

Aerosol–cloud interactions influence the climate response to AMOC weakening

by Ryan Vella & Ulrike Lohmann

- 5 Once again, we thank the editor and referees for taking the time to review our revised manuscript. Here, we reply to comments by Anonymous Referee #2 (from September 23, 2026). Our responses are presented in [blue](#).

From Anonymous Referee #2's response:

- 10 The authors have addressed my comments and have improved the study's quantification of cloud feedback changes, the comparison with previous studies, the consideration of state dependence, and the description of the experimental design. The manuscript identifies interesting new pathways by which AMOC-aerosol interactions impact cloud feedbacks. Please see additional suggestions below with line numbers referring to the tracked changes manuscript.

[We thank the referee for the additional feedback. Detailed responses below.](#)

- 15 Main Comments:

1. I would avoid the terminology “cloud adjustments” throughout the manuscript. “Cloud adjustments” usually refers to the fast response of clouds to increased CO₂ forcing before any change in surface temperature occurs, whereas here the authors are discussing surface-temperature-mediated cloud feedbacks.

- 20 [We updated the term “cloud adjustments” to cloud “changes” or “responses”. Following common usage, we reserve “feedback” for a full feedback cycle, which requires at least a mixed-layer ocean for the surface temperature to respond to the change.](#)

2. The authors now apply cloud radiative kernels to quantify the cloud feedback radiative contribution; the APRP method to calculate the surface albedo feedback; and a double, aerosol-free radiation call to diagnose the aerosol direct radiative effect. Can the authors indicate how the sum of the shortwave contributions from these three terms compares to the actual, total TOA shortwave radiation change? It would be helpful to see how well the total radiative decomposition is capturing the actual radiative changes in the model.
- 25

- [We now test the closure of the shortwave decomposition directly \(new Table S1 and Fig. R1 below\).](#)
30 [In the global mean, the simulated change in net TOA shortwave radiation \(Hosing minus Control\) is](#)

-1.12 W m^{-2} . The kernel cloud term ($+0.50 \text{ W m}^{-2}$), the APRP surface albedo term (-0.83 W m^{-2}) and the all sky shortwave effective radiative forcing due to aerosol–radiation interactions (ERF_{ari} , the aerosol direct radiative effect in the referee's comment) from the double radiation call (-0.28 W m^{-2}) sum to -0.61 W m^{-2} , or 55 % of the simulated change.

- 35 Most of the gap comes from a term that is not among the three, the change in shortwave absorption in the clear atmosphere. The Hosing atmosphere is colder (global mean surface cooling of 1.2 K) and therefore drier, so it absorbs less sunlight. We estimate this term by applying APRP to the aerosol free fluxes of the double radiation call. In these fluxes the APRP non cloud term contains no aerosol, and since ozone and the greenhouse gases are identical in both simulations, we attribute it mainly to water vapour. It amounts to -0.33 W m^{-2} . As a consistency check, the APRP non cloud term computed with aerosol (-0.63 W m^{-2}) minus ERF_{ari} gives a similar value (-0.35 W m^{-2}). Including this term, the four contributions sum to -0.95 W m^{-2} , or 85 % of the simulated change.

- The remaining -0.17 W m^{-2} is close to the difference between two estimates of the shortwave cloud term, $+0.50 \text{ W m}^{-2}$ from the kernels and $+0.34 \text{ W m}^{-2}$ from APRP. Replacing the kernel cloud term by the APRP estimate gives -1.10 W m^{-2} (open diamonds in Fig. R1). Since the APRP terms alone sum almost exactly to the simulated change, this mainly shows that the residual lies in the cloud term rather than in the other terms. Almost all (98 %) of the difference between the two cloud estimates arises poleward of 40°N , where the kernel based closure reaches only 79 % (-4.00 against -5.06 W m^{-2} , Table S1). This is where the sea ice has expanded. The shortwave kernel is evaluated with the control clear sky surface albedo, which no longer represents the brighter surface underneath the clouds, so it likely overstates the shortwave cloud term there. Both estimates show a small, positive shortwave cloud term that is much smaller than the surface albedo term, so our conclusions do not depend on which estimate is used. We have added the closure to Sect. 3.4 and as Table S1.

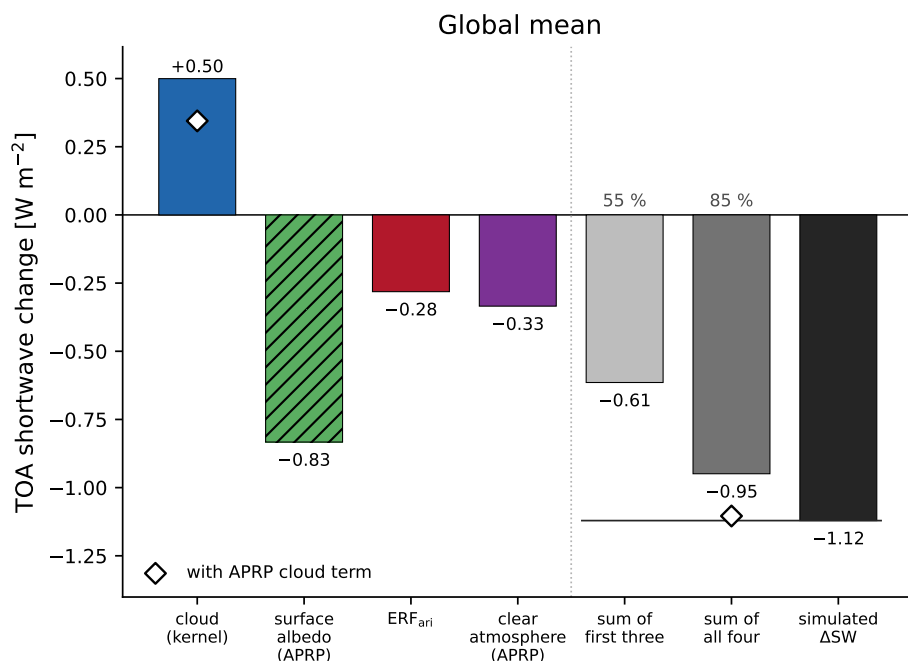


Figure R1. Closure of the global mean TOA shortwave response (Hosing minus Control). Coloured bars show the kernel cloud term, the APRP surface albedo term, the shortwave ERF_{ari} and the clear atmosphere term, attributed mainly to water vapour. Grey bars show the sum of the first three and of all four terms, with their percentage of the simulated change (black bar and line). Open diamonds show the cloud term and the four term sum when the APRP cloud estimate replaces the kernel.

The closure also clarifies what the CRE anomaly measures. The CRE is the difference between all-sky and clear-sky fluxes, so it changes whenever the clear-sky flux changes, even if the clouds do not. Here the expanded sea ice and snow cover brighten the surface. Beneath clouds, part of this brightening is hidden, so all-sky reflection increases less than clear-sky reflection (-1.12 against -2.27 W m^{-2} in the net TOA shortwave), and the CRE anomaly becomes positive even where clouds are unchanged. This clear-sky masking explains why the global mean shortwave CRE anomaly ($+1.15 \text{ W m}^{-2}$) exceeds the kernel cloud term ($+0.50 \text{ W m}^{-2}$) by 0.65 W m^{-2} . Aerosol accounts for only $+0.06 \text{ W m}^{-2}$ of this, given by the difference between the all-sky (-0.28 W m^{-2}) and clear-sky (-0.34 W m^{-2}) changes in the shortwave ERF_{ari} from the double call. The remainder mainly reflects the brighter surface of the expanded sea ice and snow cover. We have revised Sect. 3.4 and the Conclusions accordingly.

3. Would the authors consider showing maps for the cloud amount, altitude, and optical depth feedback contributions? It would be helpful to see where in space these changes are largest, particularly for the optical depth feedback. This could help illustrate the causal chain from changes in dust INPs (Figure 4b) to changes in TWP (Figure 6, 7d) to changes in the cloud optical depth feedback that offset the global cloud amount feedback.

70 This is a good suggestion. We now show maps of the cloud amount, altitude and optical depth components in the shortwave, longwave and net (new Fig. S7), and the new Fig. 10 follows the chain the referee describes in zonal means, from dust INPs to cloud water path to the kernel components.

The cloud amount term is a cooling over the North Atlantic and the northeast Pacific, where low cloud increases. The altitude term is mainly longwave and follows lower cloud tops over the North Atlantic and the southward shift of tropical deep convection. The optical depth term is a shortwave warming, 75 largest over the Nordic and Barents Seas and northern Eurasia ($+4.5 \text{ W m}^{-2}$ averaged over $60\text{--}80^\circ\text{N}$ and $20^\circ\text{W}\text{--}60^\circ\text{E}$) and along the tropical rain belt.

The second step of the chain is also clear. The shortwave optical depth term follows the change in total water path (spatial correlation of $r = -0.79$ globally and $r = -0.90$ poleward of 40°N , Fig. 10b,c), and this loss is almost entirely liquid (LWP -8.6 against IWP -0.3 g m^{-2} poleward of 40°N), consistent with 80 the WBF process removing the additional ice as precipitation, but also with the reduced moisture supply discussed below. The first step is not a simple spatial match. The dust INPs increase in the mixed phase layer peaks near 49°N , whereas the liquid loss peaks near 65°N over the expanded sea ice (Fig. 10a,b), and the water path change correlates more strongly with the surface cooling ($r = 0.61$) than with the INP increase ($r = -0.24$). Since dust and cooling increase together, the maps alone cannot separate 85 their contributions. Our evidence for the INP pathway is the regime analysis of Fig. 7, which compares clouds at the same temperature. There, the mixed-phase ice crystal number rises by 32 % and the total water path falls by 8 %. We now state this in Sect. 3.4, together with the need for an experiment with INP concentrations held at control values to quantify the dust contribution.

Fig. 10c also shows where the global offset between the cloud amount (-0.21 W m^{-2}) and optical depth 90 ($+0.38 \text{ W m}^{-2}$) terms arises. About half of the optical depth term comes from the tropics ($+0.20 \text{ W m}^{-2}$), linked to the ITCZ shift. In the shortwave, where the thinning acts, the Northern Hemisphere poleward of 30°N contributes $+0.21$ of the global $+0.60 \text{ W m}^{-2}$, compared with $+0.27$ from the tropics and $+0.12$ from the Southern Hemisphere extratropics, although part of it is offset in the longwave. The high-latitude thinning is therefore one of the two main contributors, together with the tropical circulation response, 95 and we have revised Sect. 3.4 accordingly. Over the expanded sea ice, the kernel likely overstates the shortwave thinning, since it is evaluated with the control surface albedo (see our reply to comment 2).

4. I appreciated the authors' streamlining of the discussion of Figure 7, but I still found the key mechanisms for the optical depth feedback (INP and WBF changes, I think) to be a bit buried, so that the 100 concise story presented in the abstract became less punchy and more meandering in the text. Are there ways to elevate the central story in the text, potentially through structural changes? For example, perhaps the most important points about the mixed-phase regime could be stated first before getting into the details of each regime? In earlier paragraphs discussing LWP and IWP changes in Figure 6, could it be emphasized why readers should care—that most previous studies have focused on cloud cover and 105 LWP increases in the North Atlantic, but that there are also major TWP decreases elsewhere that have important radiative impacts?

We thank the referee for this helpful suggestion and have restructured Sect. 3.3 in three ways. First, the discussion of the water path changes (Fig. 6) now opens by setting our results against previous studies. These have focused on the increase in low cloud cover and LWP over the North Atlantic, which our simulations reproduce. We now emphasise that this increase is a local exception. Poleward of 40 °N, TWP decreases over 82 % of the area, by 11.6 % on average and by about a third over the Nordic and Barents Seas. These decreases coincide with the largest positive values of the optical depth component of the cloud radiative response (new Fig. S7), so they matter for the radiative response. Second, the discussion of Fig. 7 now opens with the central result, the mixed phase pathway from enhanced dust INP through increased ice crystal number and the WBF process to the loss of cloud water, stated in one paragraph before the details of each regime. The regime paragraphs follow in order of importance, mixed phase first, then warm and cold clouds. Third, we split Sect. 3.3 into two parts, on the macrophysical response (Figs. 5 and 6) and on the microphysical pathways (Fig. 7), so that the aerosol pathway is visible in the structure of the section. The opening of the second part also states that the TWP decreases have two causes, the reduced moisture supply under the colder, more ice covered surface and the aerosol pathway through the ice phase, in line with our reply to comment 3.

Other Comments (line numbers for tracked changes manuscript) L13: Suggest deleting “masking-free” as this is assumed for kernel decompositions. Alternatively, this could say “cloud radiative kernel decomposition.”

Text was amended.

L21: Suggest clarifying that surface albedo and dust direct effects dominate the *shortwave* budget, as there might be other important longwave feedbacks that aren't shown here (like the lapse-rate feedback in the North Atlantic).

We thank the referee and agree. The terms quoted in the abstract are the cloud, aerosol and surface albedo contributions that we diagnose, not the full TOA budget, which also contains the longwave response to the cooling, including the Planck, lapse rate and water vapour responses. This response is large. Outgoing longwave radiation decreases by 2.0 W m^{-2} in the global mean, more than the 1.12 W m^{-2} decrease in absorbed shortwave radiation. We have not described the terms as dominating the shortwave budget either, because the shortwave cloud term ($+0.50 \text{ W m}^{-2}$) and the clear atmosphere term, mainly water vapour (-0.33 W m^{-2}), are comparable to or larger than the shortwave dust ERF_{ari} (-0.28 W m^{-2} , Table S1). The revised abstract therefore restricts the statement to the contributions diagnosed here and notes that the longwave response, including the Planck and lapse-rate responses, is not included. We have added a corresponding sentence to Sect. 3.4.

L35: Suggest “weakening” -> “AMOC weakening”

Text was amended.

L72: Suggest “to” instead of “through” to make the from...to...to structure clearer.

Text was amended.

L151: It could be clearer that “disabled” applies not only to “terrestrial carbon cycling” but also to “interactive carbon assimilation.”

145 Text was amended.

Figure 3b, d: Should the y-axis have latitude labels?

Figure updated.

L211: Suggest spelling out AOT as Aerosol Optical Thickness (AOT) the first time it is referenced in the text.

150 Text was amended.

L255: I found this discussion of the aerosol mass wet deposition changes a bit confusing. Could it be simpler to say that the mass wet deposition field also tends to follow the changes in precipitation, with reduced wet deposition where precipitation is reduced most, in the subpolar North Atlantic and some regions of the northern tropics? (And then add that the mass wet deposition field is increased downstream of regions with increased aerosol burden)

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We have rewritten the description of the mass wet deposition field around the two controls the referee identifies. Mass wet deposition decreases where precipitation decreases most, by 27 % over the subpolar North Atlantic and by 20 % over the Arabian Sea and India. It also decreases over the Sahara, where the reduced rainfall outweighs the larger dust burden. It increases downstream of the regions of increased aerosol burden, by 65 % over eastern Europe and western Russia and by 56 % over the Atlantic and Africa just south of the equator, where the southward shifted rain band meets the dust plume. These two controls describe the pattern well. In the Northern Hemisphere, precipitation decreases over 94 % of the area where mass wet deposition decreases, and the aerosol burden increases over 95 % of the area where it increases.

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165 Figure 9 y-axis and legend: Suggest deleting “adjustment.” I would call this the cloud feedback energetic contribution or cloud feedback radiative contribution (the feedback itself would be normalized by temperature change).

We agree and have removed “adjustment”. We now call the quantity the cloud radiative response rather than a feedback. A feedback requires the cloud change to alter the surface temperature that drives it,

170 for example a decrease in clouds causing warming that leads to further warming. With prescribed sea surface temperature and sea ice this loop cannot operate in our experiments. Figure 9 and the text have been updated, and the term is defined where the kernels are introduced in Sect. 3.4.

L645: suggest splitting up this long sentence into several sentences and indicating how each of these effects would impact the resulting cloud feedback.

175 We have split the sentence and now state how each effect would change the cloud radiative response. In a warmer background the supercooled liquid water would lie higher, above most of the additional dust, weakening the dust-driven glaciation, the optical thinning and the positive contribution. A larger precipitation reduction would raise both INPs, which strengthens the thinning, and CCN, which brighten warm clouds, so its net effect is uncertain.