

Responses to reviewer comments

The original comments are in *blue italic font*, and our response are in black font.

Reviewer #2:

This study provides a comprehensive look at daytime evolution of low cloud susceptibility to droplet number (Nd) perturbations. These susceptibilities are derived from snapshots of cloud and radiation fields taken from passive sensors (SEVIRI), onboard a geostationary satellite (Meteosat11), within a 10-by-10-degree box over the NE Atlantic region. The authors found persistent “U-shape” evolutions in cloud susceptibility, including cloud water, cloud albedo, and cloud fraction, from which they argue that polar-orbiting satellite derived cloud susceptibility underestimate the daytime-mean cloud susceptibility. They attribute the observed evolution in cloud susceptibility to two main hypotheses that they formulated and tested: i) clouds have “memory” of their past susceptibility signal associated with the cloud state they transition from; ii) cloud responses to Nd perturbations have a longer timescale than the satellite observing time interval (30 mins).

Overall, I found the study interesting and intriguing in some sense. Clearly, the authors have put in lots of thoughts on this problem and lots of efforts in interpreting these results. The manuscript is nicely constructed and organized. That being said, I do think there are some key/fundamental issues that need to be addressed and justified first. If these concerns and issues can be sufficiently addressed, I believe this work has the potential to provide new, impactful insights and make significant contribution to the field.

We are grateful to the reviewer for the thorough review of our manuscript and for providing constructive comments. Below, we provide a point-by-point response to each comment and details of the modifications made to the text and figures to address these points.

Major concerns/comments:

1. The authors adopted a methodology for deriving cloud susceptibility that uses spatial regression of cloud properties to Nd within satellite snapshots. This is done to minimize the impact from confounding meteorology. I found the extension of this approach to cloud fraction susceptibility is a bit unjustified, and I’m in general concerned about the appropriateness of applying this methodology to cloud fraction susceptibility. Cloud fraction is a tricky quantity by definition. It depends strongly on the spatiotemporal scale of one’s investigation, for example, the distribution of daily cloud fraction will look very different from that of monthly cloud fraction at any given location on Earth. The degree of spatial aggregation also strongly affects cloud fraction, e.g., cloud fraction reduces to binary (zero and one) at pixel level. Overall, I find the discussion/explanations around CF susceptibility quite vague and often led to confusion, which could potentially be related to an ill-defined methodology. Some of my specific concerns are:

1a. How confident are you that, at 25-km resolution, variations in CF is not simply coming from the geometry of the cloud field, such that one scene captures the majority of a cloud while another scene captures only a small portion of the same cloud, resulting in a large difference in cloud fraction between the two scenes, while Nd has nothing to do with it.

Thank you for raising this important point. Most of the concern pertains to stratiform clouds with an area larger than the 1-degree scene, where variations in the $0.25^\circ \times 0.25^\circ$ mean

CF could result from sampling cloud edges or the cloud center. To assess the influence of cloud geometry on the retrieved CF susceptibility, we excluded $1^\circ \times 1^\circ$ scenes with a range of 0.25° CF greater than 90%, a range of N_d smaller than 60 cm^{-3} , and the total cloud areas larger than $20,000 \text{ km}^2$. Cloud area is defined for each cloud object by the number of contiguous cloudy pixels. A total of $\sim 17,000$ scenes were removed, which accounts for $\sim 24\%$ of the samples. As shown in Figures R1-R4, compared with the original results, removing the $1^\circ \times 1^\circ$ scenes that possibly sampled different parts of the cloud with small variation in N_d do not alter the conclusions of this study. Since cloud geometry exhibited minimal impact on the overall CF susceptibility, we opted to retain these scenes with large CF variations to maintain consistency with other cloud susceptibilities. A discussion regarding this concern has been incorporated into the methodology section.

“Due to the highly variable nature of CF, variation in the 0.25° CF may result from quantifying edges or centers of the same cloud layer instead of from N_d perturbations. To test the influence of cloud geometry on the retrieved CF susceptibility, we removed any $1^\circ \times 1^\circ$ grid box with variation in the 0.25° CF greater than 0.9 while the variation in the $0.25^\circ N_d$ less than 60 cm^{-3} , and 0.25° CF in the 1° box sample the same cloud. A total of 17,000 scenes were removed, which accounts for $\sim 24\%$ of the total samples. Removing these scenes does not change the conclusions of CF susceptibility in this study (not shown), which demonstrates that cloud geometry has minimal impact on the retrieved CF susceptibility.” (Lines 215-221)

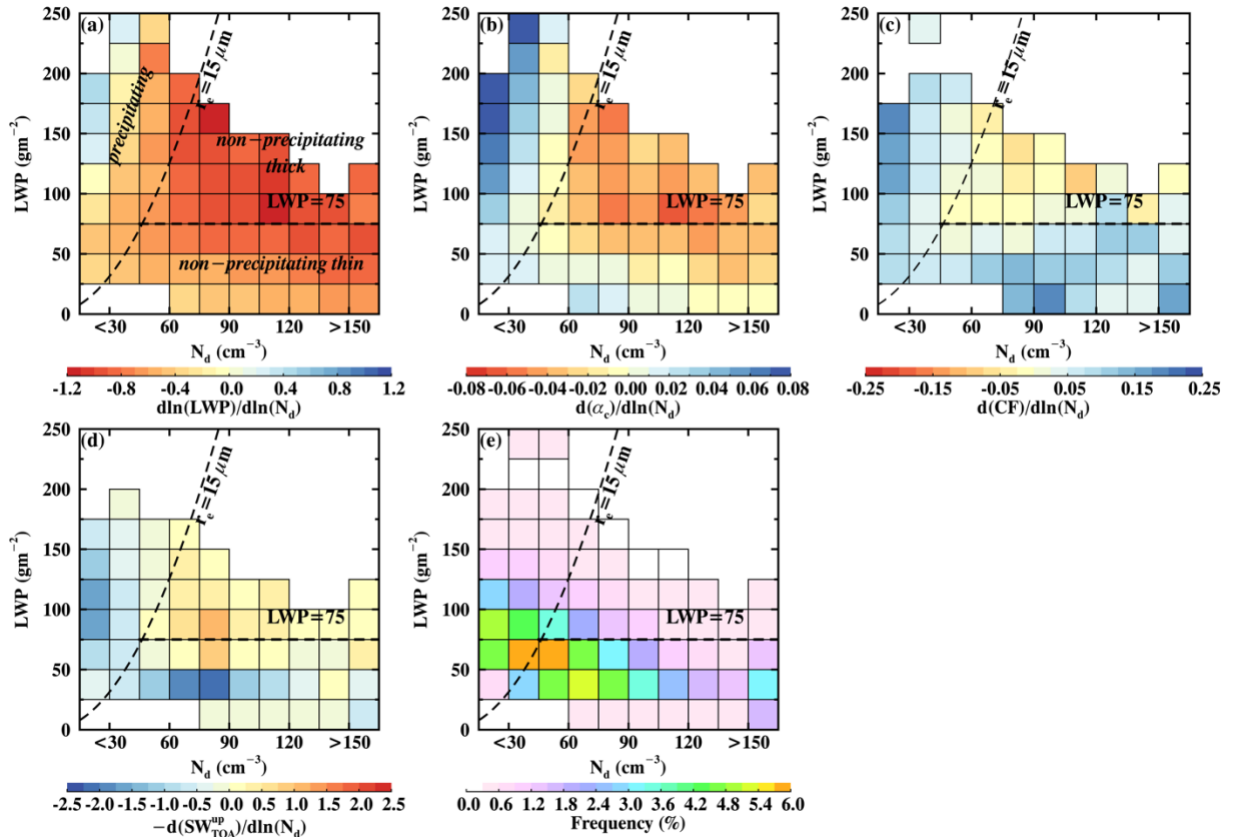


Figure R1. Same as Figure 2, but excluding scenes with large variation in 0.25° CF and small variation in $0.25^\circ N_d$.

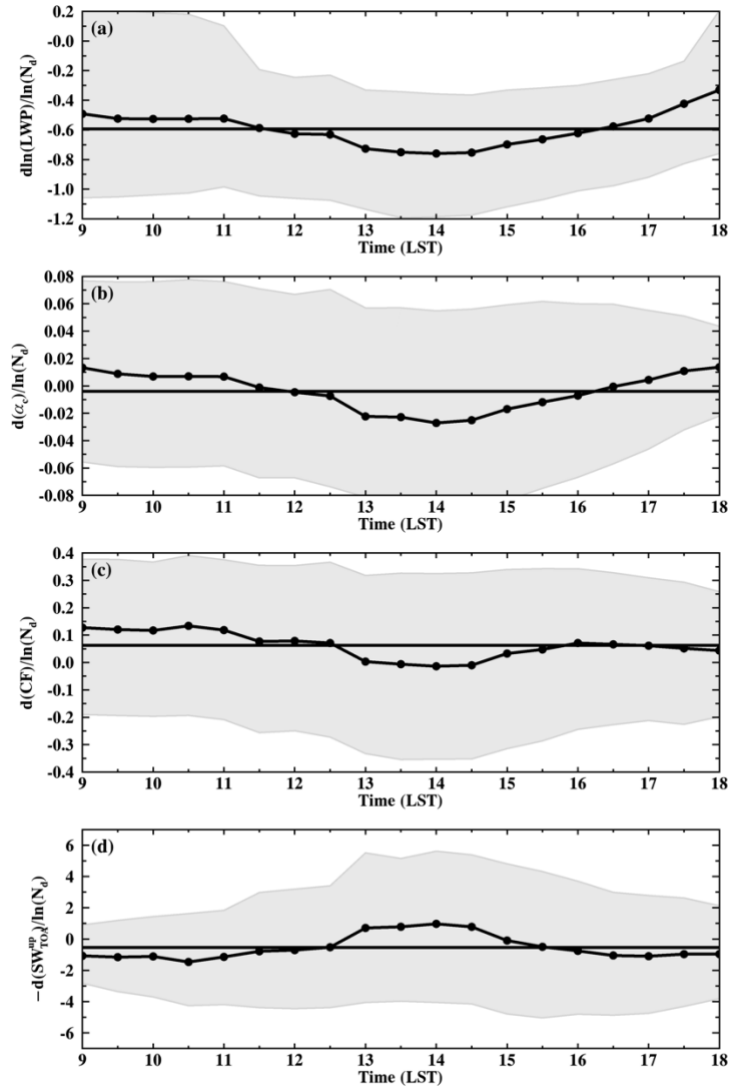


Figure R2. Same as Figure 3, but excluding scenes with large variation in 0.25° CF and small variation in $0.25^\circ N_d$.

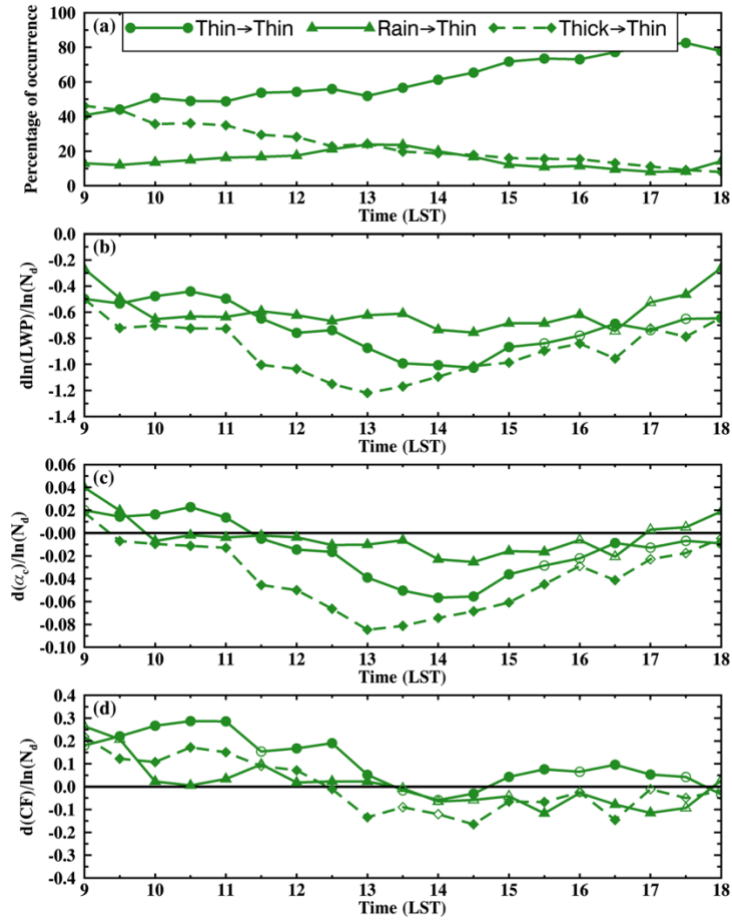


Figure R3. Same as Figure 5, but excluding scenes with large variation in 0.25° CF and small variation in $0.25^\circ N_d$.

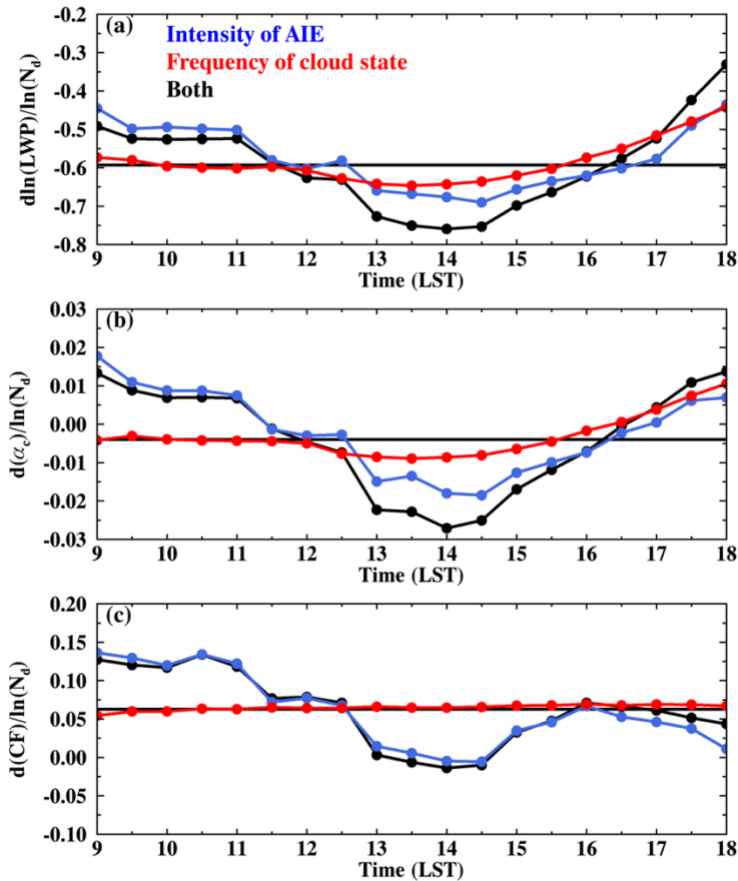


Figure R4. Same as Figure 11, but excluding scenes with large variation in 0.25° CF and small variation in $0.25^\circ N_d$.

b. On lines 335-336, the readers are directed to the next section for explanations on the CF susceptibility pattern seen in Fig. 2c. In the next section, your discussion and hypotheses testing are targeted at CF susceptibility evolutions, while I'm still missing an explanation for the non-precip thin cloud that exhibit potentials in cloud fraction enhancement.

As we explained in response to a relevant comment from Reviewer #1, increases in aerosol decrease cloud drop size and increase cloud drop number concentration near cloud top, which enhance the cloud top radiative cooling rate and the entrainment rate. The enhanced radiative cooling and entrainment induce downdraft and mixing from cloud top (e.g., Xue and Feingold, 2006). These factors contribute to destabilize the boundary layer and facilitate moisture transport from the ocean surface to clouds, thus enhance new cloud formation and extend cloud lifetime (e.g., Christensen et al. 2020). This hypothesis is consistent with and supported by the relative low CF for these clouds (Fig. S2a) and the diurnal variation in LWP susceptibility for non-precipitating thin clouds (Figure 4c). In the morning, the boundary layer is typically shallower and well-mixed with clouds coupled to the surface. Therefore, the CF susceptibility for thin clouds is large positive in the morning, and gradually decreases from morning to noon. However, the near zero CF susceptibility in the afternoon is not supported by this hypothesis. Further analyses and model simulations are needed to better understand the diurnal evolution of aerosols' impact on entrainment rate, boundary layer state, cloud cover and

lifetime to explain the observed daytime variation of CF susceptibility for non-precipitating thin clouds. The opposite signs observed in LWP and CF susceptibility suggest that the aerosol indirect effect likely redistributes cloud water horizontally, causing clouds to thin and widen. A related discussion has been added to Figure 2 on the daytime mean CF susceptibility and to Figure 5 on the daytime variation of CF susceptibility.

“A possible explanation for the increased CF is the enhanced cloud top radiative cooling rate from aerosol perturbations help to mix the boundary layer, facilitate moisture transport from the ocean surface to cloud, and therefore favor new cloud formation and extend cloud lifetime (e.g., Christensen et al. 2020). This hypothesis is consistent with and supported by the relative low CF for these clouds (Fig. S2a) and the diurnal variation in LWP susceptibility for non-precipitating thin clouds, which will be discussed in the next section. The opposite signs of LWP and CF susceptibilities indicate that the AIE might redistribute cloud water horizontally and make the thin clouds thinner and wider.” (Lines 406-411).

“Another possible explanation on the evolution of CF susceptibility is the influence of aerosols on boundary layer mixing and the evolution of boundary layer from morning to noon. The enhanced entrainment rate and radiative cooling rate from N_d perturbations help to destabilize the boundary layer and transport moisture from the ocean surface to clouds, which facilitate new cloud formation. As the boundary layer is typically well mixed in the morning with clouds coupled to the surface, this impact is strongest in the morning and gradually decrease from morning to noon. In the afternoon, on the other hand, thin clouds transition from all three states have near-zero CF responses to N_d perturbations, which cannot be explained by the hypothesis above. Further analyses and model simulations are needed to better understand the diurnal evolution of aerosols’ impact on entrainment rate, boundary layer state, cloud cover and lifetime to explain the observed daytime variation of CF susceptibility for non-precipitating thin clouds.” (Lines 551-560)

c. Fig. 11 is another example that I am having difficult times wrapping my head around. While Fig. 11a and b suggest that the frequency of occurrence of cloud state in the LWP- N_d space is indeed changing throughout the day, the null contribution from shown in Fig. 11c troubles me a bit. I guess it’s related to the pattern we see in Fig. 2c, which I still struggle to decipher.

In Figure 11, red lines represent the daytime variation contributed from the occurrence frequency of different cloud states (estimated by weighting the daytime mean cloud susceptibility with the half-hourly frequency of occurrence of clouds in the LWP- N_d parameter space), while blue lines represent the contribution from the cloud susceptibilities for different cloud states (estimated by weighting the half-hourly cloud susceptibility in the LWP- N_d parameter space with the daytime mean frequency of occurrence of clouds). As seen in Figure 6, the daytime variation in the occurrence frequency of non-precipitating thick clouds is minimal, so that red lines in Figure 11 are mainly contributed from variations in the occurrence frequency of precipitating and non-precipitating thin clouds. As shown in Figure 2, non-precipitating thin clouds are more susceptible than precipitating clouds in LWP, with daytime mean LWP susceptibilities of -0.7 vs. -0.4. Meanwhile, the occurrence frequency of non-precipitating thin clouds reaches a daily maximum in the afternoon and a daily minimum in the evening, while the occurrence frequency of precipitating clouds is highest in the evening (Figures 4 and 9). Therefore, the red line in Figure 11a is most negative in the afternoon and less negative in the evening. The same pattern is observed for albedo susceptibility in Figure 11b. On the other hand,

the daytime mean CF susceptibility for non-precipitating thin clouds and precipitating clouds are very similar at 0.08 and 0.09, respectively (Figure 2c). Therefore, contributions from the changes in occurrence frequency are muted by the similar CF susceptibilities of these two clouds in Figure 11c.

2: Regarding the explanation for the “U-shape” evolutions, it seems a bit suspicious to me that all 3 quantities show the same shape of evolution. Moreover, you use cloud transition categories to explain the observed U-shape evolution, yet you see the similar “U-shape” for individual categories, suggesting to me that there are something fundamental that has not been teased out. This makes wonder if this is due to retrieval artifacts associated with relatively high solar zenith angle during early morning and late afternoon? Smally and Lebsock (2023) made a comparison between retrieved LWP from tau & re using adiabatic assumption with microwave imager retrieved LWP, onboard geostationary satellites. They found non-negligible bias even at intermediate SZA. The same bias applies for Nd retrievals as well, in a more pronounced way I suppose, given the high order dependence of Nd calculation on re. I wonder if this “U-shape” evolution can be explained by tau & re retrieval biases as a function of SZA. To me, even small biases can produce the trend you see towards higher SZAs (i.e. towards early morning and late afternoon). I suppose one can play with some synthetic data to rule this possibility out.

Thank you for this very good question. In the study by Smally and Lebsock (2023), it was found that the ABI retrieved LWP from GOES-16 and GOES-17 has larger uncertainty at solar zenith angle (SZA) > 60-65° and viewing zenith angle (VZA) > 65°. The VZA at Azores is ~50°, which is below the VZA threshold found in Smally and Lebsock (2023). To minimize the retrieval uncertainty in r_e , τ , and N_d , we carefully screened the pixel-level Meteosat retrieval with $r_e > 3\mu m$, $\tau > 3$, $SZA < 65^\circ$, and further removed cloudy pixels at the cloud edge.

To demonstrate that the observed “U-shaped” diurnal variation of cloud susceptibilities is unlikely due to the systematic bias of r_e and τ retrievals at large SZA, we testify from the following two aspects with additional analyses.

Firstly, if the daytime variation is driven by retrieval bias at large SZA, we would expect the susceptibility exhibiting a symmetric pattern at local noon. However, as seen in Figure R5 (same as Figures 4, 6, 9 in the paper but with three cloud states combined), only the non-precipitating thin clouds show symmetric patterns in LWP and albedo susceptibilities. The LWP susceptibilities for precipitating clouds and non-precipitating thick clouds, as well as the CF susceptibilities for all three cloud states exhibit asymmetric pattern at local noon.

Secondly, we did a sensitivity test focusing on overcast clouds only, with the mean cloud fraction in the $1^\circ \times 1^\circ$ scenes larger than 0.9. At large SZA, the uncertainty of the Meteosat cloud microphysics retrievals should be smaller for stratiform clouds compare to cumulus clouds due to the plane-parallel assumption and cloud 3-D effect. Therefore, if the daytime variation in cloud susceptibilities is driven by the retrieval bias, we would expect less daytime variation in cloud susceptibilities for overcast clouds, especially in the early morning and in the evening. Contrary to this expectation, as shown in Figure R6, overcast clouds exhibit stronger and asymmetric daytime variation of LWP and albedo susceptibilities than that for all the boundary-layer clouds shown in Figure 3. For example, the magnitude of change in LWP susceptibility for overcast clouds is 1.0 compared to 0.4 for all clouds.

Based on these two arguments, the observed “U-shaped” diurnal variation of cloud susceptibilities is unlikely due to the systematic bias in r_e and τ retrievals at large SZA. We added the following discussion to the paper regarding to this comment: “In addition, the

asymmetric evolution patterns of LWP, α_c , and CF susceptibility for non-precipitating thick and precipitating clouds indicate that the daytime variation of cloud susceptibility is not due to retrieval uncertainties related to SZA. To minimize the possible retrieval uncertainties related to large SZA, all Meteosat pixel-level cloud retrievals are filtered with $SZA < 65^\circ$.” (Lines 701-704)

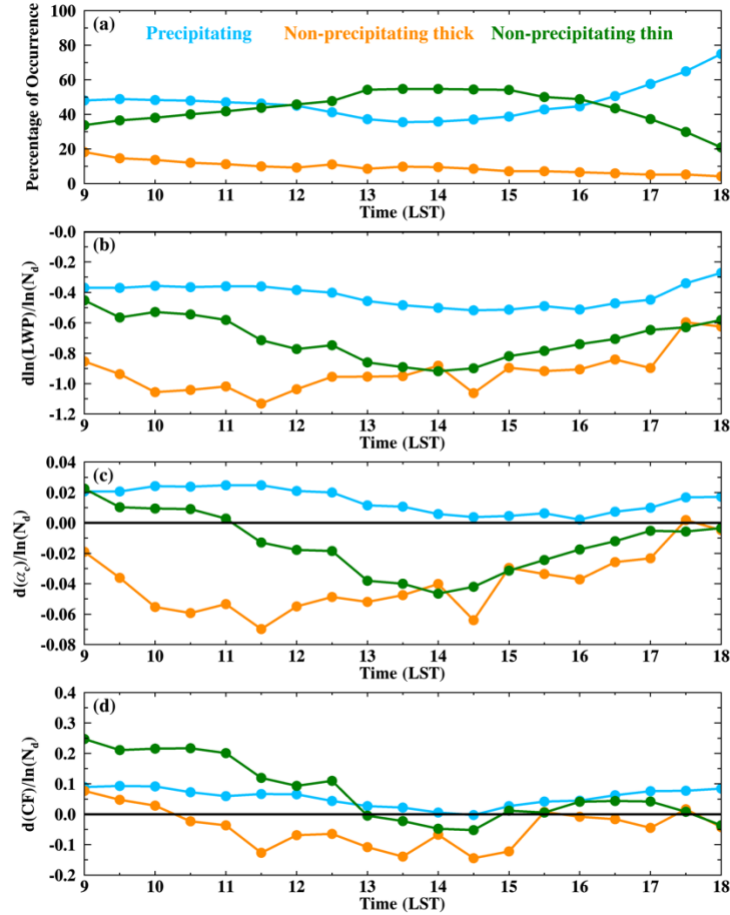


Figure R5: Daytime variation of cloud susceptibilities for three cloud states. (a) percentage of occurrence of different cloud states, (b) cloud LWP susceptibility ($d\ln(LWP)/d\ln(N_d)$), (c) cloud albedo susceptibility ($d\alpha_c/d\ln(N_d)$), and (d) cloud fraction susceptibility ($dCF/d\ln(N_d)$) for non-precipitating thin clouds. The blue lines are for precipitating clouds, the orange lines are for non-precipitating thick clouds, and the green lines are for non-precipitating thin clouds.

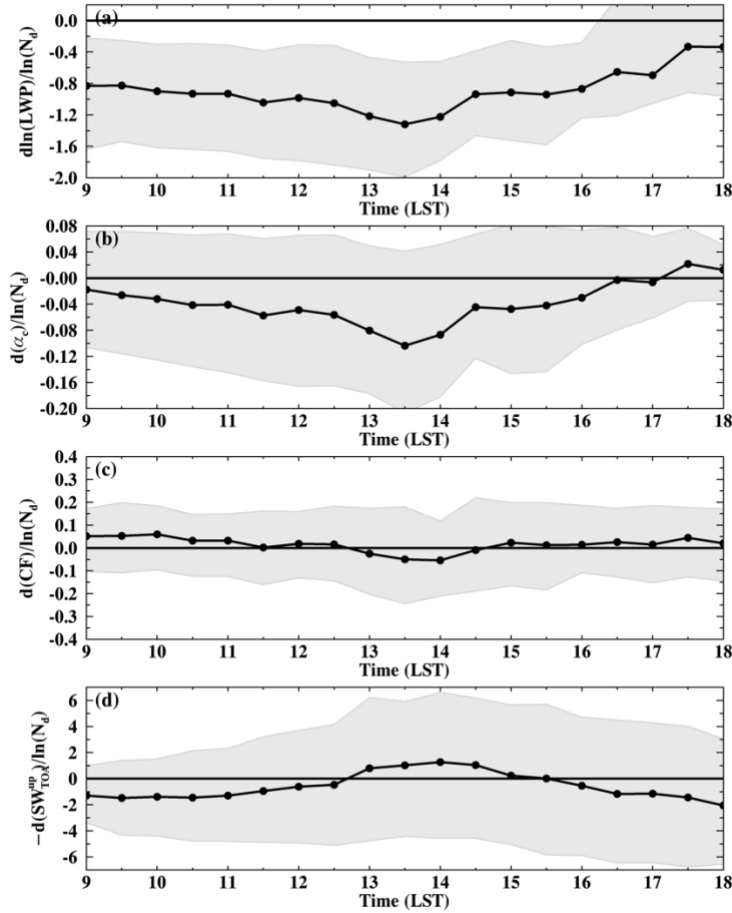


Figure R6. Same as Figure 3, but for overcast clouds with the $1^\circ \times 1^\circ$ mean cloud fraction larger than 0.9.

3. Assuming daytime evolution in cloud susceptibility is not SZA-dependent for now, an alternative explanation for the “U-shape” evolution is the change in meteorology, i.e., daytime evolution in boundary layer (BL) depth. From morning to early afternoon, BL deepens and becomes decoupled, enhancing the role of entrainment feedback in governing cloud susceptibility. In the afternoon, BL re-couples. This could possibly give you the “U-shape” evolution in cloud susceptibility. I wonder if the authors have considered this as an alternative explanation and tested it?

Thank you for providing this valuable aspect on the potential mechanism behind the “U-shape” evolution of cloud susceptibilities. To explore the influence of the boundary layer state on cloud susceptibilities, we tested using the Meteosat retrieved cloud top height and cloud base height as indicators of boundary layer depth and coupling states over the ENA region. As shown in Figures R7 and R8, the Meteosat-retrieved cloud top height and base height reach the daytime minimum between 14-16 LST, raises in the late afternoon and reaches the daytime maximum in the evening.

Therefore, the Meteosat retrieved cloud top or cloud base height likely cannot represent the boundary layer depth or cloud coupling state in the ENA region in summer. Unfortunately, there is no better indicator of cloud coupling state from the Meteosat retrievals for us to test the

influence of cloud coupling to sea surface on cloud susceptibilities. Consequently, we added a discussion on the daytime evolution of boundary layer to explain the evolution of cloud susceptibility in the paper.

“In the early morning (e.g., 9-10 LST), with higher frequency of occurrence of thick clouds transition to thin clouds, the LWP susceptibility for the thick-to-thin category is less negative compared to later time (dash line with diamond symbols in Figures 5a, b). This is likely due to the less negative LWP susceptibility for non-precipitating thick clouds in earlier time (e.g., 7-9 LST, not shown), which is because boundary layer clouds are coupled to the sea surface at night and in the early morning transporting moisture from ocean to clouds and compensate the moisture loss from aerosol enhanced entrainment (e.g., Sandu et al., 2008).” (Lines 536-541).

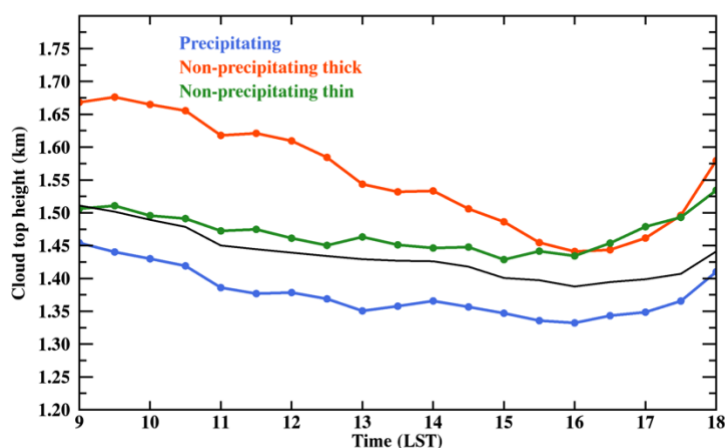


Figure R7. Daytime variation of the Meteosat retrieved cloud top height for different cloud states. The blue line is for precipitating clouds, the orange line is for non-precipitating thick clouds, the green line is for non-precipitating thin clouds, and the black line is for all warm boundary layer clouds.

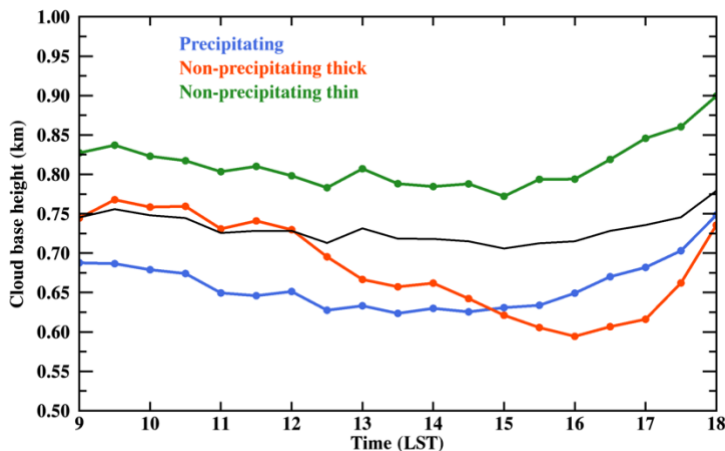


Figure R8. Same as Fig. R7, but for Meteosat retrieved cloud base height.

4. Regarding the “memory” hypothesis, I have to say that I’m quite lost in this argument, by the design of the analysis, by the inconsistency that I spotted when reasoning with this argument, and by the actual physical meaning of “memory” in the context of cloud susceptibility.

a. Fundamentally, the concept of “memory” requires a Lagrangian perspective, however, I believe all the analyses done in this study are based on a Eulerian framework. This means that the “memory” in this study is actually the domain “memory” of the clouds that were previously present in the domain, not cloud “memory” of its past states. I believe one needs to at least do a grid-box tracking, if not individual cloud tracking, to support this argument, or show that clouds are stationary/semi-stationary in the study region.

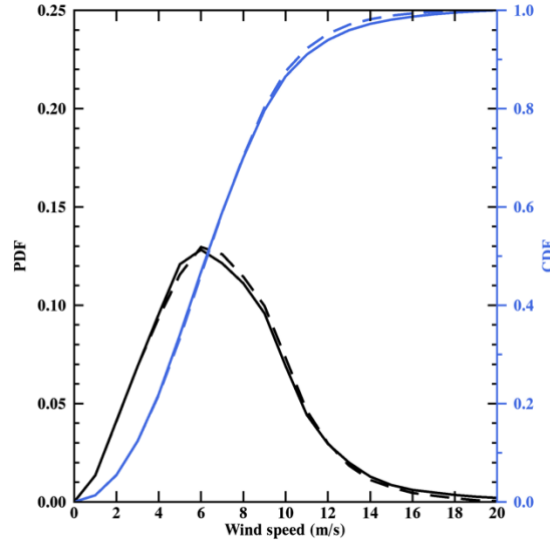


Figure R9: Probability density function (PDF, black lines) and cumulative density function (CDF, blue lines) of the 1000 to 900 hPa mean wind speed (solid lines) and the wind speed at 1000 hPa (dash lines) from the ERA5 reanalysis during the study period (July, 2018-2021).

Thank you for this constructive comment. We assessed the low-level main flow in the study region during the study period. The mean wind speed for each $1^\circ \times 1^\circ$ grid box is averaged from the 0.25-degree ERA5 data based on the central longitude and latitude of each box, and the PDF and CDF of the PBL mean wind speed for all the grid boxes in the study domain during the study period is shown in Figure R9. During the summer in the study region, low wind conditions prevail in the boundary layer, with the mean wind speed being less than 10m/s for 85% of the time and less than 7m/s for 60% of the time. Since the cloud state used in this study is defined using the mean effective radius and liquid water path for each $1^\circ \times 1^\circ$ grid box, clouds with mean wind speed weaker than 7m/s (60% of data) move less than 50 km within the two-hour tracking period, thus the cloud state still captures the majority of the original clouds within the same grid box.

To support our hypothesis that the evolution of cloud susceptibility is contributed by the transition of cloud state combined with cloud memory, instead of changing of cloud state from advection, we reproduce Figure 5, 7, 9 in the paper under low wind speed conditions (wind speed $< 7\text{m/s}$); results for non-precipitating thin clouds are shown in Figure R10. As seen in Figure R10a, the occurrence frequency of non-precipitating thin clouds transition from other three cloud states during low wind speed days exhibit similar values and daytime variation as under all wind

conditions. Additionally, under low wind speed conditions, non-precipitating thin clouds transitioned from thick clouds previously exhibit consistent more negative LWP and albedo susceptibilities than thin clouds remained thin (Figure R10b, c). Difference between the two transition groups under low wind speed conditions is slightly larger than that under all wind speed conditions.

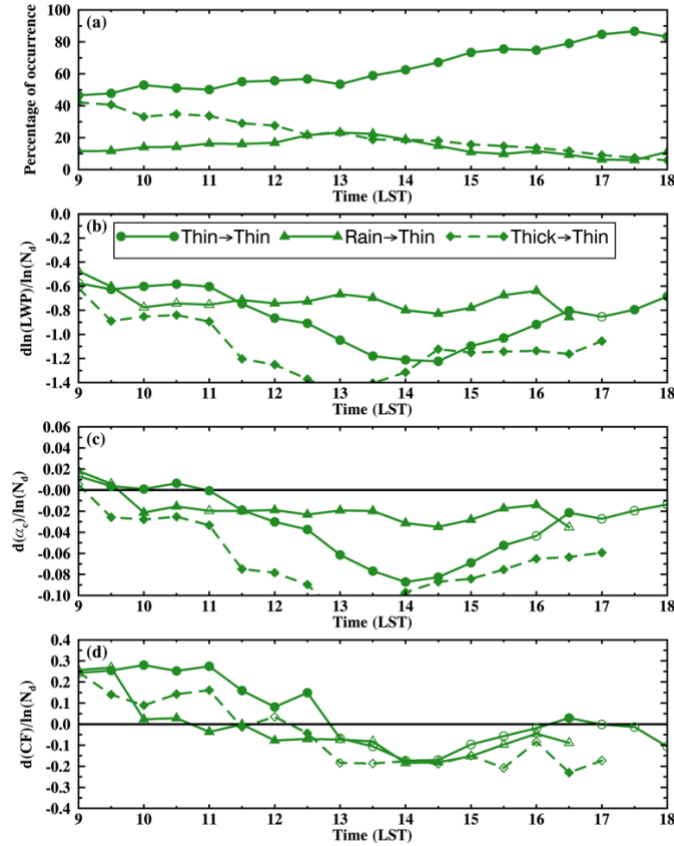


Figure R10. Daytime variation of non-precipitating thin clouds transition from non-precipitating thin clouds (thin \rightarrow thin, solid line with circle symbols), precipitating clouds (rain \rightarrow thin, solid line with triangle symbols), and non-precipitating thick clouds (thick \rightarrow thin, dash line with diamond symbols) in previous two hours with PBL mean wind speed less than 7m/s. Symbols for different state transitions are noted in (b). In (b)-(d), filled markers indicate data points that are significantly different from the other two groups ($p < 0.05$), while open markers indicate statistical insignificance.

In summary, clouds are mostly stationary in the study period and changes in cloud states in a fixed grid-box likely represent the transition of cloud state as well as its impact on cloud susceptibility from the transition. We have revised the manuscript and added a discussion on the credibility of our tracking method to the methodology section and to Fig. 5 as follow.

“To investigate the dependences of AIE on previous cloud states and quantify the influence of cloud memory on the estimated cloud susceptibility, we track the historical cloud state over a $1^\circ \times 1^\circ$ grid box for a two-hour period. During the summer in the study region, low wind conditions prevail in the boundary layer, with the mean wind speed being less than 10m/s for

85% of the time and less than 7m/s for 60% of the time (not shown). Therefore, in most cases, less than half of the clouds exit the grid box within the two hours, allowing us to track the previous cloud state within the same grid box. The influence of cloud memory is assessed by comparing the cloud susceptibilities of clouds that undergo a transition in cloud state with those that do not experience such a transition. Section 3.4 includes more details and discussions on the sensitivity of tracking time and the influence of advection on our classification.” (Lines 256-264)

“To further isolate the influence of cloud advection from the tracked transition of cloud state and cloud susceptibilities, we focus on low wind conditions with wind speed less than 7m/s when clouds are stationary during the two-hour period (60% of time). The influence of cloud state transition on cloud susceptibility is stronger with larger differences in LWP and α_c susceptibilities between clouds experienced transition in cloud state with clouds did not (not shown). Therefore, our tracking method can capture the signal of cloud state transition and its impact on cloud susceptibilities during summer in this study region.” (Lines 570-576)

b. One example of the inconsistency that I observed is that in Fig. 5, if I follow the argument correctly, thick→thin transition will lead to more negative LWP susceptibility based on the LWP-Nd plot, however, at early morning where thick→thin is the most frequently occurring type, the overall LWP susceptibility is the highest (Fig. 4b). Furthermore, how do you explain the “U-shape” in the evolution that is specific to thick→thin transition clouds, they all have the same type of “memory” according to your argument.

Based on our hypothesis, the current cloud susceptibility is influenced by both the cloud state and the cloud susceptibility at the previous time. For example, the susceptibility of thin clouds transitioning from thick clouds at 9LST depends on the susceptibility of the original thick clouds in the preceding hours. As seen in Figure R11, thick clouds are less susceptible in the early morning (7-9 LST), resulting in a less negative susceptibility for the thick→thin clouds at later time (dash line with diamond symbols in Figure 5b in the paper), even though such transitions are most frequent in the morning.

Not only the thick→thin cloud category, but also the thin→thin, the thin→thick, and the thick→thick categories exhibit “U-shaped” evolution. For example, the thin→thin cloud category exhibit a less negative LWP susceptibility from 9-11LST and it decreases to more negative from 11-14 LST (a “U-shaped” daytime evolution), which is consistent with the diurnal variation for non-precipitating thin clouds from 7-12 LST shown in Figure R11. The thin→thick cloud category exhibits a similar less negative LWP susceptibility from 9-11 LST, and it decreases to more negative from 11-14 LST (Figure 7b). The LWP susceptibility for the thick→thick cloud category decreases from around -0.8 at 9LST to -1.3 at noon (Figure 7b). The only cloud transition category that cannot be explained by our hypothesis is the rain→thick, where the LWP susceptibility is more negative in early morning. The following discussion has been added to Fig. 5 for clarity.

“In the early morning (e.g., 9-10 LST), with higher frequency of occurrence of thick clouds transition to thin clouds, the LWP susceptibility for the thick-to-thin category is less negative compared to later time (dash line with diamond symbols in Figures 5a, b). This is likely due to the less negative LWP susceptibility for non-precipitating thick clouds in earlier time (e.g., 7-9 LST, not shown), which is because boundary layer clouds are coupled to the sea surface at night and in the early morning transporting moisture from ocean to clouds and compensate the moisture loss from aerosol enhanced entrainment (e.g., Sandu et al., 2008).

Similarly, as shown in Figure 5b, differences between the thin-to-thin and thick-to-thin categories are less pronounced in the afternoon when the LWP susceptibilities of thin and thick clouds are close to each other (Figures 4b and 6b).” (Lines 535-542).

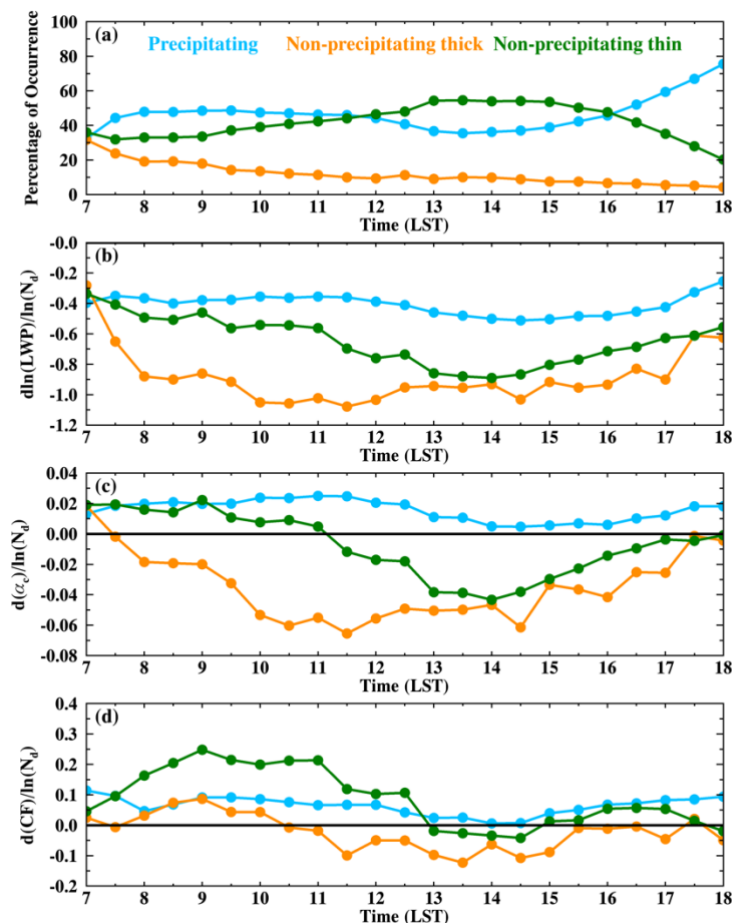


Figure R11. Same as Figure R5, except from 7 to 18 LST. Daytime variation of cloud susceptibilities for different cloud states. (a) Percentage of occurrence of different cloud states, (b) cloud LWP susceptibility ($d\ln(LWP)/d\ln(N_d)$), (c) cloud albedo susceptibility ($d\alpha_c/d\ln(N_d)$), and (d) cloud fraction susceptibility ($dCF/d\ln(N_d)$). Different colors represent different cloud states: blue for precipitating clouds, orange for non-precipitating thick clouds, and green for non-precipitating thin clouds.

c. I wonder at what timescale do you expect these clouds to detach/decorrelate from their “memory” of past states? Existing literature seems to suggest a decorrelation timescale that is much shorter than your 2-hr window, on the order of 10 to 15 mins, for marine boundary layer clouds. I wonder if you could elaborate on how does this decorrelation timescale fit in your 2-hr “memory” hypothesis?

Our hypothesis, suggesting that clouds retain the memory of ACI from their previous states, is primarily based on the timescale of cloud responses to aerosol and N_d perturbations. We believe this timescale is a different concept compared to the detachment timescale mentioned by the reviewer. For a single cloud object, its timescale is on the order of 10 to 15 mins. For cloud

systems, the decorrelation, formation, and development timescale for the system is on the order of ~20 hours for cloud fraction, and ~15 hours for cloud LWP (e.g., Eastman et al., 2016; Christensen et al., 2020). In our study, we are interested in the mean cloud state for a $1^\circ \times 1^\circ$ grid box, and the two-hour tracking window is much shorter than the timescale of the system. Additionally, for the timescale of cloud response to N_d perturbation, previous numerical simulations and satellite observations found that the LWP response is time sensitive, and its sensitivity increases with time. The LWP response takes ~4-5 hours to manifest and ~20 hours to reach the equilibrium for both precipitating (e.g., Gryspreedt et al., 2021) and non-precipitating clouds (e.g., Gryspreedt et al., 2021; Glassmier et al., 2021). Since the N_d -LWP sensitivity takes time to reach an equilibrium, we hypothesize that if the clouds undergo a state change during this time, it retains the LWP responses of its previous state.

d. I'm familiar with the concept that cloud have "memory" of their near-past state, in which clouds carry-over their past tendencies for a short period of time. However, I am afraid that I don't quite follow the argument that clouds have a "memory" of its past 'susceptibility.' I wonder if you could elaborate more on the physical mechanism of it. I believe the schematic (Fig. 8) you shown refers to the concept I mentioned, such that stronger evaporation & entrainment are carried over if the cloud just transitioned from thick to thin. It speaks to the temporal evolution of clouds, but how does this work for a "memory" of susceptibility, which is essentially a spatial regression, is less clear to me.

Thank you for raising this insightful question. The LWP susceptibility, which is a measure of rate of change in LWP with increasing N_d , is mainly driven by evaporation rate and entrainment rate at cloud top. The possible physical processes and mechanisms for clouds sustaining the memory of its LWP susceptibility is that: for an initially thick clouds with large LWP, the larger cloud top radiative cooling rate will result in a larger entrainment rate and evaporation rate near cloud top. The increased evaporative cooling from higher evaporation rate further enhances entrainment rate. The larger cloud top radiative cooling and entrainment rate also induce downdraft and mixing from cloud top, which in turn enhance entrainment rate. All of the above factors form a positive feedback loop and set up an environment favor for stronger entrainment and evaporation. These feedback and environment will not change immediately even when the cloud LWP decrease and cloud transition to a thin state. This hypothesis is supported by model simulation where they found the maximum cloud top radiative cooling rate is more related to cloud LWP and the enhanced evaporation rate from increasing aerosols is driven by the cloud top radiative cooling rate rather than by the faster evaporation from smaller droplets (Williams and Igel, 2021). Regarding the comment on the calculated susceptibility is the spatial regression of the N_d -LWP relationship, I think this quantification is based on the hypothesis that the temporal change in LWP from N_d perturbations can be represented by the spatial correlation.

Minor comments:

- *Line 36-37, 600, 669-671, the authors made the point that susceptibility derived from polar-orbiting satellites, Aqua in particular, underestimates the daily mean value of cloud susceptibly. While this is true based on the findings from this study, I would like to raise the point that this underestimation does not necessarily translate into an underestimation of the actual cloud response, as the simple arithmetic mean of susceptibility ('local derivatives') is*

not the same as a time integral of cloud responses, which is more relevant to the scaling up of radiative effects of ACI.

Thank you for the clarification. We agree that our method estimate the cloud susceptibility instead of the integrated cloud responses over time. In all these places, we carefully used the words of estimated cloud susceptibility instead of cloud responses. We added the following discussion to section 5. “Notice that both the daytime variation and the daytime mean values of cloud susceptibilities in this study are estimated based on the regression analysis on spatial data within each satellite time step with the assumption that the temporal change of cloud properties from N_d perturbations can be represented by the spatial relationships.” (Lines 814-817).

- *Line 48, I guess you need more reference here than just Albrecht 1989, as it only speaks to the precip-suppression effect.*

We added more references here: e.g., Albrecht, 1989; Xue and Feingold, 2006; Chen et al., 2014; Gryspeerd et al., 2019.

- *Line 109, note that Gryspeerd et al. (2021) did not use geostationary satellite but rather polar-orbiting satellites, i.e., Terra and Aqua.*

This sentence and paragraph have been modified. Thanks.

“Observational and modeling studies have shown that aerosol-cloud interaction processes take hours to reach the equilibrium state and the sensitivity of AIE is time dependent. For instance, Glassmeier et al. (2021) used a Gaussian-process emulation and derived the adjustment equilibration timescale for LWP to be ~ 20 hours. By tracking the ship tracks in satellite observations, Gryspeerd et al. (2021) found a similar timescale of AIE of ~ 20 hours or longer and the magnitude of LWP susceptibility increases with time. In addition, Christensen et al. (2020) discovered that influence of aerosols on cloud LWP, CF, and cloud top height persists two to three days by tracking cloud systems in satellite observations. To conclude, the sensitivity of cloud responses to N_d perturbations changes with time, the assumption that AIE has no memory of its past state likely fails.” (Lines 118-126)

- *Line 114, I thought you did not “track” any cloud or cloud field and used with the Eulerian framework, I would be more precise here to avoid confusion.*

Changed.

- *Line 137, reference for LWP calculation formular?*

Added reference here (Minnis et al. 2011, 2020).

- *Line 155, cw is a function of pressure as well.*

Modified.

- *Line 172-173, did you average tau and re first and then calculate Nd or calculate Nd first then average? This difference can induce huge bias in albedo susceptibility quantification as shown in Feingold et al. (2022, ACP).*

Thank you for the clarification and the reference. In this study, we first calculated the pixel-level N_d based on pixel-level r_e and τ using Eq. (1), then all the pixel-level cloud retrievals are averaged to 0.25-degree to smooth out noise and uncertainties from homogeneity and spatial covariation. Our averaging method is consistent with the recommendation in Feingold et al. (2022). We have modified these lines in the method section.

“As found by Arola et al. (2022) and Zhou and Feingold (2023), the retrieved cloud susceptibilities are sensitive to small-scale cloud heterogeneity, the co-variability between cloud properties and N_d , and the spatial scale of cloud organization. To reduce the biases resulting from heterogeneity and co-variability, we first average the 3-km pixel-level cloud

retrievals to a regular $0.25^\circ \times 0.25^\circ$ grid for each half-hourly time step. As suggested by Feingold et al (2022), N_d retrieval was performed at pixel-level using Eq. (1), and then averaged to a 0.25° resolution.” (Lines 194-198).

- *Line 175, note Zhou et al. (2021) used 2x2 grid box, if I recall correctly, worth double checking.*

Yes, you are right. They used a $2^\circ \times 2^\circ$ grid box. The reference has been modified.

- *Line 187, why cloudy pixels at cloud edge are set as clear?*

At cloud edge, the adiabatic assumption for the N_d retrieval is more likely to fail so that the retrieved N_d suffers larger uncertainty. As the N_d for cloudy pixels at cloud edge are removed, the CF is set as clear for those pixels for consistency in CF susceptibility. Similarly, LWP is set as NAN for those pixels.

- *Line 218-219, why you opt for a Eulerian framework here? Isn't a Lagrangian framework the appropriate choice here as you want to investigate cloud "memory"?*

As discussed in a previous comment, our analyses indicate that boundary layer clouds are mostly stationary in the study region. To assess the potential influence of cloud advection on our results, we specifically examined low wind speed conditions. Based on results shown in Figures R9 and R10, the Eulerian framework can effectively capture the signal of cloud state transition as well as its impact on cloud susceptibilities. Relevant revisions have been made here and later in Fig. 5 in the paper.

- *Line 254, what do you mean by "witnessed by clouds"?*

This sentence has been modified. “The absence of a precipitation suppression signal is likely attributed to the relatively modest precipitation occurred in this region during summer (e.g., Wu et al., 2020; Zheng and Miller, 2022), where the effect of precipitation suppression is minimal and the entrainment drying effect dominates.” (Lines 296-297).

- *Line 266, I wouldn't use "hypothesis" here as these entrainment feedback mechanisms have been previously established, using large-eddy simulations.*

Changed.

- *Line 280-281, what do you mean by "meteorological influences on clouds likely dampen the signal of the AIE..." I feel like you try to say meteorological confounding tends to obscure the AIE signal, probably need to rephrase here.*

Changed accordingly. Thanks for the suggestion.

- *Line 352-353, I don't think you have diurnal cycles, only daytime, right?*

Yes, we changed the term “diurnal” to “daytime” throughout the paper.

- *Fig. 3c, the day-to-day (or spatial variation within the 10 by 10 box) variation is huge, at a given time of the day, is it possible to tell the sign of CF susceptibility with statistical significance?*

The switch in sign for albedo susceptibility is statistically significant at a 95% confidence level based on a student's t-test. However, the switch in sign for CF susceptibility is not. We add discussion on the significance of sign of CF and albedo susceptibilities. “The switch in sign for albedo susceptibility is statistically significant at a 95% confidence level, while the switch in sign for CF susceptibility is not statistically significant.” (Lines 450-451).

- *Line 439-440 (Figure 5b), I don't follow this argument, your susceptibility for each individual transition group shouldn't be affect by their relative frequency of occurrence at a given time, if I understand your method correctly, then why fewer samples in the thick/precip→thin groups lead to less difference between the groups?*

Agree. The original sentence was not accurate enough. The difference between the rain->thin and other two groups are still pronounced and significant in the local afternoon. However, the difference between the thin->thin and thick->thin category is not significant in the afternoon, which is likely due to the similar LWP susceptibilities for thin and thick clouds as shown in Figure R10b. This sentence has been deleted.

- *Line 454-456, again, why not using Lagrangian tracking in this assessment?*

Please refer to the previous response.

- *Table. 1, I wonder if there are more effective ways of illustrating hypotheses than showing them in a table, the current structure of the table is quite difficult to decipher, at least for me. In particular the N/A boxes confuse me, and I don't see discussion of them in the main text.*

We have changed the layout of Table 1. The new table is inserted at Line 475.

- *Line 478-481, these arguments are vague, if your "memory" argument stands, shouldn't we see a lagged evolution in thin clouds compared to thick clouds, instead of similar evolution?*

Agree, the original sentence was not accurate enough. We checked the lagged correlation between cloud susceptibilities of thick clouds and cloud susceptibilities for thin clouds transitioned from thick. For all three cloud variables, the lagged correlations reach the maximum of ~ 0.75 at the fourth time step, which equals two hours. This sentence has been modified to add the lagged effect.

- *Line 488, why this is particularly prominent in the morning, I could not think of a reason following your "memory" argument.*

Agree. Similar as the previous response, the difference between the two categories is likely contributed by the evolution of LWP susceptibilities for the thin and thick clouds during the day, rather than by variations in sample numbers. This sentence has been modified as follow: "These differences are particularly prominent from late morning to noon and become not significant in the afternoon. As discussed before, difference between the thick-to-thick and the thin-to-thick categories are due to the LWP susceptibilities for thick and thin clouds of previous time, while the smaller differences in the early morning and afternoon could be attributed to cloud coupling states at these times." (Lines 606-610)

- *Line 567, worth repeating the question here.*

Done.

- *Fig. 10b, why the difference between thin→rain and thick→rain is reversed during midday, compared to early morning?*

Good question. Not only the thick-to-precipitating, but also the thin-to-precipitating categories show much less negative LWP susceptibilities than the thick and thin clouds that remain non-precipitating. Currently, we didn't find a possible explanation or related physical mechanism for this. We have modified the manuscript to clarify that the cloud memory hypothesis is less prominent for precipitating clouds transitioned from non-precipitating clouds.

"Interestingly, as non-precipitating clouds transition to precipitating clouds (Fig. 10b and c, thin \rightarrow rain, thick \rightarrow rain), their LWP and α_c susceptibilities exhibit both less negative values and smaller daytime variations compared to thin/thick clouds that remain as thin/thick (Fig. 5b and c, thin \rightarrow thin, Fig. 7b and c, thick \rightarrow thick). The underlying reason for this observation is currently unclear and worth further investigations on the sensitivity of AIE for clouds experiencing transition in cloud states, especially between precipitating and non-precipitating clouds." (Lines 675-680).

- *Line 602, “instantaneous responses of warm boundary layer clouds...” I suggest rephrasing, as what you shown in the study is basically correlations (regression slopes), not actual responses (which refer to perturbation experiments).*
Changed
- *Line 621, “instantaneous CF adjustment rate” is a bit awkward, I suggest rephrasing (see comment above).*
Changed
- *Line 643, again, established mechanisms, not hypotheses.*
Changed.
- *Font size too small in Figs. 3-7, 9-10. I suggest matching them to that of Fig. 11, which looks just fine.*
Done.
- *In Fig. 3-7, 9-11, basically all time-series figures, I strongly recommend replacing the horizontal lines indicating daytime mean values with lines indicating “0”, and one can simply label the daytime mean values on each panel. The current horizontal lines are so seductive to be seen as the zero lines.*
Done.

References

- Albrecht, B. A.: Aerosols, Cloud Microphysics, and Fractional Cloudiness, *Science*, 245, 1227–1230, <https://doi.org/10.1126/science.245.4923.1227>, 1989.
- Arola, A., Lipponen, A., Kolmonen, P., Virtanen, T. H., Bellouin, N., Grosvenor, D. P., Gryspeerdt, E., Quaas, J., & Kokkola, H. (2022). Aerosol effects on clouds are concealed by natural cloud heterogeneity and satellite retrieval errors. *Nature Communications*, 13(1), 7357. <https://doi.org/10.1038/s41467-022-34948-5>
- Bennartz, R.: Global assessment of marine boundary layer cloud droplet number concentration from satellite, *J. Geophys. Res.*, 112, D02201, [doi:10.1029/2006JD007547](https://doi.org/10.1029/2006JD007547), 2007.
- Chen, Y.-C., Christensen, M., Stephens, G. L., and Seinfeld, J. H.: Satellite-based estimate of global aerosol–cloud radiative forcing by marine warm clouds, *Nature Geosci.*, 7, 643–646, <https://doi.org/10.1038/ngeo2214>, 2014.
- Christensen, M. W., Jones, W. K., and Stier, P.: Aerosols enhance cloud lifetime and brightness along the stratus-tocumulus transition, *P. Natl. Acad. Sci. USA*, 117, 17591–17598, <https://doi.org/10.1073/pnas.1921231117>, 2020.
- Eastman, R., R. Wood, C. S. Bretherton, Time scales of clouds and cloud-controlling variables in subtropical stratocumulus from a Lagrangian perspective. *J. Atmos. Sci.* 73, 3079–3091 2016.
- Feingold, G., Goren, T., & Yamaguchi, T. (2022). Quantifying albedo susceptibility biases in shallow clouds. *Atmospheric Chemistry and Physics*, 22(5), 3303–3319. <https://doi.org/10.5194/acp-22-3303-2022>.
- Gryspeerdt, E., Goren, T., Sourdeval, O., Quaas, J., Mülmenst.d.t, J., Dipu, S., Unglaub, C., Gettelman, A., and Christensen, M.: Constraining the aerosol influence on cloud liquid water path, *Atmos. Chem. Phys.*, 19, 5331–5347, <https://doi.org/10.5194/acp-19-5331-2019>, 2019.
- Gryspeerdt, E., Goren, T., and Smith, T. W. P.: Observing the timescales of aerosol–cloud interactions in snapshot satellite images, *Atmos. Chem. Phys.*, 21, 6093–6109, <https://doi.org/10.5194/acp-21-6093-2021>, 2021.

- Glassmeier, F., Hoffmann, F., Johnson, J. S., Yamaguchi, T., Carslaw, K. S., and Feingold, G.: Aerosol-cloud-climate cooling overestimated by ship-track data, *Science*, 371, 485–489, <https://doi.org/10.1126/science.abd3980>, 2021.
- Minnis, P., Sun-Mack, S., Young, D. F., Heck, P. W., Garber, D. P., Chen, Y., Spangenberg, D. A., Arduini, R. F., Trepte, Q. Z., Smith, W. L., Ayers, J. K., Gibson, S. C., Miller, W. F., Hong, G., Chakrapani, V., Takano, Y., Liou, K., Xie, Y., and Yang, P.: CERES edition-2 cloud property retrievals using TRMM VIRS and Terra and Aqua MODIS data—Part I: Algorithms, *IEEE Trans. Geosci. Remote Sens.*, 49, 4374–4400, <https://doi.org/10.1109/TGRS.2011.2144601>, 2011.
- Minnis, P., Sun-Mack, S., Chen, Y., Chang, F., Yost, C. R., Smith, W. L., Heck, P. W., Arduini, R. F., Bedka, S. T., Yi, Y., Hong, G., Jin, Z., Painemal, D., Palikonda, R., Scarino, B. R., Spangenberg, D. A., Smith, R. A., Trepte, Q. Z., Yang, P., and Xie, Y.: CERES MODIS Cloud Product Retrievals for Edition 4—Part I: Algorithm Changes, *IEEE T. Geosci. Remote*, 11152, 1–37, <https://doi.org/10.1117/12.2532931>, 2020.
- Sandu, I., Brenguier, J., Geoffroy, O., Thouron, O., and Masson, V.: Aerosol impacts on the diurnal cycle of marine stratocumulus, *J. Atmos. Sci.*, 65, 2705–2718, 2008.
- Smalley, K. M., and M. D. Lebsock, 2023: Corrections for Geostationary Cloud Liquid Water Path Using Microwave Imagery. *J. Atmos. Oceanic Technol.*, 40, 1049–1061, <https://doi.org/10.1175/JTECH-D-23-0030.1>.
- Williams, A. S., & Igel, A. L.: Cloud top radiative cooling rate drives non-precipitating stratiform cloud responses to aerosol concentration. *Geophysical Research Letters*, 48, e2021GL094740. <https://doi.org/10.1029/2021GL094740>, 2021.
- Xue, H. and Feingold, G.: Large-Eddy Simulations of Trade Wind Cumuli: Investigation of Aerosol Indirect Effects, *J. Atmos. Sci.*, 63, 1605–1622, <https://doi.org/10.1175/JAS3706.1>, 2006.
- Zhou, X., & Feingold, G. (2023). Impacts of mesoscale cloud organization on aerosol-induced cloud water adjustment and cloud brightness. *Geophysical Research Letters*, 50, e2023GL103417. <https://doi.org/10.1029/2023GL103417>