The Arctic sea ice-cloud radiative negative feedback in the Barents and Kara Sea region

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Abstract

Shortwave cloud radiative effect (SWCRE), known as the cooling effect triggered by cloud, plays a vital role in adjusting the global radiation budget. As the Arctic gets warmer, it may become a more indispensable factor curbing this warming tendency. Research has pointed out a significant relationship between sea ice cover (SIC) and SWCRE over the Arctic during summer (June–August). Although no evidence has been found on cloud response to SIC during summer on the average of the Arctic, this study regards cloud as an inter-connection which can regulate SIC and SWCRE in a particular place: Barents and Kara Sea region (15°E–85°E, 70°N–80°N). Its SWCRE and SIC vary significantly, with their trends being 5.85 w·m⁻² and −5.87% per decade compared to those of the Arctic mean (2.93 w·m⁻² and −4.65% per decade). In this area, we find that the growing number of low-level cloud which is resulted from the loss on SIC may be accountable for the increase in SWCRE, as is shown in the correlation coefficient between low-level cloud and SIC reaches −0.4. The correlation coefficient between low-level cloud and SWCRE is 0.6. It reflects a SIC-cloud-SWCRE negative feedback. Moreover, a regression fitting model is being established to quantify the contribution of Arctic cloud in the process of slowing down the Arctic warming. It reveals that this specific region would turn into an ice-free region with sea surface temperature (SST) 1.5 °C higher than reality during 2001 if we stop the increase in SWCRE. This result presents how fascinating the contribution cloud has been making in its way slowing down the warming pace.

Keywords  Arctic cloud · Arctic sea ice · cloud effect · cooling effect

1 Introduction

Global warming is inevitable (Manabe and Stouffer 1980; Solomon et al. 2007). As the Arctic gets warm, positive sea ice cover (SIC) albedo feedback significantly accelerates the loss on SIC due to a higher solar radiation absorption on the surface (Curry et al. 1995), which is known as the Arctic amplification (Serreze et al. 2008; Serreze and Barry 2011). Under this positive feedback, sea ice area decreased at a rate of 11.4% per decade from 1979 to 2007 (Comiso et al. 2008), conversely boosting the warming pace over the Arctic land (Lawrence et al. 2008). Seemingly this positive cycle may contribute to the so-called totally ice-free Arctic.

However, cloud radiative effect may suppress this positive cycle by regulating radiation balance over the Arctic. The mechanism of cloud radiative effect differs in various regions, as shortwave cloud radiative effect (SWCRE) is closely related to the ascending motions in middle-and low-level in the Southeast of China (Li et al. 2019, 2020). And it is worth noting that, although longwave cloud radiative effect (LWCRE) takes part in the annual radiation budget adjustment in the Arctic, inducing a warming effect, SWCRE has a more outstanding influence comparing to LWCRE (Eastman and Warren 2010) during summertime when solar radiation takes part. Therefore, it is advisable to set a premium on SWCRE when discussing the role cloud displays during JJA.

Researchers before pointed out that in the Arctic, absorbed solar radiation (ASR) is mainly controlled by cloud
from May to July (Choi et al. 2014). In addition, cloud plays an essential role in polar response, especially SWCRE (Kay et al. 2008, 2012; Kay and Gettelman 2009). Under the positive SIC-albedo feedback, place with a more significant loss on SIC may gain more considerable amount on absorbed shortwave (Kay et al. 2016), which may generate more evaporation from melting sea ice, resulting in the formation of cloud (He et al. 2019). This process may have an impact on the regional cloud radiative effect. The same principle is also applicable over the Antarctic Pole (Pavolonis and Key 2003), where the change on SWCRE is more significant over the oceanic area with a greater reduction on albedo than in the continent.

Unfortunately, there is no observational evidence for cloud response to the loss on SIC in June–August (JJA) (Morrison et al. 2018, 2019). Nevertheless, one research surprisingly detected a strong association between the loss on SIC and increase in SWCRE without an inter-connection through a satellite retrieved data from NASA as well as ERA5 reanalysis dataset, revealing an existing negative feedback (Choi et al. 2020). However, SIC-cloud feedback in JJA remains to be investigated. At the same time another study found a close relationship between low-level cloud liquid water path and SIC, potentially revealing that the loss on SIC may contribute to the rise in cloud (Yu et al. 2019). Furthermore, importance has been attached to the role low-level liquid cloud displaying on balancing the multiyear SIC (Shupe and Intrieri 2004). The same result has also been found in other studies (Palm et al. 2010; Liu et al. 2012). And these above may be the reason why there is still no evidence for the existence of SIC-cloud feedback in JJA—for they were mainly concentrating on the cloud averaged across the Arctic.

In this study, we focus on a specific region in 15°E–85°E, 70°N–80°N: Barents and Kara Sea region (BK region), with most of its parts covered with sea ice or ocean. BK region has always been a place with significant variabilities, where the sea ice is transported from Arctic core to Barents Sea (Koenigk et al. 2009).

In this study, we will compare this special region to total Arctic during boreal summer and try to answer the following questions:

1. Why does BK region attract so much attention?
2. What’s the relationship between SIC, cloud and SWCRE? How can they be integrated as a feedback?

Following the instruction above, we find that SWCRE and SIC both have fascinating variations in this specific region. Enhancement in specific cloud liquid water content (CLWC) at the low level which resulted from the loss on SIC may be responsible for the rise in SWCRE (Chen et al. 2000). Considering SWCRE may not only be influenced by liquid water but also the solid one (Gultepe et al. 2014), we give a test on specific cloud ice water content (CIWC) but to find no evidential trend. Also, comparing to SIC, the impact large-scale advection flowing from other places have on CLWC is dispensable (Jouan et al. 2012). Therefore, this mechanism can be explained as a negative feedback: when the sharply melting SIC results in a rise in low-level cloud over BK region, and then raised cloud promotes the power of SWCRE. Furthermore, this local feedback is still rising dramatically compared to Arctic as a whole owing to a more significant positive feedback. Finally, when a regression fitting model is designed to predict SIC and sea surface temperature (SST) in BK region by regarding SWCRE as a constant amount, we have made an intriguing result.

2 Data and methods

Firstly, as regards to the resolution on space and time. Data used in this study are the monthly average data from ERA5 reanalysis dataset with a spatial resolution of 0.25°×0.25° from 1979 to 2020. Previous work used both the reanalysis and satellite retrieved data to confirm the quality of the dataset in the Arctic, also to arrive at a more solid conclusion (Choi et al. 2020). The dataset involves the ERA5 reanalysis dataset with a spatial resolution of 0.25°×0.25° (Hersbach et al. 2019), as well as the satellite from NASA with a coarser resolution (Loeb et al. 2018). In this study, only the former dataset is adapted for its higher precision on spatial resolution. Also, its wider time span ranged from 1979 to 2020 allow the statistical test to be more trustful. The Arctic region discussed in this study refers to the widely accepted definition which is from 66.5°N to 90°N.

Secondly, with respect to radiation fluxes. Surface net solar radiation (SSR) represents the amount of solar radiation that reaches a horizontal plane at the surface of the Earth minus the amount reflected by the Earth’s surface which is governed by the albedo. Surface net solar radiation, clear sky (SSRC) is similar to SSR but assuming clear-sky, i.e., cloudless condition. Top net solar radiation (TSR) represents the incoming solar radiation minus the outgoing solar radiation at the top of the atmosphere (TOA). Top net solar radiation, clear sky (TSRC) is also similar to TSR but assuming clear-sky which is the cloudless condition. Therefore, SWCRE can be defined as a surface parameter by subtracting SSR from SSRC. Also, we can define it as a TOA parameter by subtracting TSR from TSRC. It is noted that these two SWCRE parameters have virtually no difference in theory and calculation, for these two both representing the upward fluxes characterized by the cloud species and amount. In this article, we define SWCRE by subtracting TSR from TSRC for TOA radiation budget can be more likely to represent a planetary
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|                         | Mean (W m⁻²) | Trend  
|-------------------------|--------------|--------
|                         | MAM          | JJA    | MAM  | JJA  |
| Sub-global SSR          | 192.11       | 198.73 | 0.16* | 0.07 |
| -SWCRE                  | -44.46       | -53.66 | -0.50**| -0.68**|
| Arctic SSR              | 48.39        | 114.40 | 1.09**| 2.52**|
| -SWCRE                  | -17.22       | -68.47 | -0.85**| -2.93**|
| BK region SSR           | 58.84        | 130.19 | 4.07**| 3.30**|
| -SWCRE                  | -29.43       | -87.86 | -2.78**| -5.85**|

Table 1 Mean and trend (per decade) on SSR and -SWCRE from 1979 to 2020 in MAM and JJA over three regions: sub-global (22.5°S–90°N with whole longitudes), the Arctic and BK region. Flux radiation is positive if it is downward in the vertical direction. Asterisks and dual asterisks represent trends passing trend significance tests at 95% and 99% confidence levels, respectively.

change in radiation. In addition, although SWCRE represents a cooling effect, we specifically defined it as a positive value to discuss its role in SIC-cloud feedback for a better understanding. It also can be verified in Table 1 that -SWCRE is the opposite number to SWCRE because a cooling effect means the flux is negative and upward in the vertical direction.

Thirdly, we are involving some related cloud parameters. Total cloud liquid water path (TCLWP), vertical integral of directional cloud liquid water flux and total cloud cover (TCC) represent integrated parameters of the whole level. In ERA5 reanalysis dataset, the parameter of cloud cover is the proportion of a grid box covered by cloud occurring at specific levels of the troposphere (Gultepe and Isaac 2007). Cloud fractions vary from 0 to 1. Low cloud cover (LCC) is a single-level field calculated from cloud occurring on model levels with a pressure greater than 0.8 times the surface pressure. High cloud cover (HCC) is calculated in the same way as LCC, but for model levels with a pressure less than 0.45 times the surface pressure. Medium cloud cover (MCC) is between these two. In addition, over the Arctic Ocean, LCC is at about 840 hPa while HCC is at about 470 hPa. Cloud cover at different levels evaluated in the “Discussion” section is also the same as the description on LCC, MCC, and HCC but with a more precise spatial resolution in the vertical direction.

Following the questions raised in the “Introduction” section, we need to confirm the assumption that reduction on SIC in BK region may result in a great deal of cloud, and then cloud may affect SWCRE. We are seeking the correlation among these three main parts. After confirming the mechanism, it is preferable to see its efficiency. The regression fitting model proposed in this study is based on the relationship between ASR with SIC, SIC. Because ASR is controlled by cloud in summer and is also responsible for the melting sea ice (Choi et al. 2014). SSR, surface thermal radiation, surface sensible heat along with latent heat are added to obtain ASR, which is consistent with the aforementioned concept.

Trends used in this paper for the spatial distribution are all calculated by Mann–Kendall method, which is commonly used in quantitative trend tests (Libiseller and Grimvall 2002) associated with a significant level of 99%.

3 Trend on SWCRE in the study area

It should be noted that SWCRE only works when there’s a direct solar flux. To get an overall view on the change of SWCRE, we are paying attention to its changes in Spring (March–May, MAM) and JJA from a comprehensive perspective over the whole longitudes of 22.5°S–90°N, which is a region influenced by direct solar radiation during MAM and JJA. As is known to all that trend represents the tendency and standard deviation depicts the oscillation. Thus, clear messages revealed on the change of SWCRE are as follows: firstly, with respect to the spatial diversity, there is no significant trend or oscillation from low to mid-latitudes, while rapid elevation and severe oscillation of SWCRE appearing in the Arctic during JJA (Fig. 1b, d). Secondly, as regards to seasonal differences on trends (Fig. 1a, b) and standard deviations (Fig. 1c, d), it can be inferred that changes are more significant in JJA than those in MAM due to more absorption on incoming solar radiation and less SIC, which is why the study is focusing on SWCRE during summer.

Although a large increase in SWCRE has been observed in the Arctic from the perspective of area average, previous study did not concentrate on local areas (Choi et al. 2020). Obviously, increase in SWCRE in the whole Arctic is mainly owing to the contribution of a local variability, which occurs on the north side of the BK region, most parts between Svalbard and the BK region (Fig. 1b and d). In this area, the increase in SWCRE has reached 1.8 W m⁻² per year. Except for this region, no significant trend or oscillation has been observed in the rest of the Arctic. Therefore, it is advisable to consider a local variation when discussing SWCRE in the Arctic.

We list a table to find the differences among these three regions, which is the region affected by direct solar radiation in MAM and JJA from 22.5°S to 90°N with whole longitudes (sub-global), the Arctic region and BK region (Table 1). -SWCRE is the opposite number to SWCRE because a cooling effect implies that the flux is negative and upward in the vertical direction. Firstly, concerning to mean value on seasonal diversity, there is a large difference on radiation flux between MAM and JJA in the Arctic region, also including BK region, where mean on SSR in JJA is more than twice as large as that in MAM, and this difference is expanding on the aspect of -SWCRE. We attribute this seasonal difference to the shifting fixation by the...
movement of direct solar radiation and the change on surface albedo from MAM to JJA. Secondly, trends on both SSR and -SWCRE are significant enough in these three areas, with most of the trends passing the trend significance test at the 99% confidence level (Table 1). However, trends become clearer and clearer from the sub-global to the Arctic and to the BK region. Therefore, we are confirming the assumption that if the Arctic can be the amplifier of the global climate change, BK region may be a magnifier to the Arctic climate change from the perspective of shortwave radiation in JJA.

Moreover, it is shown that although the trend on SSR is larger than the absolute value of the trend on -SWCRE during MAM in both the Arctic and the BK region, situation may be different in JJA. During JJA, trend on -SWCRE is $-2.93 \, W\cdot m^{-2}$ per decade in the Arctic, while trend on SSR is only $2.52 \, W\cdot m^{-2}$ per decade (Table 1). In addition, trend on -SWCRE and SSR in BK region is respectively $-5.85 \, W\cdot m^{-2}$ and $3.30 \, W\cdot m^{-2}$ per decade. This indicates that although cooling effect is still weaker than warming effect in JJA in term of mean value, trend on cooling effect is getting stronger than that on warming effect. It is also revealed that trend on SSR and -SWCRE during JJA is faster in the Arctic region than that in the sub-global, including BK region. Although we cannot attribute these changes to the interannual variability of the fixation through direct solar radiation, the changes on surface albedo during JJA may be responsible for the increase in SSR. Similarly, decrease in -SWCRE, i.e., increase in SWCRE may result from the change in cloud species and amount within the whole atmosphere over the Arctic.

4 Trends on SIC and cloud in the BK region

As SSR along with SWCRE increasing significantly in the BK region during JJA, trends on diverse parameters (Fig. 2) related to surface albedo and cloud are used to capture the reasons for the changes in Table 1. Figure 2a and b are the traditional explanations for the Arctic amplification on temperature, with an upsoar in SST (Fig. 2a) on the boundary of the Arctic Ocean for the SIC-albedo positive feedback has been influencing the Arctic from the edge of the sea ice to its core. It also explains the increase in SSR within JJA (Fig. 2b), as SIC sharply decreases especially in the BK

Fig. 1 Trend (W•m⁻² per year) on SWCRE within a MAM and b JJA and its standard deviation (W•m⁻²) within c MAM and d JJA during 1979–2020. Black dots in the first row represent areas passing trend significance test at 95% confidence level.
region (−2.1% per year), resulting in a reduction on surface albedo. Therefore, the area would receive more incoming solar radiation. Moreover, as is mentioned before, SWCRE depends closely on cloud species and amount when solar radiation exists. From Fig. 2c–g, it can be found that there is an abrupt rise both in TCLWP and cloud cover, especially LCC in the BK region. In this specific area, LCC may contribute more to the trend on cloud cover, while no significant trend has been found at the rest two levels (Fig. 2e–g). Comparing the regional differences (Table 2), it can be told that mean along with trend on SST and SIC in both regions still consist with the theory that BK region may display an magnifier to the Arctic climate change, revealing a stronger positive SIC-albedo feedback in the BK region due to a faster decline on SIC compared to that in the Arctic region. However, cloud may respond differently. On the one hand, gap on mean between two regions is huge in term of TCLWP, TCC, and LCC, while there is no significant difference on MCC and HCC. This may because that average on low-level cloud water content over the BK region is much higher than the Arctic average. On the other hand, although TCLWP has a significant trend in both areas, with rate being 1.39 g·m⁻² and 2.54 g·m⁻² per decade in the Arctic and the BK region, respectively, significant trends on TCC and LCC are only found in the BK region, all these above are revealing a local particularity. Combining Fig. 2 and Table 2, it can be inferred that something must happen in this specific area, accompanying with a greater loss on SIC than that in the Arctic, a significant enhancement in LCC and an extraordinary increase in SWCRE.

5 A negative feedback running in the BK region

To better understand this local process, trend in temperature and CLWC at different level is given in Fig. 3a, b for the Arctic and BK regions. It can be clearly told that compared to the Arctic mean, which is warming mostly at the bottom of the troposphere, BK tends to warm at the surface. This different patterns on temperature warming profile together with a contrast in the sea ice loss in these two regions can have a different impact on the sea ice-air induced cloud above.

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Table 2 Mean and trend (per decade) from 1979 to 2020 within JJA over the Arctic and the BK region, respectively. Asterisks and dual-asterisks represent the trends passing trend significance tests at 90% and 99% confidence levels

|             | Arctic mean | BK region mean | Arctic trend (per decade) | BK region trend (per decade) |
|-------------|-------------|----------------|---------------------------|-------------------------------|
| SIC (%)     | 50.37       | 16.97          | −4.65**                   | −5.87**                      |
| SST (°C)    | 0.58        | 2.88           | 0.35**                    | 0.60**                       |
| TCLWP (g/m²)| 76.68       | 86.17          | 1.39**                    | 2.54**                       |
| TCC (%)     | 80.42       | 83.83          | 0.01                      | 0.46*                        |
| LCC (%)     | 64.76       | 70.51          | −0.11                     | 0.81*                        |
| MCC (%)     | 36.59       | 35.46          | −0.27                     | 0.18                         |
| HCC (%)     | 31.91       | 31.00          | 0.15                      | −0.09                        |

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Fig. 2 a–g Trends on SST, SIC, TCLWP, TCC, LCC, MCC, and HCC from 1979 to 2020 in JJA. Black dots in each subgraph represents areas passing trend significance test at the 95% confidence level.
And from Fig. 3b, we can see a sharp contrast between the trend in CLWC at low level in two regions, compared to a slight increase at low level in the Arctic. BK tends to increase sharply at the low level. We attribute this contrast not only induced directly by sea ice loss but also the different warming profile in two regions which is indirectly influenced by sea ice loss and ocean heat release. And thus, it is obvious that in terms of the Arctic mean, cloud has no response on the sea ice loss (Fig. 3c), however responses intensely in the BK region (Fig. 3d), which extends the connection 4 months leading at the low level. Moreover, from Fig. 3e, it can be inferred that cloud is more responsible for the increase in SWCRE compared to the Arctic at the low level. A negative feedback is revealed: BK’s strong sea ice-air interaction allow the newly exposed ocean to evaporate more, and thus, resulting in more low level cloud, which in turn partially replaces the excessive loss of sea ice to reflect the sunlight.

How efficient this negative feedback has performed? Followed by Fig. 3, the contribution rate on SWCRE in the BK region comparing to that of a whole region is calculated. Contribution rate for the BK region is 20% if SWCRE is evenly distributed: \((85°-15°)/360° \approx 20\%\). However, its local particularity has led the actual contribution rate reaches about 25% (Fig. 4d). Furthermore, this contribution rate is still on its mounting as is shown in the red dotted line, indicating the fact while the whole Arctic is still striving for an efficient negative feedback, BK region itself has already led the way onto the cooling mechanism and the performance is fascinating. Moreover, two record breaking sea ice loss during 2007 and 2011 together with its top SWCRE contribution in BK (Fig. 4d), associated with a remarkable connection between sea ice loss and SWCRE increase (Fig. 4a–c) suggesting a strong connection between sea ice loss and SWCRE increase.

### 6 A regression fitting model focusing on the impact SWCRE has over the Arctic region

In this section, simulations are conducted to quantify the influence of SWCRE on slowing down the warming in the Arctic and the BK region. It is a linear regression model based on the relationship between ASR and the dependent variables: SIC and SST. For detailed information, please refer to 1Appendix mentioned below. Firstly, the whole database has been put into this model, and a regression fitting model (Fig. 5, gray line) is obtained to compare with the original data on both SIC and SST (Fig. 5, black line). The result shows that this regression fitting model captures most of the variabilities in 42 years, indicating a strong relationship on ASR between SIC and SST. Secondly, we inherit the slope and intercept from the above process and use the original data of ASR as well to fit the change on SIC and SST. However, it ignores the increase in SWCRE from 1979 to 2020 and keeps SWCRE as it is in 1979 as time passes, which is designed to detect the power of SWCRE. In this case, the absorption on the surface is relatively accumulating more. The result is shocking but as expected. Both regions present a sharper trend on SIC and SST when ignoring the rising SWCRE (Fig. 5, red line), which is attributed to a
supposed condition that the negative feedback is of no significant change while the positive feedback is becoming stronger. It can be inferred that SIC in the BK region may reach its near-zero point (0.7%) in 2001 under this assumption (Fig. 5b, red line), compared with 14% stayed in the original data in 2001 (Fig. 5b, black line). Also, in 2001, SST in the constant SWCRE model is about 1.5 °C higher than the original data in the BK region (Fig. 5d, red line and black line). Similar contrasts cross the Arctic are also shown in Fig. 5a and c. It is worth noting that this assumption is just an example for highlighting the excellent function of SWCRE in regulating SIC and SST, i.e., a rough estimate on SWCRE and a linear regression model which ignores all the nonlinear coupling among SIC, SST, and SWCRE. The purpose of this study is not to discuss the inter-relationship between sea ice and SST, but to consider these two have a simplified negative bond. Their variations represent the impact induced by cloud. In conclusion, this negative feedback contributes robustly to slowing down the warming pace in the Arctic, especially in the BK region.

7 Discussion and conclusions

In this study, monthly average data from the ERA5 reanalysis dataset are used to investigate the trend on SWCRE in the northern hemisphere. The results show that the increase in SWCRE is significant in the Arctic, especially in the BK region. In this specific region, there is a strong negative feedback against the SIC-albedo positive feedback. This negative feedback can be explained as an outcome low-level cloud response to the loss on SIC in this area, and then low-level cloud continues to increase SWCRE by reflecting more incoming solar radiation. In addition, this feedback is getting stronger owing to a
stronger positive feedback comparing to the whole Arctic. We would like to propose our argument again that cloud has a highly localized variability, which varies from areas to areas, and is influenced by various combining factors. Different types of cloud may all respond to the loss on SIC in JJA but in various ways. If the average Arctic cloud has no connection with the average loss on SIC, it doesn’t mean that cloud does not respond to the loss on SIC. In some of the regions, as it is in the BK region, the response to the loss on SIC is mainly urged by the low-level cloud. And response in other regions remains to be solved. What we know is that the increase in SWCRE does not occur by chance in the Arctic, and cloud may be responsible. Finally, we quantify the influence of SWCRE in its way slowing down the warming by ignoring its increase and comparing the fitting model with the original data. A shocking result is obtained. Without the increase in SWCRE, the BK region will enter its total ice-free and warmer climate era in 2001. The main conclusions are summarized as follows:

1. The increase in SWCRE is significant in the Arctic region, especially in the BK region.
2. Cloud may be responsible for regulating the radiation budget in the Arctic during JJA.
3. In the BK region, cloud may be the main cause for adjusting the negative feedback, and this feedback is still increasing.

As we calculate the correlation coefficient between SIC and cloud cover at the same levels, which is the same as we do on SIC and CLWC. However, the correlation coefficient is relatively faint, but its trend with the rising altitudes is consistent with that of the relationship between SIC and CLWC in Fig. 3b. The same phenomenon has also been found by comparing Fig. 3a and c, with consistent trends as altitude rises but with relatively dimmer significances. We suggest that this negative feedback is determined by the coupling of cloud species and amount, such as the combination along CIWC, CLWC and cloud cover. Therefore, there may be an integration in the cloud
mechanism, and CLWC may be the main cause for the negative feedback in the BK region.

Moreover, is warming evenly distributed in the Arctic? As we know, the Arctic can be an amplifier of the global climate. Is it the same situation for the BK region? Is it reasonable to consider this region as an amplifier for the Arctic climate? Does it have a stronger positive feedback than the Arctic (Fig. 2b, Tables 1 and 2)? Furthermore, for a relatively slighter increase in the SWCRE over the last 10 years, we also investigate the same contribution rate BK region has made as is shown in Fig. 4 but for respectively three months within JJA: June, July, and August. In this case, it is found that the increase in SWCRE in July and August stopped in about 2002. Moreover, trend on SIC in the BK region within these three months also corresponds to the above result, i.e., SIC in the BK region within July and August nearly reduced to the zero-point in about 2002. The same result is also shown in Fig. 5, in last 10 years, this regression fitting model has become less capable in capturing the original feature. Therefore, we suggest that this negative feedback may rely on a certain amount of SIC floating on the ocean.

Finally, we would like to provide the uncertainties on the data used in this study. All descriptions on JJA are the mean values from June to August, and those on MAM are the mean values from March to May. These average figures may cover a more remarkable month on a specific time series. For example, we plot the same contribution rate as is shown in Fig. 4 but for three months. It shows that the increase in June may be the main force steering the increase in the average SWCRE while the increase in the other 2 months stops from 2002 to date. The same result has also been found in the reduction on SIC, i.e., SIC in the BK region within July or August reaches zero-point in recent years. Therefore, SWCRE calculated in this study just represents the mean value in JJA, i.e., maximum of SWCRE can be more powerful. In addition, owing to the near-zero point in July and August from 2002 to date, negative feedback is also weakened. Values in Tables 1 and 2, correlation in Fig. 3, and grids in Fig. 5 are all spatial average, noting that although parameters in Tables 1 and 2 may have some uncertainties owing to spatial averaging, we can still have a profound understanding by analyzing Figs. 1 and 2 as the parameters vary in each grid. As regards to the correlation coefficient, a spatio-temporal average is calculated at each level. However, we also plot the scattering (not shown in this article) between SIC and CLWC only in temporal average to remove the interannual oscillation. The result is basically the same as is shown in Fig. 3 owing to a negative connection between low-level CLWC and SIC. Furthermore, the regression fitting model does have the same uncertainties mentioned above. However, this model is only designed to emphasize the function of SWCRE, and the uncertainties can be ignored when discussing it in this study.

In summary, we exhibit that cloud does make tremendous contribution to balance the loss on SIC and the increase in SWCRE over the Arctic, especially in the BK region. In addition, more concentration should be paid on the BK region, where an intense air-sea interaction takes place. As the Arctic gets warmer, more places like the BK region would emerge.

Appendix

Regression fitting model.

The example of regression fitting model is as follows, $x_t$ stands for independent variable, $y_t$ stands for dependent variable. If we want to build a linear connection between $x_t$ and $y_t$, we can use the ordinary least squares approach.

$$ x_t \rightarrow y_t \quad (t = 1, 2, \ldots, n) $$

$$ b = \frac{\sum_{t=1}^{n} x_t y_t - n x_\text{mean} y_\text{mean}}{\sum_{t=1}^{n} x_t^2 - n x_\text{mean}^2}, \quad a = y_\text{mean} - b x_\text{mean}, \quad x_\text{mean} = \sum_{t=1}^{n} x_t / n, \quad y_\text{mean} = \sum_{t=1}^{n} y_t / n $$

The formula above is just a basic example on implementing the linear regression progress. The specific formulation on the talked data is as follows, $\text{ASR}_t$ is the independent variable while $\text{SIC}_t$ and $\text{SST}_t$ are the dependent variables. This model is designed to justify the relationship between ASR and the dependent variables: SIC and SST by comparing the fitting regression result $\text{SIC}_t'$ and $\text{SST}_t'$ to the original data $\text{SIC}_t$ and $\text{SST}_t$.

$$ \text{ASR}_t \rightarrow \text{SIC}_t' \quad (t = 1, \ldots, 42) $$

$$ b_{a, \text{SIC}} = \frac{\sum_{t=1}^{n} \text{ASR}_t \text{SIC}_t - n \text{ASR}_t \text{SIC}_t'}{\sum_{t=1}^{n} \text{ASR}_t - n \text{ASR}_t'}, \quad a_{a, \text{SIC}} = \text{SIC}_t' - b_{a, \text{SIC}} \text{ASR}_t + a_{a, \text{SIC}} $$

$$ \text{ASR}_t \rightarrow \text{SST}_t' \quad (t = 1, \ldots, 42) $$

$$ b_{a, \text{SST}} = \frac{\sum_{t=1}^{n} \text{ASR}_t \text{SST}_t - n \text{ASR}_t \text{SST}_t'}{\sum_{t=1}^{n} \text{ASR}_t - n \text{ASR}_t'}, \quad a_{a, \text{SST}} = \text{SST}_t' - b_{a, \text{SST}} \text{ASR}_t + a_{a, \text{SST}} $$

$$ (\text{ASR}^* = \sum_{t=1}^{n} \text{ASR}_t / n, \text{SIC}^* = \sum_{t=1}^{n} \text{SIC}_t / n, \text{SST}^* = \sum_{t=1}^{n} \text{SST}_t / n) $$

CONSTANT-SWCRE method is the same as the method used above but keep SWCRE as a constant figure. It is worth noting that it shares the same $b_{a, \text{SIC}}, b_{a, \text{SST}}, a_{a, \text{SIC}}, a_{a, \text{SST}}$ with the abovementioned. However, it ignores the rise in SWCRE from 1979 to 2020 and maintains SWCRE as it is in 1979 as time passes. This approach is designed to test the effect of SWCRE by comparing the CONSTANT-SWCRE result $\text{SIC}^\ast$ and $\text{SST}^\ast$, to the original data $\text{SIC}_t$ and $\text{SST}_t$.

$$ \text{SIC}^\ast_t = b_{a, \text{SIC}} (\text{ASR}_t + \text{SST}_t - 1979) + a_{a, \text{SIC}}, \quad \text{SST}^\ast_t = b_{a, \text{SST}} (\text{ASR}_t + \text{SST}_t - 1979) + a_{a, \text{SST}} $$
S: Annually mean slope on SWCRE in both regions (Arctic and Novaya) from 1979 to 2020.

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Data availability The datasets analyzed during the current study are available in the ERA5 repository, https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=overview, https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview.

Declarations

Conflict of interest The authors declare no competing interests.

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