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:

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 $\text{W·m}^{-2}\text{·decade}^{-1}$, 2000–2020; Figure 14) reveals that the cloud-induced surface cooling rate is 30% slower than previously estimated by CERES-EBAF (-1.64 $\text{W·m}^{-2}\text{·decade}^{-1}$). 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·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.

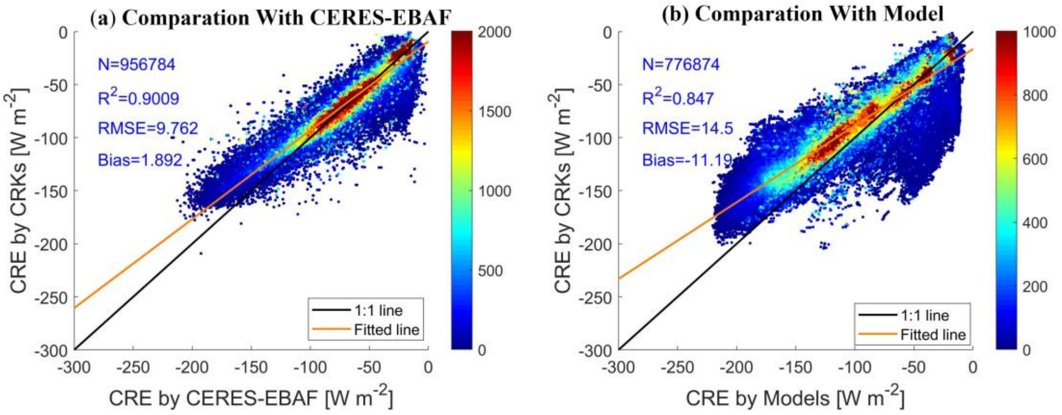

Figure 13. Comparison of cloud radiative effect (CRE) estimated by GCF-CRKs with observed and model-estimated CRE.

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 $W \cdot m^{-2} \cdot decade^{-1}$ vs. −1.64 $W \cdot m^{-2} \cdot decade^{-1}$). 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 $W \cdot m^{-2}$ 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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