Dear Reviewer,

We gratefully thank you for your time spent making constructive remarks and suggestion, which helped us improve the quality of the manuscript. Each suggested revision and comment, brought forward by the reviewer was carefully considered and responded. Below the comments of the reviewer are responded point-by-point and the revisions are indicated.

Overview 1:

This study introduces a methodology for constructing long-term, gridded surface cloud radiative kernels (GCF-CRKs) and estimating Arctic shortwave cloud radiative effects (SW CRE) using a fused cloud fraction (CF) dataset and CERES satellite observations. The authors claim their approach improves DSSR estimates and quantifies the spatiotemporal variability of CRE with greater accuracy, highlighting its application for refining climate models.

1. My major concern is this manuscript may not be suitable for Earth System Science Data (ESSD) as it does not produce a comprehensive dataset for community use, focusing instead on methodological refinements. The paper does not meet the core requirements for ESSD as it lacks the breadth and generalizability necessary for community adoption.

Response: Thank you for raising this critical concern regarding the suitability of our manuscript for ESSD. We fully acknowledge ESSD's emphasis on community-oriented datasets and would like to clarify how our work aligns with the journal's mission through three key aspects:

(1) Novelty and Completeness of the GCF-CRKs Dataset

Our study provides the first long-term (2001–2020), high-resolution (1°×1° grid), and Arctic-focused surface cloud radiative kernel dataset that explicitly quantifies the sensitivity of surface shortwave radiation to cloud fraction perturbations in every grid box, each grid box under diverse cloud microphysical conditions (e.g., optical depth, cloud-top pressure). Unlike existing top-of-atmosphere (TOA) kernels (e.g., Zelinka et al. 2012; Soden et al. 2008), GCF-CRKs reveal surface-level radiative interactions critical for polar climate studies. The dataset integrates CERES observations and radiative transfer modeling (Section 3.2–3.3), offering a comprehensive resource for diagnosing surface cloud radiative effects (SW CRE) across monthly, seasonal, and decadal scales (validated in Sections 4.4–4.5). From the concept of cloud radiative kernels (CRKs), they can quantify the response of radiative fluxes to perturbations in cloud properties, both clouds and radiation are critical components of the Earth's climate system. Therefore, CRKs are essential tools for understanding the complex interactions between clouds and radiation, which are widely used in climate community(Kramer et al., 2019; Soden et al., 2008; Shell et al., 2012; Zelinka et al., 2012; Wong et al., 2016; Zhang et al., 2021; Zhou et al., 2022; Huang and Huang, 2023; Wang et al., 2020).

(2) Community Utility and Accessibility

To maximize usability, we provide open access to GCF-CRKs via the following link: https://doi.org/10.5281/zenodo.13907217. dataset is formatted in NetCDF with CF-compliant metadata to ensure compatibility and ease of use for the scientific community. To validate the accuracy and reliability of our dataset, we have conducted several analyses: comparison with existing surface CRKs to assess consistency and accuracy **(Section 4.3)**; Interactions with different cloud parameters to evaluate their robustness and applicability **(Section 4.2)**; utilized the GCF-CRKs to compute cloud radiative forcing and analyze its spatiotemporal characteristics **(Section 4.4)**; discussed the potential of our GCF-CRKs in advancing the understanding of climate feedback mechanisms **(Section 5.3)**. By providing a more precise representation of cloud radiative effects, our GCF-CRKs can help refine the parameterization of clouds in climate models, leading to improved simulations of the Earth's energy balance. This is particularly important for the Arctic region, where cloud feedbacks play a crucial role in amplifying or mitigating climate change.

(3) Generalizability and Potential for Climate Research

We also recognize the importance of generalizability and community adoption. While our current dataset is focused on the Arctic region, the methodology we have developed can be easily adapted to other regions and datasets. Specifically, our approach provides a robust framework for extracting both the independent and coupled effects of different cloud parameters on radiative fluxes. This capability is crucial for understanding the complex interactions between clouds and radiation, and it allows researchers to isolate and quantify the contributions of individual cloud properties. This flexibility ensures that our approach can be widely applied and integrated into various climate research projects, making it a valuable tool for advancing our understanding of cloud-radiation interactions and their impacts on climate.

In summary, we believe that our study meets the core requirements of ESSD by producing a valuable and detailed dataset that can significantly contribute to climate research. Our GCF-CRKs provide a comprehensive representation of cloud radiative effects, which is essential for understanding and modeling the Earth's climate system.

We hope that our dataset will be adopted by the scientific community and used to advance our understanding of climate change and its impacts.

2. The dataset is limited in scope, focusing narrowly on CF without comprehensively incorporating critical variables such as cloud vertical structure, microphysics, or optical thickness, which are essential for accurately addressing the major uncertainties in CRE estimation. This omission undermines the dataset's ability to comprehensively address key scientific questions and limits its usability in broader climate modeling and research contexts.

Response: Thank you for highlighting this important point regarding the scope of our dataset. We agree that cloud radiative effects (CRE) are influenced by a complex interplay of cloud properties (e.g., vertical structure, microphysics, optical thickness). Below, we clarify how our methodology implicitly accounts for these variables and why focusing on cloud fraction (CF) remains scientifically rigorous and operationally advantageous for Arctic SW CRE studies:

Firstly, while GCF-CRKs used CF as the only disturbing variable, our approach inherently embeds cloud microphysical and structural variability. For each 1°×1° grid, we treat the local combination of observed cloud properties (e.g., optical depth, cloud-top pressure and so on) as a unique "cloud type" **(Section 3.2)**. These properties are held constant as non-perturbed parameters in radiative transfer simulations **(Eq. 20–23)**, meaning their radiative interactions are fully captured in the baseline flux calculations. At the same time, through the long-term gridded data, the spatiotemporal variation characteristics of different cloud parameters have also been taken into account.

Secondly, cloud fraction (CF) is a fundamental parameter that directly determines the spatial extent of cloud coverage, thereby influencing the reflection, scattering, and absorption of shortwave radiation at the surface **(Lines 75-133, Pages 3–5)**. CF is one of the most accessible and widely used variables in global climate studies, particularly in remote sensing datasets. It is readily available from satellite observations such as CERES and MODIS, with long temporal records spanning several decades(Liu et al., 2023). This extensive data availability allows for robust long-term analyses of cloud radiative effects and their trends in different climatic regions. Compared to more complex variables such as cloud vertical structure and microphysical properties, CF offers higher computational efficiency and spatial consistency. These advantages make it an ideal starting point for large-scale spatiotemporal analyses of cloud radiative effects, especially in regions like the Arctic, where cloud feedbacks play a crucial role in climate change **(Section 3.1)**.

Third, CF plays an indispensable role in the definition of cloud radiative forcing (CRE) and the cloud radiative kernel (CRK). CRE is the difference in surface radiative fluxes between all-sky and clear-sky conditions is well-established, which can be expressed by:

$$CRE = F_{all\_sky} - F_{clr} = f(F_{cld} - F_{clr}) \tag{1}$$

Where F_{cld} is the radiative flux for overcast cloudy sky, F_{all_sky} is the all-sky radiative flux, and F_{clr} is the clear-sky radiative flux, f is the CF. When the CF is 100%,

$$CRE_{cld} = F_{cld} - F_{clr} = \frac{CRE}{f} \tag{2}$$

The sensitivity of radiative flux is indicated by the CRK, which is also an effective means for quantitatively calculating climate feedback (Soden et al., 2008). It is typically calculated as the perturbation of CRE for a unit change in CF for each cloud type. Thus, the CRK can be expressed as：

$$CRK_{SFC} = \frac{\partial CRE}{\partial f} = \frac{F_{cld} - F_{clr}}{100\%} \tag{3}$$

Here, CRK_{SFC} represents the surface CRK, CRE_{cld} denotes the radiative forcing effect under completely overcast conditions. Therefore, the unit of the CRK is expressed in Wm^{-2}%$^{-1}$, indicating a differential change in the overcast CRE (Zhou et al., 2022; Zhang et al., 2021).

Finally, in this study, we have also acknowledged the limitations of using CF as the sole perturbation variable (**Lines 195-200, Pages 6-7; Lines 1030-1042, Page 38; Lines 1108-1113, Page 40**). While our current dataset focuses on CF, we have designed our methodology to be flexible and adaptable to incorporate additional cloud parameters in future work. And we will involve integrating cloud vertical structure, microphysics, and optical thickness into our methodology. This will enable us to address more complex scientific questions and improve the usability of our dataset in broader climate modeling and research contexts. We believe that our current dataset, combined with future extensions, will significantly contribute to advancing our understanding of cloud-radiation interactions and their impacts on climate.

In summary, while our current dataset focuses on cloud fraction, our methodology is designed to be adaptable and scalable. We are committed to expanding the scope of our dataset to include additional critical variables in future work, thereby enhancing its applicability and value to the climate research community.

3. The study also lacks sufficient discussion of the broader scientific implications of its findings.

Response: Thank you for emphasizing the importance of contextualizing our findings within broader climate science. We have thoroughly revised the Introduction Section (Section 1), Discussion section (Section 5.3) and Conclusions (Section 7) to explicitly articulate the significance of our work within the context of Arctic amplification, climate feedback mechanisms, and Earth system modeling.

Our quantification of Arctic SW CRE trends (−1.131 $W \cdot m^{-2} \cdot decade^{-1}$, 2000–2020; Figure 14) reveals that the cloud-induced surface cooling rate is 30% slower than previously estimated by CERES-EBAF (−1.64 $W \cdot m^{-2} \cdot decade^{-1}$). This directly responses a critical question highlighted in IPCC AR6 (Chapter 7), which regarding the role of cloud feedbacks in polar amplification. Our results demonstrate that the weaker cooling trend implies that non-cloud drivers (e.g., surface albedo loss from sea ice retreat) may contribute more significantly to Arctic warming than previously modeled. For the Greenland, this manuscript reveals that persistent high surface albedo amplifies cloud-surface multiple reflections, leading to stronger cooling (−4 $W \cdot m^{-2}$ bias vs. CERES-EBAF). The GCF-CRKs dataset provides observational constraints to address long-standing model biases.

To further elaborate on the broader implications of our findings, we have expanded the discussion section to include a detailed subsection titled "Potential Contributions of GCF-CRKs to Understanding Climate Feedback Mechanisms" **(Section 5.3)**. Here, we explore how our gridded cloud fraction radiative kernels (GCF-CRKs) can contribute to a more comprehensive understanding of cloud feedback mechanisms in the context of global climate change. Specifically, we highlight the potential for our dataset to improve the representation of cloud processes in climate models, thereby enhancing the accuracy of climate projections. Meanwhile, to ensure the rigor of our manuscript, we have added a statement in the manuscript to highlight the need for further investigation into these broader implications.

Specific technical comments:

1. The dataset is narrowly tailored to CF-related analysis and lacks general applicability for broader climate research.

Response: Thank you very much for your insightful comments. However, our GCF-CRKs dataset not only advances CF-specific analyses but also provides a foundational framework for broader climate research. As highlighted in our manuscript (Section 1 and 5.3), radiative kernels are a cornerstone of climate feedback analysis (Soden et al., 2008; Zelinka et al., 2012). By quantifying the sensitivity of surface shortwave radiation to CF perturbations, GCF-CRKs isolate the radiative contribution of cloud fraction changes—a critical step in disentangling complex cloud-climate feedbacks. This isolation is essential for diagnosing how clouds modulate Arctic amplification(Goosse et al., 2018) and surface energy budgets(Thorsen et al., 2018). For example, our dataset enables researchers to attribute observed SW CRE trends to cloud fraction variability versus other drivers (e.g., **Section 4.4**). Benchmark climate model performance by comparing simulated versus observed cloud radiative sensitivities (**Section 4.5**). These applications align with the broader goals of the IPCC community to refine climate feedback quantification. By providing radiative sensitivities at each grid cell, rather than aggregated values, GCF-CRKs allow users to diagnose spatially heterogeneous feedbacks (e.g., stronger SW CRE cooling over Greenland vs. the Beaufort Sea, **Figure 11**). This granularity addresses a key gap in existing TOA CRKs datasets (Zelinka et al., 2012), which lack the surface CRKs for regional Arctic studies.

In our previous response, we have cited numerous studies to demonstrate the wide applications of cloud radiative kernels in radiation budget analysis, climate research, and the improvement of climate models. Although our radiative kernels are based on cloud fraction (CF), they are designed to capture the spatiotemporal variability of cloud radiative parameters across different grid cells, consistent with the scientific concept of radiative kernels. Therefore, our dataset is not limited to CF-related analysis but also has the potential to contribute to broader climate research. Moreover, we have expanded the discussion section to include a detailed subsection titled "Potential Contributions of GCF-CRKs to Understanding Climate Feedback Mechanisms" (Section 5.3). This section highlights how our findings can play a significant role in regional and global energy balance studies, further emphasizing the broader applicability of our dataset. Finally, our methodology is designed to be adaptable and scalable, and thus has the potential to play a role in broader climate research.

2. The reliance on cloud fraction alone fails to address key uncertainties in cloud radiative effects. Without incorporating vertical cloud structure, microphysics, and optical thickness, the methodology cannot fully resolve critical gaps in CRE estimation.

Response: Thank you for emphasizing this critical aspect of cloud radiative effect (CRE) quantification. We fully agree that vertical cloud structure, microphysics, and optical thickness are key drivers of CRE uncertainty. Below, we clarify how our methodology implicitly addresses these variables while justifying the focus on cloud fraction (CF) as a foundational step, and we outline pathways for future extensions.

Firstly, While cloud vertical structure and microphysics are indeed important, CF remains the dominant factor governing shortwave CRE (SW CRE) at the surface in the Arctic(Liu et al., 2023). By isolating CF's radiative sensitivity, GCF-CRKs provide a critical baseline for disentangling its contribution from other cloud properties. This approach aligns with established practices in climate feedback studies, where individual variables are perturbed sequentially to isolate their impacts (Soden et al., 2008; Zhou et al., 2022). In our method, each 1°×1° grid cell is treated as a unique "cloud type" characterized by its observed monthly mean optical depth, cloud-top pressure, and other cloud properties (Section 3.2). These properties are preserved as unperturbed variables during radiative transfer simulations, ensuring that the baseline fluxes inherently reflect local cloud regimes. Moreover, the long-term analysis included the seasonal and interannual covariations between CF and other cloud properties in the process of GCF-CRKs construction.

On the other hand, most passive satellite datasets currently available are unable to directly and accurately measure cloud vertical structure, microphysics, and optical thickness. In contrast, cloud fraction (CF) can be derived with higher accuracy and spatial consistency from satellite observations such as CERES and MODIS. This makes CF a robust and accessible variable for large-scale spatiotemporal analyses. Our approach leverages the correlation between top-of-atmosphere (TOA) shortwave radiative parameters and surface radiation, combined with high-precision fused CF datasets. By using CF as the perturbation variable, we isolate its contribution to surface shortwave radiation, thereby enhancing the accuracy of downwelling surface shortwave radiation (DSSR) estimates. This method significantly improves the accuracy of DSSR estimation under partially cloudy conditions, as demonstrated by our validation experiments.

Last but not least, we recognize the importance of incorporating additional cloud parameters to address more complex scientific questions. Our methodology is designed to be flexible and adaptable. We plan to integrate vertical cloud structure, microphysics, and optical thickness into our framework in future work. This will further enhance the accuracy and applicability of our dataset.

3. The manuscript lacks adequate justification for its claims of improved CRE estimation. The validation against independent datasets and robust comparisons in high-latitude regions remain insufficient.

Response: Thank you very much for your valuable comments. To address your concerns regarding the validation of our cloud radiative effect (CRE) estimates, we have conducted additional analyses and provided more robust justifications. To evaluate the fidelity of GCF-CRKs, we calculated surface shortwave CRE (2000–2014) using output from the CMIP6-AMIP (Coupled Model Intercomparison Project Phase 6, Atmospheric Model Intercomparison Project) simulations (Eyring et al., 2021). Focusing on the Community Earth System Model Version 2 (CESM2), a widely used model with detailed cloud parameterizations, we compared CRE derived from GCF-CRKs against CRE directly simulated by CESM2. The results show strong agreement, with an R^2 of 0.847, RMSE of 14.5 W·m^{-2}, and bias of 11.19 W·m^{-2} **(Section 4.5, Figure 13b)**. This demonstrates that our kernel-based approach effectively isolates cloud fraction-driven radiative effects, capturing ~85% of the variance in model-simulated CRE. We further validated GCF-CRKs against the CERES-EBAF Ed4.2 dataset (2000–2014), achieving even higher consistency: $R^2 = 0.9009$, RMSE = 9.762 W·m^{-2}, and bias = 1.8916 W·m^{-2} (**Figure 13a**). This further supports the accuracy and reliability of GCF-CRKs. This manuscript also compared the GCF-CRKs based CRE with those from CERES-EBAF in spatial distribution, our method captures the spatiotemporal variability of CRE more accurately (**Section 4.5, Figure 12**). We believe that these additional analyses strengthen the credibility and applicability of our methodology. We will continue to refine our validation procedures and incorporate additional datasets in future work to further enhance the accuracy and reliability of our CRE estimates.

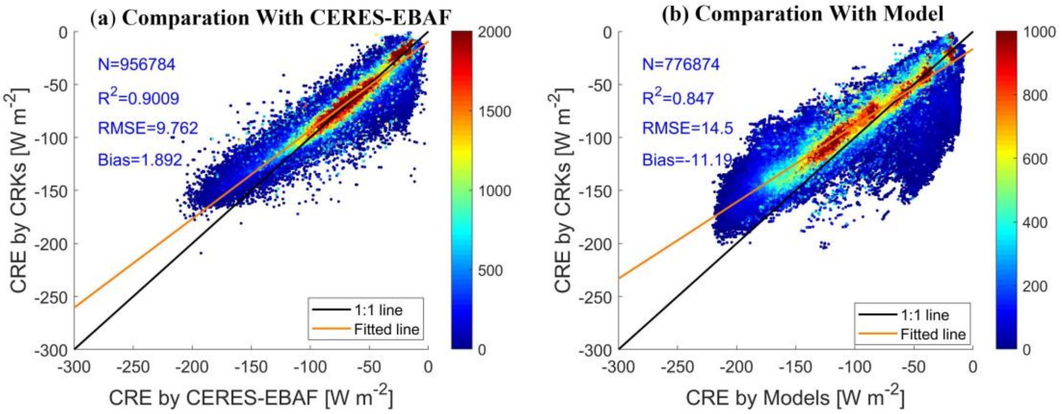

Figure 13. Comparison of cloud radiative effect (CRE) estimated by GCF-CRKs with observed and model-estimated CRE.

4. The broader scientific implications of the findings are not thoroughly explored. The relevance of these results to Arctic amplification and global climate feedback is understated and lacks context.

Response: Thank you for your valuable feedback. We appreciate your emphasis on the importance of exploring the broader scientific implications of our findings. To address this concern, we have expanded our discussion to highlight the relevance of our results to Arctic amplification and global climate feedback mechanisms. Our study provides critical insights into the role of cloud radiative effects (CRE) in Arctic amplification

(AA). The Arctic region is experiencing amplified warming compared to the global average, a phenomenon known as Arctic amplification. Our results show that the cloud-induced surface cooling rate in the Arctic is 30% slower than previously estimated by CERES-EBAF (-1.131 W·m^{-2}·decade^{-1} vs. -1.64 W·m^{-2}·decade^{-1}). This suggests that non-cloud drivers, such as surface albedo loss from sea ice retreat, may contribute more significantly to Arctic warming than previously modeled. Our dataset also reveals that persistent high surface albedo in Greenland amplifies cloud-surface multiple reflections, leading to stronger cooling (-4 W·m^{-2} bias vs. CERES-EBAF). This finding highlights the importance of accurately representing cloud radiative effects in climate models to better understand and predict Arctic amplification.

Based on your comment, we have expanded our manuscript to better elucidate the context and contextualize our findings within the broader scientific literature. Specifically, we have expanded the Introduction section to include a detailed discussion of cloud radiative forcing and its impacts on Arctic amplification and the global radiation balance **(Lines 61–180, Pages 3–4).** Additionally, we have enhanced the Discussion section by incorporating a detailed subsection titled **"Potential Contributions of GCF-CRKs to Understanding Climate Feedback Mechanisms" (Lines 961–1041, Pages 36–38).** These revisions aim to provide a clearer and more complete picture of the significance of our work within the context of current climate research. In the future, we will involve integrating cloud vertical structure, microphysics, and optical thickness into our methodology. This will enable us to address more complex scientific questions and improve the usability of our dataset in broader climate modeling and research contexts.

Thank you again for your valuable input. Your comments have been extremely helpful in improving our manuscript. We have addressed each concern by clarifying the dataset's suitability for ESSD, explaining the rationale for focusing on cloud fraction, providing robust validation results, and expanding the discussion on broader scientific implications. We believe these revisions significantly enhance the manuscript's quality and relevance.

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Overview 2:

In this paper, the authors developed a set of computationally efficient, long-term gridded surface cloud fraction radiative kernels (GCF-CRKs) to estimate cloud radiative effect in polar regions. The kernels reflect the climatological cloud properties (especially for cloud optical thickness) in the Arctic regions, so the accuracy of these kernels on downwelling surface shortwave radiation is good under current climate conditions. However, the climatological cloud properties are changing under global warming, so it is uncertain whether the GCF-CRKs still works under climate change.

Although the method might be useful for climate studies, the limitations of this method have not been well addressed, so major revisions are required.

Response: Thank you for your insightful comments. We have carefully addressed each of your concerns in our revised manuscript. For the impact of cloud optical thickness and future climate conditions, we have expanded our analysis on the temporal stability of GCF-CRKs **(Lines 924-985, Pages 34-36)** and outlined plans to use CMIP6 models to assess potential limitations under climate change. Regarding the cloud masking effect, we explain how our definition of cloud radiative forcing allows direct comparison with observations without needing to remove this effect **(Section 3.1)**. Finally, we provide a comparative analysis with existing CRK datasets **(Section 4.3)** and add a detailed discussion of the limitations of GCF-CRKs in our manuscript **(Lines 1019-1041, Pages 37-38).**

Specific comments:

1. The downwelling surface shortwave radiation is most sensible to cloud optical thickness. As the climate warms, the average optical thickness of clouds changes due to changes in cloud phase and water content, so the GCF-CRKs derived from current climate would be less accurate in future climate. This is an important limitation, and should be discussed in the paper.

Response: Thank you for your valuable suggestions. The concerns you raised regarding the impact of cloud optical thickness (Cloud Optical Thickness, TAU) on downwelling surface shortwave radiation (Downwelling Surface Shortwave Radiation, DSSR), as well as the accuracy of the gridded cloud fraction radiative kernels (GCF-CRKs) under future climate conditions, are indeed of significant scientific importance. We have already conducted a detailed analysis of the temporal sensitivity of the GCF-CRKs in the discussion section of our paper. Following your suggestions, we have further explored the stability of the GCF-CRKs within the time series.

Firstly, our study is based on a considerably long time series dataset (2000-2020). Compared with other radiative kernels that are derived from short-term data (e.g., 1 year), our research holds a distinct advantage in considering the changes in cloud parameters due to climate change. In Section 5.2 of our paper, we have provided a detailed analysis of the spatiotemporal sensitivity of the GCF-CRKs (**Lines 924-965, Pages 34-36**). We found that the values of the GCF-CRKs tend to stabilize with the accumulation of time. Specifically, when the GCF-CRKs are calculated using only 1 year of data, the values are relatively unstable, resulting in a significant deviation between the estimated cloud radiative effect (CRE) and the observed values (approximately 2.5 Wm^{-2}). However, when the data accumulation period reaches 5 years or more, the annual mean values of the GCF-CRKs gradually stabilize, and the deviation of the CRE is significantly reduced (approaching zero). This indicates that using a longer time series can effectively reduce the errors caused by interannual variability, thereby enhancing the accuracy and stability of the GCF-CRKs. Secondly, during the calculation of our radiative kernels, cloud optical thickness is treated as a non-perturbation variable. Even if it undergoes substantial changes with climate variations, its impact on the radiative kernels is limited.

The reviewer pointed out that with climate warming, the optical thickness and phase of clouds may change, which will affect the accuracy of the GCF-CRKs derived from current climate conditions. We fully agree with this viewpoint. In a newly added paragraph in Section 5.2 of our paper, we have explicitly elaborated on the potential limitations of the GCF-CRKs method in the context of climate change **(Lines 966-985, Page 36)**. Although we have demonstrated the stability and accuracy of the GCF-CRKs under current climate conditions in our paper, we are also aware that changes in cloud parameters under future climate scenarios may introduce new uncertainties. However, the primary focus of this study is to investigate the clouds and radiation effects under current climate conditions. We plan to use multiple climate models, such as the CMIP6 models, in our future research to simulate changes in cloud parameters under future climate scenarios, including cloud optical thickness, cloud phase, and cloud water content. By comparing the simulation results from different models, we aim to assess the impacts of these changes on the GCF-CRKs.

2. Cloud masking effect should be removed when the kernel results are compared to observations. (Soden et al., 2008)

Response: Thank you for your insightful comment regarding the cloud masking effect. We appreciate your attention to this important aspect of our study. The cloud masking effect refers to the obscuration of the radiative impacts of other climate feedback variables (such as temperature, water vapor, and surface albedo) by clouds. Specifically, the presence of clouds alters the radiative fluxes from the surface to the top of the atmosphere (TOA), thereby masking the direct contributions of these variables to the radiative fluxes. When analyzing the impacts of cloud feedback or other variables (such as water vapor and temperature) on radiative fluxes, it is crucial to consider the influence of the cloud masking effect to minimize the obscuration of the radiative effects of these variables by clouds (Soden et al., 2008). However, in our manuscript, we focus on the direct impact of clouds on surface shortwave radiation, namely cloud radiative forcing, rather than considering the radiative responses of other parameters to cloud feedback. Here, cloud radiative forcing is defined as the difference in radiative fluxes at the atmosphere or surface under all-sky and clear-sky conditions. For observed radiative forcing, we have:

$$CRE_{observation} = F_{all\_sky} - F_{clr} = f(F_{cld} - F_{clr}) \tag{1}$$

Where F_{all_sky} is the surface radiative flux for all sky, F_{cld} is the surface radiative flux for overcast cloudy sky and F_{clr} is the clear-sky surface radiative flux, f is the cloud fraction.

When calculating cloud radiative forcing using radiative kernels, we have:

$$CRE_{GCF-CRKs} = fCRK_{SFC} = f\frac{\partial CRE}{\partial f} = f(F_{cld} - F_{clr}) \tag{2}$$

Where CRK_{SFC} is the surface cloud radiative kernel. From this conceptual framework, it is evident that the cloud radiative forcing calculated using radiative kernels can be directly compared with the observed values without the need to remove the cloud masking effect **(Section 3.1)**. This approach is consistent with numerous studies that have demonstrated the validity of this methodology (Huang and Huang, 2023; Kramer et al., 2019; Zhou et al., 2022; Zhang et al., 2021).

In summary, while we acknowledge the importance of the cloud masking effect in broader climate feedback analyses, our study specifically targets the direct radiative impact of clouds on surface shortwave radiation. Therefore, a direct comparison between the radiative kernel-based cloud radiative forcing and the observed values is appropriate and supported by existing literature.

3. An advantage of GCF-CRK is that it avoids the uncertainty induced by cloud optical property retrievals. Theoretically, CRKs should be more accurate than GCF-CRKs if the cloud property products were accurate. In reality, the cloud properties retrieved in Arctic regions have large uncertainties due to large surface reflectivity and large solar zenith angle, that’s why GCF-CRK results is better than CRK results in some

Arctic regions.

Response: Thank you very much for your detailed review and valuable comments. We fully agree with your assessment of the importance of Cloud Radiative Kernels (CRKs) in the study of cloud radiative effects. CRKs, by quantifying the sensitivity of radiative fluxes to cloud properties such as cloud fraction and cloud optical thickness, have indeed provided a crucial tool for understanding the feedback mechanisms of clouds within the climate system. In an ideal scenario, where cloud property retrievals are highly accurate, CRKs would indeed offer more precise assessments of radiative effects. However, as you have correctly pointed out, in reality, cloud property retrievals in the Arctic regions are fraught with significant uncertainties, primarily due to high surface reflectivity and large solar zenith angles. These uncertainties introduce considerable biases in the CRK results derived from these cloud properties.

The key advantage of our Gridded Cloud Fraction Radiative Kernels (GCF-CRKs) is that they directly utilize cloud fraction (CF) as the sole perturbation parameter, thereby circumventing the uncertainties associated with cloud optical property retrievals. Compared with other cloud parameters, CF is the most readily available and widely used observational variable, with high accuracy and spatial consistency in its measurements and retrievals (Pincus et al., 2012; Zhou et al., 2022). In this study, we employ a CF dataset derived from the fusion of multi-source satellite data. This dataset leverages active satellite data to constrain the CF data from multiple passive satellites and accounts for the spatiotemporal autocorrelation of CF and uncertainties among different sensors. Compared to CF data derived from a single satellite, the accuracy of this merged dataset in the Arctic regions is enhanced by approximately 10% to 20% (Liu et al., 2023). Therefore, this dataset provides a reliable basis for the computation of GCF-CRKs. In this manuscript, we also conducted a comparative analysis between the derived GCF-CRKs and existing CRK datasets, which demonstrated a high degree of consistency overall **(Section 4.3)**. In response to the comments, we have added a detailed discussion of the limitations of GCF-CRKs in our manuscript **(Lines 1019-1041, Pages 37-38)**. However, given that there is currently no absolutely reliable surface CRK dataset available for validation purposes, we highlight our plans for future research, which include conducting a more comprehensive comparative analysis of the results from CRKs and GCF-CRKs using the same dataset.

Thank you once again for your valuable suggestions. Your feedback has been instrumental in improving our research and enhancing the quality of our manuscript.

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Overview 3:

This paper introduces a long-term gridded surface cloud fraction radiative kernels (GCF-CRKs) by leveraging the correlation between the TOA shortwave radiative parameters and surface radiation, combined with fused cloud fraction datasets from multiple satellite sources. Based on this kernel, the authors isolate the cloud radiative effect and corrected the downwelling surface shortwave radiation bias caused by cloud fractions. It is known that there are large uncertainties in cloud radiative effect derived from satellite observations in the Arctic region. The study used high quality cloud fractions data to quantify this effect and makes an important contribution. The manuscript is organized and well written. I recommend to accept this manuscript subject to minor but necessary revisions.

Response: We truly appreciate your time and effort in providing us with a positive review. Thank you very much for your valuable feedback on our manuscript, which has significantly improved the presentation of our manuscript. We have carefully considered all of your suggestions and have made the necessary revisions to our manuscript in accordance with your recommendations. In the following section, we summarize our responses to each comment from the reviewers. We believe that our responses have well addressed all concerns from the reviewers.

General comment:

1. There are many cloud parameters that contribute to cloud radiative effects, such as cloud optical thickness, effective radius of cloud particles, and others. This manuscript selects cloud fraction as the primary variable. Please discuss the rationale behind this choice and the feasibility of extending the study to include other variables in the future.

Response: We truly Thank you for your insightful comment. We appreciate your recognition of the importance of our study in addressing the uncertainties in cloud radiative effects in the Arctic region. In response to your suggestion, we have added a detailed discussion on the rationale behind selecting cloud fraction (CF) as the primary variable in Section 3.1 ("Cloud radiative effect and cloud radiative kernel") and have also discussed the feasibility of extending the study to include other variables in the future in Section 7 ("Conclusion").

First, CF is one of the most fundamental and easily obtainable cloud parameters, with high accuracy and spatial consistency in its measurements and retrievals. It directly determines the extent of cloud coverage and thus significantly influences the reflection, scattering, and absorption processes of downwelling surface shortwave radiation

(DSSR) **(Lines 82-96, Pages 3-4; Lines 116-126, Page 4)**. Compared to other cloud parameters such as cloud optical thickness (TAU) and effective radius of cloud particles, CF datasets derived from satellite observations are more readily available and have longer temporal coverage, providing a robust basis for long-term climate studies(Liu et al., 2023). Additionally, CF is a key driver of the surface energy balance and has been widely used in previous studies to quantify cloud radiative effects.

While CF is a crucial parameter, we acknowledge that other cloud properties such as TAU and effective radius also play significant roles in modulating cloud radiative effects. In the future, we plan to extend our study to include these additional variables. The framework of our current method, which utilizes radiative kernels to isolate the radiative contributions of specific parameters, can be adapted to incorporate other cloud properties. By developing separate radiative kernels for TAU and effective radius, we can quantify their individual contributions to the cloud radiative effect. This extension will provide a more comprehensive understanding of the complex interactions between clouds and radiation in the Arctic region.

2. The validation against independent datasets and robust comparisons in high-latitude regions should be emphasized.

Response: Thank you very much for your valuable comments. We fully agree that robust validation and comparison with independent datasets are crucial for establishing the credibility of our cloud radiative effect (CRE) estimates, especially in high-latitude regions. To address your concerns, we have conducted additional analyses and provided more comprehensive validation results.

To evaluate the accuracy of our cloud radiative effect (CRE) estimates, we have conducted additional analyses and provided more robust justifications. To evaluate the fidelity of GCF-CRKs, we calculated surface shortwave CRE (2000–2014) using output from the CMIP6-AMIP (Coupled Model Intercomparison Project Phase 6, Atmospheric Model Intercomparison Project) simulations(Eyring et al., 2021). Focusing on the Community Earth System Model Version 2 (CESM2), a widely used model with detailed cloud parameterizations, we compared CRE derived from GCF-CRKs against CRE directly simulated by CESM2. The results show strong agreement, with an R^2 of 0.847, RMSE of 14.5 $W\cdot m^{-2}$, and bias of 11.19 $W\cdot m^{-2}$ **(Section 4.5, Figure 13b)**. This demonstrates that our kernel-based approach effectively isolates cloud fraction-driven radiative effects, capturing ~85% of the variance in model-simulated CRE. We further validated GCF-CRKs against the CERES-EBAF Ed4.2 dataset (2000–2014), achieving even higher consistency: $R^2 = 0.9009$, RMSE = 9.762 $W\cdot m^{-2}$, and bias = 1.8916 $W\cdot m^{-2}$ (**Figure 13a**). This further supports the accuracy and reliability of GCF-CRKs. This manuscript also compared the GCF-CRKs based CRE with those from CERES-EBAF in spatial distribution, our method captures the spatiotemporal variability of CRE more accurately (**Section 4.5, Figure 12**). We believe that these additional analyses strengthen the credibility and applicability of our methodology. We will continue to refine our validation procedures and incorporate additional datasets in future work to further enhance the accuracy and reliability of our CRE estimates.

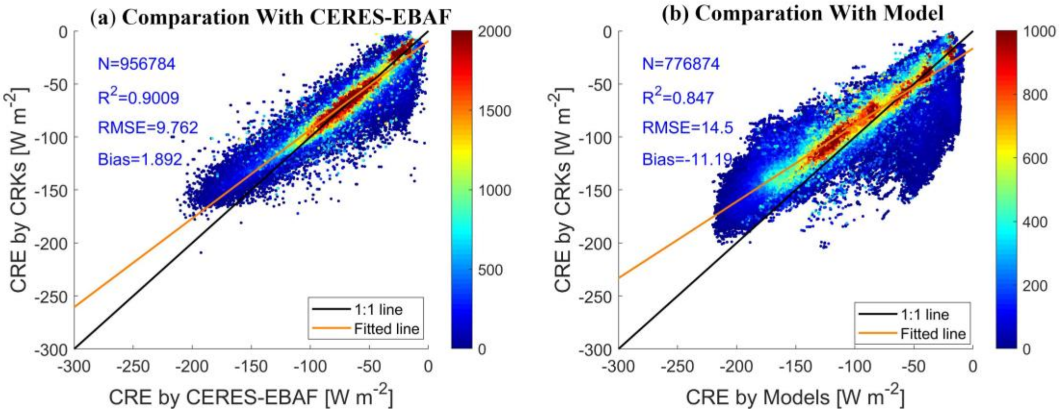

Figure 13. Comparison of cloud radiative effect (CRE) estimated by GCF-CRKs with observed and model-estimated CRE.

3. Enhance the discussion section of the paper by integrating current hot topics in climate change, such as the Arctic amplification effect. Elaborate on the potential contributions of this study's findings to understanding global climate feedback mechanisms and polar climate change.

Response: Thank you for your suggestion. In response, we have enhanced the Introduction section and the Discussion section of our paper by integrating current hot topics in climate change, particularly focusing on the Arctic amplification effect. We have elaborated on the potential contributions of our study's findings to understanding global climate feedback mechanisms and polar climate change. We expand the Introduction section to include a detailed discussion of cloud radiative forcing and its impacts on Arctic amplification and the global radiation balance **(Lines 61–180, Pages 3–4)**, thereby providing additional context for the background of this study. Additionally, we incorporate a detailed subsection in the Discussion section titled "Potential Contributions of GCF-CRKs to Understanding Climate Feedback Mechanisms" **(Lines 961–1041, Pages 36–38)**. Our study reveals that the cooling effect of clouds on Arctic surface shortwave radiation is more complex and exhibits greater spatiotemporal variability than previously recognized. Specifically, we find that the cloud-induced cooling effect is particularly pronounced over Greenland, where the radiative cooling deviation caused by clouds reaches approximately 4 Wm^{-2}. This suggests that clouds play a more significant role in regulating surface energy balance in the Arctic, potentially offsetting some of the warming effects caused by sea ice loss. The Arctic amplification effect, characterized by a warming rate that is 2 to 4 times the global average, is primarily driven by the complex interplay between sea ice loss, surface albedo feedback, and cloud radiative dynamics. Our findings indicate that the cooling effect of clouds on Arctic surface shortwave radiation has been overestimated in previous studies. This implies that the actual rate of Arctic warming could be faster than previously predicted, which has important implications for understanding polar amplification and its effects on global climate patterns.

These revisions aim to provide a clearer and more complete picture of the significance of our work within the context of current climate research. In the future, we will involve integrating cloud vertical structure, microphysics, and optical thickness into our methodology. This will enable us to address more complex scientific questions and improve the usability of our dataset in broader climate modeling and research contexts.

Thank you again for your valuable feedback. We believe that these enhancements significantly strengthen the relevance and impact of our work.

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