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 #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 2 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 1). 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.

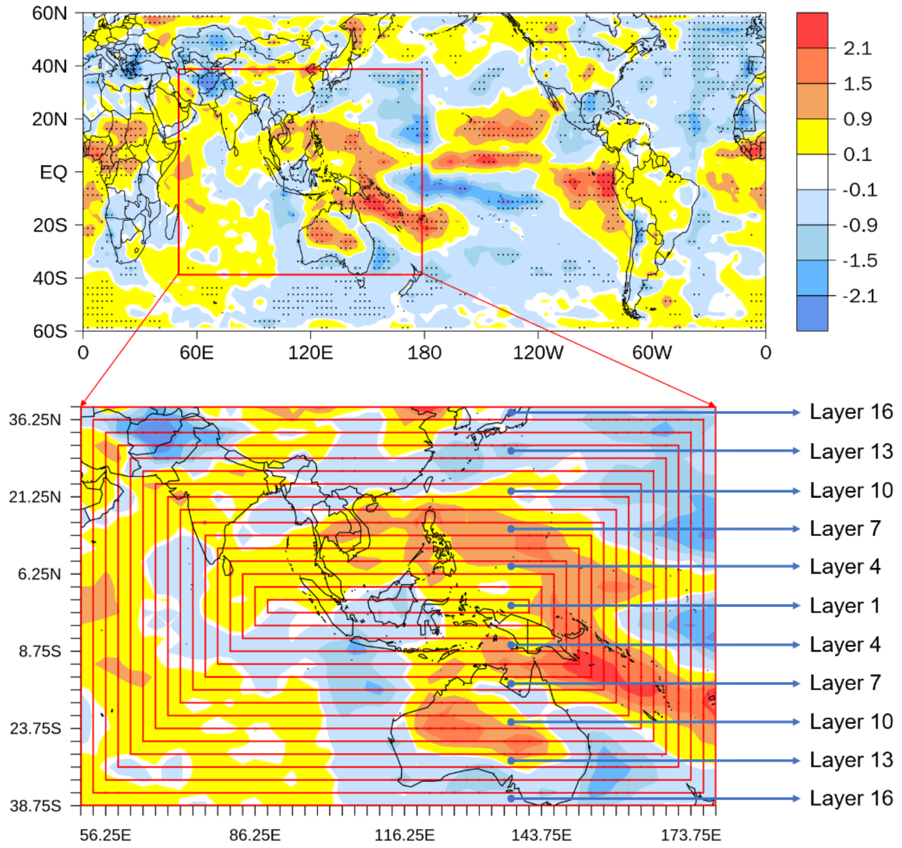

Figure 1. Maps of the 16 rectangle belts of 2.5 degree wide in both latitude and longitude centered in the middle of Kalimantan, Indonesia which is located near the major ascending/wet zone of Hadley cell. The expansion of cloud cover and precipitation relative to these belts are used as a measure of the widening of Hadley circulation.

Figures 2a and 2e 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 2a and 2e. 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 2a) or 55% of TCC (Figure 2e). 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).

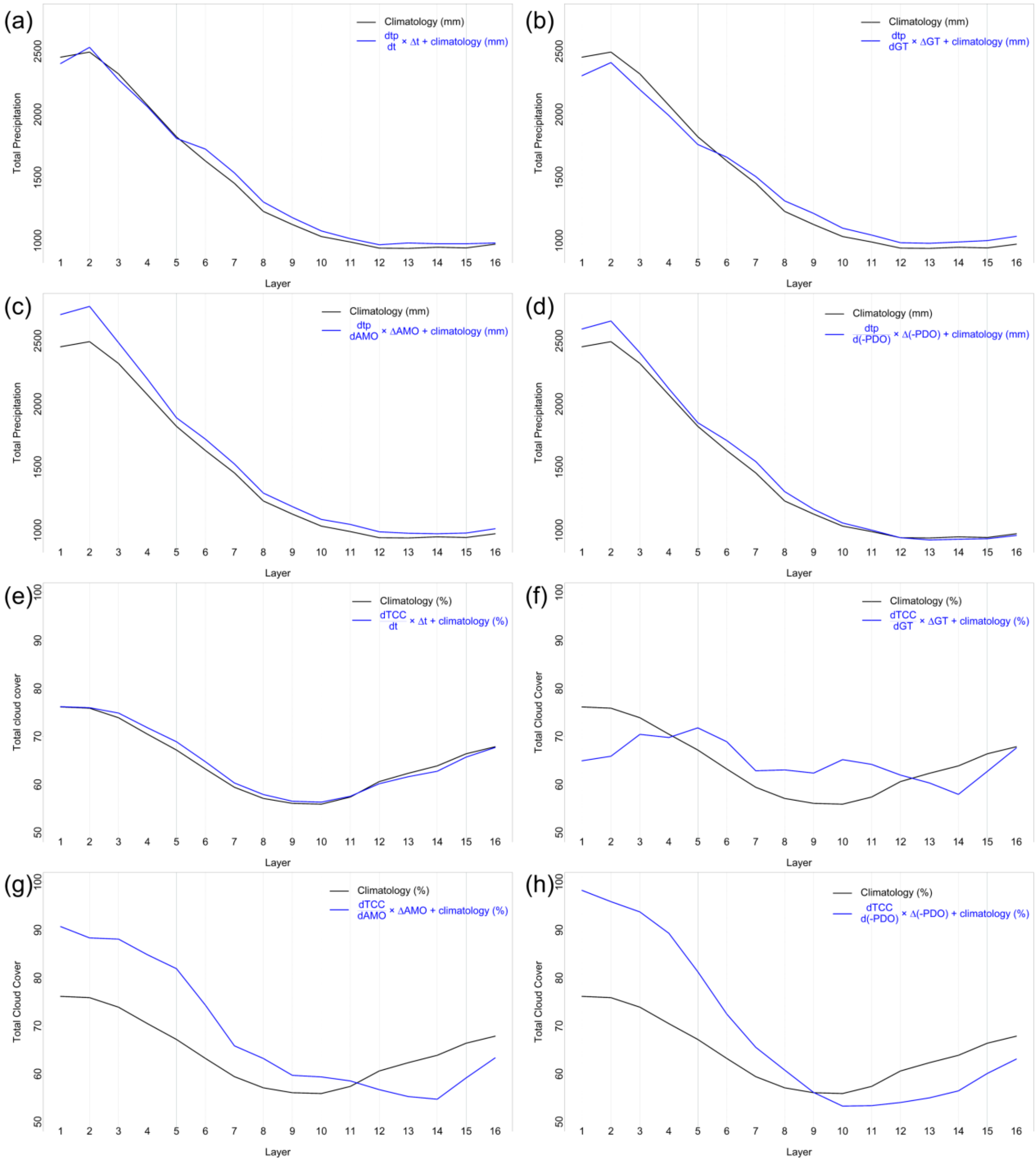

Figure 2. Changes (blue curve) from the climatology (black) during the period 1983–2009 in the annual total precipitation (mm) in the 16 belts of Figure 1 as a function of time (a), global temperature (b), AMO (c) and PDO (d). Changes from the climatology in the annual total cloud cover (%) in the 16 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 (Figure 2b) is d(TP)/d(GT)*ΔGT where ΔGT denotes difference in the global temperature between 1983 and 2009.

Figures 2b-2d show the changes (blue curve) from the climatology (1983–2009) (black curve) in the annual total precipitation 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 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 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.

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 2a-2h) 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 3 & 4 below).

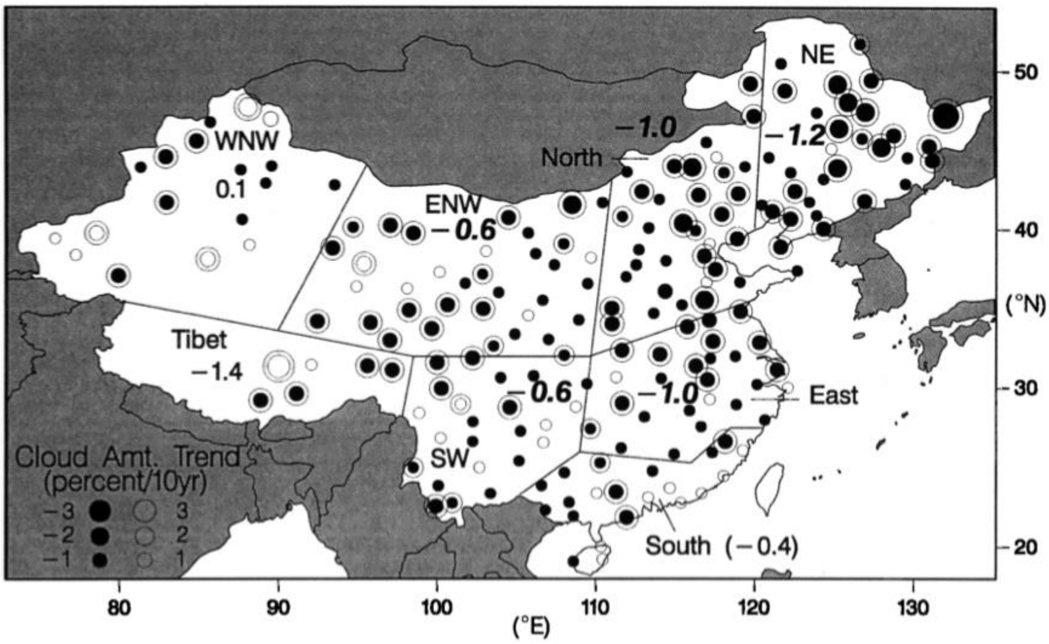

Figure 3. Trends in annual mean midday cloud amount for 1951-1994 (percent sky cover per decade). Station trend indicators with circles around them are significant at the 95% confidence level, as are regional trend values that are in bold italics (Kaiser, 1998).

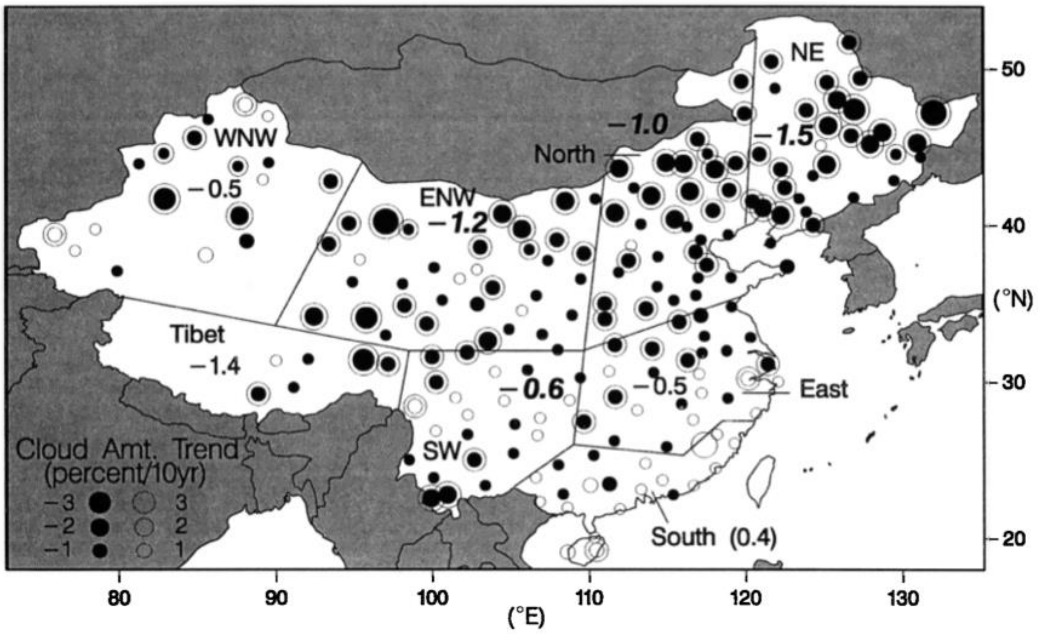

Figure 4. As in Figure R1, but for annual mean midnight cloud amount, 1954-1994 (Kaiser, 1998).

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”.

References：

Cubasch, U., and Coauthors, 2001: Projections of Future Climate Change. Climate Change 2001: The Scientific Basis., J. T. Houghton and Y. H. Ding, Eds., Cambridge Univ. Press, Ch. 9, 524–582.

Eastman R., Warren, S. G. and Hahn, C. J.: Variations in cloud cover and cloud types over the ocean from surface observations, 1954–2008, J. Climate., 24(22), 5914–5934, doi:10.1175/2011JCLI3972.1, 2011.

Kaiser, D. P.: Analysis of total cloud amount over China, 1951–1994, Geophys. Res. Lett., 25(19), 3599–3602, doi:10.1029/98GL52784, 1998.

Zhou, Y. P., Xu, K.-M., Sud, Y. C. and Betts, A. K.: Recent trends of the tropical hydrological cycle inferred from Global Precipitation Climatology Project and International Satellite Cloud Climatology Project data, J. Geophys. Res., 116, D09101, doi:10.1029/2010JD015197, 2011.