Responses to comments of "Examining cloud vertical structure and radiative effects from satellite retrievals and evaluation of CMIP6 scenarios [egusphere-2023-453]" to *Atmospheric Chemistry and Physics*.

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We would like to thank the editor Dr. Martina Krämer and the reviewers for giving constructive criticisms and comments, which are very helpful in improving the quality of this manuscript. We have made the point-by-point response to the comments and revised the manuscript accordingly. We hope that the revised version can obtain favorable approval and meet the journal requirements. The referee's comments are reproduced (*black*, *italic*) along with our replies (blue) and changes made to the text (red) in the revised manuscript. All the authors have read the revised manuscript and agreed with the submission in its revised form.

Responses to Reviewers

Anonymous Referee #1

Review of "Examining cloud vertical structure and radiative effects from satellite retrievals and evaluation of CMIP6 scenarios" by Luo et al.

This study investigates the global scale spatial pattern and vertical extent of cloud vertical structure using the new CCCM dataset. The cloud radiative effect for each classified cloud vertical structure type is quantified. In addition, long-term changes in cloud vertical structure are explored in the context of climate change using CMIP6 models. Valuable conclusions have been achieved, which can improve our understanding of cloud vertical structure, its long-term trends, and radiative effects from the perspective of satellite observations and climate models. Overall, this work addresses relevant scientific questions within the scope of ACP and presents interesting ideas using the new data and solid methods. Also, the paper is well written and the figures are displayed in a good manner. For these reasons, I would recommend its acceptance for publication in ACP after minor revisions.

Response:

We appreciate the reviewer's time in reviewing this manuscript, and thank her/him for their positive comments and valuable suggestions. Please find below a point-by-point response to the comments and a revised manuscript that takes into account the reviewer's substantive suggestions.

Detail comments:

Comment NO.1:

Line 13, the full name should be stated on the first occurrence in the Abstract. It seems that CVS stands for cloud vertical structure after reading the entire text.

Response: The reviewer indeed points to a negligence, and it is now corrected.

Changes in Manuscript:

[Page 1 Line 13 (in the "Track Changes" version)]

"…of different cloud vertical structure (CVS) types during 2007–2010"

Comment NO.2:

Line 58, "…from ground-based remote sensors and from radiosonde measurements", please strike out the second "from" in this sentence.

Response: Well spotted and corrected now.

Changes in Manuscript:

[Page 2 Line 58 (in the "Track Changes" version)]

"…from ground-based remote sensors and radiosonde…"

Comment NO.3:

Line 89-90, in the introduction, the authors state that "Due to the interference with solar and terrestrial radiation, changes in CVS can strongly affect the Earth's energy budget, even when the total cloud fraction remains constant". How to understand "strongly"? since the authors did not make an explanation or cite any references. I would recommend omitting this word unless a reasonable explanation is provided by referring to relevant literature.

Response: Excellent help by the reviewer. We omitted the word "strongly" in this sentence, and also cited references to support this viewpoint.

Changes in Manuscript:

[Page 3 Lines 89-91 (in the "Track Changes" version)]

"Due to the interference with solar and terrestrial radiation, changes in CVS can affect the Earth's energy budget, even when the total cloud fraction remains constant (Morcrette and Jakob, 2000; Liang and Wu, 2005; Wang et al., 2016)."

References:

Liang, X.-Z. and Wu, X.: Evaluation of a GCM subgrid cloud-radiation interaction parameterization using cloud-resolving model simulations, Geophysical Research Letters, 32, https://doi.org/10.1029/2004GL022301, 2005.

Morcrette, J.-J. and Jakob, C.: The Response of the ECMWF Model to Changes in the Cloud Overlap Assumption, Monthly Weather Review, 128, 1707-1732, https://doi.org/10.1175/1520-0493(2000)128<1707:TROTEM>2.0.CO;2, 2000.

Wang, X., Liu, Y., and Bao, Q.: Impacts of cloud overlap assumptions on radiative budgets and heating fields in convective regions, Atmospheric Research, 167, 89-99, https://doi.org/10.1016/j.atmosres.2015.07.017, 2016.

Comment NO.4:

Line 90-91, "Satellite observations are insufficient for examining long-term trends in CVS, not only because of the limited time records…". In my opinion, satellites have decades of records so far, and satellite-based long-term trend analyses have been conducted in previous literature. The authors could say, compared to ground-based observations and models, the satellite time records are limited. So, the expression here is not accurate, and should be rephrased.

Response: We agree with the reviewer that we should claim that satellite records are limited only when compared with ground-based observations and climate models. This sentence has been rephrased.

Changes in Manuscript:

[Page 3 Lines 91-93 (in the "Track Changes" version)]

"Satellite observations are insufficient for examining long-term trends in CVS, not only because of the limited time records compared to ground-based observations and numerical simulations, but also because it is a challenge to understand the anthropogenic influence on CVS using satellites alone."

Comment NO.5:

Line 148, one concern here is that the authors did not claim the cloud pressure boundary of the layered clouds in the CMIP6 models.

Response: The reviewer indeed has an important point. The missing information has been inserted.

Changes in Manuscript:

[Page 6 Lines 162-164 (in the "Track Changes" version)]

"Three layered clouds are categorized according to the pressure thresholds of 440 hPa and 680 hPa, i.e., high clouds (<440hPa), middle clouds (680–440 hPa) and low clouds (>680 hPa). Note that clouds that straddle two (three) pressure layers are counted as two (three) cloud layers at the same time."

Comment NO.6:

Line 276, "the SW CREs further increases as the…", change "increases" to "increase".

Response: Corrected.

Changes in Manuscript:

[Page 9 Line 280 (in the "Track Changes" version)]

"…the SW CREs further increase as…"

Comment NO.7:

Line 327-330, this sentence depicts two figures including Figs. S3 and S4, to avoid misunderstanding, should be split into two sentences.

Response: The reviewer is right indeed that this sentence needed to be separated. It is done now in the revised version.

Changes in Manuscript:

[Page 11 Lines 335-338 (in the "Track Changes" version)]

"Fig. S3 compares the total, high, middle and low cloud fractions of the two CMIP6 CALIPSO simulators MME with the total eight CALIPSO simulators MME for the historical period from 1850 to 2014. Fig. S4 further analyses the total cloud fraction correlations between the two CALIPSO simulators MME and 32 models MME for four different periods from the past to the future."

Comment NO.8:

Line 420, why do the authors think the trends in Fig. 9 is "nonlinear"? I personally cannot see a noticeable non-linearity, and suggest removing this word and only saying "noticeable".

Response: We agree with the reviewer that "nonlinear" is confusing and inaccurate. It is now removed in the revision.

Changes in Manuscript:

[Page 141 Line 430 (in the "Track Changes" version)]

"…are noticeable in the context of climate change…"

Anonymous Referee #2

Review of "Examining cloud vertical structure and radiative effects from satellite retrievals and evaluation of CMIP6 scenarios" by Luo et al.

This study aims to investigate cloud morphologies and their radiative effect on the global scale. The authors use and present the new product CCCM RelD1 and compare it with 2B-GEOPROF-LIDAR, proving the reliability of the new dataset. The CCCM dataset is used to classify the clouds into 12 classes as a function of their vertical structure. The spatial distribution and the radiative effect of each class are studied in detail and presented in a clear and complete manner.

In the second part of the paper, the authors use CMIP6 models to investigate cloud amount trends during both the historical period and future projections. A comparison between models and observation is given in order to evaluate the reliability of the time series obtained from the models.

This work addresses relevant scientific questions within the scope of ACP using clear and valid methods. Moreover, the paper is well written, it is easy to follow and the figures are very clear. Overall, I find this work to be very valuable and interesting, and I recommend its acceptance for publication in ACP after minor revisions.

Response:

We would like thank the reviewer for their time in reviewing this manuscript, and also for the positive comments and valuable suggestions. We have written a point-by-point response to the comments and revised the manuscript according to the reviewer's substantive suggestions.

Specific comments:

Comment NO.1:

Line 20: The word "variance" is generally used to indicate the square of the standard deviation. I suggest replacing it.

Response: The reviewer is right. We replaced the word "variance" with "difference".

Changes in Manuscript:

[Page 1 Line 20 (in the "Track Changes" version)]

"…show a substantial difference in…"

Comment NO.2:

Section 2.1: The authors mentioned the horizontal resolution of all the relevant instruments. However,

I would recommend mentioning also the horizontal resolutions of the two final products 2B GEOPROF-LIDAR and CCCM.

Response: We thanks the reviewer, this is a well-spotted omission. We only mentioned the resolution of 2B GEOPROF-LIDAR in Lines 135-136 but neglected the resolution of CCCM in the original manuscript. It is now added.

Changes in Manuscript:

[Page 4 Lines 118-119 (in the "Track Changes" version)]

"Here, we use the enhanced product with a horizontal resolution of 20 km and a vertical resolution of 120 to 240 m…"

Comment NO.3:

Lines 131, 147, 196: Could the authors clarify the meaning of the word "interpolation"? Does it mean "average in the 2x2 gridbox"? If so, I would suggest to substitute it with the word "average", if not, I would suggest explaining the meaning.

Response: The reviewer is certainly right. It means "average to a grid of 2° × 2°". We corrected them in the revision.

Changes in Manuscript:

[Page 5 Lines 132-133 (in the "Track Changes" version)]

"Section 2.3 describes the detailed processing methods regarding the CVS classification, irradiance flux calculation and data gridding."

[Page 5 Line 149 (in the "Track Changes" version)]

"…and then monthly averaged to a grid of 2° × 2°."

[Page 7 Line 200 (in the "Track Changes" version)]

"…are further monthly averaged to a grid of 2° × 2°."

Comment NO.4:

Lines 245-247: The negative correlation between the low cloud tops and the distance between low and upper clouds looks like an artifact coming from the definitions (e.g. given X,Y uncorrelated, then R(X,Y-X) is negative). I suggest removing these lines.

If instead, this is not the case, and if the negative correlation is significant, I suggest explaining better why.

Response: The reviewer raises an important point. It is right that this conclusion is indeed a

mathematical result, not the essence of cloud physics. We have removed it.

Comment NO.5:

Line 312: it is not clear if "high-, middle- and low-level" are identified from cloud top of the highest cloud or not. For example, are clouds of HMxL labeled high-level? Or they are included also in middle- and low-level classes?

Response: The reviewer again raises an important point. "High-, middle- and low-level" are identified from cloud pressure boundaries not from the highest cloud top pressures. Take HMxL for example, it includes high-, middle- and low-level clouds. We have added the descriptions in Sect. 2.2.

Changes in Manuscript:

[Page 6 Lines 162-164 (in the "Track Changes" version)]

"Three layered clouds are categorized according to the pressure thresholds of 440 hPa and 680 hPa, i.e., high clouds (<440hPa), middle clouds (680–440 hPa) and low clouds (>680 hPa). Note that clouds that straddle two (three) pressure layers are counted as two (three) cloud layers at the same time."

Comment NO.6:

Lines 325-330: Figures S3 and S4 are shown to compare the MME mean and the two models available for the future period. I suggest adding in the supplement material a figure similar to Figure 8, but using only GFDL-CM4 and IPSL-CM6A-LR, in order to compare them with the data in the period 2007-2010.

Response: A very valuable suggestion by the reviewer. We have added a comparison between CCCM and mean of two models (GFDL-CM4 and IPSL-CM6A-LR) during 2007–2100 in Fig. S5.

Changes in Manuscript:

[Page 11 Lines 341-343 (in the "Track Changes" version)]

"Besides the intercomparison between the models, a similar assessment result as in Fig. 8, but the relationship between average of two models (GFDL-CM4 and IPSL-CM6A-LR) and CCCM during 2007–2100, is depicted in Fig. S5."

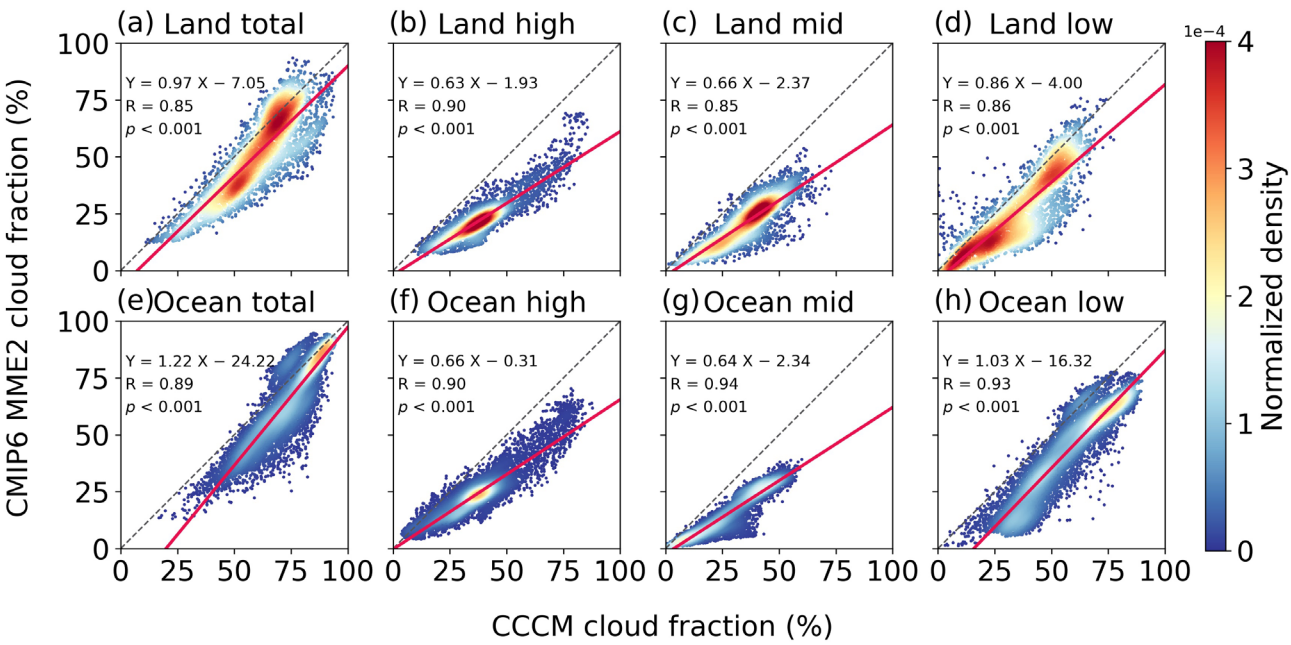

Figure S5: Normalized density plots of the 4-year (2007–2010) monthly average (a and e) total, (b and f) high, (c and g) middle and (d and h) low cloud fractions estimated from the two CMIP6 models that employ the CALIPSO simulator (GFDL-CM4 and IPSL-CM6A-LR), as average of the two models, versus the CCCM measurements over land and ocean, respectively. The regressions are represented by the red lines. The regression function, correlation coefficient (R) and *p* value are given in each subplot.

Comment NO.7:

Line 380: The "CSV" identifies just low-, middle-, and high-cloud in this line, while it identifies the 12 classes of vertical structure in the rest of the paper. Could the authors substitute "CSV" with "low-, middle-, and high-level cloud amounts"?

Response: This is a very good suggestion by the reviewer which we followed. We now make clear that only low-, middle-, and high-level cloud amounts are explored by CMIP6 data.

Changes in Manuscript:

[Page 13 Lines 389-391 (in the "Track Changes" version)]

"In addition, this work uses CMIP6 outputs to assess the long-term changes in cloud cover, and to explore variations in low-, middle-, and high-level cloud fractions during the historical and projected periods in the context of climate change."

Comment NO.8:

Figures 5 & 6: Figure 6 shows that all the CSV classes have a net cooling effect on the surface, while Figure 5 shows that there are some regions where the net CRE on the surface is positive. Could the

author comment on this?

Response: The reviewer highlights a key issue. The positive values of net CRE at the surface are generally located over bright areas (e.g., Greenland, Arctic, Antarctica) (Fig. 5i), where the cloud greenhouse effect prevails. However, when considering the global average, the net positive CREs of cloud types that dominate over these bright regions are not comparable in magnitude to the average albedo effects of the same cloud types over most other regions, ultimately resulting in net cooling at the surface. This is now reported in the revised text.

Changes in Manuscript:

[Page 10 Lines 297-300 (in the "Track Changes" version)]

"However, in terms of spatial distribution, there are positive values of net CRE observed at the surface over bright areas (e.g., Greenland, Arctic, Antarctica) (Fig. 5i), where the cloud greenhouse effect prevails. Nevertheless, when examining the global average, the net positive CREs of cloud types that dominate over these bright regions are rather small in magnitude compared to the average albedo effects of the same cloud types over most other regions, ultimately resulting in net cooling at the surface.

Technical corrections:

Comment NO.9:

Line 13: Please write CVS as full name before using the acronym in the abstract.

Response: The reviewer indeed points to a negligence, and it is now corrected.

Changes in Manuscript:

[Page 1 Line 13 (in the "Track Changes" version)]

"… of different cloud vertical structure (CVS) types during 2007–2010"

Comment NO.10:

Line 154: SSP245 and SSP585 are capitalized in this line, while they are lower letters in the rest of the paper.

Response: Well spotted and corrected now.

Changes in Manuscript:

[Page 5 Line 156 (in the "Track Changes" version)]

"…ssp245 assumes a central pathway with continued historical tendencies, while ssp585 envisions optimistic…"

Comment NO.11:

Lines 178, 185, 191: equation numbers are not correctly written.

Response: Again, excellent help by the reviewer, and it has been corrected.

Changes in Manuscript:

[Page 6 Line 182; Pang 7 Line 189, 195 (in the “Track Changes” version)]