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. The sequence of our responses is ordered by the time received, i.e. Referee #3 followed by Referee #1 and Referee #2. 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 #3 interactive comment**

The authors present two analyses concerning trends in clouds and rainfall. One uses global, satellite-observed cloud and precipitation data to show that cloud cover and precipitation trends are consistent with an expanding tropical belt. The other looks at surface-observed clouds and rain rates in China to show that light, stratiform rain and overcast clouds are declining while convective rain associated with more broken clouds is relatively more common. These results are consistent with prior work showing a widening tropical belt and a trade-off from stratiform precipitation in favor of convective precipitation.

The work addresses some very large and interesting problems using a fairly simple and easy to understand method, which is commendable. The quality and presentation of the manuscript is high and the work presents great value to the community. There are a few places where the analysis needs a bit more rigor, especially regarding the removal of long-term variation from timeseries in the correlation analysis. It is crucial that we know that the correlations we see are due to interannual variations and not due to coinciding trends. If the authors can do this bit of extra work, the results will be significantly more robust.

We appreciate very much for these encouraging comments. As shown below, we have made extensive revisions in point-by-point responses to your comments and suggestions.

**Major comments:**

There is talk of a widening Hadley cell, and the results do hint at this, but I would love to see a bit more rigor in 1) defining what your data show as the tropical belt, maybe with a zonal mean plot showing the mean clouds/precipitation for latitude zones, then 2) showing the mean trends for the same zones. You could do this globally, or for a specific region between longitude bounds.

We gratefully accept this suggestion by explicitly evaluating the widening of Hadley cell in the observed trends of precipitation and cloud cover “for a specific region between longitude bounds”. The results reveal a pleasant surprise, as Figure 3 below provides adequate evidence to show that the trend of global temperature, rather than the trends of AMO and PDO, is the primary contributor to the observed linear trend of precipitation in 1983–2009.

As a measure of the widening of Hadley circulation, we calculate and illustrate the expansion of cloud cover and precipitation as a function of 16 rectangle belts centered in the middle of Kalimantan, Indonesia which is located near the major ascending/wet zone of Hadley cell (Figure 2). Each rectangle belt is 2.5 degree wide in both latitude and longitude except the first rectangle is 5 degree wide in latitude and 55 degree wide in longitude.

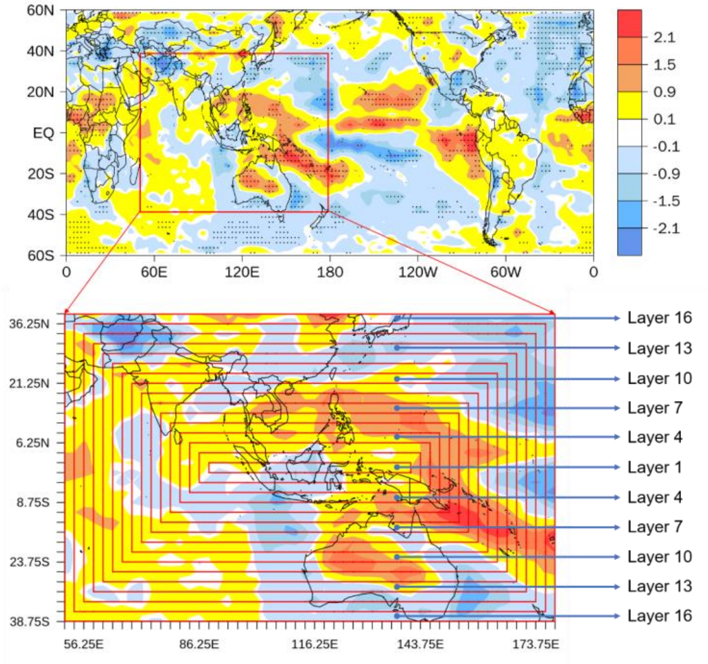


Figure 2. Maps of the 16 rectangle belts of 2.5 degree wide in both latitude and longitude centered in the middle of Kalimantan, Indonesia which is located near the major ascending/wet zone of Hadley cell. The expansion of cloud cover and precipitation relative to these belts are used as a measure of the widening of Hadley circulation.

Figures 3a and 3e depict for annual precipitation and total cloud cover, respectively, their "climatology" (black curve) and "climatology + change during 1983-2009" (blue curve). It can be seen that, for a specific value of the y-axis, the blue curve is characterized by a shift horizontally (x-axis direction) to the right (i.e. higher number of belt) of the black curve for most of Figures 3a and 3e. In comparison, there is very little upward shift in the vertical or y-axis direction, especially at low-end (belt 1 and 2) and high-end belts (belt 15 and 16). As a result, there is hardly any enhancement in total cloud cover and total precipitation. These characteristics can be interpreted as an expansion to higher latitudes and wider longitudes, i.e. widening of the Hadley and Walker circulations during the period of 1983-2009. Quantitatively the degree of expansion depends on the selected value of the y-axis, increasing quickly when the value is near 1000mm precipitation level (Figure 3a) or 55% of TCC (Figure 3e). The value of shift is typically within the range of one quarter to three quarters of a belt width (2.5 degree), or about 0.6-1.9 degree. These annual values are comparable to the poleward shift of the subtropical dry zones (up to 2° decade$^{-1}$ in June‐July‐August (JJA) in the Northern Hemisphere and 0.3–0.7° decade$^{-1}$ in June‐July‐August and September‐October‐November in the Southern Hemisphere) found by Zhou et al. (2011).

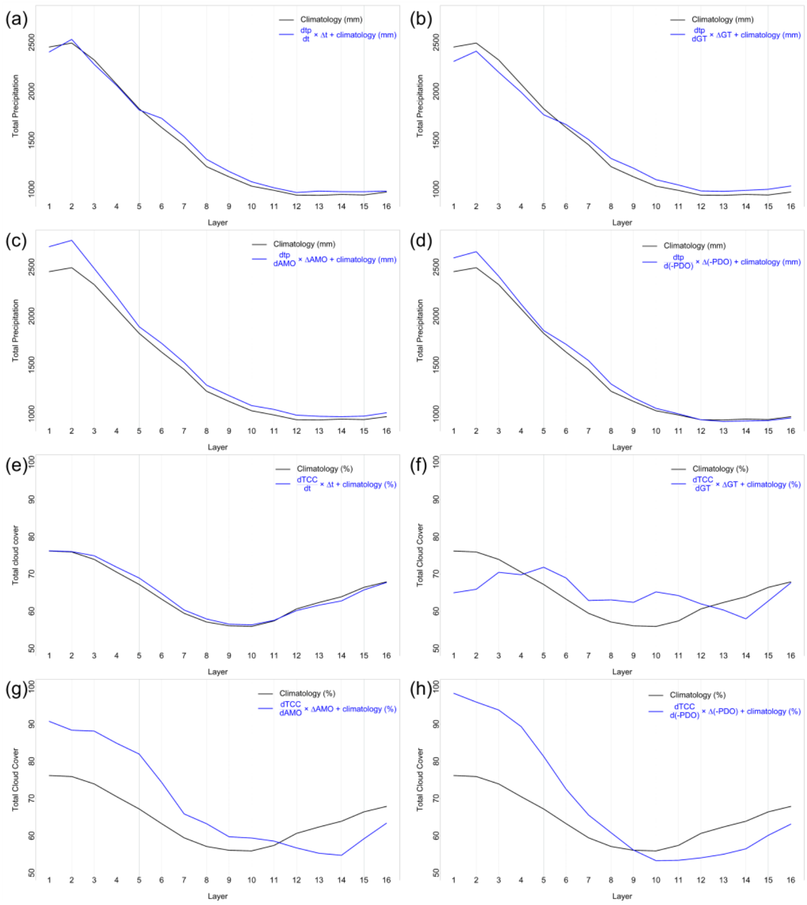


Figure 3. Changes (blue curve) from the climatology (black) during the period 1983 –2009 in the annual total

precipitation (mm) in the 16 belts of Figure 2 as a function of time (a), global temperature (b), AMO (c) and PDO (d). Changes from the climatology in the annual total cloud cover (%) in the 16 belts of Figure 2 as a function of time (e), global temperature (f), AMO (g) and PDO (h). The formula for calculating the blue curve, for instance for the changes in precipitation as a function of global temperature (Fig. 3b) is d(TP)/d(GT)*ΔGT where ΔGT denotes difference in the global temperature between 1983 and 2009.

Figures. 3b-3d show the changes (blue curve) from the climatology (1983–2009) (black curve) in the annual total precipitation of the 16 belts of Figure 2 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 (Fig. 3b), is d(TP)/d(GT)*ΔGT, where ΔGT denotes difference in the global temperature between 1983 and 2009. It can be seen that Fig. 3b (GT) agrees very well with Fig. 3a both qualitatively and quantitatively; while Figs. 3c and 3d have significantly greater positive values (significant widening) compared to the small negative values (contraction) of Fig. 3a for the inner 5 belts, resulting in a significant enhancement of the overall precipitation. This discrepancy is crucial, as the amount of 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 Figs. 3a-3d, 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 Fig. 3f agrees with Fig. 3e significantly better than Figs. 3g and 3h, 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.

In summary, the spatial distributions of the linear trends of total cloud cover and precipitation are characterized primarily by a widening of the center of precipitation (ascending/wet zone of Hadley cells) over the Maritime Continent in all directions (R. Liu et al., 2016; Zhou et al., 2011). Quantitative 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 trend of total cloud cover and precipitation in 1983–2009. The underlying mechanism driving this widening is believed to be the moisture–convection–latent heat feedback cycle under increasing SST conditions.

I'm not completely convinced by the trend/correlation analysis discussed in Figure 3 and the associated tables. Specifically, I'm concerned that linear trends in timeseries being correlated may occur coincidentally and that this could be driving much of the signal in Figure 3. The authors need to show that the relationships between global temperature and regional variations in cloud cover and precipitation are consistent when the linear trends (or long-term variability with very few independent data points) are removed. This removal could be done either by detrending the time series or by filtering out a 5-year or 10-year running mean. The maps showing significant relationships after this filtering will more clearly show how year-year global temperature variations interact with year-year cloud and precipitation variations. Basically, the idea is that if temperature is actually driving cloud and precip changes, then the relationship should be apparent on both decadal and yearly timescales. To aid in this, you could also show a few time series plots for some significant regions as an example, showing that year-year temperature and cloud variations are similar, most importantly by adding a temperature plot to Figure 2.

We agree with you on "linear trends in timeseries being correlated may occur coincidentally and that this could be driving much of the signal in Figure 3". Following your suggestion, we have re-evaluated Table 1 using detrended data of TCC, TP, GT, AMO, PDO and Niño3.4 (Table S1). The correlation coefficients are all less than 0.33, implying that consecutive yearly variabilities contribute insignificantly to the high correlation coefficients in Table 1, and the high correlation coefficients are nearly entirely contributed by the long-term linear trends of GT on PDO and AMO. One of the reasons for the lack of correlation could be due to the small consecutive yearly variabilities relative to the long-term linear trends (about 0.1) for GT on PDO and AMO (Figure S4).

Table S1 Correlation coefficients of detrended data

| R | Trend of TCC | Trend of TP |
|---|---|---|
| δ(GT) | -0.23 *** | -0.16 *** |
| δ(-PDO) | 0.33 *** | 0.10 *** |
| δ(AMO) | -0.02 | -0.16 *** |
| δ(Niño3.4) | -0.19 *** | 0.05 *** |
| δ(GT)+δ(-PDO) | 0.32 *** | 0.04 *** |
| δ(GT)+δ(AMO) | -0.21 *** | -0.18 *** |
| δ(GT)+δ(Niño3.4) | -0.22 *** | -0.17 *** |
| δ(-PDO)+δ(AMO) | 0.30 *** | 0.04 *** |
| δ(-PDO)+δ(Niño3.4) | 0.32 *** | 0.09 *** |
| δ(AMO)+δ(Niño3.4) | 0.03 ** | -0.15 *** |
| δ(GT)+δ(-PDO)+δ(AMO) | 0.29 *** | -0.01 |
| δ(GT)+δ(-PDO)+δ(Niño3.4) | 0.32 *** | 0.04 *** |
| δ(GT)+δ(AMO)+δ(Niño3.4) | -0.18 *** | -0.18 *** |
| δ(-PDO)+δ(AMO)+δ(Niño3.4) | 0.29 *** | 0.04 *** |
| δ(GT)+δ(-PDO)+δ(AMO)+δ(Niño3.4) | 0.28 *** | -0.01 |

By detrended time series, it was calculated as d(detrended TCC)/(d(detrended GT)/std(detrended GT)); linear trends are the same with the original one.

Line 105 & 106: Can you clarify this? It sounds like you mean that you chose stations that have consistent reporting throughout the year. Can you also clarify whether observation timing throughout the diurnal cycle remains consistent for those years? Are you excluding any night data if lunar illumination is insufficient, or can you show that interannual variation of daytime data is equivalent to night?

The station data used in this study are daily data. The original data we have started calculating were already in the daily time resolution. According to the introduction of this data, the daily data were averaged from four-time measurements (02:00, 08:00, 14:00, 20:00, all in local Beijing time) for each day. Therefore, the night data should be involved in this daily data.

To avoid any more concern about how night data could affect our result, here we cite Kaiser (1998) who also analyzed station data as a proof that daytime data and night data share a similar change for cloud cover (as shown in Figures R1 & R2 below).

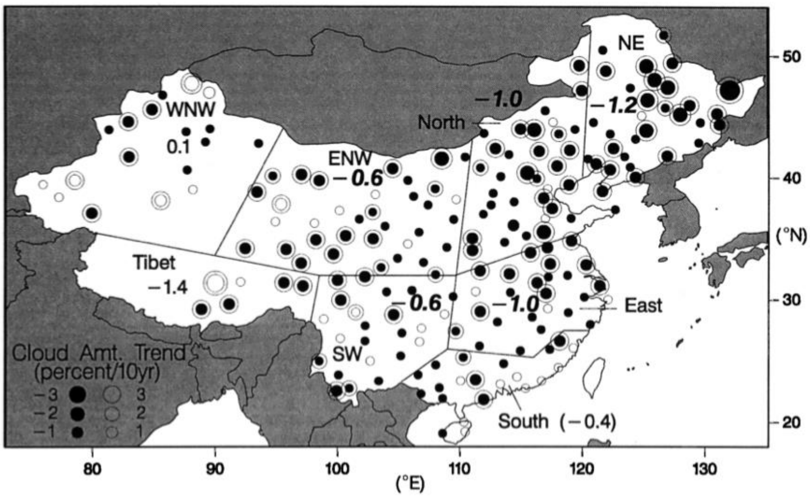


Figure R1. Trends in annual mean midday cloud amount for 1951-1994 (percent sky cover per decade). Station trend indicators with circles around them are significant at the 95% confidence level, as are regional trend values that are in bold italics (Kaiser, 1998).

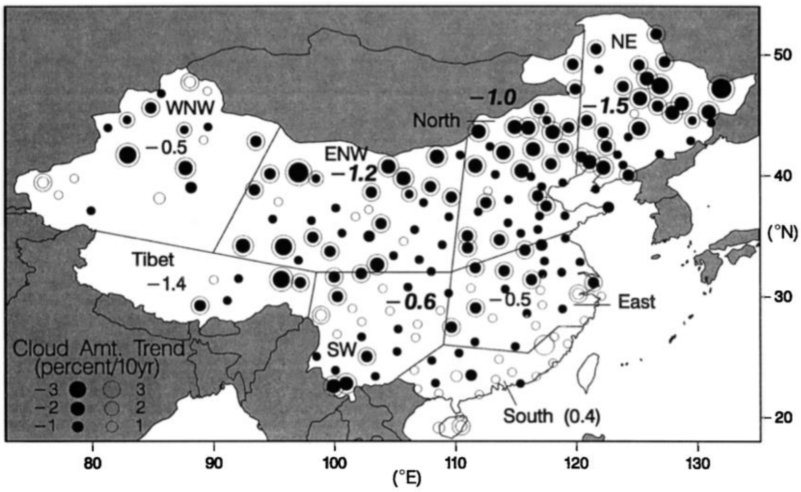


Figure R2. As in Figure R1, but for annual mean midnight cloud amount, 1954-1994 (Kaiser, 1998).

**Minor comments:**

Line 49: I think you may be referring to Eastman, Warren, and Hahn (2011) that uses ocean observations. The 2013 paper is only concerned with land stations.

Yes, we have added the reference to Eastman, Warren, and Hahn (2011).

Can you list the grid spacing of all data? The precip data is 2.5x2.5 and it appears that the clouds are at that resolution as well? The spacing itself appears appropriate, with little spurious-looking noise in the contour plots.

Done as suggested.

I think you need one more sentence describing the Norris and Evan empirical method for removing spurious trends, something like: "by removing anomalous cloud variability within individual grid boxes shown to be associated with artifact factor anomalies", which is (somewhat lazily) adapted from their abstract.

Done as suggested.

Figure 1: It's frustrating that the contours of total precipitation aren't plotted in the midlatitude storm tracks, but the trends seem to be plotted in these regions. Can you explain this discrepancy, or better yet, plot the climatological average precipitation in the regions where you plot the trends? There appear to be some regions, especially the N Atlantic where precip contours vanish. The chosen contour interval may not be sensitive enough to show variability in many regions, which is why there aren't contours plotted. Could you tighten the interval for total precip values below 900? This would really aid the paper since the southern ocean storm track and N Atlantic also appear to have a significant precipitation trends.

Thanks, we have added more contours.

Figure 5: Can you provide numbers that show what these bins mean? What intensity of rain occurs in bin 10, for instance? Line 198 says bins are 'equal'. Does this mean equal

number of obs per bin, or equal ranges of rain rate within each bin?

We have now listed the intensity range of each bin. For Line 198, the phrase has been changed to “the ten bins of equal rain rate”.

**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 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

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 2 and 3 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 Figs. 3b-3d 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 2 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 (Fig. 3b), is d(TP)/d(GT)*ΔGT, where ΔGT denotes difference in the global temperature between 1983 and 2009. It can be seen that Fig. 3b (GT) agrees very well with Fig. 3a both qualitatively and quantitatively; while Figs. 3c and 3d have significantly greater positive values (significant widening) compared to the small negative values (contraction) of Fig. 3a 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 Figs. 3a-3d, 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 Fig. 3f agrees with Fig. 3e significantly better than Figs. 3g and 3h, 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 Fig.1b below with Fig. 2e above reveals that the enhancements in precipitation in the tropics (Fig. 1b) are the major contributor to the tropical widening in observed precipitation (Fig. 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.

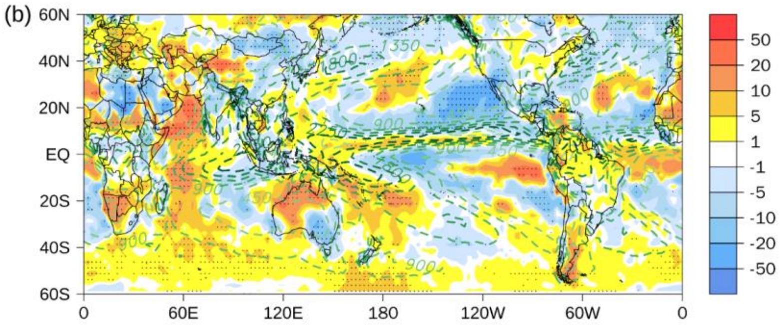


Figure 1. (b) Trends in annual total precipitation (units: % per decade) from GPCP pentad V2.2 (1983–2009). Dots indicate changes significant at the 95% confidence level. Contours indicates the climatology of total precipitation (units: mm per year).

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.

**Anonymous Referee #2**

The main focus of this paper is establishing the role of global warming, AMO, and PDO in the spatial pattern of global cloud and precipitation trends (based on global satellite records). Cloud cover and precipitation trends from Chinese meteorological stations are also examined. Unfortunately, I find a number of major flaws in this paper and do not believe that it meets the quality for publication in ACP at this time: 1) There is a lot of overlap with recent papers that have performed similar analyses, and I struggle to see how this paper provides a substantial new contribution to the peer reviewed literature. Figure 1a is nearly identical to Figure 1a in Norris et al. (2016), the PDO/AMO analysis is similar to that in Chen et al. (2019), and Adler et al. (2017) already examine contributions of the PDO and AMO to global precipitation trends. Adler, R.F., Gu, G., Sapiano, M. et al. Global Precipitation: Means, Variations and Trends During the Satellite Era (1979–2014). Surv Geophys 38, 679–699 (2017). https://doi.org/10.1007/s10712-017-9416-4 2)

We agree with the criticism that there are already numerous studies on our subject of study. However, as stated in our introduction, there is hardly any agreement on the quantitative roles of global warming, AMO, and PDO in the spatial pattern of global cloud and precipitation trends. Moreover, there are very few studies utilizing both cloud and precipitation data sets. Last but not the least, with a lot of help of all three referees' comments, we believe that in the revised manuscript we have made "a substantial new contribution" in the conclusion below: Further analysis of the widening of the Hadley and Walker circulations (Figures 3a-3h, see above) shows that the trend in global temperature, rather than those 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.

How reliable are the trends in the satellite data products? While the authors use the corrected data set of Norris and Evan (2015) to account for some of these issues in the

ISCCP data, no mention is made of the reliability of the trends in the GPCP precipitation data set (line 91). Also, no discussion is provided of the role that potential instrumentation/reporting method changes may play in the trends from the Chinese meteorological stations.

This point is well taken. In our study, the reliability of data products is mainly concerned with the precision rather than the absolute accuracy of the data. So comparison of different instruments are usually used to evaluate the reliability of the trends in the ISCCP data or GPCP precipitation data set. For example, Xie et al. (2003) found that good agreement is observed between the pentad GPCP and the gauge-based dataset of Shi et al. (2001) over the combined space–time domain. The correlation is 0.776, 0.660, and 0.688, respectively, for the total value, anomaly, and intraseasonal components of the pentad precipitation. These results imply the reliability of the GPCP pentad data is on the order of 70%, or uncertainty of 30%. For the ISCCP data set Norris and Even (2015) found that the root-mean-square difference between ISCCP and PATMOS-x grid box trends decreases from 2.0% (the amount per decade for the original data) to 0.9% (the amount per decade for the fully corrected data). Disagreement between ISCCP and PATMOS-x cloud trends may be due to differing satellite instruments and methods of cloud retrieval or remaining artifacts in the datasets.

We have made extensive comparisons of the ISCCP data and the GPCP precipitation data with corresponding data at the surface stations in China. In many cases, correlations of better than 0.7 were observed, particularly for precipitation data. Therefore, we believe that the correlation results of 0.7 or better are reliable in this study.

Shi, W., R. W. Higgins, E. Yarosh, and V. E. Kousky, cited 2001: The annual cycle and variability of precipitation in Brazil. NCEP/Climate Prediction Center Atlas, No. 9, National Oceanic and Atmospheric Administration. National Weather Service. [Available online at http://www.cpc.noaa.gov/researchppapers/ncep_cpc_atlas/9/index.html.]

3) Trends in cloud cover and precipitation are attributed to global warming, AMO, and PDO over the 1983-2009 period, yet this is a very short interval for isolating signatures from decadal modes of variability. Additionally, all three of these indices (global temperature, AMO, and PDO) experience trends over this period. So, is this period even long enough to attempt an analysis like this, because it's less than one full oscillation for the PDO and AMO? How do you have enough degrees of freedom to accurately identify the pattern of cloud and precipitation anomalies associated with the PDO and AMO and distinctly separate it from the global warming trend contribution? And, just because global temperatures are warming, it doesn't mean that concurrent trends in clouds and precipitation are necessarily caused by global warming.

Thank you for a highly significant criticism. From a different angle, the other two referees have raised the same concerns. In our response to Referee#3 (please see the response with Figures 2 and 3 above), we now have revised the manuscript by adding a quantitative evaluation of the primary tropical widening over the Maritime Continent. Shown in Figs. 3b-3d above are the changes (blue curve) from the climatology (1983–2009) (black curve) in the annual total precipitation of the 16 belts of Figure 2 as a function of global temperature (GT), AMO and PDO, respectively. The formula for calculating the blue curve, for instance for the change in precipitation as a function of global temperature (Fig. 3b), is d(TP)/d(GT)*ΔGT, where ΔGT denotes difference in the global temperature between 1983 and 2009. It can be seen that Fig. 3b (GT) agrees very well with Fig. 3a both qualitatively and quantitatively; while Figs. 3c and 3d have significantly greater positive values (significant widening) compared to the small negative values (contraction) of Fig. 3a 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 Figs. 3a-3d, we propose that the trend in global temperature, rather than those of AMO and PDO, is the primary contributor to the observed linear trend of precipitation in 1983–2009.

Similarly, it can be seen that Fig. 3f agrees with Fig. 3e significantly better than Figs. 3g and 3h, such that the trend in global temperature, rather than those of AMO and PDO, can be proposed to be the primary contributor to the observed linear trend of total cloud cover in 1983–2009.

The similarity in Figs. 1 and 3 is by construction, as the global temperature time series is dominated by an increasing trend (so any trend in clouds and precipitation will by definition be highly correlated with global temperature). It would be better to define Figure 3 using a detrended global temperature timeseries (as Reviewer #3 also suggests). Another related concern is a lack of independence of the global temperature, AMO, and PDO indices (because they all have trends over the 1983-2009 interval).

Thanks, you are right! In our response to the same question by Referee#3, we have re-evaluated Table 1 using detrended data of TCC, TP, GT, AMO, PDO and Niño3.4 (Table S1). The correlation coefficients are all less than 0.33, implying that consecutive yearly variabilities contribute insignificantly to the high correlation coefficients in Table 1, and the high correlation coefficients are nearly entirely contributed by the long-term linear trends of GT on PDO and AMO. One of the reasons for the lack of correlation in the detrended data could be due to the small ratio between the consecutive yearly variabilities and the long-term linear trends (about 0.1) for GT, PDO or AMO (Figure S4).

How can the global warming trend explain 67% of the variance in the global cloud cover trends and the AMO trend explain 49% (line 158)? You can't explain more than 100% of the variance, unless the indices are not independent of one another. In other words, it doesn't appear that the global warming, PDO, and AMO indices are actually orthogonal to one another (as is claimed on lines 166-167).

We agree there is a problem of explaining more than 100% of the variance. We didn't try to hide the problem, as we stated in the original manuscript: "PDO together with AMO and GT, obviously has a problem of over 100% explanation of the spatial variabilities of linear trends in cloud cover and precipitation. Since the trend of global SST has been removed from the PDO and AMO indexes in this study, in theory GT should be orthogonal to those of PDO and AMO." In practice the orthogonality is not attained because the trend of global SST doesn't equal to the real influence of global temperature on PDO or AMO. It is difficult to remove exactly the influence of global temperature from PDO or AMO index. This is likely the main reason of the problem of over 100% explanation.

4) The authors are examining cloud and precipitation features in the deep tropics and attributing them to a poleward shift in the Hadley cell edge and midlatitude jet streams (lines 131-132, 138-140). The expansion of the Hadley cell and poleward shift of the jet streams affects precipitation in the subtropics and midlatitudes (poleward of 30 degrees latitude), not in the deep tropics. For tropical precipitation changes, the authors need to really be comparing their results with recent changes in the ascending branch of the Hadley cell (Intertropical Convergence Zone), not the descending branch in the subtropics.

Thanks for an excellent point! In the new Fig. 3e (see above), one can see that the expansion of the Hadley cell as measured by clouds starts at belt 2 (3.75$^{o}$ latitude), i.e. the blue curve starts to move to the right of the black curve near 3.75$^{o}$ latitude. This is near the center of the ascending branch of the Hadley cell in the Maritime Continent. The expansion of the Hadley cell as measured by precipitation (Fig. 3a) starts near belt 5 (12.5$^{o}$ latitude). This is likely due to the constraint on the change of 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).

5) Section 3b seems like a separate study and to not be related to the rest of the paper. Trends in a small region are not necessarily affected by global drivers, and regional influences are not discussed at all. This data analysis also suffers from similar problems as the global analyses in section 3a (see major comments #2 and #3).

All three referees raised this important concern. We have made changes in both the abstract and the beginning of section 3.2 to better connect the global part and the analysis of data in China (see below). Moreover, we now have established a more consistent results for the two parts.

The new addition to section 3.2 is: 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 over the period of 1957–2005. The long-running data enable the analysis to be carried out over a period that AMO loses while PDO flips its linear trend. More importantly, the high-quality data allow us to make a meaningful analysis without using the correlation method, which has an intrinsic weakness in implying a cause-effect relationship as discussed above.

The revision to the abstract on this issue is: 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.

Minor Revisions Lines 20-29: The trends described in this paragraph do not appear to closely match those shown in Norris et al. (2016), especially over land and over the Indian Ocean.

We are confused by this comment. We checked and compared Figure 1 in Norris et al. (2016) with our Figure 1, they are very consistent.

Lines 54-71: Somewhere in this paragraph, it is probably worth mentioning that the constraint on global precipitation is 2–3% per K, and not 7% per K. See, for example, Jeevanjee and Romps (2018; https://doi.org/10.1073/pnas.1720683115).

Agree, this is now added in two places. One is in the 3rd paragraph of section 3.1, the other in the 7th paragraph of the same section.

Line 69, 131-132, 138-140: See major comment #4. The expansion of the Hadley cells has nothing to do with enhancement of tropical precipitation. It is related to subtropical static stability (Chemke and Polvani 2019: https://doi.org/10.1175/JCLI-D-18-0330.1). If anything, an expansion of tropical precipitation would contradict the literature, which suggests a narrowing of the Intertropical Convergence Zone in a warming climate (Byrne and Schneider 2016: https://doi.org/10.1002/2016GL070396; Su et al. 2017: https://www.nature.com/articles/ncomms15771).

We understand this is a controversial point. Please see our response to your major comment #4.

Line 160: The figure for the PDO really belongs in the main body of the paper, as it is part of the main conclusions of the paper (see abstract).

Thanks, we now have two figures (Figs.3d and 3h) for the PDO.

Line 187: No, the key difference here is that Chen et al. (2019) use the first 300 years of control model simulations to define the cloud cover patterns associated with the PDO and AMO, which avoids the issues of concurrent trends in the indices using the observations (see major comment #3 above).

We disagree on this point, because we question the credibility of climate models in the simulation of changes in clouds and precipitation as a function of AMO or PDO.

Lines 189-193: Why is the PDO deemed insignificant here? Is this based entirely on Eastman and Warren's analysis? Nothing shown in this paper appears to make the PDO less significant than the AMO (see Table 1).

Please see our response to your major comment#3. The new results on the widening of the Hadley circulation (Figs. 3a-3h above) suggest that the contribution of both PDO and AMO are insignificant compared to the global temperature increase.

Lines 208-210: Could the increase in non-precipitation days and decrease in light precipitation days reflect a change in reporting method? How do you know that these changes are in fact physical?

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.

Lines 237: Difficult to read as written. The equation should be spaced out. Figures: I would suggest inverting the color bar such that blues correspond to more clouds/precipitation and reds correspond to less.

Thanks for the suggestion. After some deliberation we choose to retain the current color bar.

Table 1: How are you evaluating significance? I have a difficult time believing that a correlation of 0.02 is still significant at the 95% confidence level. Are you taking into account autocorrelations among neighboring grid points, which would greatly reduce the number of degrees of freedom in your t-test? Table 2: Similarly, how is significance being evaluated here? A trend of 0% (see T60%) should not be statistically significant at all, especially at the 99% level.

We used the function imbedded in R named corr to do this significance test. The function corr we chose applies Pearson correlation formula:

$$r = \frac{\sum(x - m_x)(y - m_y)}{\sqrt{\sum(x - m_x)^2 \sum(y - m_y)^2}}$$

$m_x$ and $m_y$ are the means of x and y variables.

The p-value of the correlation is determined by calculating the t value as follow:

$$t = \frac{r}{\sqrt{1 - r^2}} \sqrt{n - 2}$$

then using t distribution table for the degrees of freedom: df = n-2 to get the p-value.

We believe even when the correlation coefficient r is very small, due to the big value of n (the number of samples we used in calculation), the t value should remain a very big value, therefore brings a reliable significance.

Typos Line 20: are of great importance

Thanks, changed accordingly.

Line 27: places affiliated to Australia – not sure what this means, please rephrase

Rephrased to "around Australia".

Line 98: provided by

Changed accordingly.

Line 99: retained

Changed accordingly.

Line 105-106: Incomplete sentence . . . please rewrite.

Rewritten accordingly.

Line 145: is robust

This part is rewritten.

Figure 6a: bottom 10%-40%

Changed accordingly.

# Observed Trends of Clouds and Precipitation (1983–2009): Implications for Their Cause(s)

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**Abstract.** Satellite observations (ISCCP, 1983–2009) of linear trends in cloud cover are compared to those in global precipitation (GPCP pentad V2.2, 1983–2009), to investigate possible cause(s) of the linear trends in both cloud cover and precipitation. The spatial distributions of the linear trends of total cloud cover and precipitation are both characterized primarily by the widening of Hadley circulation and poleward shifts of the jet streams associated with global warming. Our correlation studies suggest that global warming, AMO, PDO and Niño3.4 can explain 67%, 49%, 38% and negligible, respectively, of the spatial variabilities of the linear trends in cloud cover. Further analysis of the widening of the Hadley and Walker circulations 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.

## 1 Introduction

Long term changes in cloud cover are of great importance to the climate as well as the entire ecosystem. Changes in cloud cover associated with climate change remain one of the most challenging aspects of predicting future climate change. Previous studies have shown that over land, except for the Arctic, central northern Africa and the Pacific islands around Indonesia, show various decreasing trends (Eastman and Warren, 2013; Free and Sun, 2013; Mahlobo et al., 2019; Norris et al., 2016; Rajeevan and Nayak, 2017; Schulz et al., 2011). In China there are a number of studies reporting a significant decrease in total cloud cover ranging from −0.76% per decade to −0.9% per decade during the past few decades (Kaiser, 1998, 2000; Liang and Xia, 2005; Xia, 2010; Xia, 2012; Y. Liu et al., 2016). Over the ocean, the equatorial central Pacific and midlatitudes of both hemispheres, northern Atlantic, and places around Australia show also a decreasing trend. On the other hand, the tropical western Pacific, the subtropical eastern Pacific of both hemispheres, southern Atlantic, and nearly the entire Indian Ocean show increasing trends (Chen et al., 2019; Mao et al., 2019).

In a study of changes in cloud cover observed from land stations worldwide (1971–2009), Eastman and Warren (2013) found that global average trends of cloud cover suggest a small decline in total cloud cover, on the order of 0.4% per decade. Their analysis of zonal cloud cover changes suggests widening tropical belt and poleward shifts of the jet streams in both hemispheres associated with global warming. In addition, they found that changes in cloud types associated with the Indian monsoon are consistent with the suggestion of black carbon aerosols affecting monsoonal precipitation, causing drought in northern India. On the other hand, they found that northern China, where large emissions of anthropogenic aerosols exist, did not show an obvious aerosol connection. Norris et al. (2016) showed that several independent, empirically corrected satellite records exhibit large-scale patterns of cloud change between the 1980s and the 2000s that are similar to those produced by model simulations of climate with recent historical external radiative forcing. Observed and simulated cloud change patterns are consistent with poleward retreat of mid-latitude storm tracks, expansion of subtropical dry zones, and increasing height of the highest cloud tops at all latitudes. The primary drivers of these cloud changes appear to be increasing greenhouse gas concentrations and a recovery from volcanic radiative cooling. These findings are consistent in general with those of Eastman and Warren (2013).

Chen et al. (2019) investigated changes in clouds associated with decadal climate oscillations including the Pacific decadal oscillation (PDO) and the Atlantic multidecadal oscillation (AMO) by comparing cloud cover data (1983–2009) over the oceans from the International Satellite Cloud Climatology Project (ISCCP) (Schiffer and Rossow, 1983) with General Circulation Models (GCM) simulations. They found that the observed linear trends in cloud cover are more closely related to decadal variability (including PDO and AMO) than to greenhouse gases (GHG) induced warming. It should be noted that the changes/trends in cloud cover over the oceans found in Chen et al. (2019) are in good agreement with those of Eastman et al. (2011) , which were derived from synoptic observations made by observers on ships. The agreement provides credence of both data sets and the major patterns of the changes/trends in cloud cover derived in the two studies. On the other hand, the two studies differ on attributing the trends of cloud cover to global warming, PDO and/or AMO. In this context, we note that PDO, AMO and global temperature all have significant linear trends during the relatively short period 1983–2009 studied by Chen et al. (2019), while PDO did not have any trend during the period 1971–2009 studied by Eastman and Warren (2013).

Closely related to the changes in cloud cover, there are extensive reports of enhancements in heavy precipitation and reductions in the light and moderate precipitation in China (Jiang et al., 2014; Karl and Knight, 1998; Klein Tank and Können, 2003; Manton et al., 2001; R. Liu et al., 2015, 2016; S. C. Liu, 2009; Shiu et al., 2012; Sun et al., 2007; Wang and Zhai, 2008; Wu and Fu, 2013), as well as in a widespread land and oceanic areas around the globe (Adler et al., 2017; Fujibe et al., 2005; Goswami et al., 2006; Groisman et al., 2005; Karl and Knight, 1998; Klein Tank and Können, 2003; Manton et al., 2001). These changes in precipitation extremes have been attributed primarily to global warming (Allen and Ingram, 2002; R. Liu et al., 2015; Trenberth, 1998). Trenberth et al. (2003) summarized the global warming theory as follows. In the global warming environment, if everything else remains the same, the precipitation intensity of a storm should increase at the same rate as the atmospheric moisture which increases at about 7% $K^{-1}$ according to Clausius–Clapeyron (C–C) equation. They further argued that the increase in heavy rainfall can even exceed 7% $K^{-1}$ because additional latent heat released from the increased water vapor can invigorate the storm and pull in more moisture from the boundary layer. This forms a positive moisture–convection–latent heat feedback cycle (hereafter referred to as MCL–Feedback cycle). An invigorated storm (i.e. heavy precipitation) can remove more moisture than the C–C value from the atmosphere, leaving less than the C–C moisture available for light and moderate precipitation (Trenberth et al., 2003). In this context, R. Liu et al. (2016) found that as the climate warms there are extensive enhancements and expansions of the three major tropical precipitation centers–the Maritime Continent, Central America, and tropical Africa–leading to the observed widening of Hadley cells and a significant strengthening of the global hydrological cycle (Davis and Rosenlof, 2012; Eastman and Warren, 2013; Hu and Fu, 2007; Norris et al., 2016; Reichler and Held, 2005; Zhou et al., 2011).

There is a strong relationship between precipitation extremes and cloud top temperature (Arkin and Meisner, 1987; Kuligowski, 2002; Lau and Wu, 2011). Lau and Wu (2011) investigated the climatological characteristics of tropical rain and cloud systems over Tropics using the brightness temperature (BT) data obtained from Visible and Infrared Scanner (VIRS) and the precipitation data gathered from Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and Precipitation Radar (PR). It is found that the top 10% heavy precipitation appears to be associated with high cloud tops and light precipitation has a close association with low clouds.

In this study, we first examine the worldwide satellite observations (ISCCP, 1983–2009) of changes in cloud cover. These changes are compared to changes in global precipitation (Global Precipitation Climatology Project, GPCP pentad V2.2, 1983–2009), and the results are used to decipher possible cause(s) of the changes in both cloud cover and precipitation. To our knowledge, no previous paper has analysed changes in both clouds and precipitation. We then examine the reduction in cloud cover in China. Taking advantage of the extensive daily observations of cloud cover and precipitation from Chinese surface meteorological stations over a relatively long period (1957–2005), we will try to establish a quantitative matching relationship between changes in cloud cover and precipitation. The rest of this paper is organized as follows: data and methodology are presented in Sec. 2, results in Sec. 3, and a summary and conclusions in the final section.

## 2 Data and methodology

Cloud cover from ISCCP during 1983–2009 (2.5°×2.5°, monthly) is used in this study. To get rid of the influence of artifacts from changing satellite view angles, changing solar zenith angles, and other sources of spurious trends in the records, an empirical method is applied (Norris and Evan, 2015). By removing anomalous cloud variability within individual grid boxes shown to be associated with artifact factor anomalies, the spatial anomalies relative to an unknown global mean value are left. We use the annual anomalies of total cloud cover to get the spatial distribution of long term trends (https://rda.ucar.edu/datasets/ds741.5/). Precipitation data from GPCP (V2.2, 1983–2009, 2.5°×2.5°, pentad) are used in this study (Xie et al., 2003). The dataset is available from National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) at ftp.ncdc.noaa.gov/pub/data/gpcp.

In addition, annual average of global temperature anomaly from NCDC (https://www.ncdc.noaa.gov/cag/global/time-series/globe/land_ocean/ann/12/1957-2005) and PDO, AMO, Niño3.4 from NOAA Working Group on Surface Pressure (WGSP, http://psl.noaa.gov/gcos_wgsp/Timeseries/) are also used. The PDO is defined by the leading EOF mode of the monthly anomalous sea surface temperature (SST) in the North Pacific (poleward of 20° N) with global mean SST anomaly subtracted. To make sure AMO also gets rid of the influence from global mean SST, we did a revision using method provided by Trenberth and Shea (2006). The high frequency signals of both indexes are retained in this study.

Daily cloud cover and precipitation data of Chinese surface meteorological stations from China Meteorological Data Service Center are also analyzed to examine the reduction in cloud cover in China (http://data.cma.cn/site/index.html). To ensure the consistency and integrity of the data and because data on the cloud cover is available only up to 2005, we select 477 surface meteorological stations and set 1957–2005 as the study period. Total number of samples in each station are required to have less than 5% missing data during the studied periods, and each station has at least 17002 [(37 × 365 + 12 × 366) × 95%] valid records of both precipitation and cloud cover. The number of valid records in each station has a temporal variation, but results for stations selected by a much stricter standard (annual missing days ≤5 days) highly support which of the 477 stations (not shown). Figure S1 shows the spatial distribution of the stations.

Linear regression between two atmospheric parameters is evaluated by a traditional scatter correlation method. Ten categories of precipitation with increasing intensities are calculated by dividing the 49 years (1957–2005) average spectrum of precipitation into ten categories with equal precipitation amount. Some words of caution are due here that precipitation data from all 477 stations use the same thresholds for sorting different intensity categories in this study. The ranges of the 10 bins for the period of 1957–2005 are 4.0, 7.6, 11.6, 16.1, 21.4, 28.1, 37.1, 50.7, 76.4 and ≥76.4 mm day$^{-1}$. The test of significance used in this study is student's *t* test.

## 3 Results

### 3.1 Regional trends of cloud cover and precipitation

Figure 1a shows the linear trends in total cloud cover (ΔTCC/Δt) derived from corrected ISCCP D2 data set (1983–2009). The general pattern of trends over the oceans are in excellent agreement with those reported by Chen et al. (2019). The pattern is also consistent with those derived by Eastman and Warren (2013) from Extended Edited Cloud Reports Archive (EECRA) data set for 1971–2009. The linear trends of annual total precipitation (ΔTP/Δt) derived from GPCP pentad V2.2, (1983–2009) are shown in Fig. 1b. These trends are in good agreement with results of previous studies (R. Liu et al., 2016; Zhou et al., 2011). The climatological average annual precipitation rates are shown in green contours in both Figs. 1a and 1b to facilitate comparison between the patterns of clouds and precipitation.

There is a high degree of consistency between the general patterns of Figs. 1a and 1b. This can be seen by first noticing a prominent feature of a loose circle of warm color patches (increases in cloud cover and precipitation) in both Figs. 1a and 1b centered around Kalimantan, Indonesia, starting in northern Australia circling counter clockwise to the Philippines, to western China, turning southward along western Indian Ocean all the way to about 50° S, covering nearly half of the eastern hemisphere (0° E–180° E). This loose circle of warm color patches exists, albeit not at the exactly same location, in both Figs. 1a and 1b, and has an obvious effect of widening the center of precipitation (ascending/wet zone of Hadley cells) over the Maritime Continent in all directions (R. Liu et al., 2016; Zhou et al., 2011). There are also significant and extensive enhancements/widenings of precipitation centers over Central America and equatorial Africa. These enhancements/widenings have been interpreted to be an essential part of the widening of Hadley circulation and poleward shifts of the jet streams associated with global warming (Davis and Rosenlof, 2012; Eastman and Warren, 2013; Hu and Fu, 2007; Norris et al., 2016; Reichler and Held, 2005; R. Liu et al., 2016; Zhou et al., 2011).

As a measure of the widening of Hadley circulation, we calculate and illustrate the expansion of cloud cover and precipitation as a function of 16 rectangle belts centered in the middle of Kalimantan, Indonesia which is located near the major ascending/wet zone of Hadley cell (Fig. 2). Each rectangle belt is 2.5 degree wide in both latitude and longitude except the first rectangle is 5 degree wide in latitude and 55 degree wide in longitude. Figures 3a and 3e depict for annual precipitation and total cloud cover, respectively, their "climatology" (black curve) and "climatology + change during 1983-2009" (blue curve). It can be seen that, for a specific value of the y-axis, the blue curve is characterized by a shift horizontally (x-axis direction) to the right (i.e. higher number of belt) of the black curve for most of Figs. 3a and 3e. In comparison, there is very little upward shift in the vertical or y-axis direction, especially at low end (belt 1 and 2) and high end belts (belt 15 and 16). As a result, there is hardly any enhancement in total cloud cover and total precipitation. These characteristics can be interpreted as an expansion to higher latitudes and wider longitudes, i.e. widening of the Hadley and Walker circulations during the period of 1983-2009. Remarkably one can see that the expansion of the Hadley cell as measured by clouds (Fig. 3e) starts at belt 2 (3.75° latitude). This is near the center of the ascending branch of the Hadley cell in the Maritime Continent. Meanwhile, the expansion of the Hadley cell as measured by precipitation (Fig. 3a) starts at belt 5 (12.5° latitude). The reason for the difference is unknown, one possible reason could be the constraint on the 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). Quantitatively the degree of expansion depends on the selected value of the y-axis, increasing quickly when the value is near 1000mm precipitation level (Fig. 3a) or 55% of TCC (Fig. 3e). The value of shift is typically within the range of one quarter to three quarters of a belt width (2.5 degree), or about 0.6-1.9 degree. These annual values are comparable to the poleward shift of the subtropical dry zones (up to 2° decade$^{-1}$ in June-July-August (JJA) in the Northern Hemisphere and 0.3–0.7° decade$^{-1}$ in June-July-August and September-October-November in the Southern Hemisphere) found by Zhou et al. (2011). As a summary of this and last paragraphs, a logical conclusion can be drawn that the linear trends of TCC and TP are mainly characterized by a widening of the Hadley and Walker circulations in both latitude and longitude associated with global warming. These characteristics will be used in the following as key criteria for the evaluation of relative contributions of individual climate indexes to the linear trends in total cloud cover (TCC) and total precipitation (TP).

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It should be noted that, PDO together with AMO and GT, there obviously is a problem of over 100% explanation of the spatial variabilities of linear trends in cloud cover and precipitation. Since the trend of global SST has been removed from the PDO and AMO indexes in this study, in theory GT should be orthogonal to those of PDO and AMO. In practice the orthogonality is not attained because the trend of global SST doesn't equal to the real influence of GT on PDO or AMO. It is difficult to remove the influence of GT from PDO or AMO index, which is likely the main reason for the problem of over 100% explanation. Table 1 presents the correlation coefficients with Figs. 1a and 1b for various linear combinations of GT and other three climate indexes. Significant improvements of the correlation with Fig. 1a (TCC) are attained when GT is paired with AMO (0.86) or Niño3.4 (0.89). The correlation with Fig. 1b (TP) is not improved by any combination, which is understandable as the correlation coefficient of GT alone (0.93) is already very high.

Table 1 has also been evaluated for detrended data of TCC, TP, GT, AMO, PDO and Niño3.4 (Table S1). The correlation coefficients are all less than 0.33, implying that consecutive yearly variabilities contribute insignificantly to the high correlation coefficients in Table 1, and the high correlation coefficients are nearly entirely contributed by the long-term linear trends of GT on PDO and AMO. One of the reasons for the lack of correlation could be due to the small consecutive yearly variabilities relative to the long-term linear trends (about 0.1) for GT on PDO and AMO (Fig. S4).

Based on Table 1, we can conclude that the linear trends of GT, AMO and PDO all have a good probability in contributing to the observed linear trends of total cloud cover and precipitation in 1983–2009. However, the results of Table 1 do not provide any clue indicating which one of the three is the primary contributor. To address this question, we examine Figs. 3b-3d and 3f-3h to evaluate how do the trends of GT, AMO and PDO influence the observed linear trend of precipitation and total cloud cover in 1983–2009. Figs. 3b-3d show the changes (blue curve) from the climatology (1983–2009) (black curve) in the annual total precipitation (mm) of the 16 belts of Fig. 2 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 (Fig. 3b), is d(TP)/d(GT)*ΔGT, where ΔGT denotes difference in the global temperature between 1983 and 2009. It can be seen that Fig. 3b (GT) agrees very well with Fig. 3a both qualitatively and quantitatively; while Figs. 3c and 3d have significantly greater positive values (widening) compared to the small negative values (contraction) of Fig. 3a for the inner 5 belts, resulting in a significant enhancement of the overall precipitation. This discrepancy is crucial, as the quantity of 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 Figs. 3a-3d, 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 Fig. 3f agrees with Fig. 3e significantly better than Figs. 3g and 3h, 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.

A comparison of Fig.1b with Fig. 2e reveals that the enhancements in precipitation in the tropics (Fig. 1b) are the major contributor to the widening of Hadley circulation in observed precipitation (Fig. 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 widening of Hadley circulation is primarily driven by the moisture-convection-latent heat feedback.

In summary of Sec. 3.1, the spatial distributions of the linear trends of total cloud cover and precipitation are characterized primarily by a widening of the center of precipitation (ascending/wet zone of Hadley cells) over the Maritime Continent in all directions (R. Liu et al., 2016; Zhou et al., 2011). Our correlation studies show that GT, AMO and PDO can each explain significant spatial variabilities Our correlation studies show that GT, AMO and PDO can each explain significant spatial variabilities of the linear trends in cloud cover (67%, 49% and 38%, respectively) and precipitation (86%, 59% and 53%, respectively). Contribution by Niño3.4 itself is insignificant because it doesn't have any trend in 1983–2009. A linear combination of GT and AMO can explain as much as 74% and 79%, respectively, of the spatial variabilities of linear trends in cloud cover and precipitation. Further analysis of the widening of the Hadley and Walker circulations (Figs. 3a-3h) shows that the trend in global temperature, rather than that of AMO and PDO, is the primary contributor to the observed linear trend 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 warming conditions. 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. The long-term radiative effect of aerosols on the global temperature and other climate parameters are expected to be imbedded in the observed changes of these climate parameters.

Our results suggesting that the global temperature contributes the most to the trends of cloud cover is Our results suggesting that the global temperature contributes the most to the trends of cloud cover is more in line with the view of Eastman and Warren (2013), rather than with that of Chen et al. (2019)

who

suggested that AMO and PDO contributed more than the global temperature. However, it is well known that correlation method does not imply any cause–effect relationship, certainly not quantitative cause–effect relationship. Our analysis in this section have used correlation method, so were the study by Chen et al. (2019) and many studies on attributing the widening of Hadley circulation to global warming cited by Eastman and Warren (2013). In this context, we note that Eastman and Warren's analysis covered a longer period 1971–2009 in which PDO did not have any significant linear trend, and hence could not have any contribution to the linear trends of cloud cover. This conclusion which does not rely on correlation method should override those derived from correlation studies, including those associated with PDO in this section and those derived by Chen et al. (2019).

### 3.2 Trends of cloud cover and precipitation from station data in China

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 over the period of 1957–

2005. The long-running data enable the analysis to be carried out over a period that AMO loses while PDO flips its linear trend. More importantly, the high-quality data allow us to make meaningful analysis without using the correlation method, which has an intrinsic weakness in implying a cause-effect relationship as discussed above.

Data on cloud cover and precipitation from 477 surface meteorological stations provide significant higher spatial and temporal resolution and over longer time period (1957–2005 for TCC, 1957–2017 for TP) than satellite data, such that detailed analysis can be carried out to reveal fine features for different periods of time. Figure 5 shows linear trends of annual precipitation amount (ΔP) falling within each of the ten bins of equal rain rate with increasing precipitation intensity during 1957–2005. There is a significant overall shift toward higher precipitation intensity, in agreement with previous studies ( B. Liu et al., 2005; Jiang et al., 2014; Qian et al., 2007; R. Liu, 2015, 2016; S. C. Liu et al., 2009; Shiu et al., 2012; Sun et al., 2007; Wang and Zhai, 2008; Wu and Fu, 2013; Zhai et al., 2005). Specifically, the bottom 10% light precipitation decreases by (–1.5 ± 0.5)% per decade and the top 10% heavy precipitation increases by (2.7 ± 1.0)% per decade, both significant at the 99% confidence level. These values are robust over different time periods, for example for overlapping period (1983–2009) with satellite data, the bottom 10% light precipitation decreases by (–2.8 ± 1.7)% per decade and the top 10% heavy precipitation increases by (8.0 ± 3.4)% per decade, the latter is significant at the 95% confidence level. For the period 1957–2017, the bottom 10% light precipitation decreases by (–2.0 ± 0.4)% per decade and the top 10% heavy precipitation increases by (3.0 ± 0.7)% per decade, both significant at the 99% confidence level.

Linear trend of the non–precipitation days is 4.5 ± 0.2 days per decade, which is significant at the 99% confidence level (Table 2 and Fig. 6a). During the 49 year period, non–precipitation days has increased by about 22 days, which is nearly completely compensated by the decrease of light precipitation days. The bottom 10% precipitation alone has decreased by about 21 days, accounting for ~95% of the change of non–precipitation days. This value quickly approaches 100% when changes of the bottom 10%–40% precipitation days are included. This is fully expected as the number of bottom 40% precipitation days (147) account for ~90% of total precipitation days (163). In the meantime, the top 60% precipitation days barely changed.

During the 49 year period, cloud–free days has increased by about 11 days, accounting for one half of the increase of non–precipitation days (Fig. 6b and Table 2). This value quickly approaches 21 days when changes of the (0–50)% cloud cover days (CCD) are included. Twenty one days account for 95% of the increase of non–precipitation days. This is reasonable as precipitation usually does not occur when the cloud cover is less than 50%. Linear trends of the cloud–free days (CFD) and CCD are 2.3 ± 0.1 and 4.3 ± 0.2 days per decade, respectively, both significant at the 99% confidence level (Table 2). This is compensated by a reduction of 50%–100% cloud cover days (Fig. 7), mostly by the 100% overcast days. This is also logical because precipitation tends to occur when the sky is heavily overcast. Since light precipitation days account for most of precipitation days, their decrease should approximately equal to the decrease of overcast days.

So far in Sec. 3.2, we have used observed cloud cover and precipitation data from Chinese surface meteorological stations to successfully establish a quantitative matching relationship starting from the reduction in light precipitation days, to the increase of non–precipitation days, then to the increase in cloud free days and finally to the reduction of total cloud cover in China. This relationship is established via an arithmetic analysis, which is more robust than the correlation analysis. The correlation analysis tends to introduce extra uncertainties as discussed in the last section. A critical remaining question is what is the cause of the reduction in light precipitation days in China? R. Liu et al. (2015) proposed that the reduction in light precipitation days in China is part of the extensive worldwide reports of enhancements in heavy precipitation and reductions in the light and moderate precipitation (B. Liu et al., 2005; Fujibe et al., 2005; Goswami et al., 2006; Groisman et al., 2005; Jiang et al., 2014; Karl and Knight, 1998; Klein Tank and Können, 2003; Manton et al., 2001; Qian et al., 2007; R. Liu, 2015, 2016; S. C. Liu, 2009; Shiu et al., 2012; Sun et al., 2007; Wang and Zhai, 2008; Wu and Fu, 2013; Zhai et al., 2005); and the primary driving mechanism is the MCL–Feedback cycle under global warming environment proposed by Trenberth et al. (2003). We check this proposal by making the following evaluation of the trend in the bottom 10% light precipitation (B10LP) using its slope of linear regression against various climate oscillation indexes. For example, the trend of B10LP can be calculated from the trend of PDO as the following:

Calculated trend of B10LP from PDO for 1957–2005 = (△B10LP/△PDO) × (trend of PDO) = (–0.33 ± 0.09)% per decade.

Where △B10LP/△PDO is the slope of linear regression between B10LP and PDO during 1957–2005. This calculated trend should be interpreted as the maximum possible contribution to the trend of B10LP from PDO, because there may be other climate parameters contributing to the slope (△B10LP/△PDO).

Table 3 lists the trends of B10LP calculated from PDO, AMO and GT for three time periods of interest in this study: 1957–2005, 1957–2017 and 1983–2009. Niño3.4 is not listed because it has no linear trend during these periods and thus no significant contribution.

Calculated trends of B10LP from GT agree remarkably well with the observed trends in all three periods. Calculated trends of B10LP from PDO are more than a factor of five too low for both periods 1957–2005 and 1957–2017, while no significant trend is found for 1983–2009. The calculated trend of B10LP from AMO agrees with the observed value during 1983–2009, but no significant trend is found for the two longer periods 1957–2005 and 1957–2017. Since the trends of longer periods should carry more weight, results in Table 3 suggest that GT is the primary contributor to the linear trends in B10LP, contribution from PDO is about 10%, while contribution from AMO and Niño3.4 is negligible. These results are consistent with the proposal by R. Liu et al. (2015) that the reduction in light precipitation days in China is part of the extensive worldwide reports of enhancements in heavy precipitation and reductions in the light and moderate precipitation under global warming environment.

In summary of Sec. 3.2, our study suggests that the reduction of cloud cover in China is primarily driven by the MCL–Feedback cycle under global warming environment, PDO plays a secondary role, while the contribution from AMO and Niño3.4 is insignificant.

## 4 Summary and conclusions

Worldwide satellite observations (ISCCP, 1983–2009) of linear trends in cloud cover are compared to those in global precipitation (GPCP pentad V2.2 1983–2009), to decipher possible cause(s) of the trends in cloud cover. The spatial distributions of the linear trends of total cloud cover and precipitation are characterized primarily by a widening of the center of precipitation (ascending/wet zone of Hadley cells) over the Maritime Continent in all directions (R. Liu et al., 2016; Zhou et al., 2011). The underlying mechanism driving the widening is believed to be the moisture–convection–latent heat feedback cycle under increasing SST conditions (Trenberth et al., 2003). Our correlation studies show that global warming, AMO and PDO can each explain significant spatial variabilities of the linear trends in cloud cover (67%, 49% and 38%, respectively) and precipitation (86%, 59% and 53%, respectively). Contribution by Niño3.4 is insignificant. A linear combination of global warming and AMO can explain as much as 74% and 79%, respectively, of the spatial variabilities of linear trends in cloud cover and precipitation. 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. The long term radiative effect of aerosols on the global temperature and other climate parameters are expected to be imbedded in the observed changes of these climate parameters.

Taking advantage of the extensive daily observations of cloud cover and precipitation from Chinese surface meteorological stations over a relatively long period (1957–2005), a quantitative matching relationship between linear trends in cloud cover and precipitation is established via an arithmetic analysis, which is more robust than the correlation method. Furthermore, our study suggests that the reduction of cloud cover in China is also primarily driven by the moisture–convection–latent heat feedback cycle under increasing global temperature conditions (Trenberth et al., 2003), PDO plays a secondary role, while the contribution from AMO and Niño3.4 is insignificant because neither has any linear trend during 1957–2005.

Cautionary statements: It is important to note that many critical analyses in Sec. 3 have utilized some sorts of correlation analysis, which do not have any cause–effect implication, nor does a higher correlation coefficient imply a more important cause–effect relationship. The attribution of cause–effect can only be established if a mechanistic model, that is based on the cause/mechanism, can successfully reproduce the linear trends of cloud cover quantitatively. Until the model reproduction is accomplished, all correlation results should be used only as suggestions or hints of possible cause–effect relationship.
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Unfortunately, the reproduction is extremely challenging for current climate models as they tend to have large uncertainties in the simulation of key atmospheric parameters, particularly for clouds and precipitation (Flato et al., 2013). Furthermore, it should be noted that both the ISCCP and GPCP datasets have utilized IR related data to gain the final products. However, ISCCP has merged visible channels and other available channels; while GPCP has

merged microwave channels and gauge data, in fact, the microwave channels play a more important role than the IR data. In conclusion, these two datasets share relatively limited common data sources in the IR channels, but both datasets merge substantial independent data sources in the visible and microwave channels. Therefore, we believe that the correlation between cloud and precipitation should not be significantly affected by their common data source.

*Data availability.* Corrected satellite cloud cover data were obtained from NCAR UCAR RDA (https://rda.ucar.edu/datasets/ds741.5/, last access: 10 June 2020). The gridded precipitation data were obtained from NOAA NCDC at ftp.ncdc.noaa.gov/pub/data/gpcp (last access: 10 June 2020). Annual average of global temperature anomaly were obtained from NCDC (https://www.ncdc.noaa.gov/cag/global/time-series/globe/land_ocean/ann/12/1957-2005, last access: 10 June 2020) and PDO, AMO, Niño3.4 are from NOAA WGSP (http://psl.noaa.gov/gcos_wgsp/Timeseries/, last access: 10 June 2020). Daily cloud cover and precipitation data of Chinese surface meteorological stations were obtained from CMA (http://data.cma.cn/site/index.html). The data of this paper are available upon request to Shaw Chen Liu (shawliu@jnu.edu.cn).

*Author Contributions.* SL proposed the essential research idea. XZ performed the analysis. SL, XZ and RL drafted the manuscript. XW, JM and YL helped analysis and offered valuable comments. All authors have read and agreed to the published version of the manuscript.

*Competing interests.* The authors declare that they have no conflict of interest.

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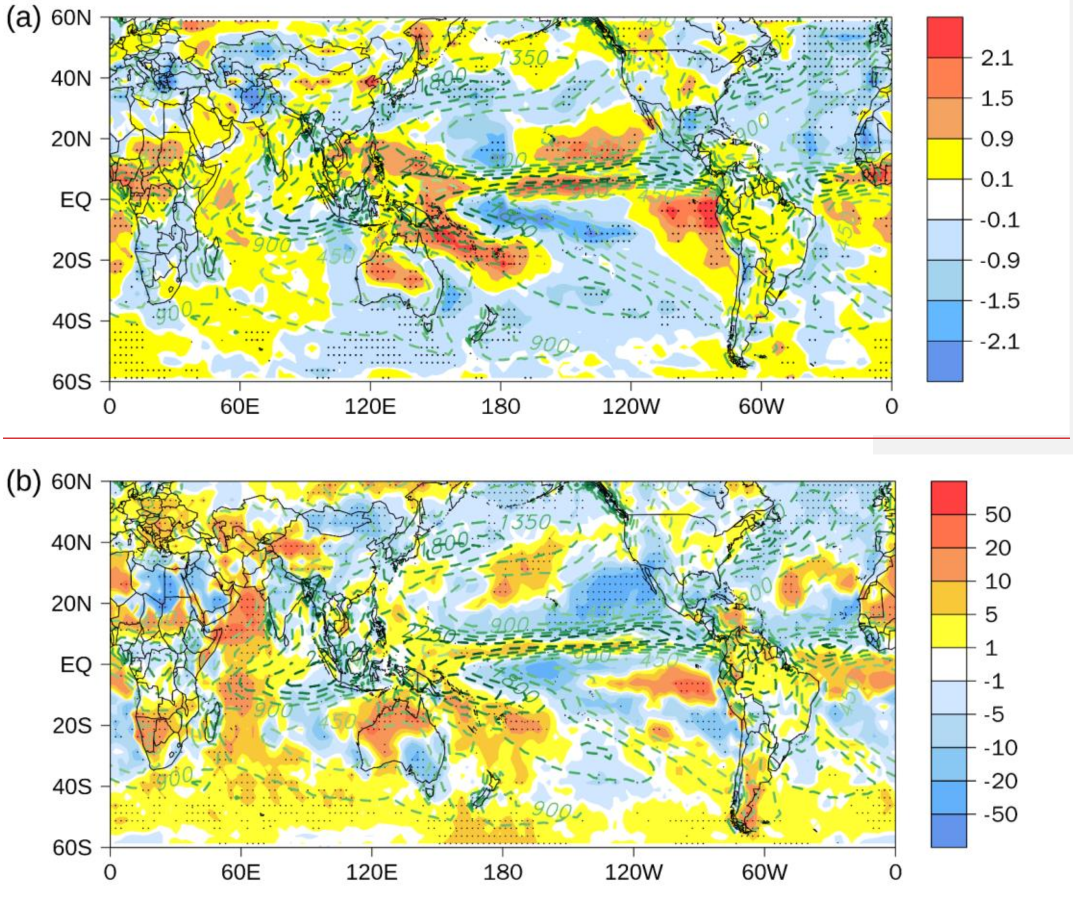


**Figure 1. (a) Trends in total cloud cover (units: % per decade) from corrected ISCCP D2 data set (1983–2009). (b) Trends in annual total precipitation (units: % per decade) from GPCP pentad V2.2 (1983–2009). Dots indicate changes significant at the 95% confidence level. Contours indicates the climatology of total precipitation (units: mm per year).**

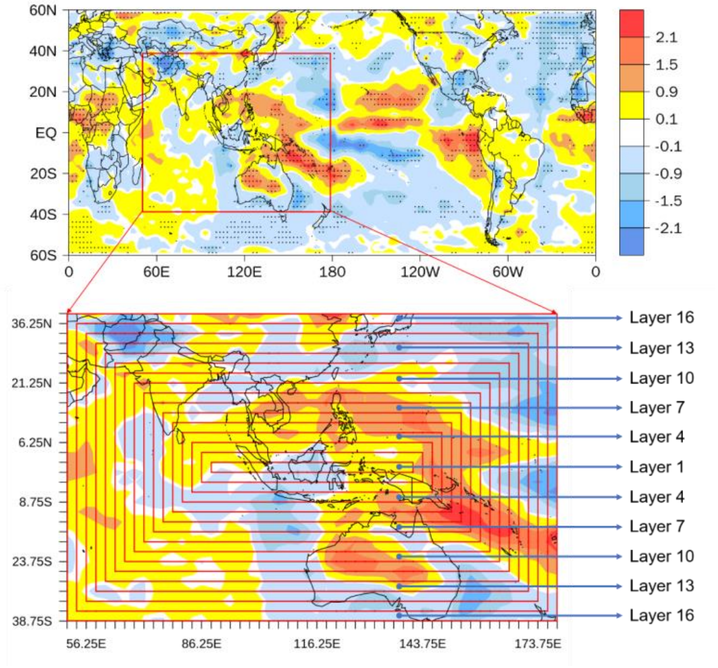


Figure 2. Maps of the 16 rectangle belts of 2.5 degree wide in both latitude and longitude centered in the middle of Kalimantan, Indonesia which is located near the major ascending/wet zone of Hadley cell. The expansion of cloud cover and precipitation relative to these belts are used as a measure of the widening of Hadley circulation.

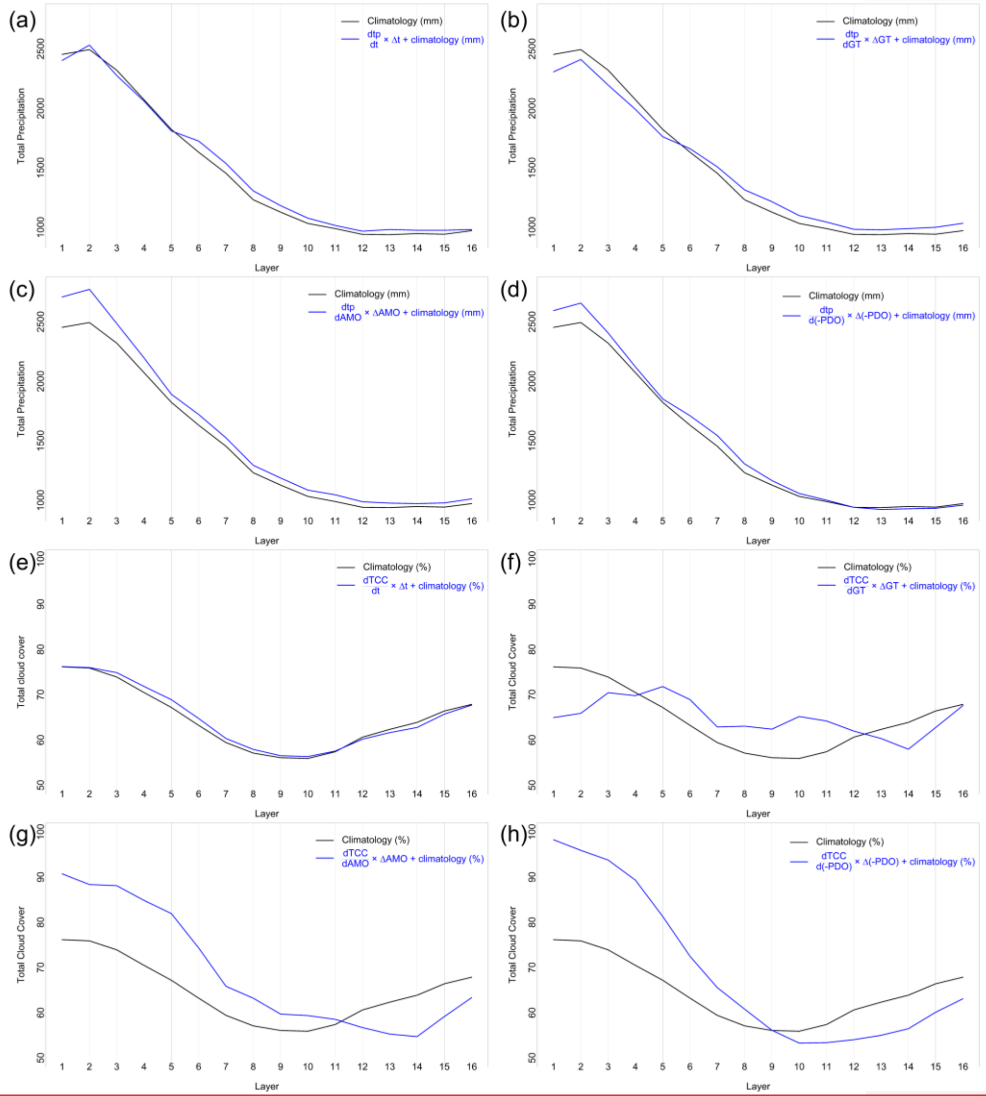


**Figure 3. Changes (blue curve) from the climatology (black) during the period 1983–2009 in the annual total precipitation (mm) in the 16 belts of Figure 2 as a function of time (a), global temperature (b), AMO (c) and PDO (d). Changes from the climatology in the annual total cloud cover (%) in the 16 belts of Figure 2 as a function of time (e), global temperature (f), AMO (g) and PDO (h). The formula for calculating the blue curve, for instance for the changes in precipitation as a function of global temperature (Fig. 3b) is d(TP)/d(GT)*ΔGT where ΔGT denotes difference in the global temperature between 1983 and 2009.**

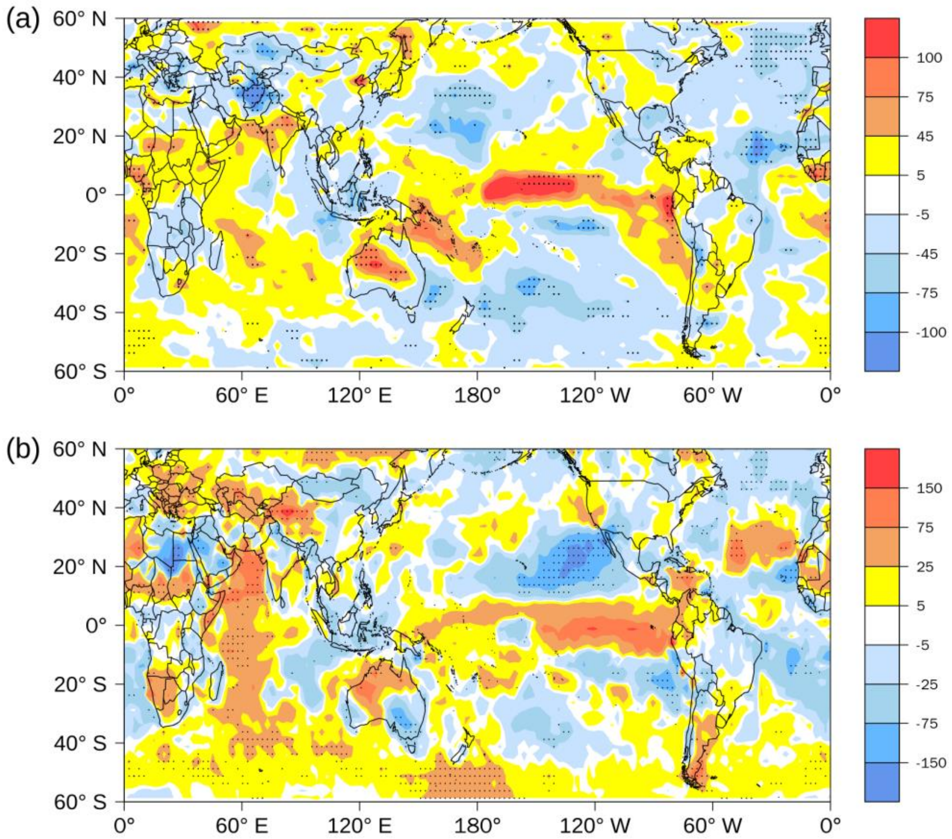


**Figure 4 (a) Slope of linear regression between total cloud cover and global temperature anomalies (units: % $K^{-1}$) at individual grids from corrected ISCCP D2 data set (1983–2009). (b) Slope of linear regression between annual total precipitation and global temperature anomalies (units: % $K^{-1}$) at individual grids from GPCP pentad V2.2 (1983–2009). Dots indicate changes significant at the 95% confidence level.**

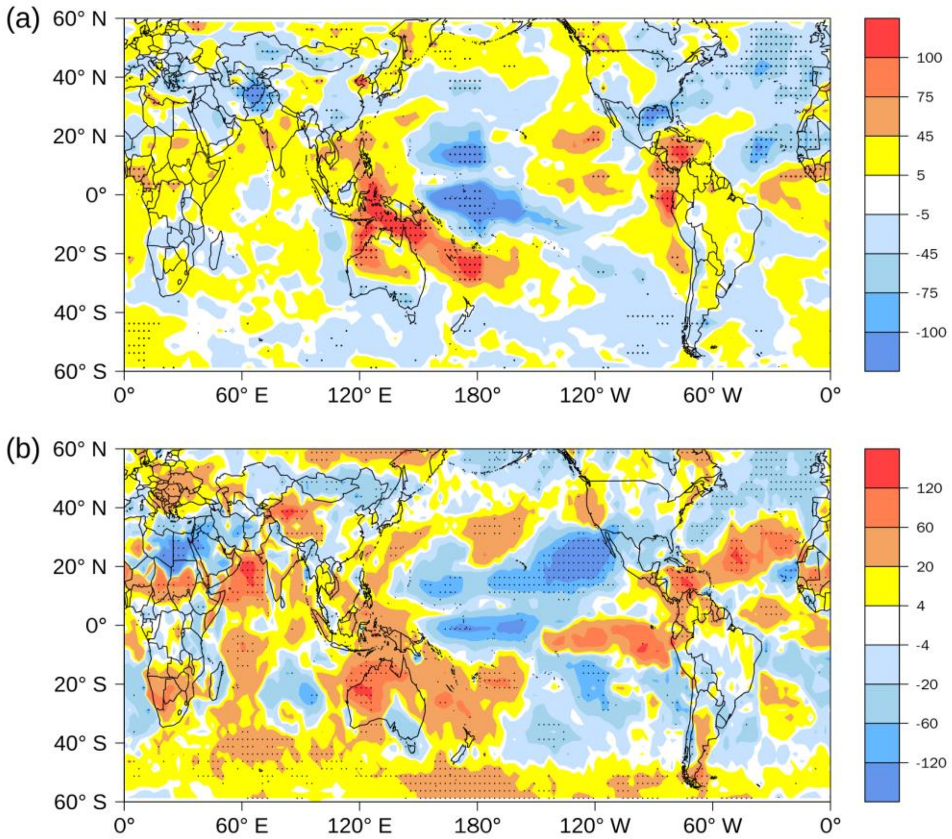


**Figure 5. (a) Slope of linear regression between total cloud cover and AMO (units: % K$^{-1}$) at individual grids from corrected ISCCP D2 data set (1983–2009). (b) Slope of linear regression between annual total precipitation and AMO (units: % K$^{-1}$) at individual grids from GPCP pentad V2.2 (1983–2009). Dots indicate changes significant at the 95% confidence level.**

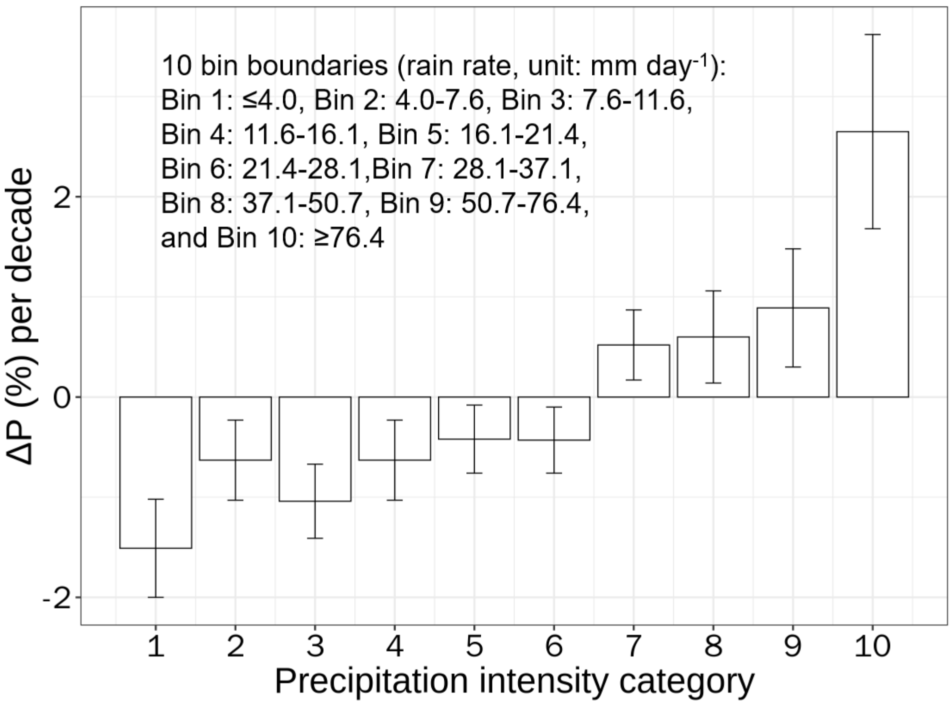


**Figure 6. Linear trends of annual precipitation amount (ΔP) falling within each of the ten intensity bins during 1957-2005. The vertical line on top of each bar denotes 1 standard error.**

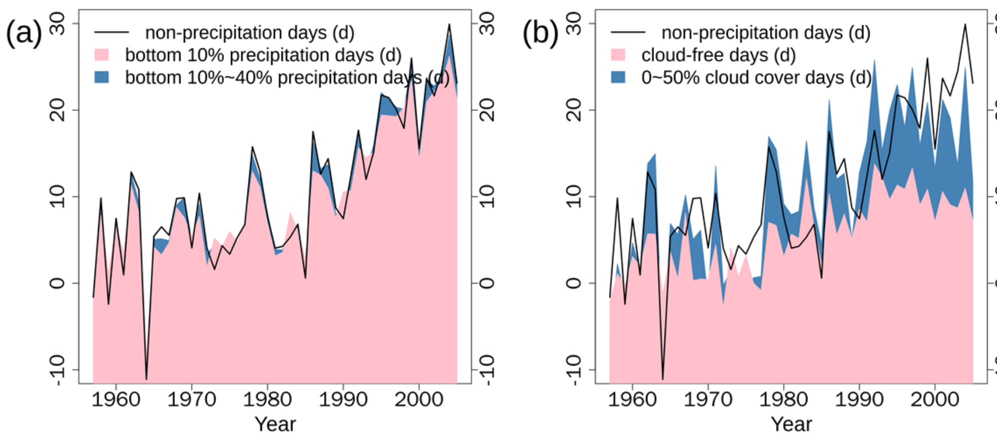


**Figure 7. (a) Time series of changes relative to the value of 1957 in non–precipitation days, bottom 10% precipitation days and bottom 10%–40% precipitation days in 1957–2005. (b) As in (a) but for changes of**

**non–precipitation days, cloud–free days and 0–50% cloud cover days. Changes are calculated as original time series subtract the value of the start year (1957).**

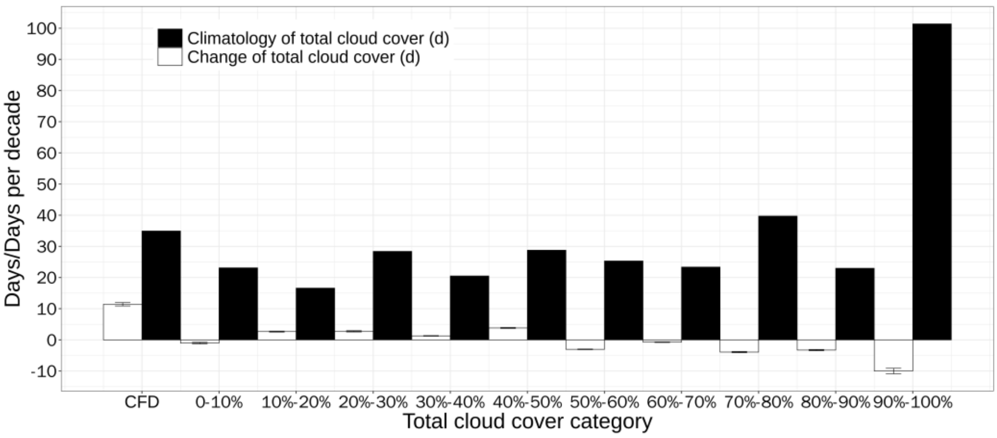


**Figure 8. Climatology (units: days) and changes (units: days per decade) in the cloudy days falling within each bin during 1957–2005. CFD denotes cloud–free days and 0–10% denotes days of cloud cover within the range of (0–10%). The vertical line on top of each bar denotes 1 standard error.**

**Table 1. Correlation coefficient between spatial distribution of trends of TCC (TP) and those calculated from changes of TCC (TP) as a function of different climatic indexes**

| R | Trend of TCC | Trend of TP |
|---|---|---|
| δ(GT) | 0.82 *** | 0.93 *** |
| δ(-PDO) | 0.62 *** | 0.73 *** |
| δ(AMO) | 0.70 *** | 0.77 *** |
| δ(Niño3.4) | -0.20 *** | 0.02 ** |
| δ(GT)+δ(-PDO) | 0.74 *** | 0.85 *** |
| δ(GT)+δ(AMO) | 0.86 *** | 0.89 *** |
| δ(GT)+δ(Niño3.4) | 0.89 *** | 0.93 *** |
| δ(-PDO)+δ(AMO) | 0.67 *** | 0.79 *** |
| δ(-PDO)+δ(Niño3.4) | 0.61 *** | 0.72 *** |
| δ(AMO)+δ(Niño3.4) | 0.65 *** | 0.73 *** |
| δ(GT)+δ(-PDO)+δ(AMO) | 0.76 *** | 0.87 *** |
| δ(GT)+δ(-PDO)+δ(Niño3.4) | 0.72 *** | 0.84 *** |
| δ(GT)+δ(AMO)+δ(Niño3.4) | 0.86 *** | 0.88 *** |
| δ(-PDO)+δ(AMO)+δ(Niño3.4) | 0.65 *** | 0.78 *** |
| δ(GT)+δ(-PDO)+δ(AMO)+δ(Niño3.4) | 0.75 *** | 0.86 *** |

Note: GT denotes global temperature anomalies. δ(GT) denotes $\Delta GT*dTCC/d(GT/GT_\sigma)$ or $\Delta GT*dTP/d(GT/GT_\sigma)$, where $\Delta GT$ is the change of GT for the studied period and $GT_\sigma$ is the standard deviation of GT, and other factors likewise. * indicates statistically significant at the 90% confidence level based on student's *t* test, ** 95% level, *** 99% level.

**Table 2. Climatology and days changed for precipitation days and cloudy days**

| | Climatology (day) | Change rate (day per decade) | Relative change rate (% per decade) | Change over 49 years (day) | Relative change over 49 years (%) |
|---|---|---|---|---|---|
| NPD | 202.5 | 4.5±0.2 *** | 2.2±0.1 *** | 22.1±1.0 *** | 10.9±0.5 *** |
| B10% | 116.9 | -4.2±0.2 *** | -3.6±0.2 *** | -20.6±1.0 *** | -17.6±1.0 *** |
| B20% | 132.0 | -4.3±0.2 *** | -3.3±0.2 *** | -21.1±1.0 *** | -16.0±1.0 *** |
| B30% | 141.2 | -4.4±0.2 *** | -3.1±0.1 *** | -21.6±1.0 *** | -15.3±0.5 *** |
| B40% | 147.5 | -4.5±0.2 *** | -3.1±0.1 *** | -22.1±1.0 *** | -15.0±0.5 *** |
| T60% | 15.0 | 0±0 *** | 0±0 *** | 0±0 *** | 0±0 *** |
| CFD | 34.9 | 2.3±0.1 *** | 6.6±0.3 *** | 11.3±0.5 *** | 32.3±1.5 *** |
| ≤50% | 152.3 | 4.3±0.2 *** | 2.8±0.2 *** | 21.1±1.0 *** | 13.7±1.0 *** |
| >50% | 212.7 | -4.3±0.2 *** | -2.0±0.2 *** | -21.1±1.0 *** | -9.9±1.0 *** |

Note: *** indicates statistically significant at the 99% confidence level based on student's *t* test. NPD denotes non-precipitation days, B10% denotes bottom 10% precipitation days, T60% denotes top 60% precipitation days, ≤50% denotes ≤50% cloud cover days and CFD denotes cloud-free days.

**Table 3 Comparison of observed linear trends of bottom 10% light precipitation with calculated trends for three time periods**

| Unit: % per decade | 1957–2005 | 1957–2017 | 1983–2009 |
|---|---|---|---|
| Observed trend | -1.51±0.49 | -2.02±0.37 | -2.44±1.29 |
| Calculated from GT | -1.81±0.24 | -2.31±0.16 | -2.96±0.70 |
| Calculated from PDO | -0.33±0.09 | -0.21±0.01 | Insignificant |
| Calculated from AMO | Insignificant | Insignificant | -2.45±0.46 |