Response to Anonymous Referee #1

Thank you very much for your constructive and careful comments. It was greatly helpful to improve the quality of the draft.

****Note) Following the request of Anonymous Referee #3, Figure 1 was divided into Figure 1 and 2. So, the figure numbers of subsequent figures were increased by 1.**

Major Comments:

1． Sizes of figures and characters in figures

Sizes of figures and characters in figures are too small to see. Figures 2, 3 and 4 should be much larger. I recommend the authors to move panels of z_{LCL}, z_{inv}, α, and 1-β_2 in these figures to supplement, and to divide Figs. 2 and 3 further in order to make the panels larger. Sizes of characters in Fig. 6, 7 should be larger. It is also desirable that sizes of tic marks of color bars in Fig. 1 and sizes of characters in Fig. 8 are larger.

- ➔ Thank you for the suggestion. Following the comment, we divided Figures 3, 4, and 5. In addition, the panels of z_{LCL}, z_{inv}, α, and 1-β_2 are moved to supplement (S1, S2, S3). The size of the characters in Fig. 7, 8 is enlarged, and the sizes of tic marks of color bars in Fig. 2 and the sizes of characters in Fig. 9 are enlarged too.

2． Labels for cloud types

Cloud types are labeled as CL11, CL6, CL5, … I understand that they are labels based directly on the WMO classification and they have some advantages. However, it is very complicated when we read the manuscript because readers cannot easily remember the labels. Could you relabel them as, for instance, Fog, St, Sc, … or FOG, ST, SC, …, or CL_Fog, CL_St, CL_St, …?

- ➔ Following the comment, we relabeled all the cloud types, and Table 2 is added to explain the abbreviations. Please see P5L10-13 in the tracked-change version.

3． Short physical explanations are needed in many parts

In many parts in the text, physical explanations that attribute the results to the characteristics of proxies are not enough. I guess they are helpful for readers even if they are just one or a few sentences. For example:

P6L22-23:

"both LTS and EIS increase, particularly over the far northern continents and Arctic area."

Please provide a suggestion of the reason why LTS and EIS increase in the situation.

- ➔ This is because noCL (no low-level cloud) can occur when inversion is strong near the surface under dry conditions. We added the explanation in P7L10-12.

P6L32-33:

"undesirable negative anomalies of LTS and EIS over the far northern continents including Arctic area get worse from CL11 to CL6 and CL7"

Please provide an interpretation of the reason why LTS and EIS show negative anomalies.

- ➔ We speculate that in these dry regions, the formation of Fog (CL11), F.St (CL6), and B.St (CL7) needs upward moisture transports from the surface, which is likely to be accompanied by the reduction of vertical stability in the lower troposphere. We added the explanation in P7L25-28.

P7L5-7: "over the Arctic, Asia, and deserts areas, LTS/EIS shows negative anomalies opposite to the increased LCA, which worsens and extends to other continents from CL5, CL84 to CL12 and CL39"

Please provide a suggestion of the reason why LTS/EIS shows negative anomalies over the areas.

- ➔ The negative correlation for Sc (CL5) can be explained by the same physical processes applied to the cases of Fog, F.St, and B.St as explained above. In the very dry regions where background LCA is very small, the onset of Cu (CL12) and Cb (CL39) in the low LTS/EIS situations will result in the increase of LCA. We added the explanation in P8L3-6.

P7L22: "LTS and EIS, which have strong ocean-land contrasts (in particular, EIS) and seasonal cycle over land."

Please explain why ELF does not have strong ocean-land contrasts and seasonal cycle over land but LTS and EIS have them.

- ➔ The weaker seasonal cycle and ocean-land contrasts of ELF may imply the opposite variations in z_{inv} and z_{LCL}. The freezedry factor also contributes to reducing the excessive seasonal cycle. We added the explanation in P8L21-22 and P8L23.

P7L24: "with a larger ELF during the night"

Please explain why ELF is larger during the night.

- ➔ This is presumably due in part to diagnosing of noCL condition as a non-zero ELF. We added the explanation in P8L24-25.

P7L34: "with systematically higher proxy values"

Can you guess why night slopes have systematically higher proxy values?

- ➔ It indicates that the product of z_{inv} and z_{LCL} during the day is larger than that during the night. We added the explanation in P9L1-5.

P7L34-35:

"both ELF and 1-β2 tend to have steeper regression slopes during the night than during the day"

Can you guess why regression slopes are steeper during the night than during the day?

- ➔ This is due in part to the diagnosis of noCL condition as a non-zero ELF, particularly, during the night when noCL conditions are frequently reported. We added the explanation in P9L6-7.

Fig. 5c: The CL0 plots in Fig. 5c are against our simple tuition from previous studies (e.g., Wood and Bretherton (2006), Kawai et al. (2017)). This may confuse readers. Please briefly explain the reason of the apparent difference between CL0 plots in Fig. 5c and conventional figures.

- ➔ In responding to your comments above and below, we included explanations on this in P7L11-12 and P9L29-32 of the tracked-change version.

P8L15: "The frequency of CL0 increases as LTS and EIS increase"

This is against our simple intuition, at least, over the ocean. What causes this increase over the ocean? Mainly where? In what season and what situation?

- ➔ We note that noCL condition is frequently reported with a strong inversion at near the surface when LTS/EIS is large. We added the explanation in P9L29-32.

P8L32: "The freezedry factor substantially contributes to the improved correlations of CL0 with ELF from β2"

Please briefly explain the physical meaning (for example, where and in what situation the factor mainly contributes to the improvement of the correlations).

- ➔ As explained in PS19, the freezedry factor is designed to reduce a diagnosed LCA in a very dry region, such that it is most effective over the far northern continents and Arctic area, particularly during winter. We added the explanation in P10L16-18.

P8L33-34:

"the frequent occurrence of CL0 on the west coast of the major continents and equatorial SST cold regions"

I guess that people do not expect that the occurrence of CL0 is frequent on the west coast of

the major continents. Please add a little more explanation or note.

- ➔ The frequent occurrence of noCL on the west coast is due to the advection of dry air from nearby continents. The frequent occurrence of noCL over the SST cold tongue is due to the warm air advection from the south. We added the explanation in P10L20-23

4 . Target areas of LTS, EIS, and ECTEI

Please emphasize repeatedly in the text for fairness that the target areas of LTS, EIS, and ECTEI are over the ocean without sea ice and it is not intended to be used over land and sea ice.

- ➔ Following your comment, we emphasized repeatedly that the target area of LTS/EIS/ECTEI are over the ocean. Please see P7L29-30 and P11L16-17 in the tracked-change version.

5 . Comparison of EIS and LTS

It is well-known that EIS is an index much better than LTS over the ocean. However, it is not so clear in the author's study. I guess readers will be confused. Please discuss a little why the superiority of EIS to LTS over the ocean is not clear in this study.

- ➔ It is well known that EIS is better than LTS in the marine stratocumulus deck regime. However, our analysis domain is not confined in the marine stratocumulus deck but extended into the entire globe with various cloud regimes. Because of this, it seems that the superiority of EIS over LTS is not clearly seen in our analysis. We briefly explained this in a revised draft in P9L11-14.

6 . Discuss pros and cons of ELF compared with LTS/EIS/ECTEI.

Pros are very clear, I guess. Cons of ELF could be, for example:

*** LTS/EIS/ECTEI tend to represent optically thick stratocumulus. It is important for earth radiation budget. Can ELF be directly used for discussions related to radiation budget?**

*** LTS/EIS/ECTEI are based on very simple concept. ELF and the proposed idea for improvement of ELF seem to be very empirical.**

(* Discussion utilizing ELF or improved ELF could be complicated to understand LCA or LCA

changes.)

(* LTS/EIS/ECTEI are very simple and easily calculated.)

① LTS/EIS/ECTEI tend to represent optically thick stratocumulus. It is important for earth radiation budget. Can ELF be directly used for discussions related to radiation budget?

- ➔ ELF is designed to predict LCA of all types of clouds, so it can be used globally to discuss the radiation budget.

② LTS/EIS/ECTEI are based on very simple concept. ELF and the proposed idea for improvement of ELF seem to be very empirical.

- ➔ While the computation of ELF or improved ELF seems more complicated than LTS/EIS/ECTEI, we think that it is not so complicated. EIS needs θ_{sfc}, θ_{700}, z_{LCL} and moist adiabatic lapse rates at z_{LCL} and z_{700} (Γ_{LCL} and Γ_{700}) to calculate, and these are all information needed to calculate ELF too (if freezedry factor is ignored).

③ Discussion utilizing ELF or improved ELF could be complicated to understand LCA or LCA changes

- ➔ ELF (or improved ELF) can be useful to understand LCA changes. Please refer to the response to the comment below.

- ➔ It seems like the apparent con of ELF is that its formulation is bit complicated and empirical. We briefly discuss of pros and cons of ELF at P15L9-12 in the tracked-change version.

7. Section 3.5

I'm afraid that proposed idea for improvement of ELF is too much empirical and complicated, although I understand the value of the challenge. Is it needed to construct a unified proxy for LCA by making a tremendous effort, even though the cloud regimes and mechanisms that produce LCA are quite different? Please discuss it a little.

- ➔ The reason why we need a more precise unified proxy may be explained in relation to the cloud feedback. As shown in our paper, the response of LCA to environment variables is non-linear and varies depending on cloud types. Thus, to investigate the climate sensitivity of low-level clouds globally, it may be good to use a unified proxy, such as ELF. The contribution of individual environment variables can be extracted by linearizing ELF formulation (e.g. $\Delta\mathrm{ELF} \approx \frac{\partial\mathrm{ELF}}{\partial z_{\mathrm{inv}}}\Delta z_{inv} + \frac{\partial\mathrm{ELF}}{\partial z_{\mathrm{LCL}}}\Delta z_{LCL} + \frac{\partial\mathrm{ELF}}{\partial \mathrm{f}}\Delta f$). In this way, we can describe the physical processes controlling low cloud feedback, which depends on cloud regimes, in a single framework. As noted by the reviewer, the development of an advanced ELF may take lots of time and effort. However, due to the reasons mentioned above, we think it is worthwhile to do that. We briefly included this discussion in P15L9-12.

8 . Short discussion on cloud feedback

In the first paragraph of the introduction, the manuscript mentions an importance of the impact of low-level clouds on the Earth's climate including cloud feedback and climate sensitivity. However, there are no descriptions or suggestions on cloud feedback later in the manuscript, although this is a critically important topic now. Although the manuscript does not discuss it at all, proxies LTS, EIS, and ECTEI cause quite different estimation of cloud feedback. LTS causes strong negative cloud feedback, EIS suggests weak negative feedback, and ECTEI suggests positive cloud feedback over the ocean (models and observations imply positive cloud feedback, that is, a decrease in low-cloud in warmer climates). Could the authors add a short discussion or comments on cloud-feedback based on ELF?

- ➔ Thank you very much for the very nice comments. As noted by the reviewer, exploring cloud feedback and climate sensitivity is an extremely important subject. Following the comments, we examined the climate sensitivity diagnosed by ECTEI, LCA, and ELF. The below figure shows the SST dependency of ECTEI, LCA, and ELF over the ocean. ECTEI is one of the unified LCA proxies which accounts SST dependency of LCA by including cloud top entrainment criteria. As shown in the figure, ECTEI is tightly dependent on SST and EIS, but the scatters of LCA and ELF are more divergent. This implies that cloud controlling factors other than SST and EIS should work for the observed LCA. Both ECTEI and ELF predict the negative LCA slope to SST for a fixed EIS, which is known to compensate the LCA increase in a warm climate in association with higher EIS. The ELF-predicted SST slope is -0.66 % K^{-1}, which is smaller than that of LCA (-1.66) and ECTEI (-0.80). This result indicates a need to develop a more advanced ELF.
- ➔ As noted by the reviewer, exploring climate sensitivity is extremely important and a huge research subject. However, a detailed examination of climate sensitivity seems to be out of the main theme of our current draft, which focused on the relationship between LCA and various proxies by cloud types.
- ➔ So, we think that it will be better to explore climate sensitivity in a separate paper in a more comprehensive way, which, in fact, is one of our future research subjects. Following the comments, this future research plan is briefly explained in the conclusion section (P15L15-

17).

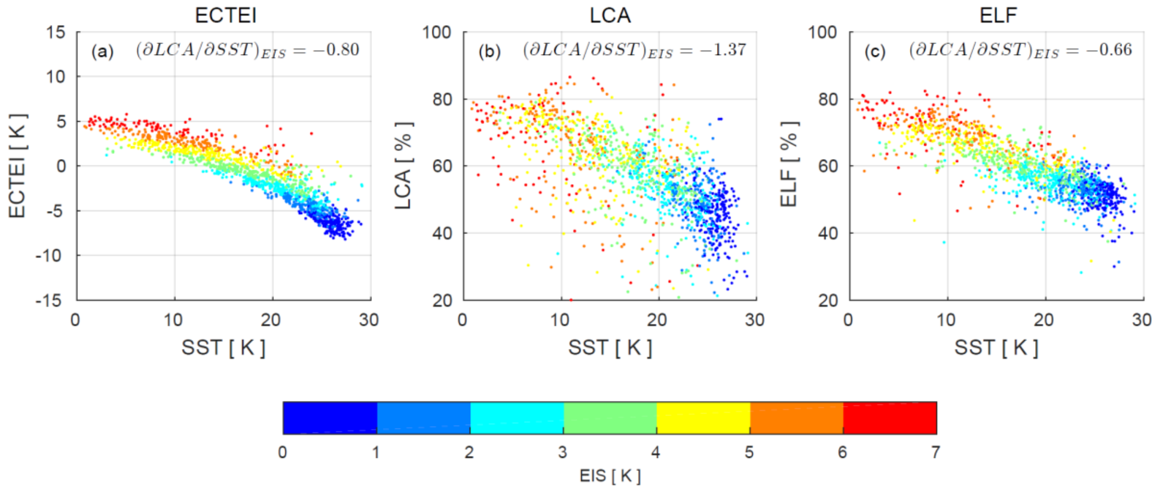

Figure 1. Scatter diagrams showing SST dependency of ECTEI, LCA, and ELF for each EIS bin (denoted by different colors). All seasonal climatologies of 5° latitude x 10° longitude ocean grids boxes between 60°N and 60°S are used in the analysis. The mean SST slope ($[\mathbf{\partial LCA/\partial SST}]_{\mathbf{EIS}}$ in units of [$\%\ \mathbf{K^{-1}}$]) denoted at the top of each panel is calculated by doing a linear regression for each EIS bin and averaging the regression coefficients of all EIS bin. For ECTEI, a conversion factor between LCA and ECTEI is assumed as dLCA/dECTEI = 3.1 $\%\ \mathbf{K^{-1}}$ following Kawai et al. (2017).

Minor comments:

Somewhere:

Is a variable β2 defined somewhere?

➔ We added the definition of β2 in P3L21-23.

P1L8-9: "the decrease in LCA when CL0 is reported and the increase of LCA when CL12 is reported"

Are "decrease" and "increase" appropriate? It is not easy to understand, especially if readers don't read the contents yet, I guess.

➔ Following the comment, we removed the wording of "increase" and "decrease", and changed them to "changes". Please see P1L8-9 in the tracked-change version.

P1L13: "the dissipation of LCA"

Is the word "dissipation" appropriate?

➔ The phrase "dissipation of" has been modified to "decrease of" for clarity. Please see P1L13 in the tracked-change version.

P7L31: "a high EIS located outside of the plotting range" Can't you widen the range of the figure?

➔ Following the comment, we have widened the range of the figure. Following the comment of referee #2, the squared regression coefficients (R^2) without Fog are added in Figure 6. Thus, we rewrote the sentence. Please see Figure 6 and P8L31-34 in the tracked-change version.

P8L5: "Figure 6 is the cumulative plot"

Caption in Fig.6: "Cumulative FQ"

Is Fig. 6 a cumulative plot? I though this is just a percentage plot.

➔ The more appropriate name of the plot is "stacked percentage plot". Please see the caption of Figure7 and P9L16 in the tracked-change version.

Caption of Fig. 5:

Explain the difference between open and filled symbols.

➔ Thank you for pointing out. We added the explanation in the caption of Figure 6.

Fig. 6c, 6e:

Why do LTS (and also EIS) have a large difference between daytime and night time over the ocean? It is understandable that there is a large difference over land (LTS and EIS is smaller in daytime). But why over the ocean also? I thought diurnal variations of LTS and EIS is negligible over the ocean because the SST diurnal variation is very small.

➔ It seems that the reviewer mis-interpreted Fig.7c and 7e. As was explained in the caption of Fig.7, "The bright and dark colors in each bar denote the fractions during the daytime and nighttime, respectively", instead of representing the values of LTS (or EIS) during the daytime and nighttime.

Fig.6e: Please briefly explain the reason why the black line is very insensitive to EIS over the ocean. I guess many readers will be embarrassed because they often see the very clear relationship between LCA and EIS over the ocean in several papers (e.g., Wood and Bretherton (2006), Kawai et al. (2017)). Please clarify the cause of the differences.

➔ As explained before, the high correlation between EIS and LCA reported in previous studies is mainly for the case of stratocumulus (CL5, CL6, CL84). In our study, however, we are examining the correlation across the entire low cloud types, such that the correlation between EIS and LCA is not large, as shown in Fig.6. This explanation is added in P9L32-34.

Caption of Fig. 6:

100 -> 100 %

➔ Corrected. Please see the caption of Figure 7.