# Replay to the review of ”Opposing trends of cloud coverage over land and ocean under global warming” by Liu et al. submitted to Atmospheric Chemistry and Physics

We would like to thank the editor and the reviewers for their efforts and beneficial feedback that have helped us to clarify our manuscript. All the comments have been addressed in a point-by-point manner. The manuscript and Supplemental Information (SI) have been revised accordingly. Please see below the specific answers to all the comments (marked in blue). Citations from the revised manuscript appear in *italics.*

## Response to Reviewer #1

Reviewer #1 (Comments to the Author):

**General comments:**

Generally, the authors invested quite a lot into the reworking of the MS. Now it is in much better state. Some caveats and comments are provided below.
Answer: Thank you for the time and effort invested in reviewing our manuscript. We appreciate your insightful feedback, which helped us to improve our work. Please refer to our detailed answers below.

**Specific comments:**

1. Dataset (lines 70-85). First datasetS should be plural here. Secondly, in fact you use 2 cloud datasets with additional Nino index. I suggest to specify this in the description alternatively to what you pose now (3 datasets).

Answer: The text has been revised as suggested:

"*2.1 Datasets*

*The study uses two datasets and a temperature-based Niño index*"

2. Lines 90-95 – still insufficient justification for computing relative humidity. The answer given to Reviewer 2 is also somehow vague. The best justification (or opposite) would be to give a comparative picture with RH(2) computed from dew point in the Supplementary. By the way, what are the problems here (mentioned in the answer to Rev 2).

Answer: Thank you for this comment. We originally chose to use the RH value at 50 hPa above the surface because we think it represents well the humidity conditions at the lower troposphere, which are linked to convective cloud formation mechanisms. We wanted to minimize the potential effects of local vegetation and buildings that are represented in ERA5 surface parametrization, and that's why we used the RH at 50 hPa above the surface and not the RH at 2 m. The effects of the surface parameterization may introduce noise in this link between RH near the surface and cloud cover, as indeed captured by their slightly weaker correlations as presented in Fig. 5a. Nevertheless, based on this comment and for supporting better our results, we added the revised SI the requested analysis of $RH_{2m}$ (Fig. S4c–d and Supplementary Text 6) and a relevant short discussion:

Revised text in the Results section:"*The statistically significant $RH_{NS}$ trends and additional trend analysis of $RH_{2m}$ lead to similar conclusions, see fig. S4 and Supplementary Text 6.*"

Additional analysis which we added to the SI:"*6. $RH_{NS}$ trend significance and trend analysis of RH at 2 meters ($RH_{2m}$)*

*Here, we explore the significance of estimated linear trends in Near-Surface RH ($RH_{NS}$) and trend maps of $RH_{2m}$ as complementary information to the results presented in the Main Text. Figure S4a) presents a global picture of the $RH_{NS}$ trend (the same as Fig. 6a of the Main Text). Figure S4b) presents only the significant values (the insignificant results are coloured as gray). As shown, most of the continental trends in $RH_{NS}$ are statistically significant and most maritime trends are statistically insignificant. Figures S4c) and S4d) present the results of the same analysis but for the $RH_{2m}$ (in %). Since $RH_{2m}$ is not provided by ERA5, per grid box and month, we calculated it using ST (in K) and dew point temperature at 2 meters ($Td_{2m}$, in K) according to the following formula (water surface is assumed):*

$$\mathrm{RH_{2m}} = 100 \times \mathrm{e}^{17.502\left(\frac{\mathrm{Td_{2m}}-273.16}{\mathrm{Td_{2m}}-32.19}-\frac{\mathrm{ST}-273.16}{\mathrm{ST}-32.19}\right)}$$

*The significance and similar continental patterns from this analysis further support the reduction in low-level RH as the most plausible explanation for the decreased continental cloud coverage, while other variables are likely to be responsible for changes in maritime cloud coverage.*”

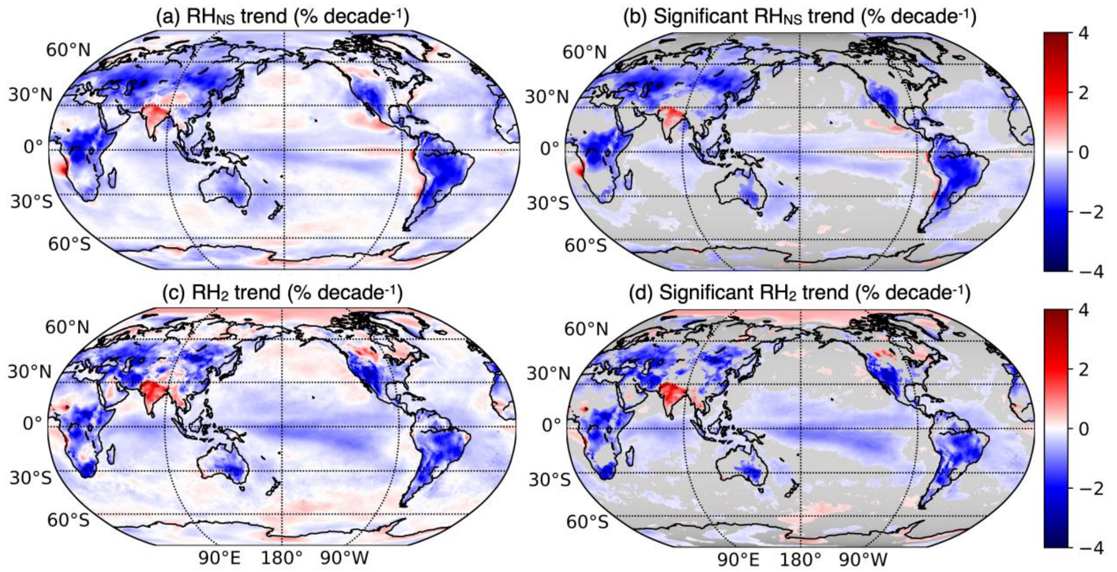

*Figure S4: Trends in $RH_{NS}$ and $RH_{2m}$ during 1979–2020. (a) A map of global trend in $RH_{NS}$; (b) A map of $RH_{NS}$ trend that is statistically significant at the level of 0.05 (p-value $<$ 0.05, two-tailed t-test); (c–d) the same as a–b but for $RH_{2m}$. The insignificant results are coloured in gray in panels (b) and (d).*

3. Lines 105-110. In the description of EOF analysis most important to mention that this is essentially linear procedure.

Answer: Thank you, this point is emphasized better now in the revised manuscript. Please see the details below:

“*EOF analysis is a linear decomposition method of multivariate signals that is widely used in meteorology and oceanography (Lorenz, 1956; Preisendorfer and Mobley, 1988), aiming at extracting spatial modes (i.e., patterns) of variability and study their* *time-evolution. It decomposes any given spatiotemporal field into a set of orthogonal independent EOF modes in the spatial domain whose temporal variations are encoded by the corresponding Principal Components (PCs). With the proper interpretations, these linearly independent modes can provide useful clues about the physics and dynamics of the investigated system; see e.g. Schnur et al. (1993), Dunkerton (1993) and Dror et al. (2021).*"

4. Around line 125 – can you enrich your new fig 2 by the graph from figure R1 (replay to Rev 1). It is important to discuss definite break in 2000 for marine cloud cover. In fact there is no trend, i.e. the trend is implied by this definite break

Answer: We would like to thank the reviewer for this insightful comment. To give a better explanation for this break, we have added a detailed analysis to the revised SI (Fig. S1 and Supplementary Text 2) and relevant text to the Results section, which you can be seen below:

Revised text in the Results section: "*In contrast, the lack of a consistent trend in TCC suggests that perturbations other than a warming climate might dominate the global TCC variability. For example, the break in the trend around the year 2000 can be attributed to the trend in the maritime clouds over the tropical Atlantic and the western part of tropical Pacific (see fig. S1 and Supplementary Text 2) and is likely to be associated with the previously reported phase change of AMO and PDO at the 2000s (Hong et al., 2022).*"

The analysis and text added to the revised SI:"*2. Breaking in annual global mean Total Cloud Cover (TCC) around year 2000*

*Our results reveal a clear break in the time series of the annual TCC, around the year 2000 as it can be observed in Fig. 2d of the Main Text. Here, we perform a more detailed analysis of this time series by separating it into our 3 analyzed domains: global, land and ocean. The results reveal that this break accurring around the year 2000 is mainly contributed by maritime clouds (blue curve in Fig. S1a), more specifically, those over the tropical Atlantic (oceans between 30 °S–30 °N and 110 °W–22 °E, Fig. S1c) and the western part of tropical Pacific (oceans between 30 °S–30 °N and 120 °E–30 °W, Fig. S1d). The Atlantic Multi-decadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO) are known to be the most active climate oscillations over the identified regions (Deser et al., 2010; Li et al., 2021), with a characteristic periodicity of decades and have shown to have clear phase changes around the 2000s (Hong et al., 2022). Interestingly enough, over the Tropical Atlantic, the time series indicates an oscillation with a decreasing phase until ~1994 followed with an ascending phase for the next two decades, in consistency with the fingerprint of the AMO; while over the western Pacific, the sharp break observed over the years 2000–2001 may be attributed to the PDO.*

*This break in the time series of the mean annual TCC may affect locally the trend estimations over the Atlantic and western Pacific, but it is not likely to be the main driver of the trend mode as documented for the global TCC; see Figs. 4c–d) of the*

*Main Text. Indeed, one notices from Fig. 4c of the Main Text that the regions with larger anomalies are observed over land, the Indian Ocean, and the Eastern Pacific, while no obvious breaking is observed around year 2000; in the corresponding time series shown in Figs. S1a), S1b), and S1e). In PC2 of TCC and the annual global mean surface temperature (Fig. 4d of the Main Text), the 2000-breaking is present but to a lesser extent than in TCC anomaly over e.g. Western Pacific (Fig. S1d) and actually contributes to the trend as many other local variations occurring over other time windows, supporting its unprevailing influence to the trend mode found in the Main Text.*”

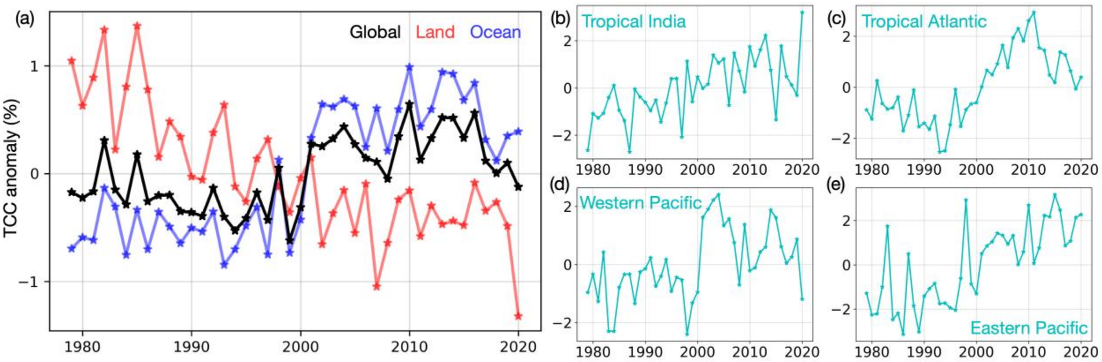

*Figure S1: Time series of the anomaly of annual mean TCC over different regions, compared to the 1979–2020 average. TCC anomaly over the (a) global (black curve), land (red curve), and oceans (blue curve), (b) tropical India (oceans between 30 °S–30 °N and 22–120 °E), (c) tropical Atlantic (oceans between 30 °S–30 °N and 110 °W–22 °E), (d) western Pacific (oceans between 30 °S–30 °N and 120 °E–30 °W), and (e) eastern Pacific (oceans between 30 °S–30 °N and 30–110 °W).*

Additional references:

1. *Hong, J. S., Yeh S. W., and Yang Y. M.: Interbasin interactions between the Pacific and Atlantic Oceans depending on the phase of Pacific decadal oscillation and Atlantic multidecadal oscillation. Journal of Climate, 35, 2883–2894, doi.org/10.1175/JCLI-D-21-0408.1, 2022.*

5. Line 175. The sentence “Consequently, the cloud coverage in regions of positive anomalies over the central to eastern Pacific (red shades in Fig. 4a) has a tendency to increase during El Niño years and to decrease during La Niña years” in fact not directly following from the previous one. Thus, the use of “consequently” is doubtful. Additional statement needed here in between to justify the concept (El-Nino vs La Nina)

Answer: We revised the text to make it clearer.Please see our revised text below.

For the concept of El Niño and La Niña:“*An episode of large positive values in PC2 coincides with large positive ONI-values, indicating a strong warm phase of ENSO; i.e. El Niño events leading to an unusual increase in sea surface temperature over the central and Eastern tropical Pacific Ocean. Analogously, episodes of large negative values for this PC2 coincide with large negative ONI-values, corresponding to strong* *cold phases of ENSO (La Niña events, the cold counterpart of El Niño) (Neelin et al., 1998).*"

For the sentence mentioned:"*It suggests that maritime Southeast Asia and the Western Pacific are anti-correlated with the PC and hence the ONI (blue shades in Fig. 4a), meaning the cloud coverage in regions of positive anomalies over the central to eastern Pacific (red shades in Fig. 4a) has a tendency to increase during El Niño years and to decrease during La Niña years.*"

6. As I pointed earlier – discussion is really poor and this section needs to be upgraded. The best way is to get back to the Intro and go through the Intro statements pointing to what was added value in the work done and what was not.

Answer: We thank the reviewer for this helpful comment. Following this suggestion, we have revised the discussion to place better our findings within the research background. In addition, we have moved the text discussing the comparison between our results and previous studies from the Results section to the Discussion section. Please see the revised Discussion paragraphs below:

"*The reported trends in cloud coverage are consistent with several previous estimations that were based on long-term observations and historical simulations. A few examples are the reported decreasing trend over land as revealed by surface observations (Warren et al., 2007), and the general increasing trend detected over the tropics and eastern subtropics, by analysis of satellite observations and historical simulations (Norris and Evan, 2015; Zhou et al., 2016; Norris et al., 2016). Another example is the analysis of the observed liquid water path from the Multisensor Advanced Climatology of Liquid Water Path (MAC-LWP) dataset, which showed an increasing trend over most of the oceans (Manaster et al., 2017). However, there are some contradictions between our findings and previously reported satellite observations, which show a decreasing trend over most of the Congo Basin and increasing trend over most of the northeast tropical Atlantic over the last decades (1983–2009) (Norris and Evan, 2015). Also, some model-based future-climate prediction studies suggest a decrease in marine stratocumulus cloud coverage in warmer climate conditions (Forster et al., 2021; Zelinka et al., 2016). This discrepancy may stem from many reasons including the uncertainties related to long-term cloud observations (Norris and Evan, 2015), the inaccuracies related to cloud simulations (Stevens and Bony, 2013), the limitations of the ERA5 data (e.g., the quality depends on the assimilated observations) (Hersbach et al., 2020), and the varying global warming patterns in the future (Zhou et al., 2016; Gulev et al., 2021).*

*The revealed opposing trends of continental and maritime cloud coverage highlight the land-ocean contrast under global warming. The detailed analysis we presented of correlations between annual cloud coverage and thermodynamic variables taken from ERA5 (207 in total) further suggests that the decreasing trend in relative humidity is the main driver of the decreased trend in continental clouds cover. Because of the limited availability of water vapor sources over land, terrestrial clouds are more likely to be humidity-limited. Relative humidity measures how far a given specific* *humidity is from saturation per given temperature and pressure and is, therefore, a fundamental measure of cloud formation. In particular, relative humidity near the surface dictates the initial conditions of a rising air parcel. In a warming climate, over the continents, near-surface relative humidity is expected to decline (Byrne and O'Gorman, 2018) and is likely to affect cloud formation similarly. Over the warming oceans, for which the water vapor reservoir is not limited, enhanced evaporation can supply additional water vapor and hence partly cancel changes in relative humidity due to temperature increasing. Therefore, trends of near-surface relative humidity and their links to cloud coverage over the oceans are less distinct.*"

## Response to Reviewer #2

Reviewer #2 (Comments to the Author):

**General comments:**

I thank the authors for their work revising the manuscript.
Answer: We thank the reviewer again for the important comments that helped us making this paper clearer.

**Specific comments:**
1. One thing that might be a useful number to provide in the manuscript is the actual $R^2$ between MODIS TCC and the ERA5 that are using. They do provide EOFs, which show a consistent ITCZ position, but it would be useful to have the $R^2$ since it gives the shared variance. For instance line 85, where the authors state that TCC essentially captures the spatiotemporal characteristics, it is impossible to know what essentially means. The statement could be very easily updated to say that it captures xx% of the spatiotemporal variability. This could also be added in line 125. The correlation between different EOFs could be noted instead of simply saying 'essentially'.

Answer: The covariance based on Spearman's ρ have been added in the revised manuscript to give quantitative estimations. Please find more details below:

"*First to set the stage and to explore modes and sensitivities in the ERA5 TCC dataset as compared to direct measurements we conducted an area-weighted EOF analysis on annual TCC anomalies and compared it with the observed CF from MODIS; see Fig. 1. To mimic the MODIS CF observations, we resampled ERA5 TCC data to a grid with a horizontal resolution of 1 ° and considered only a subset of data between 60 °S to 60 °N during 2003–2020. The subset of ERA5 TCC captures well the leading modes of the MODIS CF, and about 60 % of the total variance (Spearman's ρ = 0.77; see Supplementary Text 1). Figure 1 shows the three dominant EOF modes and PCs of the annual ERA5 TCC and MODIS CF anomalies. The very similar explained variances (as indicated in the title of the EOF panels of Fig. 1) as well as spatial patterns in EOFs (Spearman's ρ = 0.84, 0.83, and 0.75 for the 1st, 2nd, and 3rd EOFs, respectively), and temporal evolution of the PCs (Spearman's ρ = 0.99, 0.89, and 0.88 for the 1st, 2nd, and 3rd PCs, respectively) suggest that although the ERA5 TCC is by definition simulated, the underlying model characteristics and assimilation techniques are able to reproduce essential variations of cloud coverage when compared to observations.*"

2. Line 133: is there progressively greater uncertainty back towards 1979 in this analysis as there is substantially less data going into the reanalysis before the era of plentiful satellite data?

Answer: Thank you for this comment. Yes, the accuracy/uncertainty of ERA5 data is not uniform throughout the study period, and it has also spatial dependence. It depends on the quality and quantity of the assimilated observations. In earlier times or over regions with less high-quality observations, the accuracy/uncertainty is expected to be lower/larger. And because of the shortage of well-calibrated cloud observations before MODIS, it is hard to estimate this effect on our results. We have added relevant text to the revised Discussion section, to clarify the limitations of the ERA5 dataset:

"*However, there are some contradictions between our findings and previously reported satellite observations, which show a decreasing trend over most of the Congo Basin and increasing trend over most of the northeast tropical Atlantic over the last decades (1983–2009) (Norris and Evan, 2015). Also, some model-based future-climate prediction studies suggest a decrease in marine stratocumulus cloud coverage in warmer climate conditions (Forster et al., 2021; Zelinka et al., 2016). This discrepancy may stem from many reasons including the uncertainties related to long-term cloud observations (Norris and Evan, 2015), the inaccuracies related to cloud simulations (Stevens and Bony, 2013), the limitations of the ERA5 data (e.g., the quality depends on the assimilated observations) (Hersbach et al., 2020), and the varying global warming patterns in the future (Zhou et al., 2016; Gulev et al., 2021).*"

3. Line 185: There are techniques to look at how different EOFs correlate. For instance on line 187, the authors note that this is an ENSO-associated behavior. Is that based on spatial or temporal correlation in the PC? There are EOF based techniques to find coupled patterns using EOFs (Bretherton et al. 1992). I am not saying the authors necessarily need to go into the depth of the aforementioned reference, but the covariance between the surface temperature and cloud EOFs could be quantified. This could potentially be combined with the $R^2$ of the TCC from ERA5 and observations.

Answer: In this work, the ENSO- and warming-associated behavior is identified by temporal correlations of the PCs. The remarkable similarity is first shown on the plot and to quantify it we use the covariance between surface temperature and cloud EOFs, by estimating the Spearman's $\rho$ (= 0.88, p-value = $3.28\times10^{-14}$, two-tailed t-test) between the annual global mean surface temperature and PC2 in TCC. We note also the similarity between spatial EOF patterns and previous results provides additional validation for the explanation of corresponding EOF modes.

## References:

1. Bretherton, C. S., C. Smith, and J. M. Wallace, 1992: An Intercomparison of Methods for Finding Coupled Patterns in Climate Data. Journal of Climate, 5, 541–560, https://doi.org/10.1175/1520-0442(1992)005<0541:AIOMFF>2.0.CO;2.