Dear Reviewer,

Thank you for your valuable comments and suggestions. Your concerns regarding the impact of cloud optical thickness (Cloud Optical Thickness, TAU) on downwelling surface shortwave radiation (Downwelling Surface Shortwave Radiation, DSSR) and the potential limitations of the GCF-CRKs under future climate conditions are indeed crucial scientific issues. We appreciate your insights and have carefully considered them in our revisions.

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:

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

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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