Dear Editor,

We appreciate the prompt review and would like to thank the three Reviewers' perceptive and helpful comments and suggestions on our manuscript entitled "Observed Trends of Clouds and Precipitation (1983–2009): Implications for Their Cause(s)", Author(s): Xiang Zhong et al., MS No.: acp-2020-577, MS type: Research article. We have carefully considered all comments and suggestions and carried out major revisions as suggested. We believe that the revisions have resulted in a significantly improvement of the paper. Listed below are point-by-point responses to all comments and suggestions of the three reviewers (Reviewer's points in black, our responses in blue).

Anonymous Referee #1

Summary

This is a relatively straightforward paper that reassess changes in both cloud cover and precipitation, and the possible causes of these changes. Which is an important endeavor. Using global satellite data (e.g., corrected ISCCP data and GPCP data), the authors first show similar changes in cloud cover and precipitation, particularly over the Maritime continent, and suggest these changes are largely consistent with widening of the tropical belt (and the moisture-convection-latent heat feedback). They go on to associate a significant percentage of these changes mainly to global warming, but also the AMO. These results are based on correlation/regression analysis alone. In a C1 ACPD Interactive comment Printer-friendly version Discussion paper somewhat disconnected Part 2 of the paper, the authors focus on China, and investigate clouds and precipitation trends from nearly 500 surface stations over a longer time period. Here, the authors argue the decrease in cloud cover and overall shift toward higher precipitation intensity is due to global warming, and the moisture-convection latent heat feedback.

Comments

In terms of the indices that are looked at to understand the cloud and precipitation changes, the authors focus on global mean temperature, as well as the PDO, ENSO

(Nino3.4 SST) and AMO. However, Norris et al. (2016) also argued for the importance of volcanic aerosol in explaining the cloud changes (as described in the Introduction). To some extent, this volcanic aerosol signal should appear in the global mean surface temperature. Any thoughts on how to disentangle this? Any thoughts on the possible importance of volcanic aerosol, and recovery from their cooling? Or is this not important, based on the authors analysis?

This is a very perceptive point. In our deliberation of potential contributors to the cloud and precipitation changes, we have been concentrating on the familiar large-scale climate oscillations but seemingly overlooked relatively short period or regional climatic forcing such as the volcanic aerosol signal of Pinatubo in 1992–1993. It can be seen in a newly added Figure S4 in the Supplement, the Pinatubo signal shows a clear depression in the global temperature of about 0.2 degree in 1992–1993 and recovery in 1994–1995. So the Pinatubo aerosol signal is imbedded in the global temperature change. In regard to how to disentangle this volcanic signal, we believe it would be a great topic for a future study.

The conclusion that the PDO is not very important to the cloud and precipitation changes (which the authors argue are primarily due to tropical widening) is inconsistent with several studies that have argued the PDO is associated with tropical widening/contraction. For example:

Allen, R., Norris, J. & Kovilakam, M. Influence of anthropogenic aerosols and the Pacific Decadal Oscillation on tropical belt width. Nature Geosci 7, 270–274 (2014). https://doi.org/10.1038/ngeo2091

And more generally, others have argued for the importance of natural variability in driving recent tropical expansion (as opposed to global warming, at least over the relatively short time period considered). For example:

Allen, R. J., and M. Kovilakam, 2017: The Role of Natural Climate Variability in Recent Tropical Expansion. J. Climate, 30, 6329–6350 C2 ACPD Interactive comment Printer-friendly version Discussion paper

Mantsis, D. F., Sherwood, S., Allen, R., and Shi, L. (2017), Natural variations of tropical width and recent trends, Geophys. Res. Lett., 44, 3825– 3832, Grise, K. M., and Coauthors, 2019: Recent Tropical Expansion: Natural Variability or Forced Response?. J. Climate, 32, 1551–1571 Can these points, particularly the prior conclusion related to the importance of natural variability, be commented on and incorporated into the paper? ˇ The conclusion that the cloud and precipitation changes are consistent with tropical widening is a bit "hand-wavy". Can the authors better quantify this, with an actual analysis of the data, in the context of tropical edge displacements?

We appreciate this important comment which was also raised above by Referee#3. In our response to Referee#3 (please see the response with Figures 1 and 2 above), we now have revised the manuscript by adding a quantitative evaluation of the primary tropical widening over the Maritime Continent.

Regarding the importance of PDO, shown in Figures 2b-2d above are the changes (blue curve) from the climatology (1983–2009) (black curve) in the annual total precipitation (mm) of the 16 belts of Figure 1 as a function of global temperature (GT), AMO and PDO, respectively. The formula for calculating the blue curve, for instance for the changes in precipitation as a function of global temperature (Figure 2b), is d(TP)/d(GT) ×ΔGT, where ΔGT denotes difference in the global temperature between 1983 and 2009.

It can be seen that Figure 2b (GT) agrees very well with Figure 2a both qualitatively and quantitatively; while Figures 2c and 2d have significantly greater positive values (significant widening) compared to the small negative values (contraction) of Figure 2a for the inner 5 belts, resulting in a significant enhancement of the overall precipitation. This discrepancy is crucial, as the global total annual precipitation, which is equal to global evaporation and determined by the global surface energy budget, increases with global temperature at a rather small rate of about 2%–3% K^{-1} (Cubasch et al., 2001). Therefore, based on the results of Figures 2a-2d, we propose that the trend in global temperature, rather than that of AMO and PDO, is the primary contributor to the observed linear trend of precipitation in 1983–2009. Similarly, it can be seen that Figure 2f agrees with Figure 2e significantly better than Figures 2g and 2h, such that the trend in global temperature, rather than that of AMO and PDO, can be proposed to be the primary contributor to the observed linear trend of total cloud cover in 1983–2009.

It is also unclear how the authors associate tropical widening to the moisture-convection-latent heat feedback. This feedback in largely a thermodynamic feedback, related to global warming and CC scaling. And it seems to largely explain why we would expect less light/moderate precipitation, but more heavy precipitation, under warming. So how does it also explain tropical widening? Is dynamics not important here? Several dynamical mechanisms have been proposed.

Trenberth et al. (2003) summarized the global warming hypothesis by explaining that the precipitation intensity of storms should increase at about the same rate as atmospheric moisture, which is about 7% K^{-1} according to the Clausius–Clapeyron equation. The precipitation intensity could even exceed the 7% K^{-1} because additional latent heat released from the increased water vapour could invigorate the storm and pull in more moisture from the boundary layer, forming a positive feedback cycle (i.e. the moisture-convection-latent heat feedback cycle) and leaving less moisture available for light and moderate precipitation. A comparison of Figure 1 below with Figure 2e above (in our response to referee 3) reveals that the enhancements in precipitation in the tropics (Figure 1) are the major contributor to the tropical widening in observed precipitation (Figure 2e). Since it has been shown by Liu et al. (2016) that the enhancements in precipitation in the tropics are nearly entirely driven heavy precipitation (strong convections), we propose that the tropical widening is primarily driven by the moisture-convection-latent heat feedback.

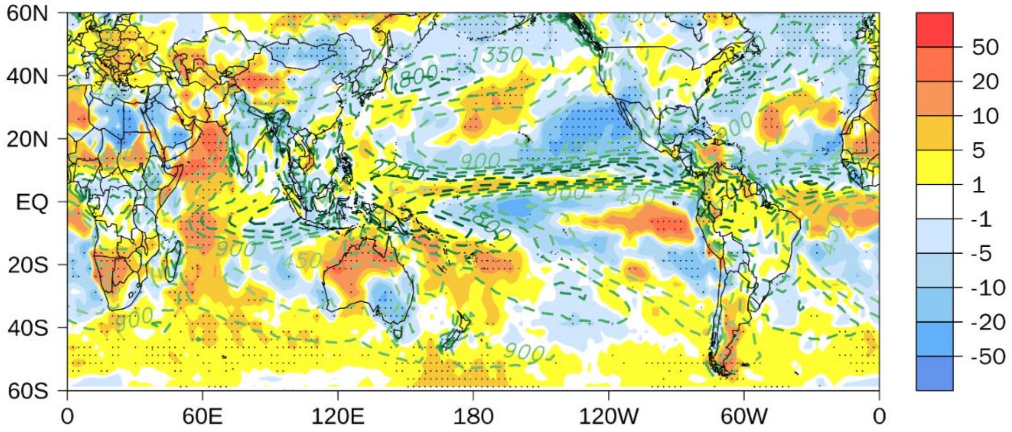

Figure 1. Trends in annual total precipitation (units: % per decade) from GPCP pentad V2.2 (1983–2009). Dots indicate changes significant at the 95% confidence level. Contours indicates the climatology of total precipitation (units: mm per year).

L179 "Direct effect of anthropogenic aerosols on clouds and precipitation in the tropical zone is expected to be small as the majority of aerosol emissions are at northern hemisphere mid–latitudes." Is this true? Aren't there quite a lot of tropical aerosol emissions, for example biomass burning? I suggest including the time series of the climate indices used here (perhaps in the Supplement). The AMO that the authors use is said to have the global warming signal removed. It would be nice to see what this looks like (as well as the other indices, e.g., PDO).

Excellent point, we have included the time series of the climate indices used in the Supplement (Figure S4). We also have replaced the remark of "Direct effect of anthropogenic aerosols on clouds and precipitation…" with "Direct effects of anthropogenic aerosols on clouds and precipitation tend to be regional and/or sub-yearly time scale, which are beyond the scope of discussion in this study."

Can the authors better connect part 1 (global analysis) and part 2 (China analysis) of this paper? At the least, the authors can add a statement to the abstract that indicates they extend the global analysis by similarly investigating connections between clouds and precipitation in China, which has a large number of long-running, high-quality surface weather stations, etc. Or something similar, etc. The abstract also seems to contradict itself. The global analysis largely attributes cloud and precipitation changes to global warming and the AMO. But then the China analysis says the cloud and precipitation changes are largely due to global warming and the PDO, with AMO (and ENSO) playing an insignificant role, consistent with the global analysis. The only thing consistent is the dominance of global warming, right? AMO is important for the global analysis, but is not important for the China analysis.

Thanks for a very thoughtful and helpful comment! We have significantly revised the abstract to better connect part 1 (global analysis) and part 2 (China analysis) of this paper, and to address consistency between part 1 and part 2, as shown below.

Further analysis of the widening of the Hadley and Walker circulations (Figures 3a-3h) shows that the trend in global temperature, rather than that of AMO and PDO, is the primary contributor to the observed linear trends of total cloud cover and precipitation in 1983–2009. The underlying mechanism driving this widening is proposed to be the moisture–convection–latent heat feedback cycle under global temperature conditions. The global analysis is extended by investigating connections between clouds and precipitation in China, which has a large number of long-running, high-quality surface weather stations in 1957–2005, which reveals a quantitative matching relationship between the reduction in light precipitation and the reduction of total cloud cover. Furthermore, our study suggests that the reduction of cloud cover in China is primarily driven by the global temperature conditions, PDO plays a secondary role, while the contribution from AMO and Niño3.4 is insignificant, consistent with the global analysis.