Response to Reviewer 1:

Reviewer comments in italics
Author comments in upright text

Review of "A Lagrangian Perspective on the Lifecycle and Cloud Radiative Effect of Deep Convective Clouds Over Africa" by W. K. Jones et al.

Jones et al. analyze geostationary satellite observations to investigate the diurnal cycle and radiative effects of tropical deep convective clouds over Africa and the tropical Atlantic Ocean. They use a novel cloud-tracking algorithm that allows them to investigate the clouds from a Lagrangian point of view. This analysis shows that individual anvil clouds can have a wide range of radiative effects depending on the time of day that they initiate. Thus, changes in the diurnal cycle of convective cloud be an important and underappreciated climate-feedback mechanism.

I believe that the research topic is highly relevant, the analysis is well done, and the writing and figures are clear and concise. I have only a few comments and suggestions for improvements, which are listed below. I therefore recommend minor revision for the manuscript.

General Comments

My only main comment about the paper is that the discussion about how the results relate to the existing cloud-climate feedback literature is not as specific as I hoped it would be. The authors make a compelling case that changes in the diurnal cycle of convection could be an important and understudied climate-feedback mechanism, but the discussion about how to address this challenge is not very clear. Can the results of the current study help to estimate the diurnal-cycle-induced climate feedback? If not, then what are some ways that we might make progress on this in the future? Have any physical mechanisms been proposed that would change the timing or amplitude of the convective diurnal cycle as the climate changes? Does the community have the necessary analysis methods to diagnose this feedback? As far as I know, none of the current methods of cloud-feedback analysis can diagnose feedbacks from changes in the diurnal cycle of clouds, so I'm not even sure that the community has the proper tools to study this rigorously. I think that a more specific discussion about how the results relate to the existing cloud-feedback literature and potential future directions would improve the end of the paper. It would also align well with the introduction, which discusses anvil-cloud feedback mechanisms at length.

We have included further discussion on this topic in the conclusion. It is, however, still uncertain whether we can investigate such a feedback at present. The traditional approach to assessing anvil feedbacks using GCMs is unlikely to be appropriate as they do a poor job representing the diurnal cycle and lifecycle of DCCs. While convective-resolving models do a better job at this, it is not yet clear whether they can assess anvil feedbacks, and whether they do a good job of representing changing convective processes in a changing climate. In addition, separating the effects of convective processes and cirrus processes on anvils is a major challenge. We have included the two paragraphs below discussing this:

"Changes in the diurnal cycle of convection may not have a large impact on net anvil CRE over the ocean due to the mostly uniform occurrence of convection throughout the day. Over land, however, the afternoon peak of convection at around 3 pm solar time (see fig. 5) coincides with a time at which anvil CRE is very sensitive to shifts in the diurnal cycle (fig. 13 b). Furthermore, a reduction or increase in the number of DCCs occurring at a specific time of day may change the net CRE of anvils without any change in the CRE of individual DCCs.

Diagnosing a diurnal cycle related anvil cloud feedback in climate models may however be difficult. Beydoun et al. (2021) found that changes in anvil lifetime contributed little to CRE feedbacks in a cloud-resolving radiative-convective equilibrium model. It is unclear how well the diurnal cycle of convection and convective lifecycle are represented in such a model, although convective-resolving models have been found to model these better than parameterised climate models (Prein et al., 2015; Feng et al., 2023). Disentangling the impacts of convective processes and anvil cirrus processes on anvil lifecycle and CRE is also a key challenge. Here, the use of model experiments such as that of Gasparini et al. (2022) may help better understand the impacts of both processes on anvil Cloud Radiative Effect (CRE) and the potential for climate feedbacks."

Specific Comments

Line 161 "we only detect and track the thick portion of the anvil in this article": Can you be more specific about what "thick portion" means? For example, can you state the minimum cloud visible optical thickness that can be tracked by the algorithm?

We have conducted a number of idealized, 1D radiative transfer simulations using libRadtran to assess the sensitivity of SEVIRI to anvil clouds at different heights and optical depths. We find that, using the detection thresholds in this study, the thick anvil detection is sensitive to optical depths between 1 and 1.5. This is backed up by the median of the minimum retrieved optical depth of tracked anvils of 1.45, and this value is likely high due to the inability to accurately retrieve OD at nighttime when many anvils dissipate. While this captures most of the CRE of anvil clouds, we agree that all CRE values are likely biased low by the inability to detect thin anvils. The following paragraph has been updated:

"Due to the lack of sensitivity of the SEVIRI SWD to thin ice clouds, we only detect and track the thick portion of the anvil in this article. The WVD channel of SEVIRI is capable of detecting anvils with optical thicknesses of approximately 1–1.5 (see supplementary fig. S1). However, the closer spacing and narrower bandwidth of the SEVIRI LW window channels (see supplementary fig. S2), along with the higher noise means that the SWD is less sensitive to thin cirrus compared to instruments such as the GOES-16 ABI (see supplementary fig. S3). The anvils tracked in this paper have a median retrieved minimum optical depth of 1.45, although this value is likely biased high as many anvils dissipate at night when accurate satellite retrievals of optical depth are not available. While this sensitivity captures much of the CRE of DCC anvils (Berry and Mace, 2014) the long lifetimes of dissipating thin anvils may have a significant warming contribution to net anvil CRE (Horner and Gryspeerdt, 2023). As a result, it is expected that the anvil CRE measured in this study are biased low."

In addition, a number of supplementary figures have been added, which are reproduced below:

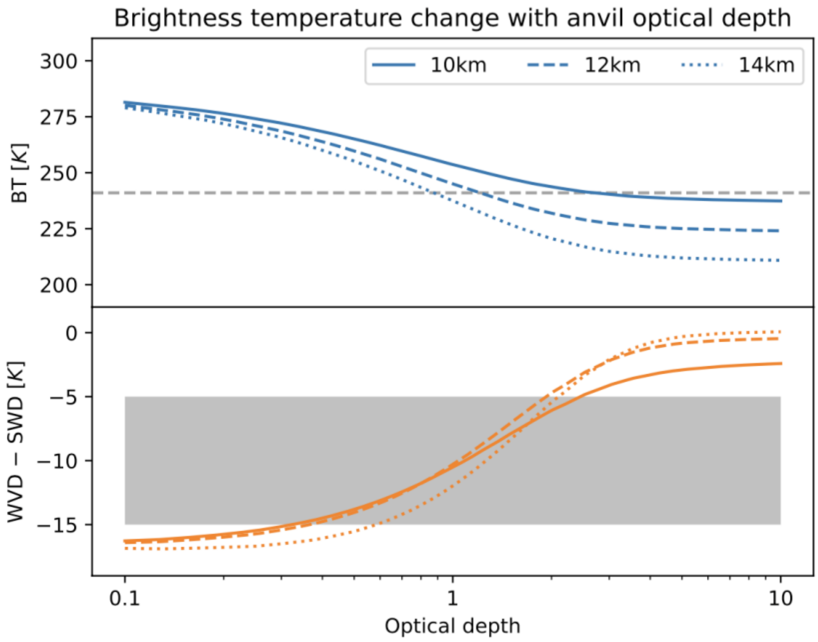

Figure S1. Simulated sensitivity of the SEVIRI 10.8 µm BT (top) and WVD minus SWD (bottom) to anvil clouds of varying optical thickness at heights of 10, 12 and 14 km. The LibRadTran model was used to estimate the observed radiances, and all simulations used ice clouds with cloud top particle effective radius of 20 µm. The grey dashed line shows the 241 K BT, which, although commonly used as a threshold for anvil detection in satellite imagery, shows large sensitivity of the minimum optical thickness detected with the height of the anvil cloud. The grey region in the lower plot shows the range of temperatures in which the edge of the anvil is detected, as described in Jones et al. (2023). Similar sensitivity is found for all three cloud heights, with the optical depths of around 1–1.5 seen in the middle of the hysteresis region. The median minimum retrieved optical depth of all tracked anvils in our dataset is found to be 1.45, although this value is biased high by the inability to retrieve optical depth accurately at night-time.

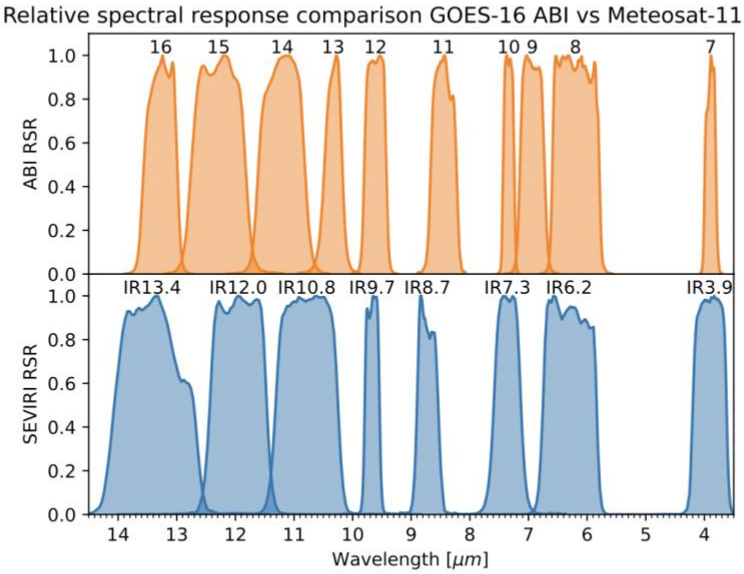

Figure S2. Comparison of the relative spectral response (RSR) functions for the GOES-16 ABI and Meteosat-11 SEVIRI thermal IR channels. The LW window channels on ABI (channels 13 and 15) have a wider spacing than those of SEVIRI (channels IR10.8 and IR12.0). This wider spacing allows ABI to be more sensitive to the emissivity difference of ice clouds at wavelengths between 10 and 12 mum, and so it is better able to detect thin cirrus clouds.

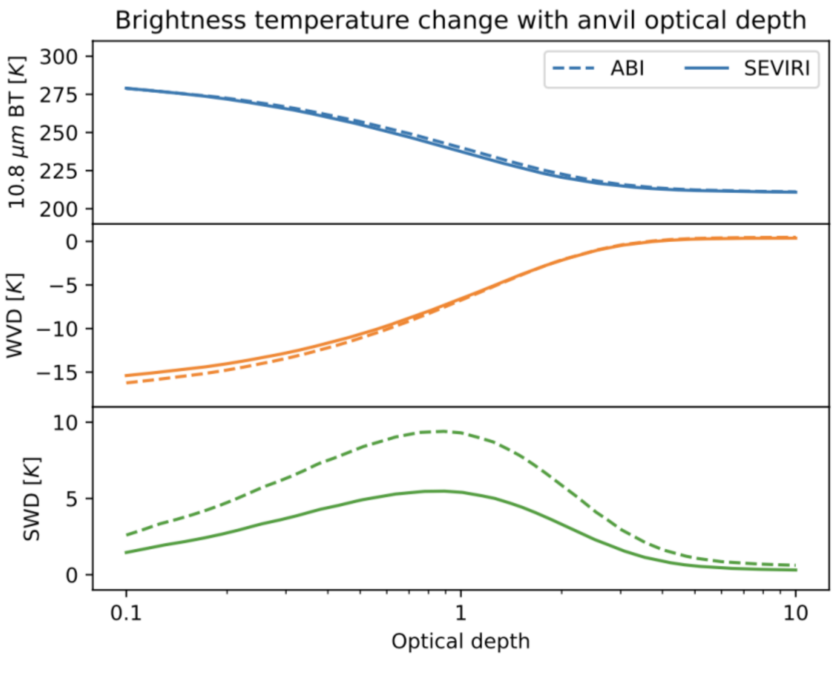

Figure S3. Comparison of the sensitivities of ABI (dashed lines) and SEVIRI (solid lines) to anvil clouds of different optical thickness, usin the LibRadTran simulation of an anvil at 14 km as used in fig. S1. The 10.8 µm BT (top panel) and WVD (middle panel) show very simila values for both instruments. The simulations of the SWD (bottom panel) show that SEVIRI is only about half as sensitive as ABI to thin ic clouds.

Section 4.2: I think the current analysis in this section is well done, but I wonder if an even stronger signal would emerge if the analysis was performed separately with land-based convection and ocean-based convection. I think that oceanic clouds are typically larger, longer lasting, and have less intense convection than land-based clouds, so the land- ocean contrast may alias into the statistics in Fig. 6 and Fig. 7.

While we considered investigating land-sea differences in this study, the domain area covering mostly land combined with the time range in which the ITCZ is at its Northernmost extent meant that only a small proportion of detected DCCs were over the sea (11%). As a result, we decided that this amount was too small for meaningful analysis. We have added the following sentence to the manuscript to make this clear:

"While the studied domain contains both land and sea regions, only a small proportion of tracked DCCs occurred over sea (11%), and so we have not separated the analysis of land and oceanic DCCs in this article."

We are currently performing a subsequent study over a larger domain in which we are investigating land-sea contrasts in anvil CRE.

Line 284: This paragraph is written in a way that seems to imply that the average anvil- cloud net CRE must remain near zero as the climate changes. I'm not aware of any convincing physical mechanism or conservation law that would require the net anvil-cloud CRE to remain near zero. Can you please explain why you think it will remain near zero or acknowledge the possibility that it will not remain near zero?

The paragraph was not intended to apply that, but rather how shifts in the diurnal cycle could oppose anvil CRE feedbacks. The paragraph has been reworded to better discuss how changes in the diurnal cycle of convection could affect anvil CRE, without implying that this is part of a restoring mechanism. Please see the following updated paragraphs:

"It is apparent from figs. 11 and 12 that the observed neutral net anvil CRE is not only due to a balance between the SW and LW, but also from a balance of the cooling effect of daytime DCCs and the warming effect of those occurring at night. If the number of DCCs occurring during the daytime were to reduce we would expect a net warming effect without any change to the CRE of individual DCCs. As the diurnal cycle of convection over the ocean is nearly uniform, we should expect little impact on anvil CRE from changes in the time of convective initiation. However, over land, where convective activity is much more common in the afternoon, changes in the diurnal cycle may have a much larger effect on anvil CRE.

Furthermore, fig. 13 b highlights that differences in anvil temperature are linked to the diurnal cycle of anvil CRE as colder anvils tend to have longer lifetimes. As a result, if warming surface temperatures lead to the invigoration of DCCs, the warming effect we would see would be larger than the LW effect from the change in anvil temperature alone. Surface warming may also result in an earlier time of convective initiation, resulting in a cooling feedback."

Technical Corrections

Line 15: The word "distribution" is used twice in the sentence. Consider changing to "We find that the anvil cloud CRE of our tracked DCCs has a bimodal distribution."

Corrected

Line 227 (and elsewhere): I think the name "Genio" should be "Del Genio"

This was due to an error in the bibtex, and has been corrected throughout

Line 279 "We see that, as expected, mean anvil CRE becomes more positive with increasing CTT": Should this be "mean anvil CRE becomes less positive or more negative
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Line 308: change "outsize" to "outsized"

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Additional references:

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Response to Reviewer 2:

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We have included further discussion on this topic in the conclusion. It is, however, still uncertain whether we can investigate such a feedback at present. The traditional approach to assessing anvil feedbacks using GCMs is unlikely to be appropriate as they do a poor job representing the diurnal cycle and lifecycle of DCCs. While convective-resolving models are better in this regard they are not yet well constrained by observations. In addition, separating the effects of convective processes and cirrus processes on anvils is a major challenge. We have included the two paragraphs below discussing this:

"Changes in the diurnal cycle of convection may not have a large impact on net anvil CRE over the ocean due to the mostly uniform occurrence of convection throughout the day. Over land, however, the afternoon peak of convection at around 3 pm solar time (see fig. 5) coincides with a time at which anvil CRE is very sensitive to shifts in the diurnal cycle (fig. 13 b). Furthermore, a reduction or increase in the number of DCCs occurring at a specific time of day may change the net CRE of anvils without any change in the CRE of individual DCCs.

Diagnosing a diurnal cycle related anvil cloud feedback in climate models may however be difficult. While Beydoun et al. (2021) found that changes in anvil lifetime contributed little to CRE feedbacks, this study used a radiative-convective-equilibrium model with no diurnal cycle of insolation. Although convective-resolving models have been found to model the diurnal cycle an lifecycle of DCCs better than parameterised climate models (Prein et al., 2015; Feng et al., 2023), but lack good observational constraints. Disentangling the impacts of convective processes and anvil cirrus processes on anvil lifecycle and CRE is also a key challenge. Here, the use of model experiments such as that of Gasparini et al. (2022) may help better understand the impacts of both processes on anvil CRE and the potential for climate feedbacks."

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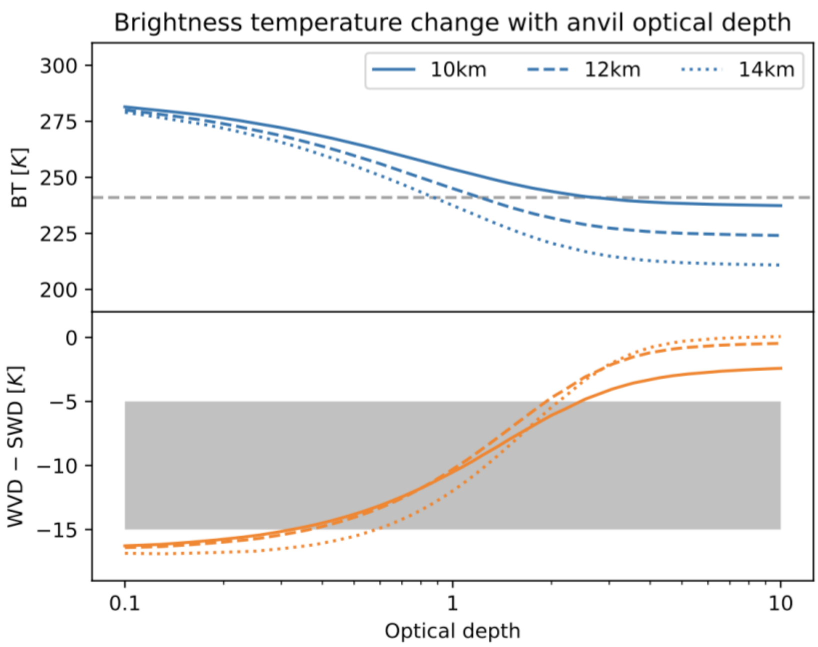

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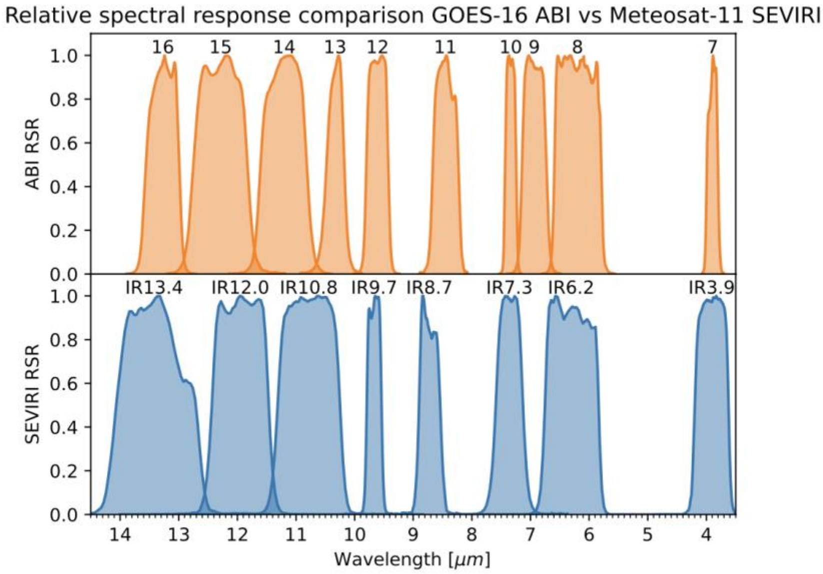

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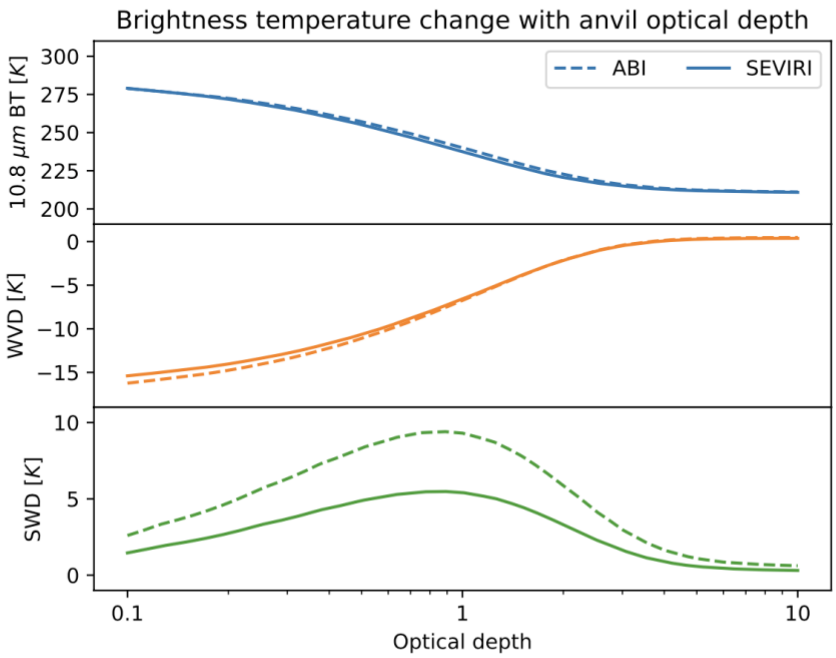

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Other changes:

There have been several minor changes made to the manuscript to address issues not raised by either reviewer. These are as follows:

1. Recalculation of CRE bias using updated CERES EBAF Ed 4.2 data after an error in the fluxes over certain scenes was corrected. The new bias is calculated as -1.87 (new), -2.02 (SW) and +0.15 (LW). This results in a small change to the net anvil CRE calculate at $-0.94\pm0.91 Wm^{-2}$. This change does not affect the findings of the paper overall.
2. Update of the figures to better meet ACP guidelines.
3. Addition of a supplementary figures file to show greater detail on some technical aspects of the article.