiation fluxes~~ the factors influencing SWcre are responsible for the sharp contrast ~~between~~in the correlation found in the polar regions ~~and the rest of the world.~~. Indeed, SWsfc and SWcre (Fig. ~~2gh~~3gh) show the sharpest and most significant contrast between the polar regions and the rest of the world (Fig. S2 is similar to Fig ~~2~~. 3 but only significant ~~correlation~~correlations at the 95% confidence level are reported in blue and red colors). ~~On average~~Overall, climate models are able to reproduce the spatial pattern of the observed SW correlation, but also show a large inter-model spread ~~concerning~~in the spatial extent of the phenomena (Fig. ~~3~~4 and S3). On the other hand, several models completely fail ~~at reproducing this fundamental~~to reproduce the correlation. ~~Indeed,~~ ACCESS1-3, MIROC5, CanESM2 and CSIRO-Mk3-6-0 models ~~shows~~show negative correlation over Antarctic continent in contrast to observed positive correlation. ~~Also, some~~Some models, like IPSL-CM5B-LR, GISS-E2-R and bcc-csm1-1 ~~completely~~, fail to reproduce the observed negative correlation over the Southern Ocean. This suggests that these models ~~made~~contain misrepresentations of the relationships SWcre and NETsfc likely resulting from errors in ~~simulating~~ the relationships between sea ice ~~extend~~, surface albedo, cloud cover/thickness, and~~/or~~ their ~~relationships between~~ influence on surface radiative ~~flux and cloud properties, which~~fluxes that could severely impact their projections. Moreover, Fig. 4 demonstrates that simple correlations between NETsfc and the individual radiation budget terms represents a powerful metric for climate model evaluation allows for a quick check for realistic surface radiation budget variability in polar regions.

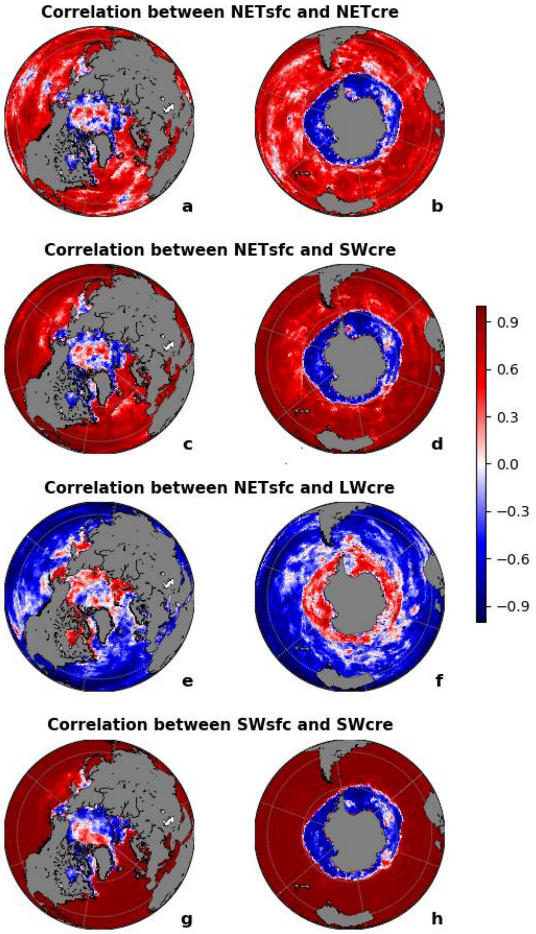

Figure ~~2~~3 Correlation between TOA CRE and surface radiation budget terms over 2001-2016 from CERES measurements for the ~~northern hemisphere~~Northern Hemisphere (aceg) and ~~southern hemisphere~~Southern Hemisphere (bdfh) polar sea. ~~The positive correlation (~~Positive correlations shown by the red color~~)~~ ~~means~~indicate that ~~the~~ years with ~~cooler surface~~less NETsfc coincide with ~~the~~ years where ~~cloud plays~~NETcre has a ~~more~~stronger cooling ~~role~~effect and *vice versa*.

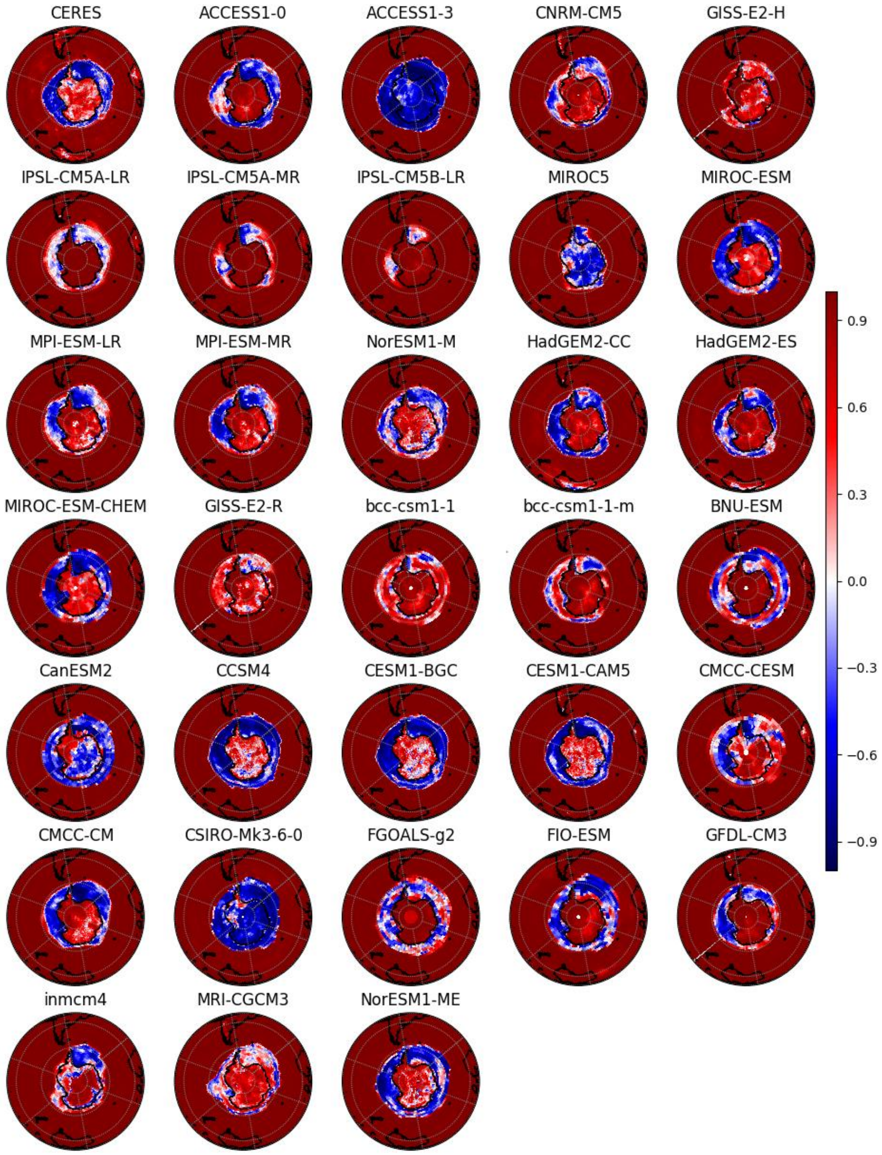

Figure ~~3~~4 Correlation between SWcre and ~~net solar radiation at the surface~~ SWsfc shown by 32 CMIP5 earth system models and ~~Satellites~~ CERES ~~over~~between 2001~~-~~ and 2016 over ~~southern hemisphere~~the Southern Hemisphere.

3.2 Effects of sea ice concentration change

~~The~~ We illustrate that the apparent ~~paradox~~ contradiction over the polar seas between NETcre and NETsfc found in Fig ~~2ab~~3ab is ~~mainly~~ caused by the factors contributing to the SW ~~part of the radiative budget.~~fluxes. This can be explained by: (I) ~~On the one hand,~~ SWcre can change even if cloud properties ~~stay~~are held constant ~~and the~~ due to the changes in clear-sky radiation changes induced by changes in sea ice (and surface albedo) ~~decreases, SWcre will become increasingly negative (cooling) while more of the incoming shortwave reaches the~~ When surface albedo is reduced, the surface ~~will~~absorbs more sunlight at the surface resulting in a greater SWtotal. At the same time, SWclear increases since the lower albedo allows a larger fraction of the extra downwelling SW at the surface to be absorbed (~~warming~~see Fig. 1). Therefore, SWcre becomes more negative even in the absence of cloud changes (a purely surface-related effect); (II) On the other hand, the relationship between cloud cover/thickness and sea ice~~,~~ could lead to cloudier Polar seas ~~are expected~~ under melting sea ice (Abe et al., 2016; Liu et al., 2012) ~~which means~~such that the SWcre decreases (increasing the amount of SW reflected back to space by clouds, see Fig. 1), thus the cloud cooling effect ~~of clouds~~ is enhanced concurrently with melting sea ice (a purely cloud-related effect). Both of these factors occur simultaneously.

Over the Antarctic seas, analysis of the year-to-year changes in ~~surface downward SW radiation (~~SWdown~~)~~ stratified in ~~bins of~~ 2% ~~of sea ice concentration (~~SIC~~)~~ bins retrieved from satellite microwave radiometer measurements (see section 2.7) shows an increase in SWdown with increased SIC and *vice-versa* (Fig. ~~4a~~5a). This ~~demonstrates~~suggests that years with higher SIC also have fewer and/or thinner clouds (Liu et al., 2012) (Fig. ~~5~~6), larger SWdown~~,~~ and also ~~have~~ larger upward SW radiation (SWup) (Fig. ~~4b), thanks~~5b), due to ~~the high sea ice~~ higher surface albedo (Fig. S4~~) that overcompensates for the increased SWdown. As a consequence~~). Consequently, these years ~~also~~ show a ~~lower~~ more negative SWsfc (Fig. ~~4c~~5c) and thus are characterized by stronger surface cooling. Furthermore, ~~less~~fewer clouds ~~means~~implies a reduction of the cloud cooling ~~role of cloud~~effect (less negative SWcre) as described above in process (II), this accounts for ~~34%±~~34 ± 1% ~~of~~ (Fig. 7d) of the total change in SWcre, and as described in process (I) the increase in the surface albedo also makes SWcre less negative and explains ~~66%±~~66 ± 2% of the observed change (~~Supplement section 1 and~~ Fig. ~~6). This explains~~7d). Thus, the observed negative correlation between SWcre and SWsfc over the polar seas ~~and~~results from the ~~opposite observed change~~larger effects of ~~SWcre and SWsfc (Fig 4cde~~process (I) than (II). Similar results are found over the Arctic Ocean with slightly different sensitivity (Fig. S5, S6). This difference is tied to differences in sun angle/available sunlight, as Antarctic sea ice is concentrated at lower latitudes than Arctic sea ice.

Using the regression relationships derived from our composite analysis, we ~~can~~ estimate the magnitude of the cloud effect. ~~.~~For the Antarctic system, we use the numbers found in Figure ~~4e~~5e, where we find ~~at~~ the annual ~~level, the~~mean relationship between NETsfc (in W/m^2) and SIC~~,~~ (fraction between 0 and 1), and NETcre (in W/m^2) and SIC~~.~~ (fraction between 0 and 1).

ΔNETsfc=(-36.61±0.72)ΔSIC (~~1~~18)

ΔNETcre=(47.03±1.01)ΔSIC (~~2~~19)

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~~In case of~~When excluding the CRE, the ΔNET sfc would be equal to (-36.61-47.03) ΔSIC =-83.64 ΔSIC.

We ~~estimated~~estimate that the ~~cloud feedbacks in the Antarctic system~~ existence of clouds and their property variations are damping ~~by 47.03/83.64= 56%~~ the potential increase in the ~~surface radiative flux (~~NET sfc~~)~~ within the Antarctic system due to ~~ice melting on~~ the surface ~~radiative budget mainly through surface~~ albedo~~. The uncertainties of that number are~~ decrease from sea ice melt by 56% (47.03/83.64). The uncertainty is calculated by summing the uncertainties shown in equation (~~1~~18) and (~~2~~19) as follows: (0.~~72~~72^2+1.~~01)/~~$01^2)^{1/2}$/83.64=2%.

Similarly, over the Arctic (Fig. S5), we ~~estimate~~compute the cloud ~~feedbacks from sea ice loss~~influence on the surface net radiative budget ~~to be~~that covaries with sea ice loss is 47±3~~%.~~%, in agreement with the study of Sledd and L'Ecuyer (2019).

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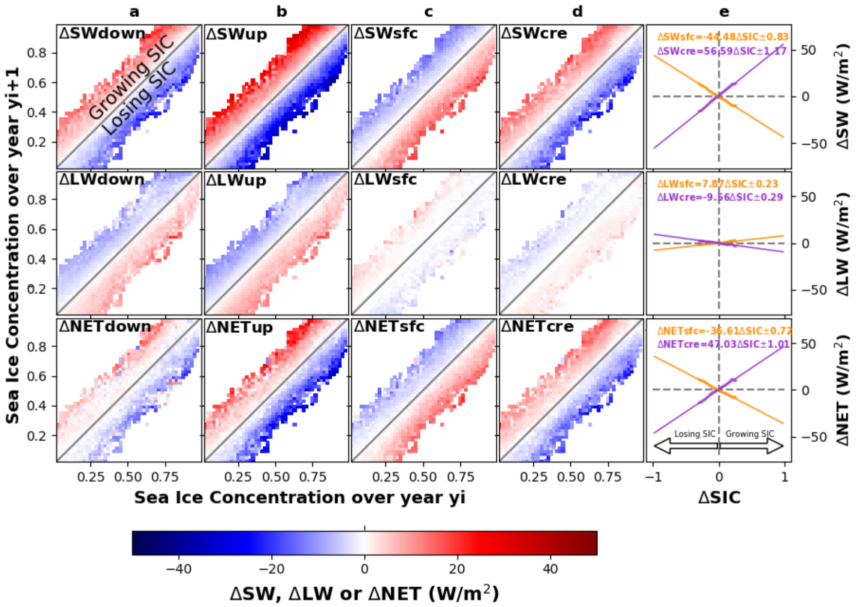

Figure ~~4~~5 Annual changes in SW, LW and NET as function of SIC.~~-~~ Annual changes in SW (top), LW (middle) and NET (bottom) of radiative down (a), up (b), sfc=down-up (c) and cre (d) over Antarctic sea as function of SIC change between two consecutive years y_{i+1} and y_i from 2001-2016 time period. The top triangles in (c top) refers to the increase (growing) in SIC while the blue color means a reduction (cooling) in SWsfc. Whereas, the top triangles in (d) refers to the increase in SIC while the red color means an increase (decreasing the cooling role of clouds) in SWcre. Each dot in column (e) ~~represent~~represents the average of one parallel to the diagonal in (c) or (d) as described in the ~~Supplement section~~Section 2.7.

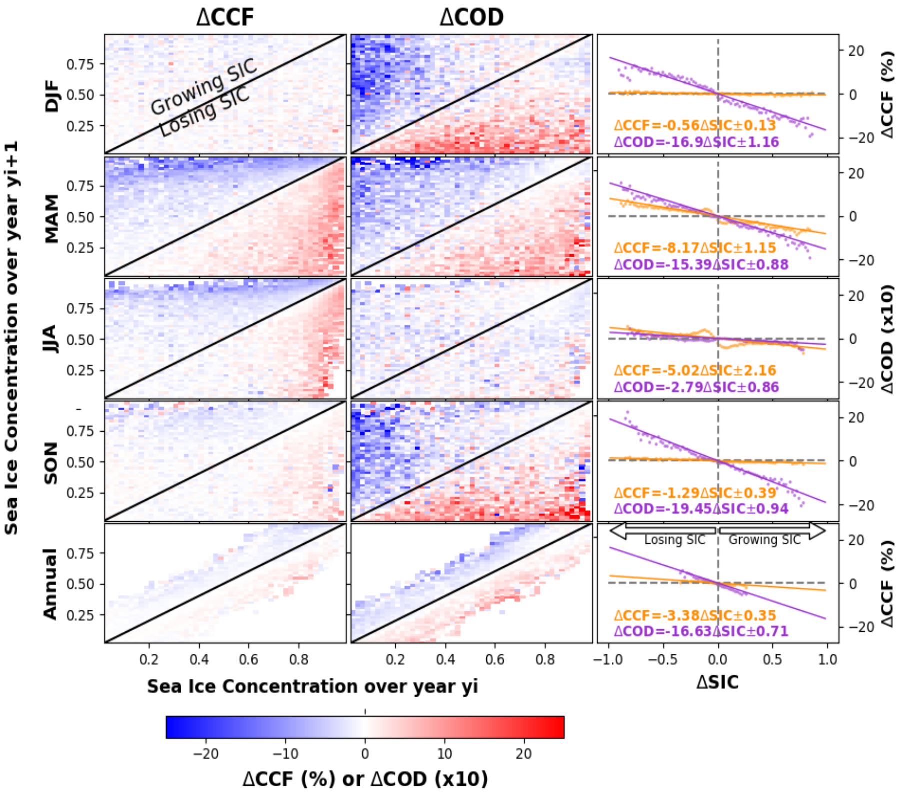

Figure ~~5~~6 Seasonal and annual changes in cloud cover fraction (CCF) and cloud optical depth (COD) over the Antarctic polar sea region as a function of SIC change between two consecutive years y_{i+1} and y_i from 2001-2016 time period. In order to use the same scale, COD has been multiplied by a factor 10. The top triangles in the two first columns ~~refers~~refer to the increase (growing) in SIC while the blue color means a reduction in CCF or COD.

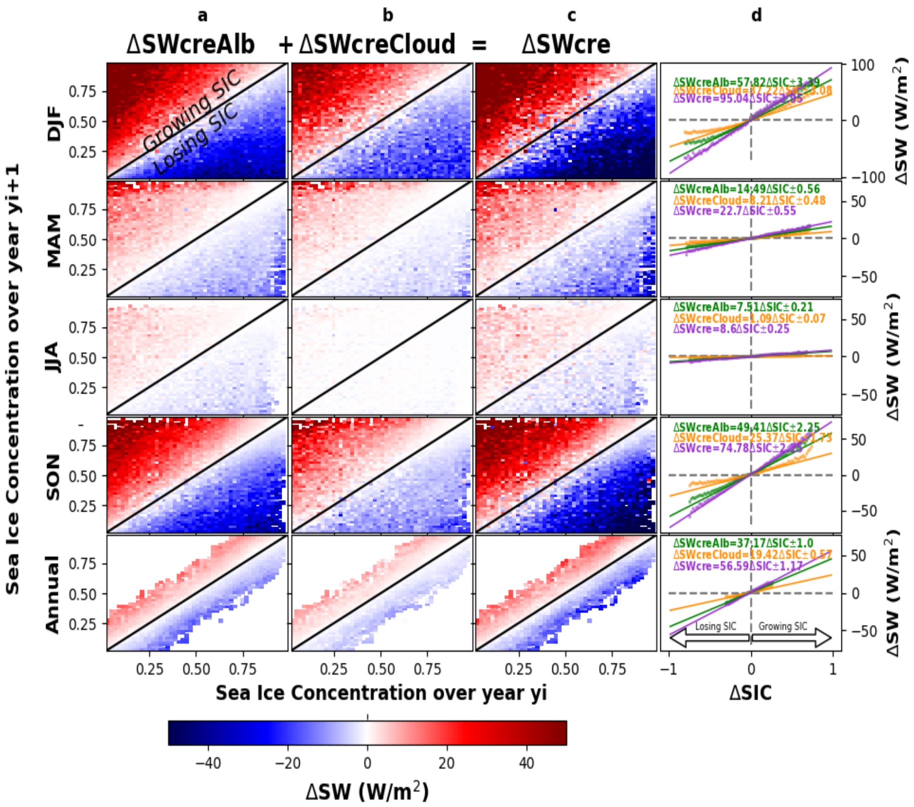

Figure ~~6~~7 Seasonal and annual changes in SWcreAlb, SWcreCloud and SWcre over the Antarctic polar sea region as function of SIC change between two consecutive years y_{i+1} and y_i from 2001-2016 time period. ~~All the~~The analysis ~~are~~is based on method described in section 2.7 and observations from satellites data.

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Altogether ~~these~~the results ~~show that polar sea ice and~~suggest clouds ~~interplay in a way that~~ substantially ~~reduces~~reduce the ~~overall~~ impact of ~~the~~ sea ice loss~~. In fact, with melting of~~ on the surface radiation budget and thus the observed sea the sea ice ~~the cooling effects of clouds are enhanced.~~albedo feedback. This effect in the polar climate system leads to a substantial reduction (56±~~3~~2% over the Antarctic and 47±3% over the Arctic) of the potential increase in NET sfc ~~following~~ in response to sea ice loss. This magnitude is similar to a previous study (Qu and Hall 2006) showing across a climate model ensemble that clouds damped the TOA effect of land surface albedo variations by half. Sledd and L'Ecuyer (2019) also determined that the cloud damping effect (also referred to as cloud masking) of the TOA albedo variability results from Arctic sea ice changes was approximately half. Despite this mechanism, ~~in the Arctic~~ the sharp reduction in Arctic surface albedo has ~~been dominating~~dominated the recent change in the surface radiative budget and has led to a significant increase in NET sfc since 2001~~.~~ in the CERES data (Duncan et al. 2020). These results demonstrate that the ~~interannual variability of~~trends in polar surface radiative fluxes ~~is currently controlled~~are driven by ~~variations~~reductions in SIC and surface albedo~~,~~ and that ~~cloud effects only mitigate the effects but not invert the trends~~ clouds have partly mitigated the trend (i.e., a damping effect ~~from a negative feedback~~). Our findings highlight the importance of processes that control sea ice albedo (i.e. sea ice dynamics, snowfall, melt pond formation, and the deposition of black carbon), as the surface albedo of the polar seas in regions of seasonal sea ice is crucial for the climate dynamics.

3.3 Sensitivity of the surface energy budget to variability of sea ice concentration

Our results are consistent with other recent studies ~~(Taylor et al., 2015)~~(Taylor et al., 2015; Morrison et al. 2018) that demonstrate a ~~cloud cover fraction (~~CCF~~)~~ response to reduced sea ice in fall/winter but not in summer (Figure ~~7a~~8a) over the Arctic Ocean. The lack of a summer ~~time~~ cloud response to sea ice loss is explained by the prevailing air-sea temperature gradient ~~in summer~~, where near surface air temperatures are frequently warmer than the surface temperature~~.~~ (Kay and Gettelman 2009). Surface temperatures in regions of sea ice ~~melting~~melt hover near freezing due to the phase change, whereas the atmospheric temperatures are not constrained by the freezing/melting point. ~~Thus, despite~~Despite reduced sea ice cover, strong increases in surface evaporation (latent heat) are limited (Fig. ~~7mn~~8mn), as also suggested by the small trends in surface evaporation rate derived from satellite-based estimates (Boisvert and Stroeve, 2015; Taylor et al., 2018). We ~~thus~~ argue that the strong increase of ~~SWcre~~SWcreCloud under decreased sea ice observed during summer is ~~mainly~~ induced by ~~higher~~larger values of ~~cloud optical depth~~COD (Fig. ~~7a~~8a), which ~~depends directly~~depend on ~~the cloud thickness and~~ the liquid or ice water content. We also show that the relationships derived from our observation-driven analysis match the projected changes in the Arctic and Antarctic surface energy budget in the median CMIP5 model ensemble (Fig. ~~7~~8). However, ~~the~~we find a large spread amongst climate models that indicates ~~that there is still~~ considerable ~~room for improvement~~uncertainty.

Analyzing the seasonal cycle of the sensitivity of the surface energy budget to SIC variability, we found that SWsfc (SWcre) explains most of the observed changes in the NET sfc (NET cre) during summer, while LWsfc plays a minor role (Fig. ~~7~~8). In contrast, during winter LWsfc (LWcre) explains most of the observed changes in the NET sfc (NET cre). In general, the median of the 32

CMIP5 (Taylor et al., 2012) climate models captures the observed sensitivity of the radiative energy budget and cloud cover change to SIC but the spread between climate models is large, especially for ~~cloud cover fraction.~~CCF. We have to note here that, the numbers reported in ~~figure 7~~Figure 8 are for 100% SIC loss, while the ones reported in the previous figures (Fig. ~~4,~~ 5, 6 and ~~6~~7) are for 100% SIC gain ~~which explain~~, explaining the opposite sign ~~between them~~.

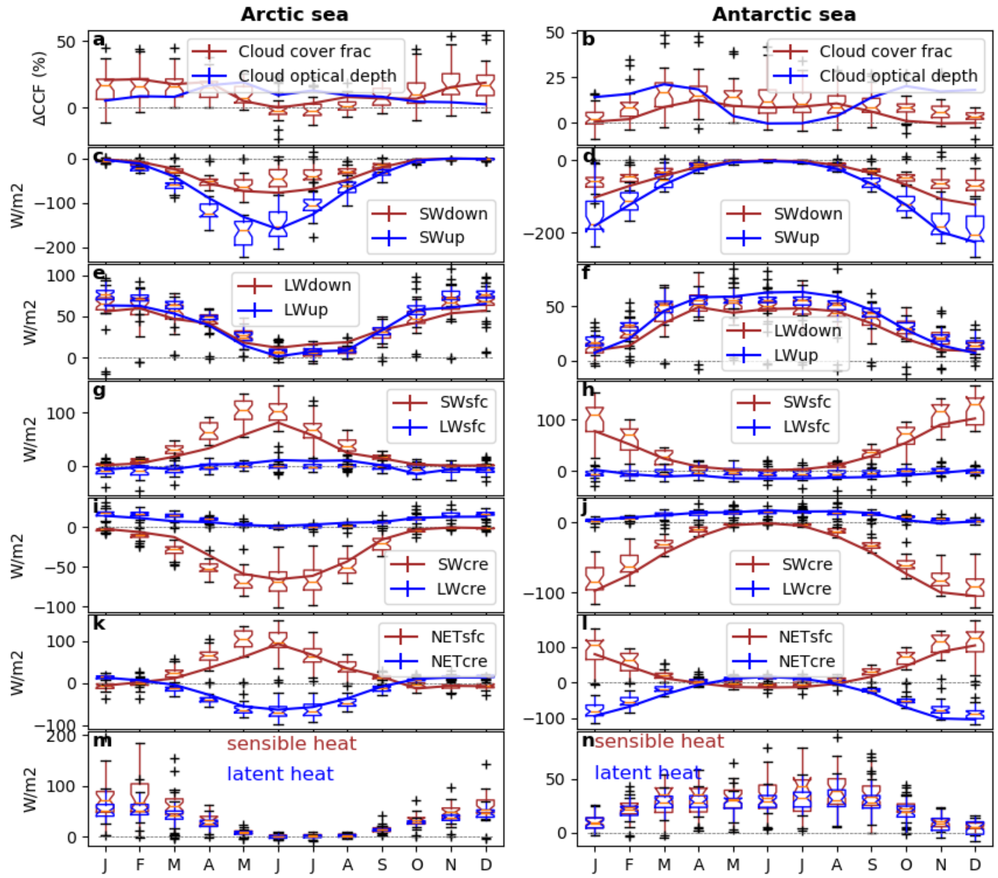

Figure ~~7~~8 Monthly change in different terms of the radiative energy balance, cloud optical depth (COD) and cloud cover fraction (CCF) extrapolated from ~~observation~~observations for ~~an~~a hypothetical 100% decrease in SIC over the areas where ~~we observed~~ SIC change was observed during the period 2001-2016. This ~~change~~ estimate came from the use of a linear interpolation of the change of different parts of the energy ~~balance~~budget, COD and CCF as function of a change in SIC coming from all possible combinations of ~~couples~~couplets of consecutive years for a given month from 2001 to 2016 and for all ~~gridcells~~grid cells for which SIC is larger than zero in one of the two years~~. Observations~~ (see section 2.7). CERES data are shown by solid lines (the standard deviation of the slopes are also reported but are too small to be visible) while CMIP5 models are shown by boxplot and the box (are in same color as observations) represents the first and third quartiles (whiskers indicate the 99% confidence interval and black markers show outliers). In order to use the same scale, COD has been multiplied by a factor 10.

3.4 Projections and uncertainties of cloud radiative effects on surface energy budget

~~In~~Under the ~~future, under rcp8~~RCP8.5 scenario (a ~~conservative~~ business as usual case~~); (~~Taylor et al., 2012), CMIP5 models show an increase in SWsfc over the Arctic Ocean (Fig. ~~8a) coherent~~9a) consistent with the expected large decrease in the SIC (Comiso et al., 2008; Serreze et al., 2007; Stroeve et al., 2007). This increase in SWsfc ~~happens~~occurs despite the relatively large, concurrent and opposing change in cloud cooling effect (SWcre). Future LW fluxes ~~of LW~~ (Fig. ~~8e~~9c) will likely play a ~~minor~~smaller but non-negligible role on total energy budget by further increasing ~~the surface net radiative fluxes,~~ NET sfc (Fig. ~~8e),~~9e) and ~~damping the cooling effect of clouds~~reducing NET cre. In addition, CMIP5 models ~~shows~~show clearly that by 2100, the magnitude of the decrease in NET cre is slightly ~~lower~~smaller that the increase in NET sfc (Fig. ~~8e~~9e) over Arctic Ocean. While the Antarctic ~~Ocean show~~polar sea region shows the opposite (Fig. ~~8f~~9f). This is in line with the estimated dampening effect of clouds coming from CERES over 2001-2016 that is about 47±3% in the ~~arctic~~Arctic and 56±2% in the Antarctic. Indeed, the stronger cloud damping effect in the Antarctic region cause the NET cre to become even more negative than the Arctic (Fig. 9gh).

Large uncertainties remain ~~on~~in the decline rate of summer sea ice and the timing of the first occurrence of a sea ice-free Arctic summer (Arzel et al., 2006; Zhang and Walsh, 2006). The reason behind the large spread between climate models is still debated (Holland et al., 2017; Simmonds, 2015; Turner et al., 2013). ~~For~~In this ~~scope here~~study, we explored the ~~mean~~ annual mean Arctic and Antarctic sea-ice extent trend ~~coming~~ from 32 CMIP5 models and find ~~high~~a large positive correlation with the simulated trend in the SWdown (Figure ~~8gh~~9gh). This analysis suggests that the models showing a larger trend in cloud cover also show larger decreases in sea-ice extent and ~~clearly demonstrate the strong coupling of these two variables also in the modelling context.~~suggest that a stronger coupling of these two variables may occur in the future. However, the direction of causality between the two variables is unclear. We also note that from the 32 models tested, only few show consistent trends in both SWdown and SIC over 2001-2016 (Figure 9gh).

4. Conclusion

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The manuscript ~~deals with~~addresses two ~~controversial topics in~~ important climate science topics, namely the role of clouds and the fate of polar sea ice. The work is ~~fully~~ grounded ~~on~~in a long time series of robust satellite observations that allowed us to document an important ~~negative feedback~~ damping effect in the polar ~~clouds~~cloud-sea ice system~~.~~ using a unique inter-annual approach. Our results agree with several previous works that approached the problem from a different perspective (Hartmann and Ceppi 2014; Sledd and L'Ecuyer 2019). In addition, we show how 32 state-of-the-art climate models represent ~~this feedback~~aspects of the surface radiation budget over the polar seas.

Our data-driven analysis shows that polar sea-ice and clouds interplay in a way that substantially reduces the ~~overall~~ impact of the sea ice loss~~. In simple words, we~~ on the surface radiation budget. We found that ~~with melting of the~~when sea ice ~~the cooling role of clouds~~cover is ~~enhanced, therefore mitigating the potential climate impacts of sea- ice loss.~~ reduced between two consecutive years that the cloud radiative effect becomes more negative, damping the total change in the net surface energy budget. The magnitude of this effect is important~~: satellite reveals~~. Satellite data indicates that the ~~increase in~~more negative cloud ~~cover/thickness correlated with sea ice melting is reducing by half~~radiative effect reduces the potential increase of net radiation at the surface~~. Third of this half i~~f by approximately half. One-third of this cloud radiative effect change is induced by the direct change in cloud [illegible]

In addition, we demonstrated that the models that ~~shows~~show larger trends in polar sea ice extent ~~are systematically the same that show lower tendencies~~ also show larger trends in surface ~~incoming~~net solar radiation ~~(clouds).~~. In order to understand current and future climate trajectories, model developments should aim ~~to the reduction of~~ at reducing uncertainties in the representation of [illegible] polar seas. Present-day Arctic and Antarctic cloud properties strongly influence the model simulated cloud damping effect on the radiative impacts of sea ice loss.

Future cloud ~~dynamics~~changes and sea ice ~~trajectories~~evolution represent major uncertainties in climate projections due to the multiple ~~and~~ relevant pathways through which cloudiness and sea ice ~~feeds~~feed back on ~~the~~ Earth's climate system (Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, 2007). Our evidence derived from Earth observations ~~may substantially reduce~~provides additional insight into the ~~uncertainty on the covariation between~~ coupled radiative impacts of polar clouds and the changing sea ice cover (Fig. ~~7), constrain future~~8) that may provide a useful constraint on model projections and ultimately improve ~~the~~our understanding of present and future polar climate. At the very least, our results demonstrate a simple correlation analysis between the net surface radiation budget and individual radiation budget terms that can be used to quickly evaluate climate models for realistic surface radiation budget variability in polar regions. Ultimately, our ~~finding~~findings on the interplay between cloud and sea-~~-~~ice may support an improvement in the model representation of the cloud-ice ~~feedback, a mechanism~~interactions, mechanisms that may substantially affect the speed of the polar sea-~~-~~ice retreat, which in turn has a broad impact on the climate system, on the Arctic environment and on potential economic activities in the Arctic ~~regions~~region (Buixadé Farré et al., 2014).

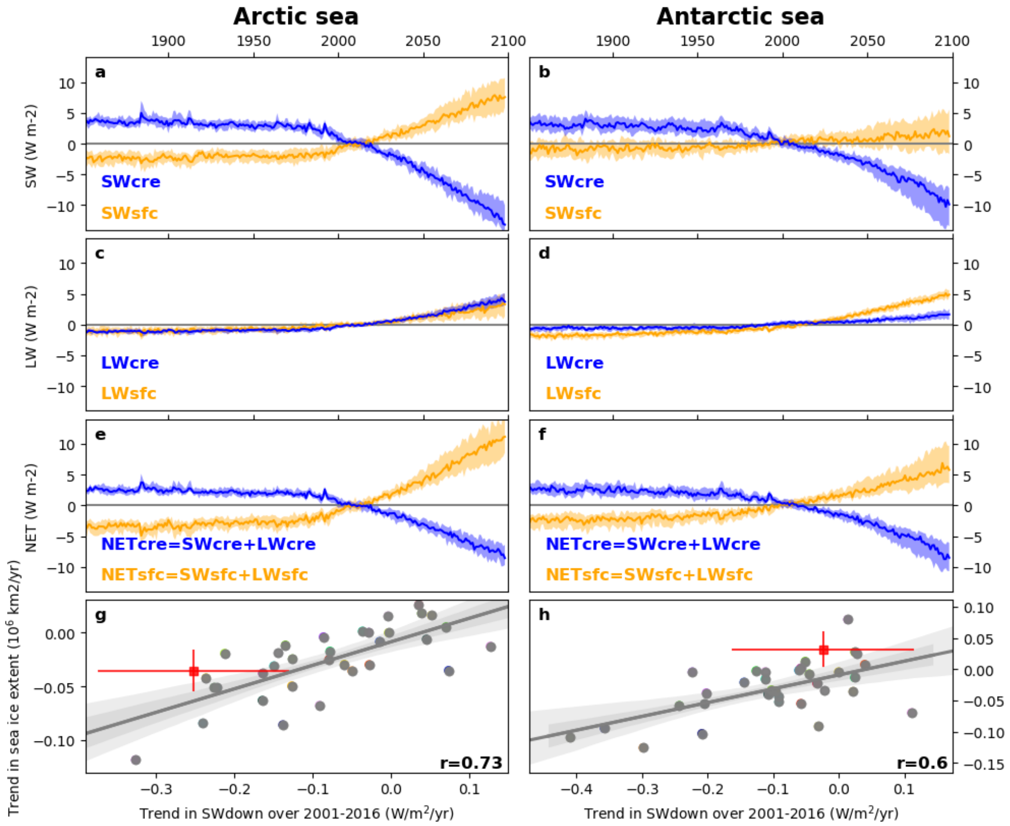

Figure ~~8~~9 Time series of the anomaly in respect to the whole period 1850-2100 of the radiative flux ~~over the period 1850-2100~~. Mean modeled SWcre, LWcre and NETcre (blue) and surface SWsfc, LWsfc and NETsfc (orange) anomalies over the 1850-2100 period under rcp8.5 scenario averaged over the Arctic sea. The solid line shows the median, where the envelope represents the 25 and 75 percentile of the 32 CMIP5 models. The linear regression (grey solid line and its 68% (dark grey envelope) and 95% (light grey envelope) confidence interval) between: the trend in SWdown and trend in sea ice extent (g and h); of the 32 CMIP5 climate models shown by grey dots over 2001-2016. The observed trends are shown by red colors where confidence interval refers to standard error of the trend.

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Author Contributions: RA designed the study and performed the analysis. RA, AC, PCT and LGS contributed to the interpretation of the results. RA, PCT, AC and GD drafted the paper. All authors commented on the text.

Competing interests: The authors declare no competing financial interests.

Additional information: The programs used to generate all the results are made with Python. Analysis scripts are available by request to R. Alkama.

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