Invariability of Arctic Top-of-Atmosphere Radiative Response to Surface Temperature Changes

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Abstract

Recent studies have used satellite data to estimate the response of top-of-atmosphere (TOA) radiative fluxes to surface temperature changes in the Arctic. The satellite-observed radiative response is indicative of Arctic climate sensitivity that determines future Arctic warming. However, it remains ambiguous whether the satellite-observed radiative response is invariable because the time period covered by satellite data reflects a rapidly changing transient Arctic climate state with considerable sea ice loss. Using NASA’s Clouds and Earth’s Radiant Energy System (CERES) observations from 2000 to 2018, this study evaluates the invariability of the radiative response by comparing the radiative response of the high sea ice concentration (SIC) period to that of the low SIC period. The results show that the net radiative response remains approximately unchanged regardless of the SIC (−0.19 ± 0.44 and 0.15 ± 0.16 W m⁻² K⁻¹ for high and low SIC periods, respectively). In addition, seven of the 11 models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) demonstrated that the modeled radiative responses are stable. The ERA-interim reanalysis estimates show that regionally confined changes in individual radiative feedbacks such as albedo, lapse rate, water vapor, and clouds do not vary considerably. Consequently, we infer that the radiative response in the Arctic may remain stable even under rapid Arctic climate change. Hence, the Arctic climate sensitivity can be quantified with present satellite observations.

1. Introduction

Many previous studies have documented that global climate sensitivity is not stationary based on long-term climate model simulations (Andrews et al., 2015; Armour et al., 2013; Gregory & Andrews, 2016). The inhomogeneous evolution of surface warming patterns and regionally different internal physical feedback processes can alter the top-of-atmosphere (TOA) radiative balance even without changing the global mean surface temperature. In these cases, the response of TOA radiative flux to mean surface temperature change may considerably vary with time under drastic changes in the climate system.

The Arctic climate system, in particular, changes more quickly than the global average due to the accelerated melting of the Arctic sea ice throughout recent decades. The decreasing trend in the sea ice extent or concentration will likely continue (Comiso et al., 2017; Stroeve & Notz, 2018), affecting climate variables such as surface albedo, lapse rate, water vapor, and clouds (Flanner et al., 2011). The uncertainties in the physical behavior of the Arctic climate system result from various impacts of these climate variables on the TOA radiation budget (Kageyama et al., 2020; Van der Linden et al., 2014).

The question at issue concerns the fact that most of the recent polar-orbiting satellites that observe the Earth’s TOA radiative fluxes only cover a short time period (from 2000 to the present); therefore, currently observed radiative response restrictively reflects the transient warming trend only in the present Arctic climate system. A substantial difference between the satellite-observed Arctic radiative response of the present and that of the future would occur if the Arctic climate sensitivity varies with time. If this is the case, the currently observed Arctic radiative response cannot be used for the estimation of future Arctic warming. Thus, it is important to examine the invariability of the satellite-observed Arctic radiative response to surface temperature change under varying Arctic sea ice concentrations (SICs).

To address this issue, we investigate the differences in the Arctic radiative response to changes in the surface temperature under two different climate states, one with smaller SICs and the other with larger SICs, using Clouds and Earth’s Radiant Energy System (CERES)-retrieved TOA radiative fluxes. In addition, the individual feedback components of the Arctic radiative response were analyzed using various climate variables.
such as albedo, lapse rate, water vapor, and clouds from the ERA-Interim (ERAI) reanalysis data set. Lastly, we examine whether state-of-the-art climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) are in line with the observational results.

2. Methodology
2.1. Data Description

The TOA radiative response to changes in surface air temperature (hereafter, radiative response) under two different climate states are compared. The satellite-observed radiative response and the albedo feedback over the Arctic are calculated using 1°-gridded monthly outgoing shortwave ($R_{\downarrow SW}$), outgoing longwave ($R_{\downarrow LW}$), and incoming net ($R_{\downarrow NET}$) radiative fluxes at the TOA as well as surface albedo ($\alpha$) from NASA’s CERES Synoptic 1-degree (SYN1deg) Edition 4A data products (Loeb et al., 2018). Additionally, the lapse rate and water vapor feedback strengths over the Arctic are calculated using 1°-gridded monthly surface air temperatures (SATs) and vertical temperature ($t$) and specific humidity ($q$) profiles from the ERAI monthly reanalysis data set provided by the ECMWF (European Center for Medium-Range Weather Forecasts) (Dee et al., 2011). Although the ERAI data sets have a warm wintertime bias over sea ice, it reasonably reproduces the trends of near-surface and lower-tropospheric warming over the Arctic region (Simmons & Poli, 2015), and the estimated individual radiative feedback strengths are independent of the type of reanalysis data sets, which include ERAI, Japanese 55-year reanalysis (JRA-55), and Modern Era Retrospective-Analysis for Research and Applications (MERRA) (Zhang et al., 2018).

The different climate conditions are categorized into high and low SIC periods based on the late summer SIC using the monthly 1°-gridded SIC data from the NOAA Optimum Interpolation (OI) Version 2 High-Resolution Dataset for the period between 2000 to 2018 (Reynolds et al., 2002). This is because the absorbed shortwave radiation at the TOA and downward longwave radiation at the surface over the Arctic region are closely related to the amount of Arctic sea ice melting during the late summer (Choi et al., 2014; Kapsch et al., 2016). The monthly time series of the mean Arctic SIC levels have clearly reached historic minima in recent years (e.g., 2007, 2012, and 2016) during the late summertime (August to September). Therefore, the year corresponding to the top (bottom) 50% of the late summer SIC levels is classified as the high (low) SIC period. The high SIC period includes the 9 years in which anomalously positive SIC peaks occurred (2000–2006, 2009, and 2013), and the low SIC period includes the 10 years in which anomalously negative SIC peaks occurred (2007, 2008, 2010–2012, and 2014–2018). The average late summer SIC level in the low SIC period is 7.5% less than that in the high SIC period (28.5% and 21.0% for the high and low SIC periods, respectively). Furthermore, to improve the reliability of the results, the radiative responses from the years when the SIC values reflect the top and bottom 25% of the late summer SIC levels are analyzed. The SIC values that make up the top 25% of the SIC levels are found during the years of 2000, 2001, 2003, 2004, and 2006, whereas those that make up the bottom 25% of the SIC levels are found during the years of 2007, 2012, and 2015–2017. Because the number of years in the high and low SIC period is different, standard errors are calculated to determine the statistical significance.

The modeled radiative response is analyzed based on the climate models participating in the CMIP6 over a 100-year period from 2001–2100 using monthly gridded $R_{\downarrow NET}, R_{\downarrow SW}, R_{\downarrow LW}, SAT$, and SIC data (Eyring et al., 2016; O’Neill et al., 2016). $R_{\downarrow NET}$ is calculated by deducting $R_{\downarrow SW}$ and $R_{\downarrow LW}$ from the TOA incident SW radiation. The 100-year time series of the aforementioned variables are reprocessed by combining historical simulations (2001–2014) and Shared Socioeconomic Pathways 2–4.5 (SSP245) simulations (2015–2100). In this study, a moderate climate forcing scenario (SSP245) is chosen to estimate the modeled radiative response, which is almost identical to the current Arctic climate state. Among the many climate models in the CMIP6, we selected 11 models (MRI-ESM 2-0, MPI-ESM 1-2-HR, MIROC6, IPSL-CM6A-LR, GFDL-ESM 4, EC-Earth3, CanESM5, INM-CM5-0, INM-CM4-8, EC-Earth3-Veg, and CESM2-WACCM) that provide both historical and SSP245 simulation outputs while containing all the aforementioned variables. In the climate model simulations, the years corresponding to the top (bottom) 25% and 50% of the late summer SIC levels are classified differently in each model.

All the variables from the CERES, ERAI, and CMIP6 data sets were used as monthly anomalies. A 12-month running mean was applied to the time series of those anomalies to retain the radiative feedback processes.
with timescales spanning longer than 1 month and exclude any nonfeedback factors (e.g., strong seasonality and autonomous cloud variations) (Hwang et al., 2019).

### 2.2. Calculation of Radiative Response and Individual Feedback Strengths Over the Arctic

Based on the linearized energy balance framework that the changes in the TOA radiative imbalance ($\Delta R$) caused by external radiative forcing ($\Delta Q$) results in surface temperature changes ($\Delta T_s$) as described by the formula $\Delta R = \Delta Q - \frac{\Delta T_s}{\delta}$, radiative responses can be used to estimate climate sensitivity parameter(s) (Bony et al., 2015; Donohoe et al., 2014; Forster & Gregory, 2006; Gregory et al., 2004).

Radiative responses at the TOA can be estimated from the linear regressions of $dR_{\text{NET}}^\downarrow$ on the $d$SAT:

$$\text{Radiative Response} = \frac{dR_{\text{NET}}^\downarrow}{d\text{SAT}}$$  \hspace{1cm} (1)

where $d$ is the time-dependent perturbation and the net radiative response can be separated into the SW and LW radiative responses ($-dR_{\text{SW}}^\uparrow/d\text{SAT}$ and $-dR_{\text{LW}}^\uparrow/d\text{SAT}$, respectively). The positive sign indicates the response of incoming TOA radiative flux, whereas the negative sign indicates a response of outgoing TOA radiative flux to the increase in SAT. Here, SAT is used as an indicator of Arctic surface temperature change because the change in the ice-covered Arctic ocean is driven by sensible and latent heat fluxes that strongly depend on the SAT (Rigor et al., 2000).

In this study, a radiative response is composed of individual radiative feedback components such as albedo ($\lambda_\alpha$), water vapor ($\lambda_q$), lapse rate ($\lambda_L$), and clouds ($\lambda_c$) from climate model outputs or reanalysis estimates. Based on the combined Kernel-Gregory method, each feedback component can be calculated by Taylor series expansion:

$$\frac{dR_{\text{NET}}^\downarrow}{d\text{SAT}} = \sum_x \frac{\partial R_x}{\partial x} \frac{dx}{d\text{SAT}} = \sum_x \lambda_x, \; x = \alpha, \; t, \; q, \; \text{and} \; c$$  \hspace{1cm} (2)

where $\frac{\partial R_x}{\partial x}$ is the monthly radiative kernel obtained from the large-ensemble simulations of CAM5 (Pendergrass et al., 2018). The lapse rate feedback, which is the radiative effect due to the changes in the temperature difference between the upper atmosphere and surface, is derived from the formula $\lambda_L = \frac{\sum_{z=\text{TOA}} - \text{surface} \frac{\partial R_x}{\partial T_z} d(T_u - \text{SAT})}{d\text{SAT}}$. Based on the adjustment method from Soden et al. (2008), cloud feedback is calculated from the sum of the cloud radiative forcing (CRF = $R_{\text{all-sky}} - R_{\text{clear-sky}}$) and the difference between clear- and all-sky individual radiative feedback ($\sum_x R_x^\text{clear-sky} - R_x^\text{all-sky}$, $x = \alpha, \; t, \; \text{and} \; q$). The CRF is derived from the CERES TOA radiative fluxes. However, external radiative forcing is ignored because an effect of an increase in greenhouse gas concentrations on the radiative forcing can be assumed to be relatively small during the short time span in this study (Trenberth et al., 2015). The sum of the individual feedback parameters is not exactly the same with the net radiative response when confining the region to the Arctic (Hwang et al., 2018). This is related to the dynamically derived horizontal energy flux that can also affect Arctic radiative response (Hwang et al., 2018; Lindzen, 2020). This study, however, does not address this dynamical response because it is outside the scope of this paper.

### 3. Results

#### 3.1. Regionally Confined Changes in Individual Arctic Radiative Feedback

Generally, an SW radiative response is determined by ice-albedo and cloud feedbacks, whereas an LW radiative response is mostly determined by water vapor, lapse rate, but also cloud feedbacks. To understand the mechanisms behind the radiative response over the Arctic, a comparison between the distribution of individual radiative feedbacks, such as ice-albedo, water vapor, temperature, and clouds, in high and low SIC periods is performed (Figure 1). Overall, each individual feedback in the high SIC period shows a spatially inhomogeneous strong feedback signal, whereas those in the low SIC period show a feedback signal that is spatially homogeneous.
In Figure 1a, a strong positive ice-albedo feedback signal distinctively appears over the Barents-Kara Seas in the high SIC period and disappears in the low SIC period. Over the Barents-Kara Seas, where the sea ice is highly variable, the more the sea ice melts, the more the SW radiation is absorbed. Because the Arctic is closer to open water conditions, the variability of the ice-albedo is smaller, and the Arctic ocean uniformly absorbs the SW radiation. Therefore, in the low SIC period, distinctive positive ice-albedo feedback signals over the Barents-Kara Seas are reduced compared with those in the high SIC period.

Similarly, the regional distribution of the lapse rate feedback in the high SIC period shows distinctive strong positive signals, particularly over the Greenland Sea and the area between 60°E and 90°E where the Kara Sea is located (Figure 1b). In contrast, the lapse rate feedback in the low SIC period indicates a uniform intensity throughout the Arctic. In the Arctic, surface warming is greater than upper tropospheric warming. This is because the extra heat from the Arctic warming is confined to the lower atmosphere due to the high atmospheric static stability caused by the cold ice-covered surface, which results in strong lapse rate feedback (Bintanja et al., 2011; Pithan & Mauritsen, 2014). Thus, regionally enhanced positive lapse rate feedback can be found in the high SIC period. However, in the low SIC period, ice-free oceans tend to increase the heat flux from the ocean to the atmosphere, resulting in reduced static stability in the lower troposphere. Therefore, a relatively homogeneous geographic pattern of positive lapse rate feedback can be found over the Arctic in the low SIC period. The water vapor feedback in the low SIC period is slightly negative, whereas in the high SIC period, it is slightly positive (Figure 1c). However, the contribution of water vapor feedback on the radiative response is extremely small because its signal strength is close to zero.

In Figure 1d, regionally negative cloud feedback can be found in the high SIC period, whereas relatively weak positive cloud feedback spreads over the Arctic in the low SIC period. This study assumes that cloud feedback depends on both the CRF observed from the CERES satellite and the cloud radiative effect calculated from the difference between all- and clear-sky conditions in each individual feedback (Soden et al., 2008). Because the cloud fraction remains fixed under sea-ice retreat during the melting season, the high cloud coverage over the melted areas significantly reduces the response of the SW reflection to warming (Choi et al., 2020; He et al., 2019). Hence, the negative SW radiative effect induced by the clouds, which
distinctively appear over the Barents-Kara Seas, is weakened in the low SIC period. However, sea ice loss gives rise to an increase in the Arctic clouds amount in the fall season, which results in strengthened longwave cloud radiative effects by increasing the amount of latent and sensible heat into the atmosphere. Therefore, the positive LW radiative effect induced by clouds is increased in the low SIC period. Although the distributions of individual radiative feedback between high and low SIC periods differ regionally, the regional changes do not affect the radiative feedback of the entire Arctic region. This is because the “mean” Arctic individual radiative feedback such as ice-albedo, lapse rate, water vapor, and clouds remain unchanged despite the Arctic sea ice loss (Figure 2). For example, the mean Arctic ice-albedo feedback strength in the low SIC period is not statistically different from that in the high SIC period (0.46 ± 0.50 and 0.39 ± 0.08 W m⁻² K⁻¹ for the high and low SIC periods, respectively) at the 95% confidence level. Similarly, the mean Arctic lapse rate feedback, the major contributor to the LW feedback processes, remains the same in both the high and low SIC periods (1.76 ± 0.68 and 1.77 ± 0.12 W m⁻² K⁻¹ for the high and low SIC periods, respectively) at the 95% confidence level. The water vapor feedback also remains constant in both SIC conditions, but its strength is negligibly small. Meanwhile, there is a slight difference between the mean cloud feedback in the high SIC period compared with that in the low SIC period, unlike other individual feedback parameters; however, the difference is statistically insignificant at the 95% confidence level. The mean Arctic net cloud feedback in the low SIC period is positive, whereas it is negative in the high SIC period (0.40 ± 0.08 and −0.04 ± 0.57 W m⁻² K⁻¹ for the low and high SIC periods, respectively). This is because the negative SW cloud feedback in the low SIC period is slightly weakened (−0.10 ± 0.07 and −0.38 ± 0.48 W m⁻² K⁻¹ for the low and high SIC periods, respectively) and the positive LW cloud feedback in low SIC period is enhanced (0.56 ± 0.30 and 0.32 ± 0.23 W m⁻² K⁻¹ for the low and high SIC periods, respectively) across the Arctic (these values are not shown in this figure) as previously observed in Figure 1. Furthermore, all the mean Arctic individual feedback strengths also remain the same for the top and bottom 25% of the SIC levels.
Consequently, stable mean individual feedback strengths, which are attributed to the regionally confined individual radiative feedback changes in the Arctic, may also indicate that the radiative responses remain unchanged and are independent of the SIC retreat.

3.2. Invariability of Radiative Response in the Arctic

Figure 3 represents the satellite-observed net, SW, and LW radiative responses for high and low SIC periods. The radiative response is positive (negative) when incoming (outgoing) radiative fluxes at the TOA is increased due to surface warming, implying climate system energy gains (losses). For the case in which high and low SICs are categorized based on the top and bottom 50% of the SIC levels estimated in the late summer for each year, the SW radiative response in the high SIC period (0.48 ± 0.48 W m⁻² K⁻¹) shows almost the same value as that in the low SIC period (0.49 ± 0.12 W m⁻² K⁻¹). This implies that the response of SW radiation hardly changes regardless of high or low Arctic SICs. Additionally, the LW radiative responses between the high and low SIC periods are not statistically different, although the magnitude of the LW radiative response in low SIC period is slightly smaller than that in the high SIC period (−0.60 ± 0.38 and −0.38 ± 0.11 W m⁻² K⁻¹ for the high and low SIC periods, respectively). Similarly, for the case in which high and low SIC periods are categorized based on the top and bottom 25% of the SIC levels estimated in the late summer for each year, both the SW and LW radiative responses remain unchanged between the high and low SIC periods at the 95% confidence level.

Overall, both cases that evaluate the radiative responses based on the top/bottom 25% and 50% of the SIC levels demonstrate that the net radiative responses (i.e., the sum of the SW and LW radiative responses) under the two different SIC periods are not significantly different from each other. In the case that assessed the top and bottom 50% of the SIC levels, the magnitude of the net radiative response in low SIC period is slightly positive (0.15 ± 0.16 W m⁻² K⁻¹), whereas it is slightly negative in high SIC period (−0.19 ± 0.44 W m⁻² K⁻¹). The opposite occurs in the case assessing the top and bottom 25% of the SIC levels (0.45 ± 0.63 and −0.25 ± 0.30 W m⁻² K⁻¹ for the high and low SIC periods, respectively). Although their differences are statistically insignificant, one point that deserves to be highlighted is the stronger effect that the LW radiative response has on the net radiative response compared to the SW radiative response. Sea ice
retreat has been regarded as a significant influential factor in the variation of SW radiation by changing the surface albedo; however, it mainly tends to affect outgoing LW radiation by changing the released turbulent heat flux, horizontally transported heat flux, or clouds.

Consequently, radiative responses remain unchanged regardless of the change in climate state caused by sea ice loss at the present time. This constancy implies the invariability of the radiative response in the Arctic climate system, ultimately indicating the viability of stable estimations of future Arctic warming from current satellite-observed TOA radiative fluxes.

Lastly, to identify how well up-to-date climate models capture the properties of the radiative responses from the satellite observations, we investigated the differences in the modeled radiative responses between the high and low SIC periods for a 100-year period (from 2001 to 2100) using 11 CMIP6 climate models. The degree of future Arctic warming is modeled with a wide spread because the physical and dynamical feedback processes in the Arctic may work differently in each model. Nevertheless, the majority of climate models that were analyzed in this study show that present Arctic radiative responses may not easily change in the near future. In Figure 4, the overlapping significance range with the zero reference line indicates that radiative responses in the high SIC period are not statistically different from those in the low SIC period.
comparing the radiative responses between the top and bottom 50% of the SIC levels, seven models (MRI-ESM 2-0, MPI-ESM 1-2-HR, MIROC6, IPSL-CM6A-LR, GFDL-ESM 4, EC-Earth3, and CanESM5) out of the 11 models reveal that the radiative response is likely to remain the same regardless of SICs. Similarly, in the comparison of radiative responses between the top and bottom 25% of the SIC levels, six models also support the same assertion that the radiative responses are independent of SIC.

Nevertheless, some of the climate models do not agree with the observational results, implying that predicted Arctic warming may be overestimated or underestimated. INM-CM5-0, INM-CM4-8, and EC-Earth3-Veg show that the radiative response in the low SIC period is smaller than that in high SICs, whereas CESM2-WACCM shows that the radiative response in low SICs is larger than that in the high SIC period. These significant differences in the modeled radiative response between the high and low SIC periods are mostly due to the changes in SW radiative response since the differences in LW radiative response are close to zero in most of these models (not shown in this study). In other words, if the phasing of the SW anomalies in the climate models is sensitive to sea ice loss, the projected Arctic warming is likely to be amplified or dampened compared with the real Arctic climate system. Therefore, modeling sea ice variability, the interaction between sea ice and clouds, and the effect of these parameters on SW radiation should be improved for more accurate Arctic warming predictions.

4. Discussion and Concluding Remarks

In this study, satellite observed-TOA radiative fluxes reveal that the Arctic radiative response is likely to remain unchanged under sea ice retreat. No significant differences in SW and LW radiative responses between high and low SIC periods were found over the Arctic region because the mean Arctic individual feedback strengths for ice-albedo, lapse rate, water vapor, and clouds remain statistically constant. All of the individual feedback parameters in the low SIC period show relatively homogeneous geographic patterns compared with those in the high SIC period. However, this regional contrast in geographic patterns between the low and high SIC periods does not appreciably affect the Arctic climate feedback components.

Nevertheless, several interesting findings are worth noting. First, the net radiative response becomes slightly positive from negative values mainly due to the LW radiative effect, and the cloud feedback shows a slight difference in feedback strength between high and low SIC periods compared with the other feedback components, although statistically significant changes were not found in this study. Additionally, the bias of the radiative response in the low SIC period is considerably smaller than that in the high SIC period. One possible explanation is that the geographic patterns of individual climate feedback strengths in the high SIC period are regionally different, whereas the geographic patterns in the low SIC period are relatively homogeneous over the Arctic region. That is, each individual feedback process that actuates differently in different regions can immediately affect the radiative fluxes regardless of the mean Arctic temperature change, producing large biases in the relationship between the mean Arctic radiative fluxes and the mean Arctic temperature change for low SIC period (Gregory & Andrews, 2016).

By analyzing the 11 CMIP6 models for both present and near future simulations, seven models demonstrate similar results to the satellite observations in that the Arctic radiative response to surface warming remains statistically unchanged even if sea ice loss changes the Arctic climate state. Furthermore, the inconsistency between the observations and climate models is mostly induced by the SW radiation response. Therefore, advancing the understanding of the SW feedback mechanisms associated with sea ice variability and cloud properties is critical to making further progress in improving Arctic warming predictions. However, the Arctic radiative fluxes in 100 years or under extreme climate states, for example, when more than half of the sea ice disappears, are expected to behave completely differently. Therefore, the possible time span or Arctic SIC threshold in which the radiative responses can retain their stability should be further investigated.

Arctic climate sensitivity is controlled by the balance between the TOA radiative imbalance and dynamically driven horizontal energy fluxes (Hwang et al., 2019; Lindzen, 2020). If both the radiative response and dynamical response remain stable under changes in the mean Arctic state, Arctic climate sensitivity may also remain unchanged. This study reveals that both observations and the majority of the climate models show that the Arctic radiative response is insensitive to sea ice loss in the present and near future, although it is premature to predict how the Arctic climate state will change in the far future beyond 100 years.
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Data Availability Statement
The data sets were downloaded from https://esgf-node.llnl.gov/search/cmip6/. CERES SYN1deg can be downloaded from https://ceres.larc.nasa.gov/data/#syn1deg-level-3. The European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis is available online at https://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=sfc/.
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