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

Xiang Zhong[1], Shaw Chen Liu[1], Run Liu[1], Xinlu Wang[1,2], Jiajia Mo[1], and Yanzi Li[1]

[1]Institute for Environmental and Climate Research, Jinan University, Guangzhou, 511486, China
5 [2]Hangzhou AiMa Technologies, Hangzhou, 311121, China

Correspondence to: Shaw Chen Liu (shawliu@jnu.edu.cn) and Run Liu (liurun@jnu.edu.cn)

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
10 by the widening of Hadley circulation and poleward shifts of the jet streams associated with global warming. Our studies suggest that global warming, AMO and PDO can explain 67%, 49% and 38%, respectively, of the spatial variabilities of the linear trends in cloud cover. 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. Analysis of the cloud cover and precipitation data (1957–2005) from Chinese surface meteorological stations reveals a quantitative matching relationship
15 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 moisture–convection–latent heat feedback cycle under increasing global temperature conditions, PDO plays a secondary role, and the contribution from AMO and Niño3.4 is insignificant, consistent with the global analysis.

1 Introduction

20 Long term changes in cloud cover is 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
25 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 affiliated to 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).

Atmospheric
Chemistry
and Physics
Discussions

Open Access

EGU

30   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

35   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

40   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

45   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 and Warren (2013), which are derived from synoptic observations made by observers on ships. The agreement provides credence

50   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

55   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

60   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 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). After removing the spurious variability, 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 providing by Trenberth and Shea (2006). The high frequency signals of both indexes are remained in this study.

100   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 has less than 5% missing data, during the studied periods, each station has at least 17002 [$(37 \times 365 + 12 \times 366) \times 95\%$] valid records of both
105   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
110   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

115 ### 3.1 Regional trends of cloud cover and precipitation

Figure 1a shows the linear trends in total cloud cover ($\Delta TCC/\Delta t$) 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 ($\Delta TP/\Delta t$) derived from GPCP pentad V2.2, (1983–2009)
120   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
125   centered around the Java Island (western side of Maritime Continent), 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

Atmospheric
Chemistry
and Physics
Discussions

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

130 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); and thus will be used as a key criterion for the evaluation of relative contributions of individual climate indexes to the linear trends in total cloud cover (TCC)

135 and total precipitation (TP). There are also good agreements between Figs. 1a and 1b on an enhancement in the Intertropical Convergence Zone (ITCZ) of the Pacific, and a long stretch of enhancement starting from the eastern Pacific of equatorial South America to the eastern Atlantic Ocean (12° S–0°, 120° W–0°). As a summary of this paragraph, a straightforward logical conclusion can be drawn that the linear trends of TCC and TP are mainly characterized by a widening of Hadley circulation and poleward shifts of the jet streams associated with global warming (Davis and Rosenlof, 2012; Eastman and Warren, 2013;

140 Hu and Fu, 2007; R. Liu et al., 2016; Norris et al., 2016; Zhou et al., 2011).

The consistent relationship between Figs. 1a and 1b is further substantiated in terms of temporal variability. Figure 2 shows time series of the anomaly of annual total cloud cover (%) and the annual average total precipitation (1000 mm) over the eastern Maritime Continent (20° S–10° N, 130° E–160° E). There is a very good correlation (0.75) between anomalies of annual total cloud and total precipitation. Similar good correlations prevail in extensive regions worldwide. These good

145 correlations give more confidence that the consistent relationship between Fig. 1a and 1b are robust.

A critical question remaining is whether other climate parameters than global warming may also contribute to the linear trends of TCC and TP, particularly AMO and PDO which also have significant linear trends during the relatively short period of 1983–2009 of this study? This is addressed in the following.

Figures 3a and 3b depict slopes of linear regressions of TCC and TP against the annual average global temperature anomaly

150 (GT) at each grid point, i.e. $\triangle$TCC/$\triangle$GT and $\triangle$TP/$\triangle$GT, respectively. The circle of warm color patches around the Java Island, which symbolizes the widening of Hadley circulation, is highly visible in both Figs. 3a and 3b. The enhancement/widening of the precipitation centered over equatorial Africa can also be clearly seen. These agreements between Figs. 1a and 2a; and between Figs. 1b and 2b are substantiated by the relatively high correlation coefficients of 0.82 and 0.93, respectively (Table 1), suggesting that global warming can explain approximately 67% and 86%, respectively, of the spatial

155 variabilities of linear trends in cloud cover and precipitation. The slopes of linear regressions of TCC and TP against AMO at each grid point are plotted in Fig. 4a and 4b. The general patterns match reasonably well with those of Figs. 1a and 1b, respectively. The correlation coefficients between Figs. 1a and 4a, and between Figs. 1b and 4b, are slightly less than those of global temperature at 0.70 and 0.77, respectively (Table 1), implying that AMO can explain about 49% and 59%, respectively, of the spatial variabilities of linear trends in cloud cover and precipitation.

160 Due to limited space, figures for PDO and Niño3.4 corresponding to Figs. 3a and 3b are presented in the Supplement. The correlation coefficients of Niño3.4 with Figs. 1a and 1b are very low at –0.20 and 0.02, respectively (Table 1). A major reason

for the low correlation coefficient is the lack of any linear trend in Niño3.4 during 1983–2009. Correlation coefficients of PDO with Figs. 1a and 1b are 0.62 and 0.73 (Table 1), respectively, slightly less than those of AMO. These correlation coefficients imply that PDO can explain approximately 38% and 53%, respectively, of the spatial variability of linear trends in cloud cover

165   and precipitation.

Since the trend of global SST has been removed from PDO and AMO in this study, interannual variability of GT should be orthogonal to those of PDO and AMO. 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

170   combination, which is understandable as the correlation coefficient of GT alone (0.93) is already very high.

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). The underlying mechanism driving this widening is believed to be the moisture–convection–latent heat feedback cycle under increasing SST conditions. Our correlation studies show that GT, AMO

175   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. 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–

180   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.

The significant contributions of AMO and PDO to the trends of cloud cover are consistent with the findings of Chen et al. (2019). On the other hand, our results suggesting that GT contributes the most to the trends of cloud cover is more in line with that of Eastman and Warren (2013), rather than Chen et al. (2019) who suggested that AMO and PDO contributed more than

185   GT. These differences should not be a serious concern because 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

190   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). This leads to a concluding remark for Sec. 3.1: our study suggests that global warming (GT) and AMO are major contributors to the linear trends of cloud cover and precipitation observed in 1983–2009; while contribution by PDO and Niño3.4 is insignificant.

Atmospheric
Chemistry
and Physics
Discussions

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

195 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 equal bins 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

200 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)%

205 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

210 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.

215 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

220 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

225 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

230 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)

235 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 = ($\triangle$B10LP/$\triangle$PDO) × (trend of PDO) = (−0.33 ± 0.09)% per decade.

Where $\triangle$B10LP/$\triangle$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

240 climate parameters contributing to the slope ($\triangle$B10LP/$\triangle$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

245 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

250 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.

255 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

260 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

265 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

270 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.

275 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.

280 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). Finally, there is an issue that both the cloud (ISCCP) and precipitation (GPCP pentad) datasets have utilized IR related data to gain their final products. However, the cloud dataset has merged visible channels and other available channels; while the precipitation dataset has merged microwave channels and gauge data, in fact, the microwave channels play a more important role than the IR data.

285 Therefore, we believe that the correlation between cloud and precipitation should not be significantly compromised 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

290 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

Atmospheric
Chemistry
and Physics
Discussions

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).

295

References

Adler, R. F., Gu, G., Sapiano, M., Wang, J.-J., and Huffman, G.J.: Global precipitation: Means, variations and trends during
310   the Satellite Era (1979–2014), Surv. Geophys., 38: 679-699, doi:10.1007/s10712-017-9416-4, 2017.
Arkin, P. A. and Meisner, B. N.: The relationship between large-scale convective rainfall and cold cloud over the western hemisphere during 1982-84, Mon. Weather Rev., 115(1), 51–74, doi:10.1175/1520-0493(1987)115<0051:TRBLSC>2.0.CO;2, 1987.
Chen, Y.-J., Hwang, Y.-T., Zelinka, M. D. and Zhou, C.: Distinct patterns of cloud changes associated with decadal
315   variability and their contribution to observed cloud cover trends, J. Clim., 32(21), 7281–7301, doi:10.1175/JCLI-D-18-0443.1, 2019.
Davis, S. M. and Rosenlof, K. H.: A multidiagnostic intercomparison of tropical-width time series using reanalyses and satellite observations, J. Clim., 25(4), 1061–1078, doi:10.1175/JCLI-D-11-00127.1, 2012.
Eastman, R. and Warren, S. G.: A 39-yr survey of cloud changes from land stations worldwide 1971–2009: Long-term
320   trends, relation to aerosols, and expansion of the tropical belt, J. Clim., 26(4), 1286–1303, doi:10.1175/JCLI-D-12-00280.1, 2013.
Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C. and Rummukainen, M.: Evaluation of climate models, in Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report

325   of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, pp. 741–866, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., doi: 10.1017/CBO9781107415324.020, 2013.

Free, M. and Sun, B.: Time-varying biases in U.S. total cloud cover data, J. Atmos. Ocean. Technol., 30(12), 2838–2849, doi:10.1175/JTECH-D-13-00026.1, 2013.

330   Fujibe, F., Yamazaki, N., Katsuyama, M. and Kobayashi, K.: The increasing trend of intense precipitation in Japan based on four-hourly data for a hundred years, SOLA, 1, 41–44, doi:10.2151/sola.2005-012, 2005.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S. and Xavier, P. K.: Increasing trend of extreme rain events over India in a warming environment, Science, 314(5804), 1442–1445, doi:10.1126/science.1132027, 2006.

Groisman, P. Y., Knight, R. W., Easterling, D. R., Karl, T. R., Hegerl, G. C. and Razuvaev, V. N.: Trends in intense

335   precipitation in the climate record, J. Clim., 18(9), 1326–1350, doi:10.1175/JCLI3339.1, 2005.

Hu, Y. and Fu, Q.: Observed poleward expansion of the Hadley circulation since 1979, Atmos. Chem. Phys., 7(19), 5229–5236, doi:10.5194/acp-7-5229-2007, 2007.

Jiang, Z., Shen, Y., Ma, T., Zhai, P. and Fang, S.: Changes of precipitation intensity spectra in different regions of mainland China during 1961–2006, J. Meteorol. Res., 28(6), 1085–1098, doi:10.1007/s13351-014-3233-1, 2014.

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

Kaiser, D. P.: Decreasing cloudiness over China: An updated analysis examining additional variables, Geophys. Res. Lett., 27(15), 2193–2196, doi:10.1029/2000GL011358, 2000.

Karl, T. R. and Knight, R. W.: Secular trends of precipitation amount, frequency, and intensity in the United States, Bull.

345   Am. Meteorol. Soc., 79(2), 231–241, doi:10.1175/1520-0477(1998)079<0231:STOPAF>2.0.CO;2, 1998.

Klein Tank, A. M. G. and Können, G. P.: Trends in indices of daily temperature and precipitation extremes in Europe, 1946-99, J. Clim., 16(22), 3665–3680, doi:10.1175/1520-0442(2003)016<3665:TIIODT>2.0.CO;2, 2003.

Kuligowski, R. J.: A self-calibrating real-time GOES rainfall algorithm for short-term rainfall estimates, J. Hydrometeorol., 3(2), 112–130, doi:10.1175/1525-7541(2002)003<0112:ASCRTG>2.0.CO;2, 2002.

350   Lau, K.-M. and Wu, H.-T.: Climatology and changes in tropical oceanic rainfall characteristics inferred from Tropical Rainfall Measuring Mission (TRMM) data (1998–2009), J. Geophys. Res., 116, D17111, doi:10.1029/2011JD015827, 2011.

Liang, F. and Xia, X. A.: Long-term trends in solar radiation and the associated climatic factors over China for 1961-2000, Ann. Geophys., 23(7), 2425–2432, doi:10.5194/angeo-23-2425-2005, 2005.

Liu, B., Xu, M., Henderson, M. and Qi, Y.: Observed trends of precipitation amount, frequency, and intensity in China,

355   1960-2000, J. Geophys. Res. D Atmos., 110(8), 1–10, doi:10.1029/2004JD004864, 2005.

Liu, R., Liu, S. C., Cicerone, R. J., Shiu, C.-J., Li, J., Wang, J. and Zhang, Y.: Trends of extreme precipitation in eastern China and their possible causes, Adv. Atmos. Sci., 32(8), 1027–1037, doi:10.1007/s00376-015-5002-1, 2015.

Liu, R., Liu, S. C., Shiu, C.-J., Li, J. and Zhang, Y.: Trends of regional precipitation and their control mechanisms during 1979–2013, Adv. Atmos. Sci., 33(2), 164–174, doi:10.1007/s00376-015-5117-4, 2016.

360 Liu, S. C., Fu, C., Shiu, C.-J., Chen, J.-P. and Wu, F.: Temperature dependence of global precipitation extremes, Geophys. Res. Lett., 36(17), L17702, doi:10.1029/2009GL040218, 2009.

Liu, Y., Wang, N., Wang, L., Guo, Z. and Wu, X.: Variation of cloud amount over China and the relationship with ENSO from 1951 to 2014, Int. J. Climatol., 36(8), 2931–2941, doi:10.1002/joc.4529, 2016.

Mahlobo, D. D., Ndarana, T., Grab, S. and Engelbrecht, F.: Integrated climatology and trends in the subtropical Hadley cell,

365 sunshine duration and cloud cover over South Africa, Int. J. Climatol., 39(4), 1805–1821, doi:10.1002/joc.5917, 2019.

Manton, M. J., Della-Marta, P. M., Haylock, M. R., Hennessy, K. J., Nicholls, N., Chambers, L. E., Collins, D. A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T. S., Lefale, P., Leyu, C. H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C. M., Pahalad, J., Plummer, N., Salinger, M. J., Suppiah, R., Tran, V. L., Trewin, B., Tibig, I. and Yee, D.: Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961-1998, Int. J. Climatol., 21(3), 269–

370 284, doi:10.1002/joc.610, 2001.

Mao, K., Yuan, Z., Zuo, Z., Xu, T., Shen, X. and Gao, C.: Changes in global cloud cover based on remote sensing data from 2003 to 2012, Chinese Geogr. Sci., 29(2), 306–315, doi:10.1007/s11769-019-1030-6, 2019.

Norris, J. R. and Evan, A. T.: Empirical removal of artifacts from the ISCCP and PATMOS-x satellite cloud records, J. Atmos. Ocean. Technol., 32(4), 691–702, doi:10.1175/JTECH-D-14-00058.1, 2015.

375 Norris, J. R., Allen, R. J., Evan, A. T., Zelinka, M. D., O'Dell, C. W. and Klein S. A.: Evidence for climate change in the satellite cloud record, Nature, 536, 72–75, doi:10.1038/nature18273, 2016.

Qian, W., Fu, J. and Yan, Z.: Decrease of light rain events in summer associated with a warming environment in China during 1961-2005, Geophys. Res. Lett., 34(11), 1–5, doi:10.1029/2007GL029631, 2007.

Rajeevan, M. N. and Nayak, S.: Observed climate variability and change over the Indian region, edited by M. N. Rajeevan

380 and S. Nayak, Springer Singapore, Singapore., 2017.

Reichler, T. and Held, I.: Widening of the Hadley cell over the past 40 years, paper presented at the conference on climate variability and change, in Conference on Climate Variability and Change, American Meteorological Society, Cambridge, Mass., 2005.

Schiffer, R. A. and Rossow, W. B.: The International Satellite Cloud Climatology Project (ISCCP): The first project of the

385 World Climate Research Programme, Bull. Am. Meteorol. Soc., 64(7), 779–784, doi:10.1175/1520-0477-64.7.779, 1983.

Schulz, N., Boisier, J. P. and Aceituno, P.: Climate change along the arid coast of northern Chile, Int. J. Climatol., 32(12), 1803–1814, doi:10.1002/joc.2395, 2011.

Shiu, C.-J., Liu, S. C., Fu, C., Dai, A. and Sun, Y.: How much do precipitation extremes change in a warming climate?, Geophys. Res. Lett., 39(17), L17707, doi:10.1029/2012GL052762, 2012.

390 Sun, Y., Solomon, S., Dai, A. and Portmann, R. W.: How Often Will It Rain?, J. Clim., 20(19), 4801–4818, doi:10.1175/JCLI4263.1, 2007.

Trenberth, K. E.: Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change, Clim. Change, 39(4), 667–694, doi:10.1023/A:1005319109110, 1998.

Trenberth, K. E. and Shea, D. J.: Atlantic hurricanes and natural variability in 2005, Geophys. Res. Lett., 33, L12704,
395   doi:10.1029/2006GL026894, 2006.

Trenberth, K. E., Dai, A., Rasmussen, R. M. and Parsons, D. B.: The changing character of precipitation, Bull. Am. Meteorol. Soc., 84(9), 1205–1217, doi:10.1175/BAMS-84-9-1205, 2003.

Wang, X. and Zhai, P.: Changes in China's precipitation in various categories during 1957-2004, J. Trop. Meteorol., 24(5), 459–466, doi:10.16032/j.issn.1004-4965.2008.05.019, 2008.

400   Wu, F. and Fu, C.: Change of precipitation intensity spectra at different spatial scales under warming conditions, Chinese Sci. Bull., 58(12), 1385–1394, doi:10.1007/s11434-013-5699-0, 2013.

Xia, X.: Spatiotemporal changes in sunshine duration and cloud amount as well as their relationship in China during 1954–2005, J. Geophys. Res., 115(7), D00K06, doi:10.1029/2009JD012879, 2010.

Xia, X.: Significant decreasing cloud cover during 1954–2005 due to more clear-sky days and less overcast days in China
405   and its relation to aerosol, Ann. Geophys., 30(3), 573–582, doi:10.5194/angeo-30-573-2012, 2012.

Xie, P., Janowiak, J. E., Arkin, P. A., Adler, R., Gruber, A., Ferraro, R., Huffman, G. J. and Curtis, S.: GPCP pentad precipitation analyses: An experimental dataset based on gauge observations and satellite estimates, J. Clim., 16(13), 2197–2214, doi:10.1175/2769.1, 2003.

Zhai, P., Zhang, X., Wan, H. and Pan, X.: Trends in total precipitation and frequency of daily precipitation extremes over
410   China, J. Clim., 18(7), 1096–1108, doi:10.1175/JCLI-3318.1, 2005.

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.
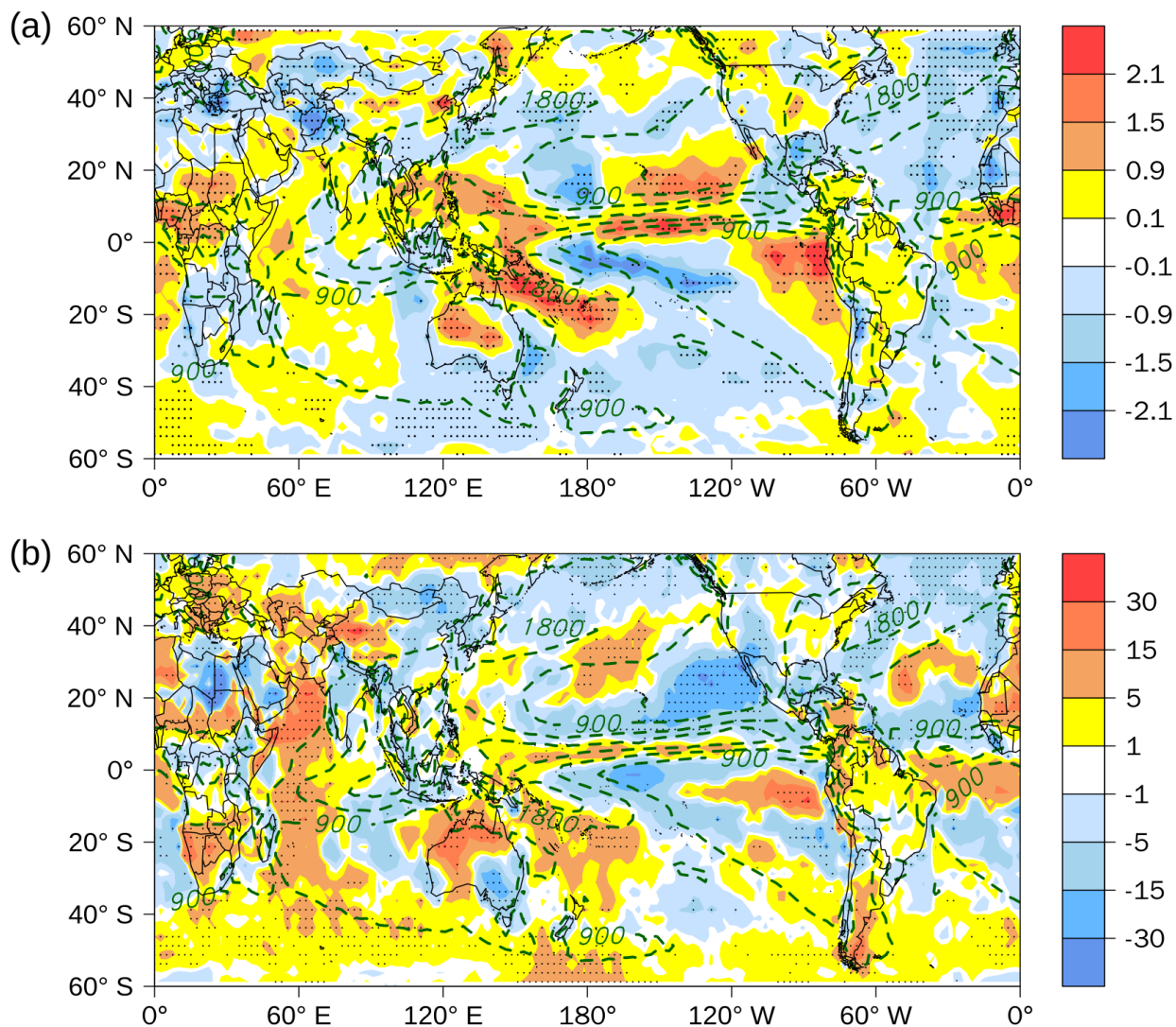
415

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).
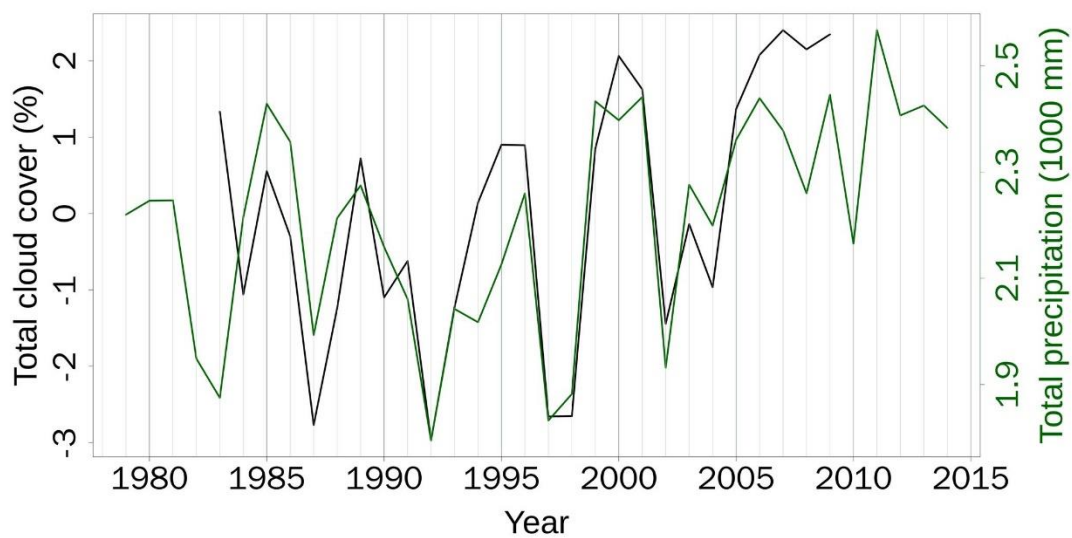
420

Figure 2. Time series of the anomaly of annual total cloud cover (%) and the annual average total precipitation (1000 mm) in the eastern Maritime Continent (20° S-10° N, 130° E-160° E).

Atmospheric
Chemistry
and Physics
Discussions

Open Access

EGU
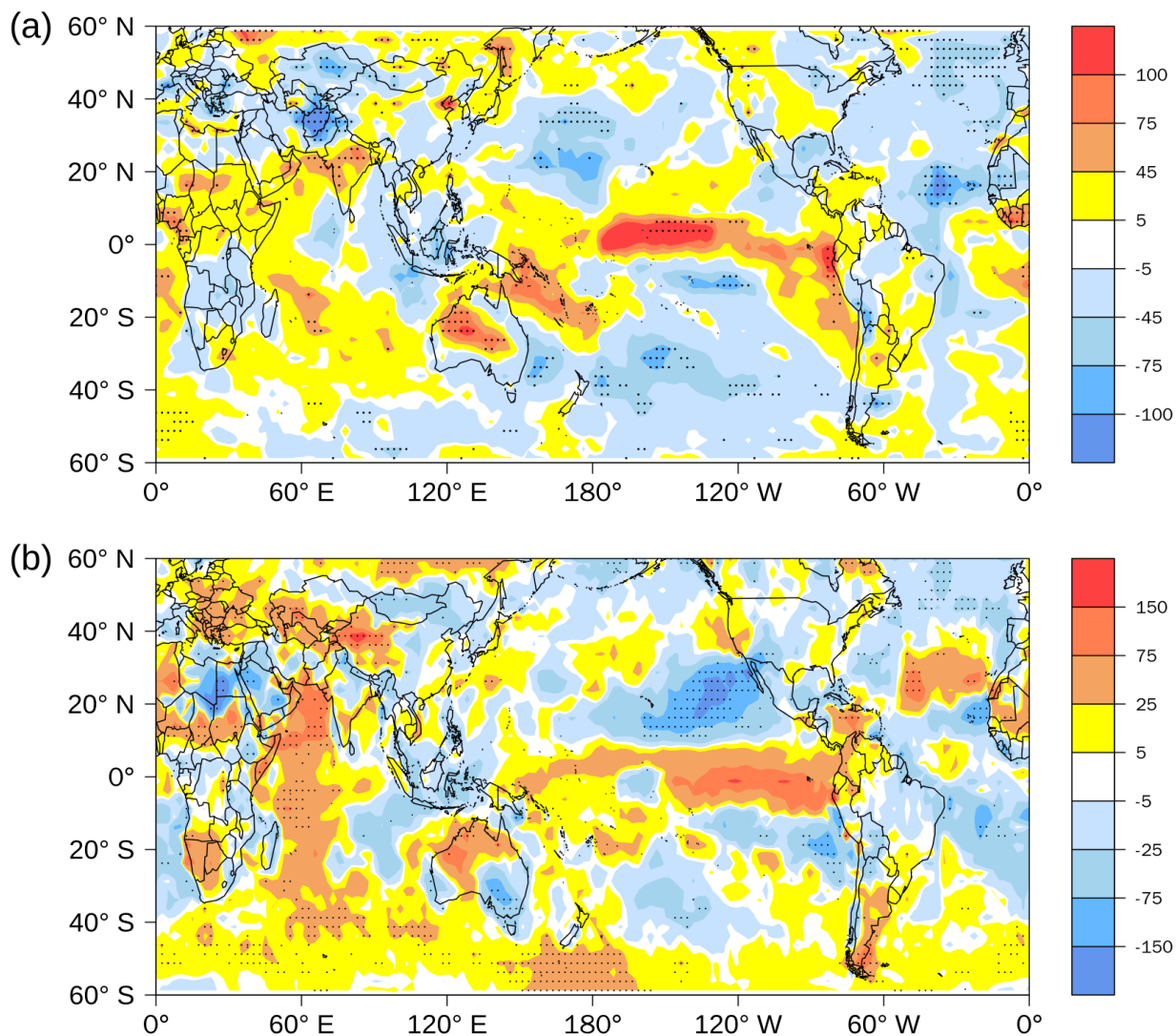
Figure 3. (a) Slope of linear regression between total cloud cover and global temperature anomalies (units: % K⁻¹) at individual grids from corrected ISCCP D2 data set (1983–2009). (b) Slope of linear regression between annual total precipitation and global temperature anomalies (units: % K⁻¹) at individual grids from GPCP pentad V2.2 (1983–2009). Dots indicate changes significant at the 95% confidence level.
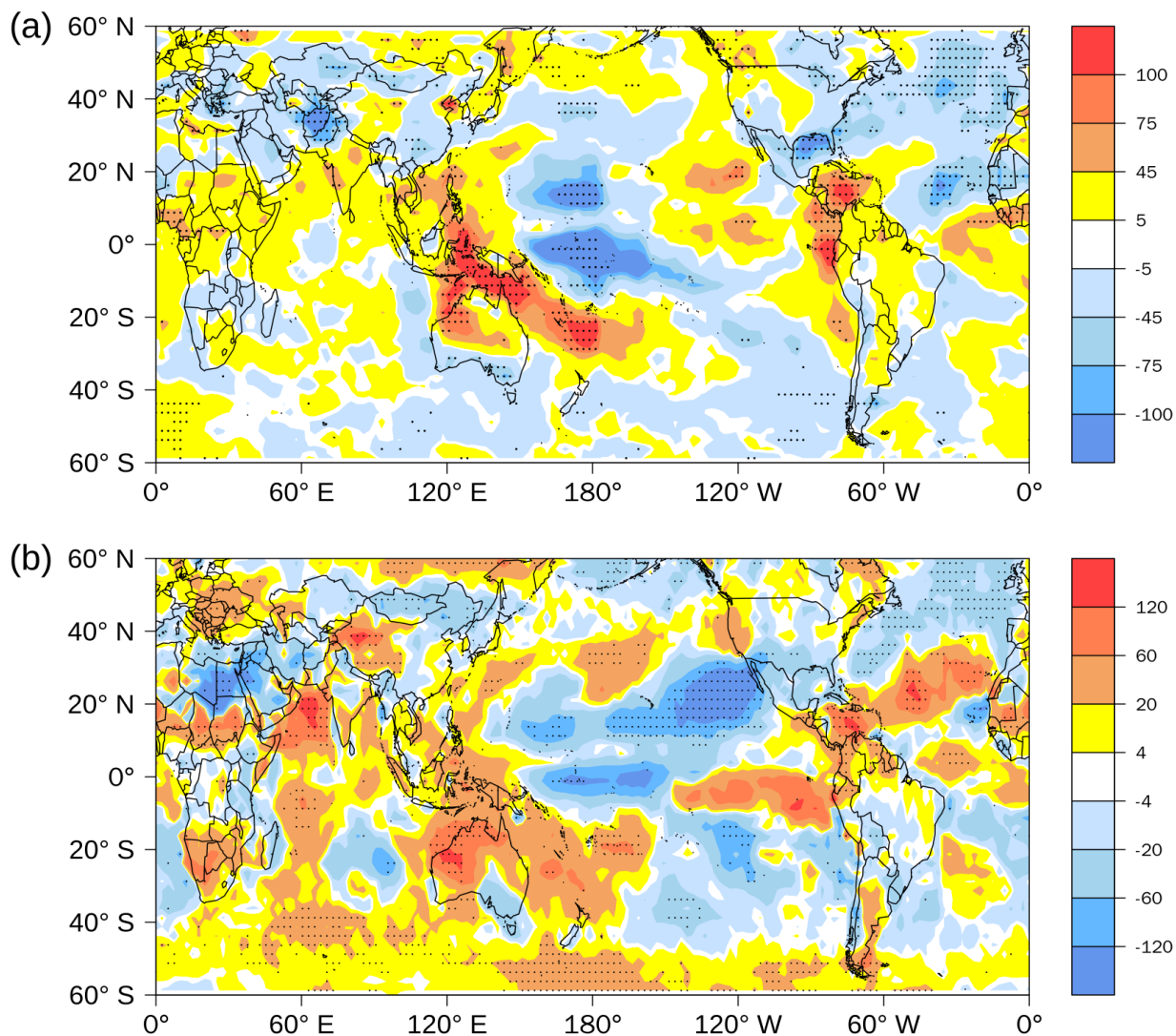
Figure 4. (a) Slope of linear regression between total cloud cover and AMO (units: % K^{-1}) at individual grids from corrected ISCCP D2 data set (1983–2009). (b) Slope of linear regression between annual total precipitation and AMO (units: % K^{-1}) at individual grids from GPCP pentad V2.2 (1983–2009). Dots indicate changes significant at the 95% confidence level.

Atmospheric
Chemistry
and Physics
Discussions
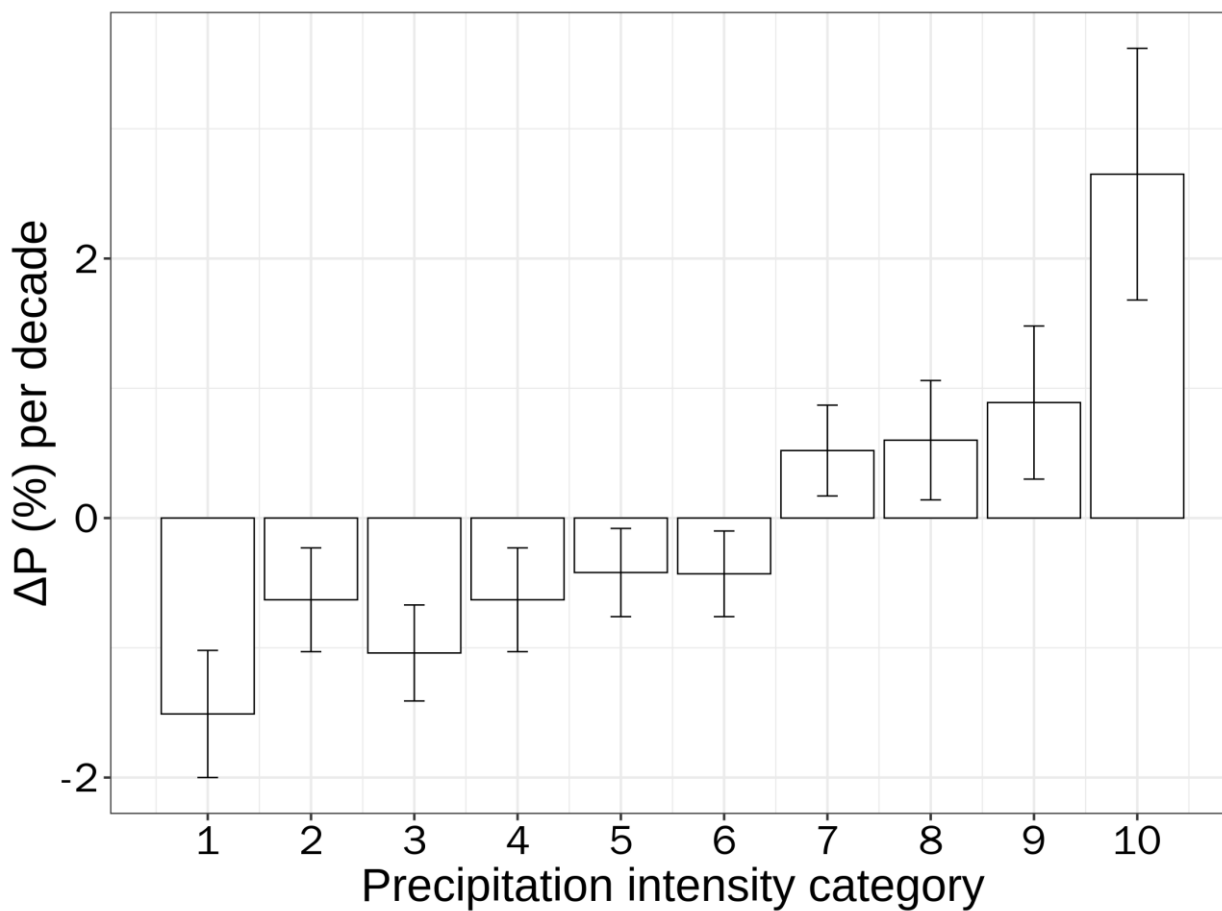
Figure 5. Linear trends of annual precipitation amount (ΔP) falling within each of the ten intensity bins during 1957-2005. The vertical line on top of each bar denotes 1 standard error.

Atmospheric
Chemistry
and Physics
Discussions
Open Access
EGU
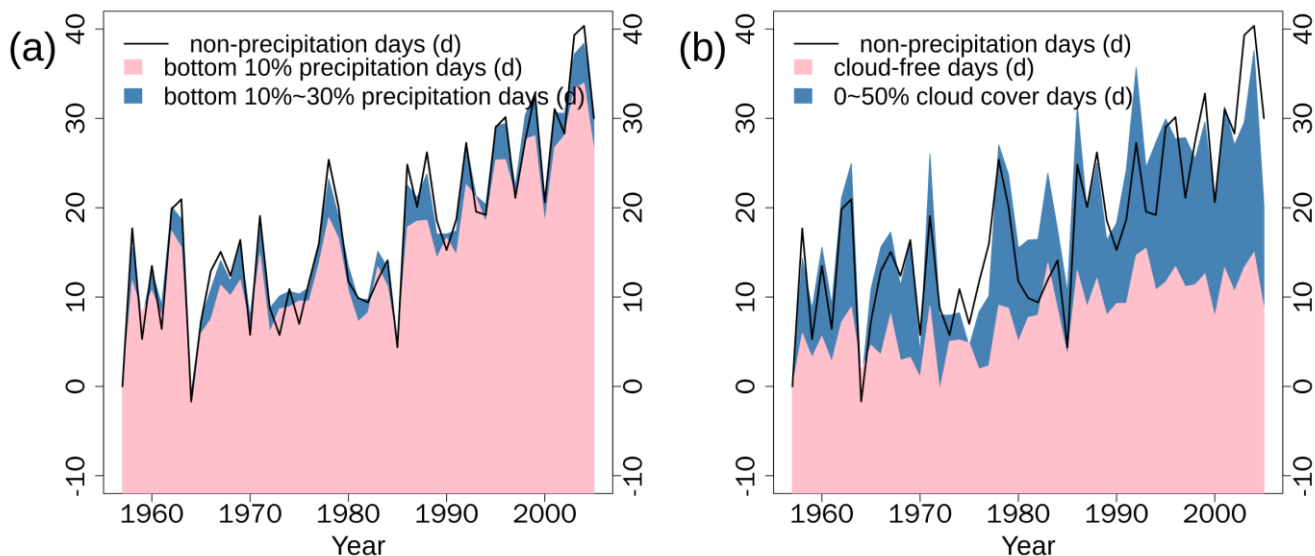
Figure 6. (a) Time series of changes relative to the value of 1957 in non–precipitation days, bottom 10% precipitation days and bottom 10%–40% precipitation days in 1957–2005. (b) As in (a) but for changes of non–precipitation days, cloud–free days and 0–50% cloud cover days. Changes are calculated as original time series subtract the value of the start year (1957).
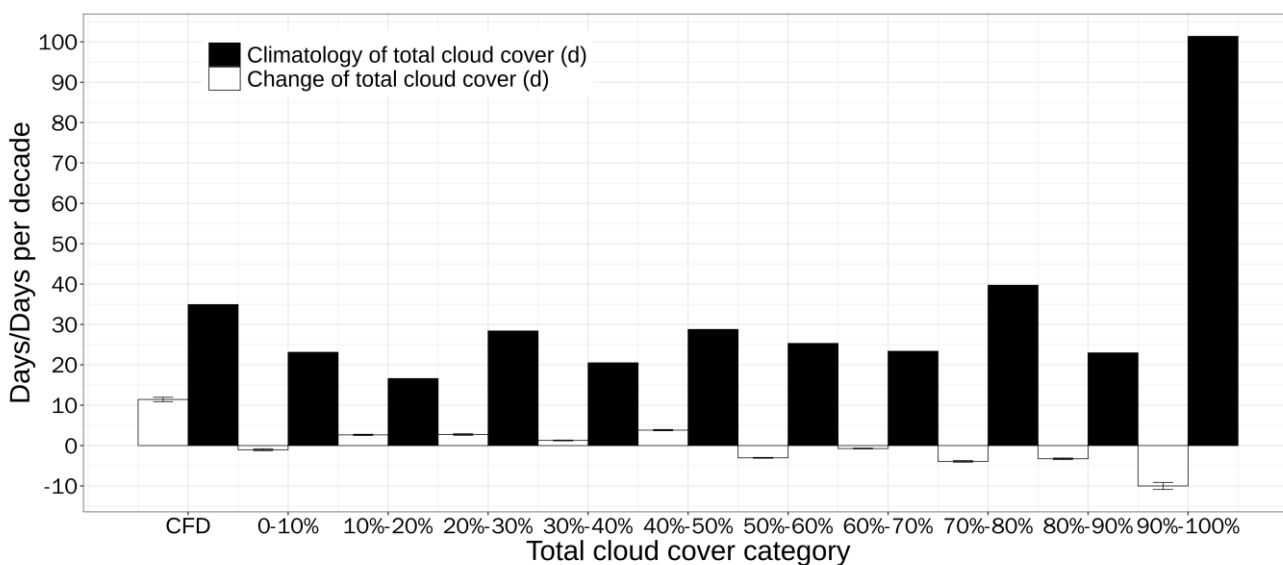
440

Figure 7. 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.

445

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 ΔGT is the change of GT for the studied period and GT_σ 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

460