https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

The Cryosphere Discussions
Open Access
EGU

Clouds damp the impacts of Polar sea ice loss

Authors: Ramdane Alkama[1*], Alessandro Cescatti[1], Patrick C. Taylor[2], Lorea Garcia-San Martin[1], Herve Douville[3], Gregory Duveiller[1], Giovanni Forzieri[1] and Didier Swingedouw[4]

Affiliation:

[1] European Commission, Joint Research Centre, Via E. Fermi, 2749, I-21027 Ispra (VA), Italy

[2] NASA Langley Research Center, Hampton, Virginia

[3] Centre National de Recherches Meteorologiques, Meteo-France/CNRS, Toulouse, France

[4] EPOC, Universite Bordeaux 1, Allée Geoffroy Saint-Hilaire, Pessac 33615, France

***Correspondence to:** Ramdane Alkama (ram.alkama@hotmail.fr)

Abstract

Clouds play an important role in the climate system through two main contrasting effects: (1) cooling the Earth by reflecting part of incoming solar radiation to space; (2) warming the Earth by reducing the loss of thermal energy to space. Recently, a significant amount of attention has been given to the influence of clouds on the Arctic surface energy budget. Studies have argued that clouds cover fraction is not respoding to reduced sea ice in summer. Taking a different perspective in this work using CERES data and 32 CMIP5 climate models, we find that the shortwave cooling effect of clouds strongly influences the surface energy budget response to changes in sea ice cover. The results illustrate that the cloud cooling effect operates in a counter-intuitive manner of the polar seas: 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. An increase in absorbed solar radiation when sea ice retreats (surface albedo change) explains $66 \pm 2\%$ of the observed signal. The remaining $34 \pm 1\%$ are due to the increase in cloud cover/thickness. This interplay between clouds and sea ice reduces by half the increase of net radiation at the surface that follows the sea-ice retreat, therefore damping the surface energy budget impact of polar sea ice loss. We further highlight how this process is represented in some climate models.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

1. Introduction

Radiation from the sun is the primary energy source to the Earth system and is 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) 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 atmosphere emit thermal energy back to space, called outgoing longwave (LW) radiation, resulting in a loss of energy (Fig. 1). The balance between these energy exchanges determine Earth's present and future climate. 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), impacting sub-polar ecosystems (Cheung et al., 2009; Post et al., 2013) and possibly mid-latitude climate (Cohen et al., 2014).

Clouds play an important role in modifying the radiative energy flows that determine 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 relative to clear skies (Fig 1). These cloud effects on Earth's radiation budget can be gauged using 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 (SW) cloud radiative effect (SWcre) is negative since clouds reflect incoming solar radiation back to space resulting in a cooling effect. Alternatively, the longwave cloud radiative effect (LWcre) is positive since clouds reduce the outgoing LW radiation to space generating a warming effect (Harrison et al., 1990; Loeb et al., 2018; Ramanathan et al., 1989).

In this study, we use the Clouds and the Earth's Radiant Energy System (CERES) top-of-atmosphere (TOA) radiative flux dataset and 32 CMIP5 climate models to estimate the relationship between the CRE and the Earth's surface radiation budget.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

The Cryosphere Discussions

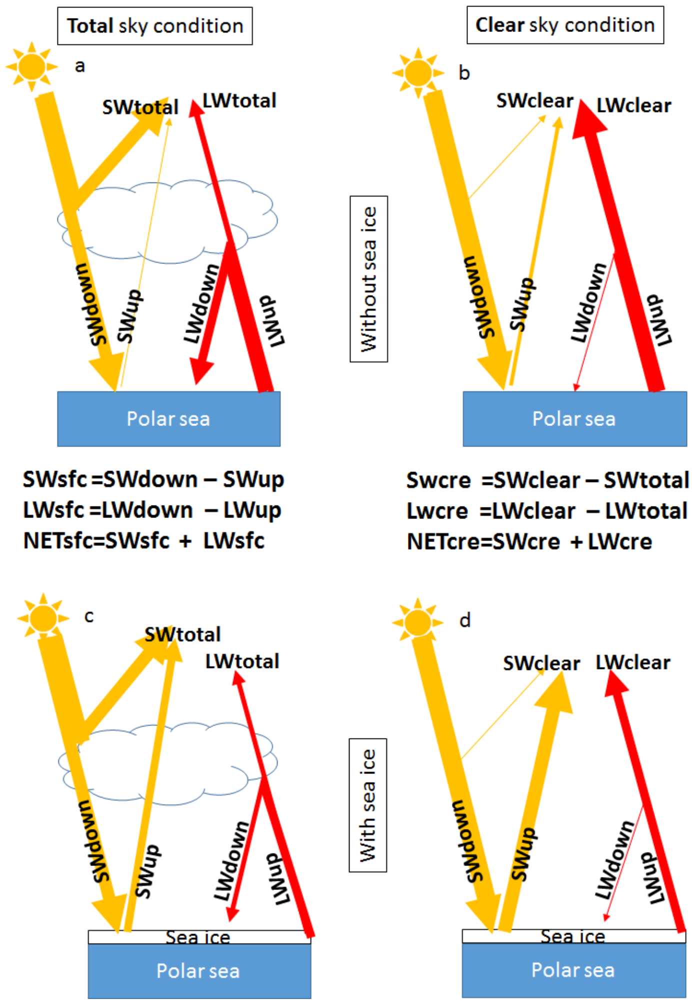


Figure 1 Schematic representation of radiative energy flows in polar seas under total sky conditions (a, c) and clear sky conditions (b, d) for two contrasting surface conditions: without sea ice (a, b) and with sea ice (c, d).

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, defined as the difference in net irradiance at TOA between total-sky and clear-sky conditions. Using the CERES EBAF Ed4.0 (Loeb et al., 2018) flux measurements and CMIP5 modeled flux, CRE is calculated by taking the difference between clear-sky and total-sky net irradiance flux at the TOA.

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

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

The Cryosphere Discussions

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

$$\mathbf{NET}_{cre}=\mathbf{SW}_{cre}+\mathbf{LW}_{cre} \quad (3)$$

2.2 Earth's surface radiative budget: The net SW and LW flux at the surface (SW_{sfc} and LW_{sfc}, respectively) is calculated as the difference between incoming $\mathbf{SW}_{down}$ ($\mathbf{LW}_{down}$) and outgoing $\mathbf{SW}_{up}$ ($\mathbf{LW}_{up}$) as shown in equations 4 (5).

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

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

$$\mathbf{NET}_{sfc}=\mathbf{SW}_{sfc}+\mathbf{LW}_{sfc} \quad (6)$$

2.3 CERES EBAF Ed4.0 Products: For all surface and TOA radiative flux quantities, we used the NASA CERES Energy Balanced and Filled (EBAF) monthly data set (CERES EBAF-TOA_Ed4.0), providing monthly, global fluxes on a 1-degree latitude by 1-degree longitude grid.

The CERES EBAF product is a standard source for estimating surface irradiance at the global scale (Loeb et al., 2018). In this study, we used CERES surface longwave (LW) and shortwave (SW) radiative fluxes to investigate the influence of clouds on the variability in the Arctic surface energy budget in conjunction with variations in sea ice. CERES EBAF-TOA-Surface products have demonstrated improved the accuracy of TOA-surface irradiance computations relative to other sources (e.g., meteorological reanalysis), and the errors/uncertainties between observed monthly mean irradiances and EBAF-TOA-Surface fluxes are small (Kato et al., 2013).

2.4 Sea ice concentration: Sea ice concentration (SIC) data are from the National Snow and Ice Data Center (NSIDC, http://nsidc.org/data/G02202). This data set provides a Climate Data Record (CDR) of SIC from passive microwave data. It provides a consistent, daily and monthly time series of SIC from 09 July 1987 through the most recent processing for both the North and South Polar regions (Peng et al., 2013; W. Meier, F. Fetterer, M. Savoie, S. Mallory, R. Duerr, 2017). The data is on a 25 km x 25 km grid. We used the latest version (Version 3) of the SIC CDR created with a new version of the input product, from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data.

2.5 Polar seas: We defined polar seas as the seas where we observed monthly SIC 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 budget and project their future changes, we used an ensemble of simulations conducted with 32 earth system models (models used are shown in Figure 3 and S3) contributing to the Coupled Model Intercomparison

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

Project Phase 5 (CMIP5) (Taylor et al., 2012). These model experiments provided: historical runs (1850-2005) in which all external forcings are consistent with observations and future runs (2006-2100) using the RCP8.5 emission scenarios (Taylor et al., 2012). The comparison with the satellite data is made over 2001-2016. To make this comparison, we merged historical runs 2001-2005 with RCP8.5 2006-2016.

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 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). We find a positive correlation between the net annual CRE (NETcre=SWcre+LWcre) and net annual surface radiative flux (NETsfc=SWsfc+LWsfc) over much of the global ocean between 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. 2ab). We split the NETcre into SWcre and LWcre and explore their correlation with the NETsfc. We find that the SWcre (Fig. 2cd) shows similar patterns of correlation as before (Fig. 2ab) but with a stronger magnitude, while LWcre generally shows the opposite correlations (Fig. 2ef). This suggests that SW radiation fluxes are responsible for the sharp contrast between the polar regions and the rest of the world. Indeed, SWsfc and SWcre (Fig. 2gh) show the sharpest and most significant contrast between the polar regions and the rest of the world (Fig. S2 is similar to Fig. 2 but only significant correlations at 95 confidence level are reported in blue and red colors). On average, climate models are able to reproduce the spatial pattern of the observed SW correlation, but show a large inter-model spread concerning the spatial extent of the phenomena (Fig. 3 and S3). On the other hand, several models completely fail at reproducing this fundamental correlation. Indeed, ACCESS1-3, MIROC5, CanESM2 and CSIRO-Mk3-6-0 models shows negative correlation over Antarctic continent in contrast to observed positive correlation. Also, 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 contain misrepresentations of the relationships between sea ice extent, cloud cover/thickness, and/or their influence on surface radiative fluxes that could severely impact their projections.

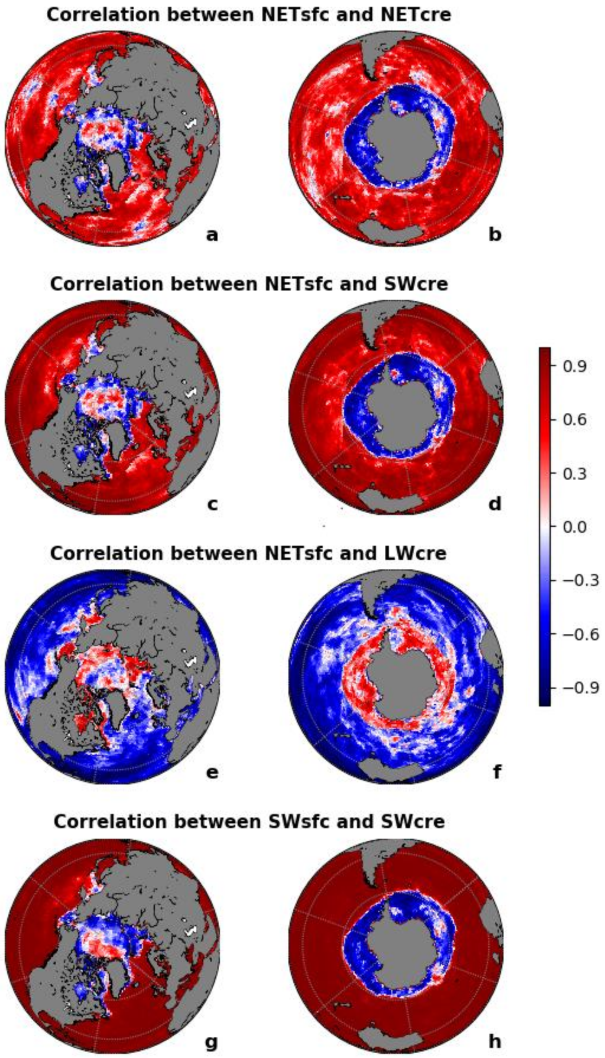
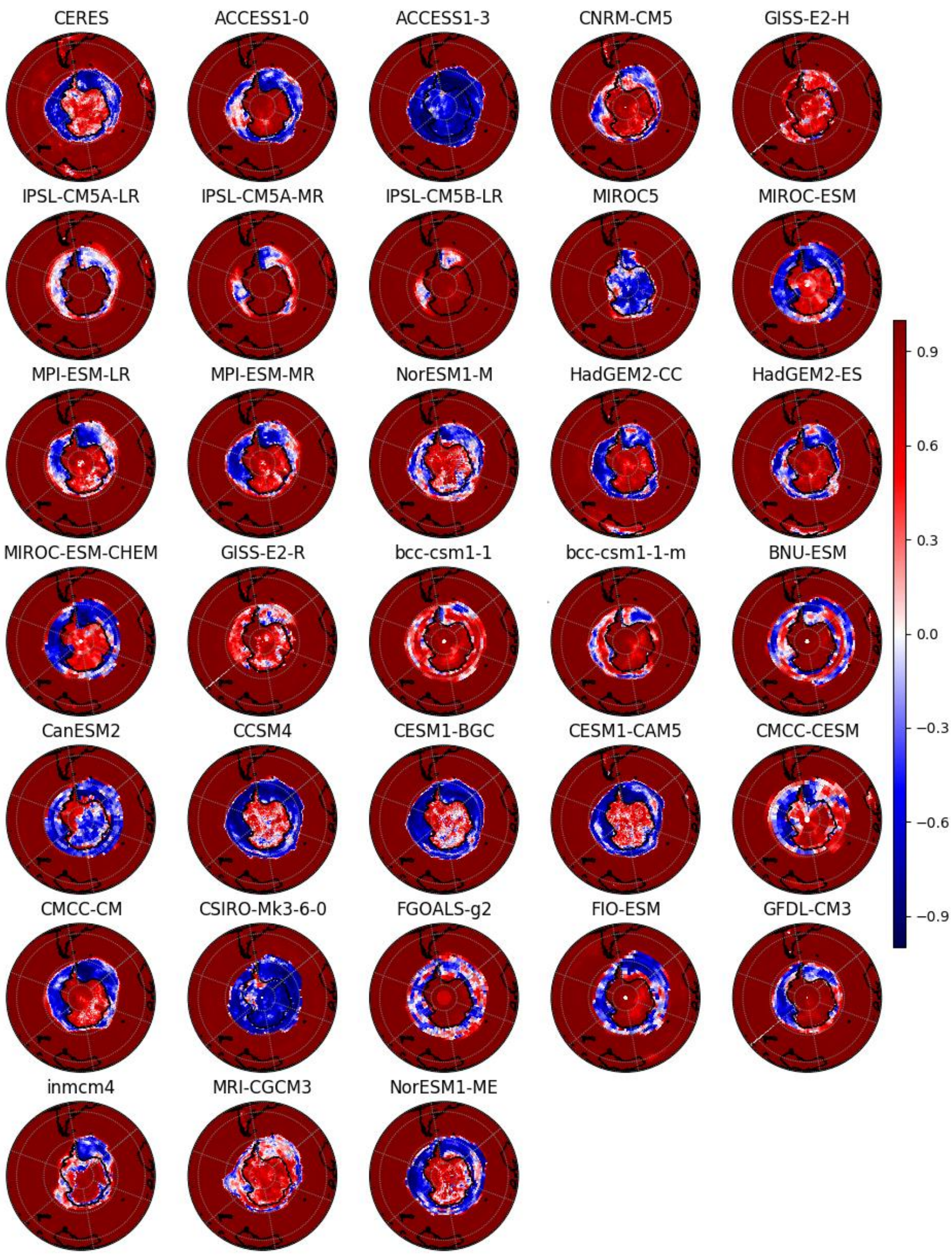


Figure 2 Correlation between TOA CRE and surface radiation over 2001-2016 from CERES measurements for the Northern Hemisphere (aceg) and Southern Hemisphere (bdfh) sea. Positive correlations (red color) indicate that years with less NETsfc coincide with years NETcre has a stronger cooling effect and *vice versa*.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

The Cryosphere Discussions
Open Access
EGU



151

152 **Figure 3** Correlation between SWcre and SWsfc shown by 32 CMIP5 earth system models and
153 CERES between 2001 and 2016 over the Southern Hemisphere.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

3.2 Effects of sea ice concentration change

We illustrate that the apparent paradox between NETcre and NETsfc found in Fig 2ab is caused by the factors contributing to the SW fluxes. This can be explained by: (I) On the one hand, if cloud properties stay constant and the sea ice (albedo) decreases, SWcre will become increasingly negative (cooling) while more of the incoming shortwave that reaches the surface will be absorbed (warming); (II) On the other hand, the relationship between cloud cover/thickness and sea ice could lead to cloudier Polar seas under melting sea ice (Abe et al., 2016; Liu et al., 2012) such that the SWcre cooling effect is enhanced concurrently with melting sea ice.

Over the Antarctic seas, analysis of the year-to-year changes in surface downward SW radiation (SWdown) stratified in 2% SIC bins retrieved from satellite microwave radiometer measurements shows an increase in SWdown with increased SIC and *vice-versa* (Fig. 4a). This suggests that years with higher SIC have fewer and/or thinner clouds (Liu et al., 2012) (Fig. 5), larger SWdown, and also larger upward SW radiation (SWup) (Fig. 4b), due to the high sea ice albedo (Fig. S4). As a consequence, these years also show a lower SWsfc (Fig. 4c) and thus are characterized by surface cooling. Furthermore, fewer clouds implies a reduction of the cloud cooling effect (less negative SWcre) as described above in process (II), this accounts for 34%±1% *o*f 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%±2% of the observed change (Supplementary section 1 and Fig. 6). This explains the observed negative correlation between SWcre and SWsfc over polar seas and the opposite observed change of SWcre and SWsfc (Fig 4cde). 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 where we find at the annual level, the relationship between NETsfc and SIC, and NETcre and SIC.

$$\Delta NETsfc=(-36.61\pm0.72)\Delta SIC \quad (1)$$

$$\Delta NETcre=(47.03\pm1.01)\Delta SIC \quad (2)$$

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

We estimate that the cloud changes in the Antarctic system are damping by 47.03/83.64= 56% the potential increase in the surface radiative flux (NETsfc) due to sea ice melting on the surface radiative budget through the surface albedo decrease. The uncertainties of that number are calculated by summing the uncertainties shown in equation (1) and (2) as follows: (0.72+1.01)/83.64=2%.

Similarly, over the Arctic (Fig. S5), we estimate the cloud influence on the surface net radiative budget that covaries with sea ice loss is 47±3%.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

The Cryosphere
Discussions
Open Access

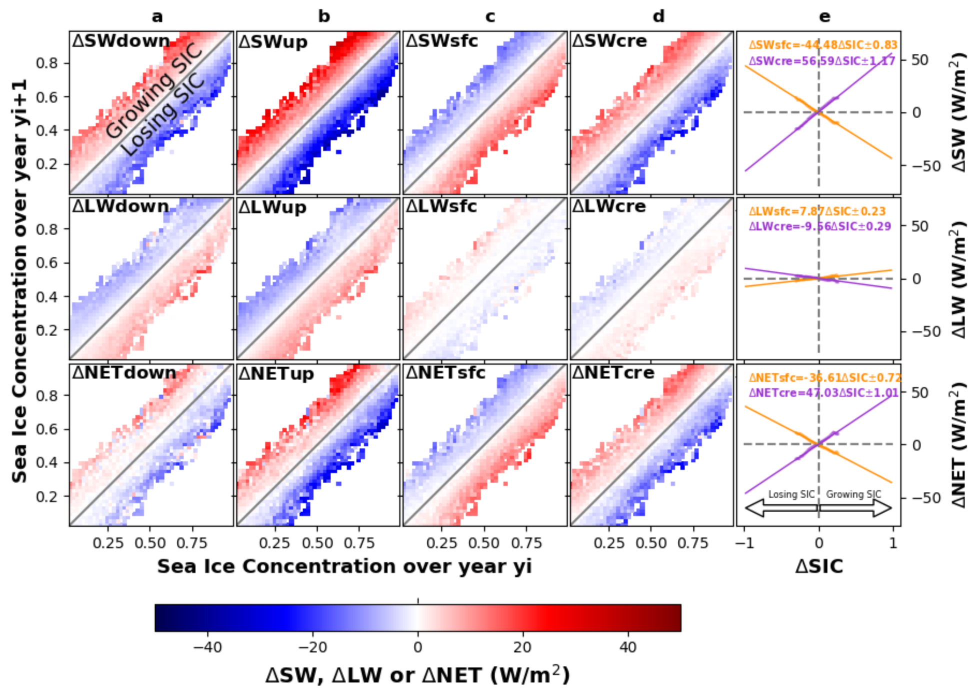


Figure 4 Annual changes in SW, LW and NET as function of SIC. Annual changes in SW (top), LW (middle) and NET (bottom) of radiative down (a), up (b), sfc=down-up (c) and cre (d) over Antarctic sea as function of SIC change between two consecutive years y_{i+1} and y_i from 2001-2016 time period. The 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) represents the average of one parallel to the diagonal in (c) or (d) as described in the Supplement section 2.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

The Cryosphere
Discussions
Open Access

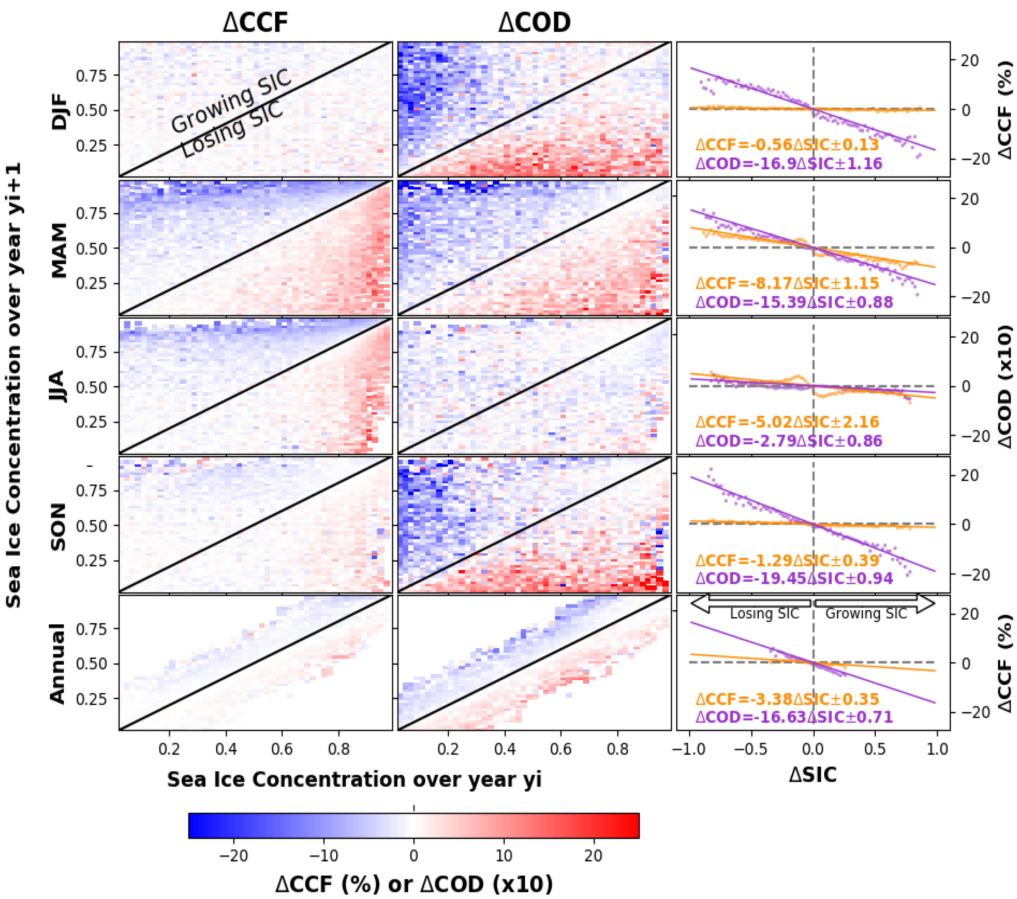


Figure 5 Seasonal and annual changes in cloud cover fraction (CCF) and cloud optical depth (COD) over the Antarctic polar sea region as a function of SIC change between two consecutive years y_{i+1} and y_i from 2001-2016 time period. In order to use the same scale, COD has been multiplied by a factor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

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

The Cryosphere
Discussions
Open Access

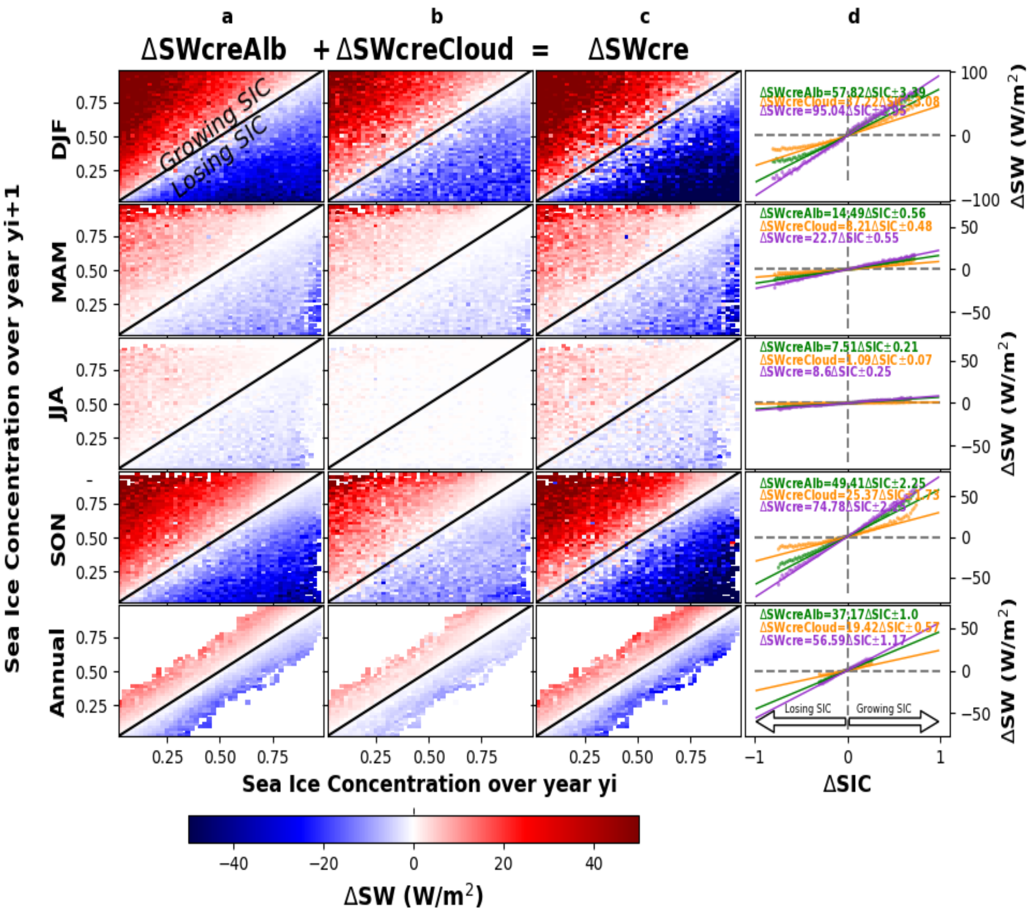


Figure 6 Seasonal and annual changes in SWcreAlb, SWcreCloud and SWcre over the Antarctic polar sea region as function of SIC change between two consecutive years y_{i+1} and y_i from 2001-2016 time period. The analysis is based on observations from satellites data.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

Altogether these results suggesting that polar sea ice and cloud covarying in a way that substantially reduces the overall impact of the sea ice loss. In fact, with melting of the sea ice the cooling effects of clouds are enhanced. This effect in the polar climate system leads to a substantial reduction (56±3% over the Antarctic and 47±3% over the Arctic) of the potential increase in NETsfc in response to sea ice loss. Despite this mechanism, the sharp reduction in Arctic surface albedo has been dominating the recent change in the surface radiative budget and led to a significant increase in NETsfc since 2001. These results demonstrate that the interannual variability of polar surface radiative fluxes is currently controlled by variations in SIC and surface albedo, and that cloud effects only mitigate the effects but not invert the trends (i.e., a damping effect). 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) that demonstrate a cloud cover fraction (CCF) response to reduced sea ice in fall/winter but not in summer (Figure 7a) 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. Surface temperatures in regions of sea ice melting hover near freezing due to the phase change, whereas the atmospheric temperatures are not constrained by the freezing/melting point. Despite reduced sea ice cover, strong increases in surface evaporation (latent heat) are limited (Fig. 7mn), 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 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), which depends directly on 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). However, the large spread amongst climate models indicates that there is still considerable 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 NETsfc (NETcre) during summer, while LWsfc plays a minor role (Fig. 7). In contrast, during winter LWsfc (LWcre) explains most of the observed changes in the NETsfc (NETcre). 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. We have to note here that, the numbers reported in Figure 7 are for 100% SIC loss, while the ones reported in the previous figures (Fig. 4, 5 and 6) are for 100% SIC gain and explains the opposite sign.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

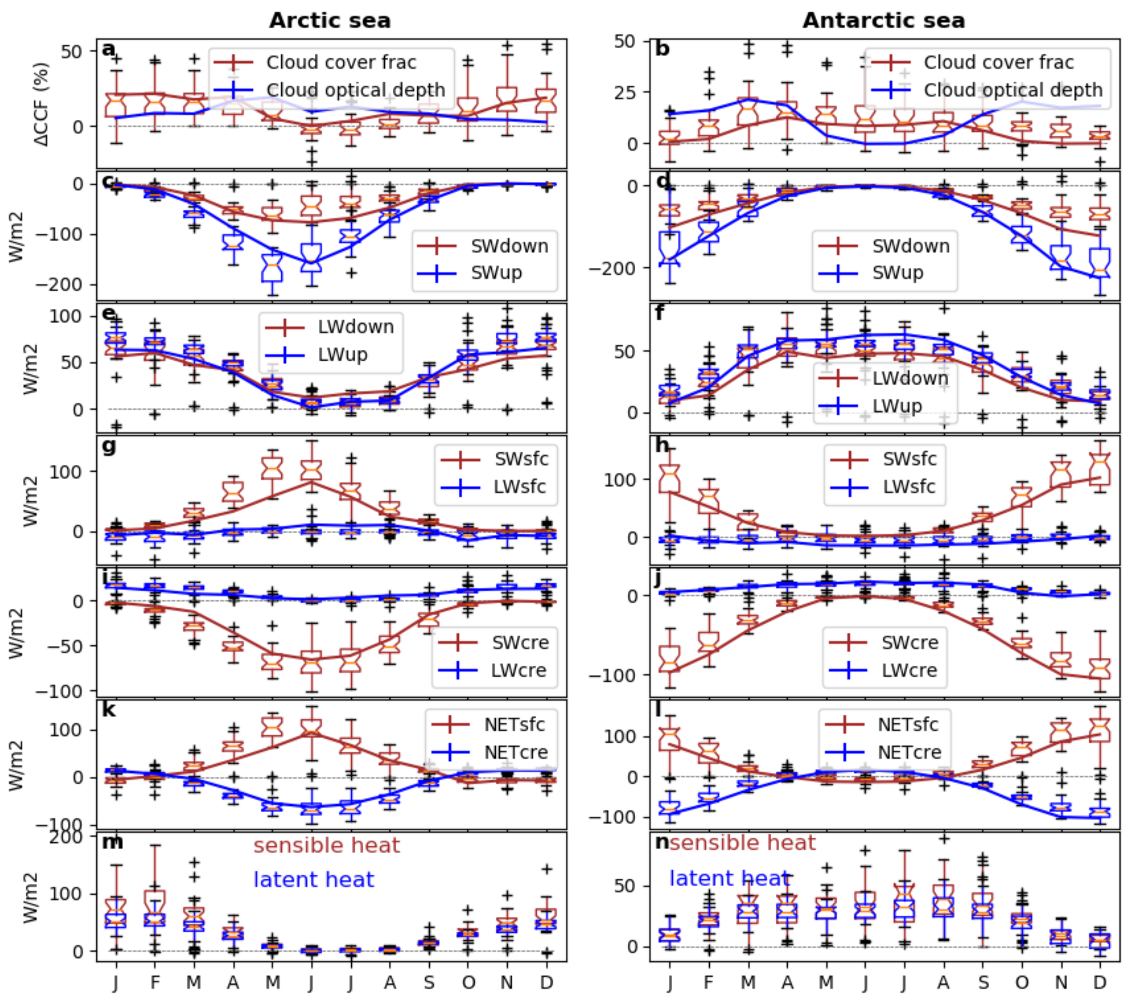


Figure 7 Monthly change in different terms of the radiative energy balance, cloud optical depth (COD) and cloud cover fraction (CCF) extrapolated from observation for an hypothetical 100% decrease in SIC over the areas where we observed SIC change during the period 2001-2016. This change estimate came from the use of a linear interpolation of the change of different parts of energy balance, COD and CCF as function of change in SIC coming from all possible combinations of couples of consecutive years for a given month from 2001 to 2016 and for all grid cells for which SIC is larger than zero in one of the two years. Observations 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.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

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

In the future, under RCP8.5 scenario (a business as usual case) (Taylor et al., 2012), CMIP5 models show an increase in SWsfc over the Arctic Ocean (Fig. 8a) coherent 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 despite the relatively large, concurrent and opposing change in cloud cooling effect (SWcre). Future fluxes of LW (Fig. 8c) will likely play a minor but non-negligible role on total energy budget by further increasing the surface net radiative fluxes, NETsfc (Fig. 8e), damping the cooling effect of clouds NETcre. In addition, CMIP5 models shows clearly that by 2100, the magnitude of the decrease in NETcre is slightly lower that the increase in NETsfc (Fig. 8e) over Arctic Ocean. While the Antarctic polar sea region shows the opposite (Fig. 8f). 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 and 56±2% in the Antarctic.

Large uncertainties remain on 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). In this study, we explored the mean annual Arctic and Antarctic sea-ice extent trend coming from 32 CMIP5 models and find a high positive correlation with the simulated trend in the SWdown (Figure 8gh). 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.

4. Conclusion

The manuscript deals with two important and controversial topics in climate science, namely the role of clouds and the fate of polar sea ice. The work is grounded in a long time series of robust satellite observations that allowed us to document an important damping effect in the polar clouds-sea ice system. In addition, we show how 32 state-of-the-art climate models represent this feedback.

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. We found that when sea ice cover is reduced between two consecutive years that the cooling effect of clouds increased, damping the total change in the net surface energy budget. The magnitude of this effect is important. 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. One-third of this half if induced by the direct change in cloud cover/thickness. While 2/3rd of this effect is the result of changing surface albedo. This finding challenges the classic view that minimizes the relationship between summer clouds and sea ice concentration (Taylor et al., 2015), and demonstrates that less sea ice, even during summer, leads to thicker clouds that reduces the fraction of solar energy reaching the surface.

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

In addition, we demonstrated that the models that shows larger trends in polar sea ice extent are the same that show smaller trends in surface incoming solar radiation (clouds). In order to understand current and future climate trajectories, model developments should aim to reduce uncertainties in the representation of polar cloud processes and their relationships with sea ice cover. The observation-driven findings reported in the manuscript could be instrumental for this scope.

Future cloud changes and sea evolution represent major uncertainties in climate projections due to the multiple and relevant pathways through which cloudiness and sea ice 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 the uncertainty on the covariation between polar clouds and the changing sea ice cover (Fig. 7), constrain future model projections and ultimately improve the understanding of present and future polar climate. Ultimately, our findings on the interplay between cloud and sea ice may support an improvement in the model representation of the cloud-ice feedback, a mechanism that may 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 Arctic regions (Buixadé Farré et al., 2014).

https://doi.org/10.5194/tc-2019-283
Preprint. Discussion started: 19 December 2019

The Cryosphere
Discussions
Open Access

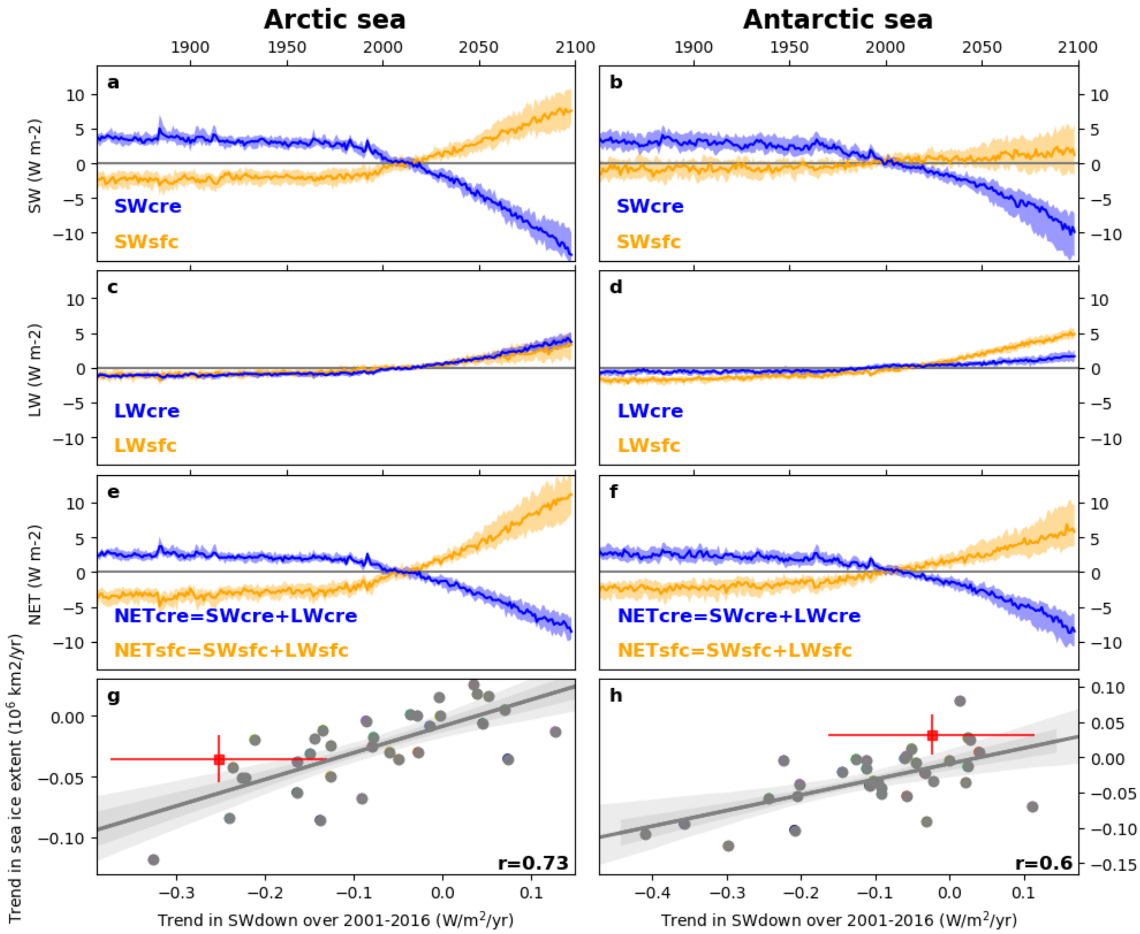


Figure 8 Time series of the anomaly of the radiative flux over the period 1850-2100. Mean modeled SWcre, LWcre and NETcre (blue) and surface SWsfc, LWsfc and NETsfc (orange) anomalies over the 1850-2100 period under rcp8.5 scenario averaged over the Arctic sea. The solid line shows the median, where 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.

Acknowledgments: The authors acknowledge the use of Clouds and the Earth's Radiant Energy System (CERES) satellite data version 4.0 from https://ceres.larc.nasa.gov/index.php, sea ice concentration data from National Snow and Ice Data Center (NSIDC) http://nsidc.org/data/G02202, as well as the modeling groups that contributed to the CMIP5 data archive at PCMDI https://cmip.llnl.gov/cmip5/.

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.

References:

Abe, M., Nozawa, T., Ogura, T. and Takata, K.: Effect of retreating sea ice on Arctic cloud cover in simulated recent global warming, Atmos. Chem. Phys, 16, 14343–14356, doi:10.5194/acp-16-14343-2016, 2016.

Arzel, O., Fichefet, T. and Goosse, H.: Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs, Ocean Model., 12(3-4), 401–415, doi:10.1016/J.OCEMOD.2005.08.002, 2006.

Boisvert, L. N. and Stroeve, J. C.: The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder, Geophys. Res. Lett., 42(11), 4439–4446, doi:10.1002/2015GL063775, 2015.

Buixadé Farré, A., Stephenson, S. R., Chen, L., Czub, M., Dai, Y., Demchev, D., Efimov, Y., Graczyk, P., Grythe, H., Keil, K., Kivekäs, N., Kumar, N., Liu, N., Matelenok, I., Myksvoll, M., O'Leary, D., Olsen, J., Pavithran.A.P., S., Petersen, E., Raspotnik, A., Ryzhov, I., Solski, J., Suo, L., Troein, C., Valeeva, V., van Rijckevorsel, J. and Wighting, J.: Commercial Arctic shipping through the Northeast Passage: routes, resources, governance, technology, and infrastructure, Polar Geogr., 37(4), 298–324, doi:10.1080/1088937X.2014.965769, 2014.

Charlock, T. P. and Ramanathan, V.: The Albedo Field and Cloud Radiative Forcing Produced by a General Circulation Model with Internally Generated Cloud Optics, J. Atmos. Sci., 42(13), 1408–1429, doi:10.1175/1520-0469(1985)042<1408:TAFACR>2.0.CO;2, 1985.

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R. and Pauly, D.: Projecting global marine biodiversity impacts under climate change scenarios, Fish Fish., 10(3), 235–251, doi:10.1111/j.1467-2979.2008.00315.x, 2009.

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J. and Jones, J.: Recent Arctic amplification and extreme mid-latitude weather, Nat. Geosci., 7(9), 627–637, doi:10.1038/ngeo2234, 2014.

Comiso, J. C., Comiso, J. C., Parkinson, C. L., Gersten, R., Stock, L., Parkinson, C. L., Gersten, R. and Stock, L.: Accelerated decline in the arctic sea ice cover, Geophys. Res. Lett. [online] Available from: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.419.8464 (Accessed 30 March 2018), 2008.

Graversen, R. G., Mauritsen, T., Tjernström, M., Källén, E. and Svensson, G.: Vertical structure of recent Arctic warming, Nature, 451(7174), 53–56, doi:10.1038/nature06502, 2008.

Harrison, E. F., Minnis, P., Barkstrom, B. R., Ramanathan, V., Cess, R. D. and Gibson, G. G.: Seasonal variation of cloud radiative forcing derived from the Earth Radiation Budget Experiment, J. Geophys. Res., 95(D11), 18687, doi:10.1029/JD095iD11p18687, 1990.

Holland, M. M., Landrum, L., Raphael, M. and Stammerjohn, S.: Springtime winds drive Ross Sea ice variability and change in the following autumn, Nat. Commun., 8(1), 731, doi:10.1038/s41467-017-00820-0, 2017.

Kato, E., Kinoshita, T., Ito, A., Kawamiya, M. and Yamagata, Y.: Evaluation of spatially explicit emission scenario of land-use change and biomass burning using a process-based biogeochemical model, J. Land Use Sci., 8(1), 104–122, doi:10.1080/1747423X.2011.628705, 2013.

Liu, Y., Key, J. R., Liu, Z., Wang, X. and Vavrus, S. J.: A cloudier Arctic expected with diminishing sea ice, Geophys. Res. Lett., 39(5), n/a–n/a, doi:10.1029/2012GL051251, 2012.

Loeb, N. G., Doelling, D. R., Wang, H., Su, W., Nguyen, C., Corbett, J. G., Liang, L., Mitrescu, C., Rose, F. G., Kato, S., Loeb, N. G., Doelling, D. R., Wang, H., Su, W., Nguyen, C., Corbett, J. G., Liang, L., Mitrescu, C., Rose, F. G. and Kato, S.: Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Top-of-Atmosphere (TOA) Edition-4.0 Data Product, J. Clim., 31(2), 895–918, doi:10.1175/JCLI-D-17-0208.1, 2018.

Peng, G., Meier, W. N., Scott, D. J. and Savoie, M. H.: A long-term and reproducible passive microwave sea ice concentration data record for climate studies and monitoring, Earth Syst. Sci. Data, 5(2), 311–318, doi:10.5194/essd-5-311-2013, 2013.

Post, E., Bhatt, U. S., Bitz, C. M., Brodie, J. F., Fulton, T. L., Hebblewhite, M., Kerby, J., Kutz, S. J., Stirling, I. and Walker, D. A.: Ecological consequences of sea-ice decline., Science, 341(6145), 519–24, doi:10.1126/science.1235225, 2013.

Ramanathan, V., Cess, R. D., Harrison, E. F., Minnis, P., Barkstrom, B. R., Ahmad, E. and Hartmann, D.: Cloud-radiative forcing and climate: results from the Earth radiation budget experiment., Science (80-.)., 243(4887), 57–63, doi:10.1126/science.243.4887.57, 1989.

Serreze, M. C., Holland, M. M. and Stroeve, J.: Perspectives on the Arctic's Shrinking Sea-Ice Cover, Science (80-.)., 315(5818), 1533–1536, doi:10.1126/science.1139426, 2007.

Simmonds, I.: Comparing and contrasting the behaviour of Arctic and Antarctic sea ice over the 35 year period 1979-2013, Ann. Glaciol., 56(69), 18–28, doi:10.3189/2015AoG69A909, 2015.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. T. and H. L. M.: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. [online] Available from: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html (Accessed 2 July 2018), 2007.

Stroeve, J., Holland, M. M., Meier, W., Scambos, T. and Serreze, M.: Arctic sea ice decline: Faster than forecast, Geophys. Res. Lett., 34(9), doi:10.1029/2007GL029703, 2007.

Taylor, K. E., Stouffer, R. J. and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, Bull. Am. Meteorol. Soc., 93(4), 485–498, doi:10.1175/BAMS-D-11-00094.1, 2012.

Taylor, P., Hegyi, B., Boeke, R. and Boisvert, L.: On the Increasing Importance of Air-Sea Exchanges in a Thawing Arctic: A Review, Atmosphere (Basel)., 9(2), 41, doi:10.3390/atmos9020041, 2018.

Taylor, P. C., Kato, S., Xu, K.-M. and Cai, M.: Covariance between Arctic sea ice and clouds within atmospheric state regimes at the satellite footprint level, J. Geophys. Res. Atmos., 120(24), 12656–12678, doi:10.1002/2015JD023520, 2015.

Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., Hosking, J. S., Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J. and Hosking, J. S.: An Initial Assessment of Antarctic Sea Ice Extent in the CMIP5 Models, J. Clim., 26(5), 1473–1484, doi:10.1175/JCLI-D-12-00068.1, 2013.

W. Meier, F. Fetterer, M. Savoie, S. Mallory, R. Duerr, and J. S.: NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center., , doi:https://doi.org/10.7265/N59P2ZTG, 2017.

Zhang, X. and Walsh, J. E.: Toward a Seasonally Ice-Covered Arctic Ocean: Scenarios from the IPCC AR4 Model Simulations, J. Clim., 19(9), 1730–1747, doi:10.1175/JCLI3767.1, 2006.