Response to Reviewer #2 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 reviewer for taking the time to review our manuscript and provide such beneficial comments that helped us improve our work and better demonstrate our findings. We have carefully considered each of the comments and addressed them in a point-by-point manner. The manuscript and Supplemental Information (SI) have been revised accordingly.

Please see below the specific answers to all comments (marked in blue). Citations from the revised manuscript appear in *italics*.

General comments:

Based on the use of a model cloud data set (ERA5) being treated as observations, I recommend a rejection (see detailed comments below). Overall, the authors may find it easy to either spin their paper towards a model only paper, or to substitute in a collection of different long-term observations (a suggested list is provided below).

Answer: We appreciate the thoughtful and constructive feedback. In the revised manuscript and SI, we have taken your comments regarding the description of cloud coverage from ERA5 into account and updated the text accordingly to ensure that the distinction between reanalysis and observations is clear. We agree that using ERA5 provides some limitations. We have updated the motivation for using this data and provided a more conclusive discussion about our results and how they compare with previous studies based on long-term observations. Please see our detailed answers below.

Specific comments:

1. Line 27: Zelinka 2020 doesn't look at trends.

   Answer: We thank the reviewer for this correction. The word "trends" has been revised to "tendencies" in the new manuscript.

   "*Previous works that examined tendencies in cloud coverage under a warmer climate show substantial discrepancies among them (Gettelman and Sherwood, 2016; Ceppi et al., 2017; Zelinka et al., 2020).*"

2. Line 40 (or somewhere similar): you may be interested in (Andrew Manaster et al., 2017).

   Answer: We thank the reviewer for this recommendation. The study by Manaster et al. (2017) provides an in-depth analysis of trends in both observed and simulated cloud liquid water path (LWP). Their discussion of the potential effect of inter-annual variability on forced trends is highly relevant to the points we are making. Therefore, we added it as a reference in the revised manuscript.

   "*Besides the uncertainties tied to observations and modeling, the sensitivity of clouds to temperature patterns (Zhou et al., 2016) and other large-scale climate drivers (Manaster et al., 2017; Gulev et al., 2021) can also lead to discrepancies between estimations of cloud coverage trends over different periods and regions.*"

   Moreover, the trend in observed LWP from the Multisensor Advanced Climatology of Liquid Water Path (MAC-LWP) dataset (1988–2014) suggests consistent results (Fig. 4a and c in Manaster et al., 2017) with our findings (Fig. 4c in our revised manuscript). For example, see the increasing trend in LWP over most tropical and eastern subtropical oceans which is consistent with the increased cloud coverage in our warming-associated mode. Therefore, we have also referenced this work when discussing our results.

"*Additionally, analysis in observed liquid water path from the Multisensor Advanced Climatology of Liquid Water Path (MAC-LWP) dataset yields increasing trends over most oceans (Manaster et al., 2017). These increasing patterns suggest consistent results with our findings as well because the value of liquid water path for cloud-free atmosphere is considered as 0.*"

3. Line 60: Is the cloud cover in this study all based on ERA5? ERA5 is not giving observed cloud properties. ERA5 is just a global circulation model nudged to observations. The relevant properties that are nudged to observations, as state here, thermodynamic properties. These are used with a cloud scheme to generate cloud properties. See for instance https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview and the discussion of specific rain content. At least according to https://wcd.copernicus.org/preprints/wcd-2020-26/wcd-2020-26-manuscript-version2.pdf the scheme in question is (Tiedtke, 1993) with a few tweaks. If there is not an observed cloud data set, then this study presents an evaluation of the Tiedtke scheme as implemented by ECMWF in response to thermodynamic variability nudged towards observations.

   Answer: We thank the reviewer for raising this major point, which helped us to better justify the use of ERA5 cloud coverage in our study. We have updated the manuscript and added analysis accordingly to provide more detailed information on the advantages and limitations of using ERA5, as well as our specific reasons for selecting this dataset for our analysis. More specifically, information was added about ERA5 calculation of cloud cover. A comparison of cloud coverage EOF analysis using ERA5 and MODIS data sets, for 2003 – 2020, was added to the revised manuscript, to validate and justify the use of ERA5 data and EOF analysis.

   And we thank the reviewer for recommending Binder et al. (2020), which provides a perspective on the weather scales used to evaluate cloud cover estimations from ERA5. Their results emphasize the ability of ERA5 to essentially capture the observed cloud patterns, though some small- and mesoscale structures are missed. Therefore, we have included this work as a reference in the revised manuscript. Once again, we appreciate the helpful feedback provided by the reviewer.

   Below, you will find the revised text in the Materials and Methods section and the newly added analysis (Fig. 1 in the revised manuscript) in the Results section:

   Revised text in the Materials and Methods section: "*ERA5 is a state-of-the-art reanalysis dataset and has been validated as the most reliable one for climate trend* *assessment (Gulev et al., 2021). In ERA5, the cloud fields are calculated using prognostic equations based on assimilated meteorological (thermodynamic and dynamic) variables that are optimally constrained by observations (Hersbach et al., 2019). The TCC is then calculated as a diagnostic parameter based on the prognostic cloud cover field using a generalized cloud overlap assumption based on a stochastic cloud generator. This assumption means that the degree of overlap between two cloudy layers becomes more random as the vertical distance between the layers increases; see more details in Barker (2008). The calculated TCC has been shown to essentially capture the spatiotemporal characteristics of measured cloud coverage on climatic (Yao et al., 2020) and weather scales (Binder et al., 2020).*"

Newly added analysis in the Results section: "*First to set the stage and to explore modes and sensitivities in the ERA5 TCC data 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. Figure 1 shows the three dominant EOF modes and PCs of the annual ERA5 TCC and MODIS CF anomalies. The very similar explained variance, spatial patterns in EOFs, and time evolution in PCs suggest that although ERA5 TCC is a simulated parameter, the model and assimilation techniques are able to reproduce essential variations of observed cloud coverage.*"

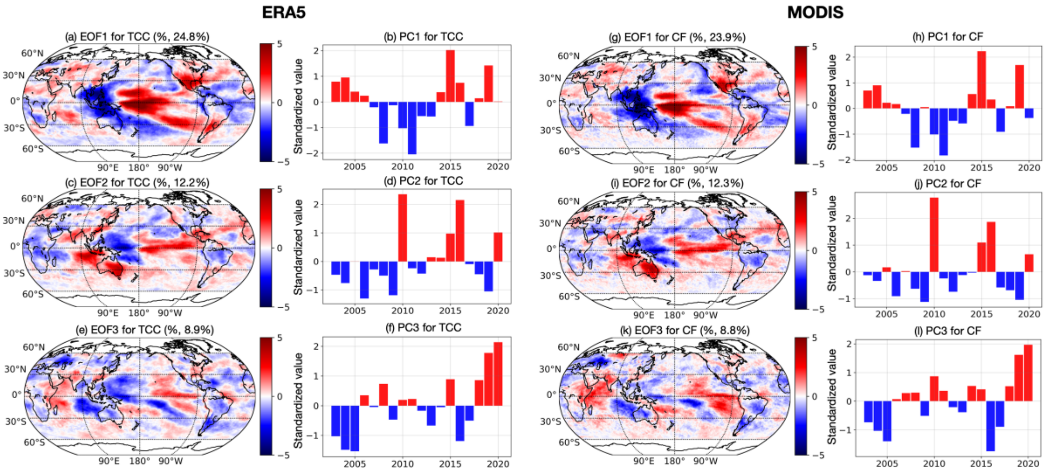

Figure 1: The three dominant EOF modes and their corresponding PCs of the annual cloud coverage anomaly (unit: %) from ERA5 (a–f) and MODIS (g–l) during 2003–2020. (a, g) The scaled leading EOF mode (EOF1, amplified by the standard deviation of its PC). (b, h) The standardized leading PC (PC1, divided by its standard deviation). (c, i) The scaled second EOF mode (EOF2). (d, j) The standardized second PC (PC2). (e, k) The scaled third EOF mode (EOF3). (f, l) The standardized third PC (PC3). The values given in the parenthesis of the title of

panels a, c, e, g, i and k are the explained variances. The red and blue bars in panels b, d, f, h, j and l highlight the positive and negative PC values, respectively.

Added references:

1. Binder, H., Boettcher, M., Joos, H., Sprenger, M., and Wernli, H.: Vertical cloud structure of warm conveyor belts–a comparison and evaluation of ERA5 reanalysis, CloudSat and CALIPSO data. Weather and Climate Dynamics, 1, 577–595, doi.org/10.5194/wcd-1-577-2020, 2020.
2. Barker, H.W.: Representing cloud overlap with an effective decorrelation length: An assessment using CloudSat and CALIPSO data. Journal of Geophysical Research: Atmospheres, 113, doi.org/10.1029/2008JD010391, 2008.
3. Platnick, S., King, M.D., Ackerman, S.A., Menzel, W.P., Baum, B.A., Riédi, J.C., and Frey, R.A.: The MODIS cloud products: algorithms and examples from Terra, IEEE Transactions on geoscience and Remote Sensing, 41, 459-473, doi.org/10.1109/TGRS.2002.808301, 2003.

4. Line 70: Why not just use 2m RH?

   Answer: We thank the reviewer for this comment. ERA5 does not provide this parameter. There is an option to calculate it using the 2m temperature and dew point, and the surface pressure. This calculation is also not free of problems. Moreover, our analysis shows that RH at 925 hPa is the best correlated meteorological parameter with the cloud cover over land (see Fig. 5a in the revised manuscript). We checked it and the RH at 50 hPa above the surface is very close to RH at 925 hPa over major part of the continents. Therefore, we used in our manuscript the RH_{NS}, as RH at a pressure level that is 50 hPa above the surface to further explore the link between RH and cloud amount.

5. Because this study is using reanalysis clouds to try and say something about observed trends, I find it impossible to evaluate the rest of this paper. Their analysis seems of good quality and internally consistent, beyond the basic issue of using model output as observations. I think that the authors have established a nice analysis framework and if they could utilize the many other long term cloud observations (ship observations, PATMOS-X, ISCCP, MAC-LWP, as in (Norris et al., 2016)) they will be able to have some nice, consistent results. As is, I recommend a reject with encouragement to resubmit when observed clouds are used.

   Answer: We appreciate the constructive feedback and encouragement. In response to this comment, we have updated the manuscript and SI to clarify the distinction between reanalysis and observations.

   For clarity, we have divided the following answer into a few subsections: (5.1) changes in the Introduction section that better justify our choice of using ERA5 cloud cover data rather than long-term cloud observations; (5.2) revised discussion in the Results section that better describes our results and how they compare with studies of long-term observations; and (5.3) a list of added references.

(5.1) Changes in the Introduction section that better justify our choice of using ERA5 cloud cover data rather than long-term cloud observations:

We could not use long-term observational datasets for our global trend analysis due to their severe limitations. We need cloud product that is uniformly sampled over the globe for performing EOF analysis, therefore in-situ observations are not suitable for that. With respect to long-term satellite observations, their limitations regard technical issues such as orbit drifting, calibration, replacement of platforms and so on that bias the real physical trend. Until now, we don't have a good method to decouple these artifacts from real signals. A good example for this is the results shown in Norris and Evan (2015) presenting the trend patterns using the two longest satellite observations (ISCCP and PATMOS-X), after an empirical correction of the artifacts. It can be seen in the figure below (Figure. R1) that the two datasets are inconsistent and show completely different trend patterns; adapted from Fig. 6 in Norris and Evan (2015). It means that those datasets can not be trusted regarding trend analysis.

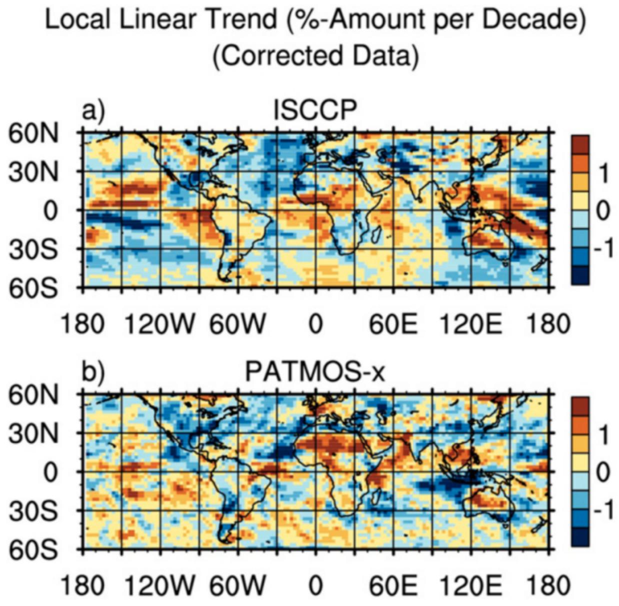

Figure R1: Local linear trend in daytime-only total cloud fraction monthly anomalies for (a) ISCCP after removal of cloud variabilitity associated with satellite zenith angle changes, solar zenith angle changes, and large-scale spatially coherent cloud changes, and (b) PATMOS-x after removal of cloud variabilitity associated with solar zenith angle changes and large-scale spatially coherent cloud changes. The trends are calculated from July 1983 to December 2009. Adapted from Fig. 6 in Norris and Evan (2015).

The revised text in the Introduction section is given below:

"*Previous works that examined tendencies in cloud coverage under a warmer climate show substantial discrepancies among them (Gettelman and Sherwood, 2016; Ceppi et al., 2017; Zelinka et al., 2020). Even estimations for the same cloud type vary between studied periods, locations, datasets, and models (e.g., Norris and Evan, 2015; Zhou et al., 2016; Zelinka et al., 2017; Karlsson and Devasthale, 2018). Key factors in these discrepancies are related to data uncertainties due to measurement errors in observational datasets, on one hand (Chepfer et al., 2014), and the unsatisfactory representation of clouds in climate models, on the other (Stevens et al., 2013). For example, long-term surface observations, such as cloud coverage from the International Comprehensive Ocean – Atmosphere Data Set (ICOADS, Freeman et al., 2017) and the Extended Edited Cloud Reports Archive (EECRA, Hahn and Warren, 1999; Hahn et al., 2012), suffer from non-uniform sampling, changes in the synoptic-code format and stations, and limited coverage (e.g., Eastman et al., 2011; Aleksandrova et al., 2018). On the other hand, long-term satellite records, such as cloud coverage from the International Satellite Cloud Climatology Project (ISCCP, Rossow and Schiffer, 1999), the Pathfinder Atmospheres – Extended dataset (PATMOS-X, Heidinger et al., 2014), and the cloud component in the European Space Agency's (ESA) Climate Change Initiative (CCI) programme (Cloud_cci, Stengel et al., 2017), suffer from changing view geometries and orbit drifts (e.g., Evan et al., 2007; Norris and Evan, 2015). While attempts are being made to correct some of these issues in satellite observations, those corrections may remove actual cloud tendencies at a global scale (e.g., Norris and Evan, 2015; Norris et al., 2016). In addition, those corrected products show significant discrepancies between linear trends in their cloud coverage (Norris and Evan, 2015). As for climate models, the representation of clouds in a coarse resolution grid is subordinate to the small-scale parameterization schemes employed, accounting in a limited way for the full range of scales involved therein (Zelinka et al., 2016; Zelinka et al., 2020).*"

(5.2) Revised discussion in the Results section that better describes our results and how they compare with studies based on long-term observations:

For supporting our claims we conducted an additional analysis to compare our results with linear trends in cloud cover from long-term observations. Figure R2 shows the results. Cloud cover as taken from in-site observations (EECER NDP-026D, Hahn et al., 2012) and corrected satellite observations (PATMOS-X and ISCCP, Norris and Evan, 2015) are considered.

As is shown, the disagreements between long-term cloud observations are clear. For linear trends in cloud coverage from corrected ISCCP, we still see unnatural patterns, such as the discontinuances over Pacific Ocean, Indian ocean and the adjacent

Southern Ocean. But generally speaking, wherever the satellite trends agree with the sign, ERA5 show consistent results. Also, the decreasing cloud cover trend over most of the land agrees well with the in-situ observations.

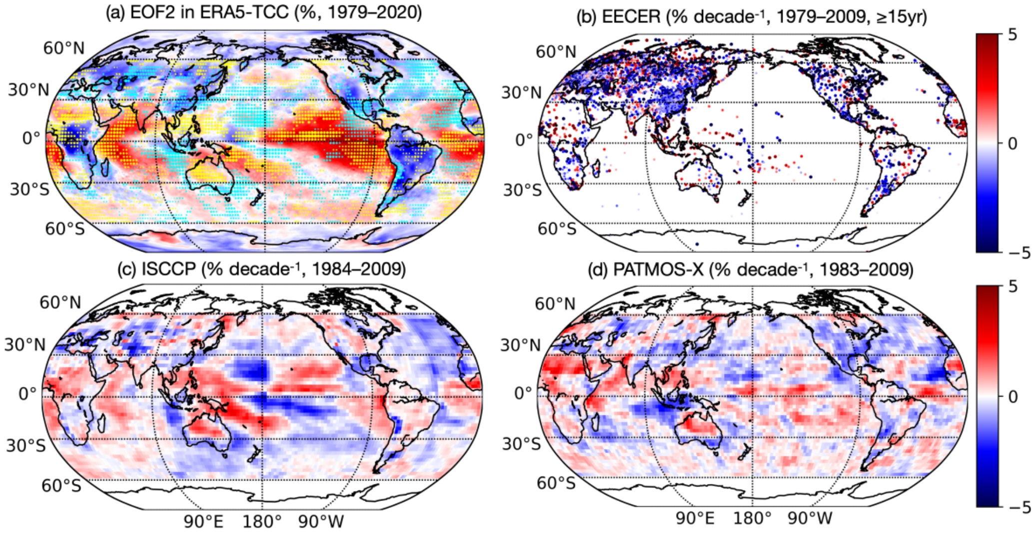

Figure R2: Comparison of trend-mode in cloud coverage from ERA5 and local linear trend in daytime-only total cloud fraction annual anomalies from observations. (a) the scaled second EOF mode (trend-like) for TCC from ERA5 during 1979 – 2020 (same as Fig. 4c in the revised paper); linear trends in cloud coverage from (b) EECER during 1979 – 2009, (c) empirically corrected ISCCP during 1984 – 2009, (b) and empirically corrected PATMOS-X during 1983 – 2009. Note that panel b contains all stations with no less than 15 years of observations. The yellow (cyan) dots in panel a indicate areas with positive (negative) trends in both cloud coverage from both corrected ISCCP and PATMOS-X.

Since previous studies have already provided detailed investigations about these patterns, we didn’t add Fig. R2 to our manuscript. Rather, we gave a more comprehensive comparison between our findings and results from previous studies in the Discussion section of the revised manuscript, please see details below:

“*The reported trends are consistent with previously-made estimations based on long-term observations and historical simulations, such as the general decreasing trend over land revealed by surface observations (Warren et al., 2007), and the general increasing trend over tropics and eastern subtropics revealed by satellite observations and historical simulations (Norris and Evan, 2015; Zhou et al., 2016; Norris et al., 2016). Additionally, analysis in observed liquid water path from the Multisensor Advanced Climatology of Liquid Water Path (MAC-LWP) dataset yields increasing trends over most oceans (Manaster et al., 2017). These increasing patterns suggest consistent results with our findings as well because the value of* *liquid water path for cloud-free atmosphere is considered as 0. However, there are some contradictions with satellite observations, which show decreasing trends over most of the Congo Basin and increasing trends over most of the northeast part of tropical Atlantic (Norris and Evan, 2015). Also, some model-based future-climate prediction studies suggested a decrease in marine stratocumulus cloud coverage in warmer climate conditions (Forster et al., 2021; Zelinka et al., 2016).*”

(5.3) The list of added references:

4. Aleksandrova, M., Gulev, S.K. and Belyaev, K.: Probability distribution for the visually observed fractional cloud cover over the ocean. Journal of Climate, 31, 3207 – 3232, doi.org/10.1175/JCLI-D-17-0317.1, 2018
5. Freeman, E., Woodruff, S.D., Worley, S.J., Lubker, S.J., Kent, E.C., Angel, W.E., Berry, D.I., Brohan, P., Eastman, R., Gates, L., and Gloeden, W.: ICOADS Release 3.0: a major update to the historical marine climate record. International Journal of Climatology, 37, 2211 – 2232, doi.org/10.1002/joc.4775, 2017.
6. Hahn, C.J., and Warren, S.G.: Extended edited synoptic cloud reports from ships and land stations over the globe, 1952 – 1996, United States, doi.org/10.2172/12532, 1999.
7. Hahn, C.J., Warren, S.G., and Eastman, R.: Cloud Climatology for Land Stations Worldwide, 1971-2009 (NDP-026D) (No. NPD-026D), United States, doi: 10.3334/CDIAC/cli.ndp026d, 2012.
8. Heidinger, A.K., Foster, M.J., Walther, A., and Zhao, X.T.: The pathfinder atmospheres – extended AVHRR climate dataset. Bulletin of the American Meteorological Society, 95, 909 – 922, doi.org/10.1175/BAMS-D-12-00246.1, 2014.
9. Manaster, A., O’Dell, C.W., and Elsaesser, G.: Evaluation of cloud liquid water path trends using a multidecadal record of passive microwave observations. Journal of Climate, 30, 5871-5884, doi.org/10.1175/JCLI-D-16-0399.1, 2017.
10. Rossow, W.B., and Schiffer, R.A.: Advances in understanding clouds from ISCCP. Bulletin of the American Meteorological Society, 80, 2261 – 2287, doi:10.1175/1520-0477(1999)080,2261:AIUCFI.2.0.CO;2, 1999.
11. Stengel, M., Stapelberg, S., Sus, O., Schlundt, C., Poulsen, C., Thomas, G., Christensen, M., Carbajal Henken, C., Preusker, R., Fischer, J., and Devasthale, A.: Cloud property datasets retrieved from AVHRR, MODIS, AATSR and MERIS in the framework of the Cloud_cci project, Earth System Science Data, 9, 881 – 904, doi.org/10.5194/essd-9-881-2017, 2017.

6. Alternately, the authors can rewrite this as a model-only paper using ECMWF along

with GCM output and contrast how GCM EOF patterns differ.

Answer: We believe that following the reviewers comments the revised version of the paper explains better the usage of the ERA5 and gives better, more careful context to the shown results.

References:

1. Andrew Manaster, Christopher W. O'Dell, & Gregory Elsaesser. (2017). Evaluation of Cloud Liquid Water Path Trends Using a Multidecadal Record of Passive Microwave Observations. Journal of Climate, 30(15), 5871–5884. https://doi.org/10.1175/jcli-d-16-0399.1
2. Norris, J. R., Allen, R. J., Evan, A. T., Zelinka, M. D., O'Dell, C. W., & Klein, S. A. (2016). Evidence for climate change in the satellite cloud record. Nature, 536(7614), 72–75. https://doi.org/10.1038/nature18273
3. Tiedtke, M. (1993). Representation of Clouds in Large-Scale Models. Monthly Weather Review, 121(11), 3040–3061. https://doi.org/10.1175/1520-0493(1993)121<3040:ROCILS>2.0.CO;2