A counterexample of aerosol suppressing light rain in Southwest China during 1951–2011

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Abstract

Surface meteorological observation data and aerosol optical depth (AOD) data from 1951–2011 were analyzed for Tengchong city, which is a clean city in Southwest China. A significant reduction of light rain, accompanied by an increase of visibility and a decrease of droplet number concentration and droplet size, was observed. Thus, the observed light rain reduction in Tengchong was not associated with an increase of aerosols. The main cause of the reduction in light rain was the decrease of relative humidity in the layer between 850 to 500 hPa, which was induced mainly by the increase of temperature. This counterexample indicates that there are some evidences on the short-term scale, but the depression of light rain by aerosols on the long-term scale remains controversial.

Keywords: light rain; aerosol; warming; water vapor; Tengchong

1. Introduction

In recent years, increases in precipitation were found primarily for heavy and extreme precipitation events in the United States (Karl and Knight, 1998), Europe (Klein Tank and Können, 2003), Southeast Asia and the South Pacific (Manton et al., 2001), and China (Zhai et al., 2005). At the same time, reduction of light rain is an aspect of climate change, which has important effects on drought and agriculture. Light rains decreased in China (Gong et al., 2004; Fu et al., 2008), Europe, North America, and Asia (Qian et al., 2010; Huang and Wen, 2013). Moreover, the most distinct reductions of light rain, in terms of amount and days, were for lower intensity light rains (Qian et al., 2007; Liu et al., 2011).

A decrease of cloud droplet radius accompanied by an increase of cloud droplet numbers was observed in cases of aerosol pollution (Warner and Twomey, 1967), and observed aerosol depression of precipitation has been reported (Zhao et al., 2006; Rosenfeld et al., 2007). In addition, a significant increase of the cloud droplet number concentration and a reduction of droplet sizes, which led to significant reductions in rainfall frequency and amount, were found by simulations (Qian et al., 2009). Short-term simulation from a bin and bulk microphysics model also identified a similar mechanism (Fan et al., 2012). In addition, the water vapor holding capacity of the atmosphere increases in warmer environment compared to that in colder environment according to the Clausius–Clapeyron equation (Trenberth et al., 2003), which means that the dew-point temperature is harder to achieve in a warming environment with stationary water vapor content. Light rain is the transition rainfall grade between stronger rainfall and no rainfall and should be more sensitive to the changes of temperature and water vapor than other stronger rainfall grades. Recently, the warming and the change of water vapor content were identified as two important factors for the decrease of light rain in Eastern China, but the influence of aerosols on the long-term reduction of light rain remained uncertain in this region due to the simultaneous occurrence of severe air pollution, warming, and changes of water vapor content (Wu et al., 2015).

While light rain reduction has been found in many regions of the world (Qian et al., 2010; Huang and Wen, 2013), aerosol optical depth (AOD) was not always high in regions with light rain decreases. Other research has shown distinct spatial variations in the AOD in China and that the significant increase of aerosol occurred mainly after 1996 (Guo et al., 2011), but the light rain reduction in China began in the 1960s (Fu et al., 2008). These observations have raised questions about the role of aerosols in suppressing light rain on the long-term scale.

In this paper, we present a long-term diagnostic analysis of aerosols and light rain reduction in Tengchong city in Southwest China to examine this proposition. The data and methods are presented in Section 2 and the results and analysis in Section 3, followed by the conclusions.

2. Data and methods

Tengchong is a small city located in the western part of Yunnan province, which is a plateau in the low-latitude belt in Southwest China, and the
The earliest meteorological records in Tengchong date back to 1951. In recent decades, the ecological environment in Tengchong city has been protected very well, and no significant anthropogenic air pollutant emissions or wide-scale land use and cover changes have occurred in the city and adjacent regions. While the Tengchong meteorological station was relocated twice, in 1956 and 1987, it moved only 600 and 150 m, respectively, which should not result in significant differences in the long-term rainfall and temperature data. These characteristics of the Tengchong station permit examination of the background climate changes.

The daily surface observation data for 1951–2011, including rainfall amount, visibility, cloud fraction, relative humidity (RH) and temperature, and the daily radiosonde data for 1984–2013, including temperature and specific humidity from 850 to 500 hPa, were used in this study. The dataset observed by the CMA observation network including the Tengchong station passed the homogeneity and quality tests and was therefore regarded as the most credible dataset in China (Song et al. 2004). The CMA rainfall grade standards used in our analysis, in which measured daily rain rates were classified into five grades of intensity: light (0.1–10 mm d\(^{-1}\)); moderate (10–25 mm d\(^{-1}\)); heavy (25–50 mm d\(^{-1}\)); storm (50–100 mm d\(^{-1}\)); and downpour (>100 mm d\(^{-1}\)).

Visibility is often used as an indicator of atmospheric purity and can be influenced by the extinction effects of humid air, aerosols, and some types of air pollutants. Daily visibility before 1980 in China was recorded according to 10 ranks based on distance, and these mean distances were subsequently used to replace each visibility rank record before 1980. To identify the extinction by aerosols and its effects on light rain well, the sunny visibility data were selected according to the following three conditions: (1) observation time must be at 0600 UTC; (2) data with near-surface RH more than 70% were excluded; and (3) data with total cloud cover more than 40% were rejected (Wu et al., 2012). In addition, the daily AOD data with 1°×1° resolution observed by the moderate resolution imaging spectro-radiometer (MODIS) over Tengchong during 2001–2014 were used to analyze the influences of aerosols on the light rain changes.

Composite analysis was used to determine the impacts of aerosols, temperature, and water vapor content on light rain amount. Years of abnormal meteorological parameters were determined in the composite analysis based on the principle that the time series of the meteorological parameters should be normalized; then, if the value was more (less) than 1 (−1), its corresponding year was deemed as a positive (negative) abnormal year (Wu et al., 2015). Additionally, Student’s t-test was used to determine the significance of the data. The linear trend coefficient was calculated using the least-squares method.

3. Results and analysis

The temporal changes of different rainfall grades in Tengchong during 1951–2011 are shown in Figure 1.

**Figure 1.** Temporal changes of anomalies for annual four-grade rainfall amounts and rainfall days in Tengchong city (from top to bottom: (a) light rain, (b) moderate rain, (c) heavy rain, (d) storm, (e) total rainfall). T and Rst stand for the climatic tendency and the linear trend coefficient, respectively. Superscripts \(^a\), \(^b\), and \(^c\) refer to the correlation coefficients statistically significant at the 90, 95, and 99% levels, respectively.
There was a significant decrease in the amount and days of light rain during the recent 50 years (Figure 1(a)), and the linear trend coefficients were significant according to the $t$-test at the 99% level. The decreases of light rainfall amounts and light rain days were more significant after the middle of the 1980s than before. However, there were no statistically significant trends in both the moderate and the storm rainfall amounts and days (Figure 1(b) and (d)), but the heavy rainfall amounts and days increased significantly during 1951–2011 (Figure 1(c)). In addition, the total rainfall amount had a statistically insignificant increasing trend of 0.85 mm a$^{-1}$ (Figure 1(e)), which was due to the increases of heavy and storm rainfall amounts. However, the total rainfall days decreased at the rate of $-1.44$ da$^{-1}$, which was statistically significant at the 99% level, and the distinct decrease of the total rainfall days could be attributed to the significant reduction of light rain days at the rate of $-1.68$ da$^{-1}$. Similar reductions of light rainfall in the background of the total rainfall increase were also found in many other regions (Gong et al., 2004; Qian et al., 2007; Fu et al., 2008).

The temporal changes of visibility, sunny visibility, and AOD are shown in Figure 2. The visibility and the sunny visibility showed increasing trends of 0.07 and 0.05 km a$^{-1}$, respectively, during 1951–2011 and were statistically significant according to the $t$-test at the 99% level. The MODIS AOD data were available only after June 2000 and showed a weakly decreasing trend during 2001–2014. The increases of visibility and sunny visibility and the decrease of AOD indicated that the air quality of Tengchong was well protected in the last 50 years. The correlation coefficients and the composite analyses between light rain amount and visibility, sunny visibility, visibility on light rain days, and AOD are shown in Tables 1 and 2, respectively. A statistically significant correlation coefficient was found between light rain amount and visibility only, and other correlation coefficients between light rain amount and sunny visibility, visibility on light rain days, and AOD were statistically indistinctive. The results of composite analysis revealed some insignificant visibility and AOD differences between the higher and lower light rainfall amount years. Therefore, the pronounced decreases of light rainfall amount and light rainfall days in the long-term observation data, especially after 1980, could not be explained by the increase of aerosol, as reported in other polluted regions (Zhao et al., 2006; Qian et al., 2009; Fan et al., 2012; Fu and Dan, 2014).

In earlier research, another mechanism of light rain reduction was reported (Wu et al., 2015), in which the light rain in many regions of Eastern China was distinctly affected by the low-level RH, which in turn was dominated by the warming and the change of water

![Figure 2](image-url). Temporal changes of annual visibility, sunny visibility, AOD, and their annual means on light rain days in Tengchong city. $T$ and $Rst$ stand for the climatic tendency and the linear trend coefficient, respectively. Superscript $a$ refers to the correlation coefficients statistically significant at the 99% levels.

| Light rainfall amount | Visibility | Sunny visibility | Visibility on light rain days | MODIS AOD | MODIS AOD on light rain days | RH | RH on light rain days |
|-----------------------|------------|-----------------|-------------------------------|----------|----------------------------|----|----------------------|
| Correlation coefficient | $-0.34^a$ | 0.02            | 0.00                          | $-0.24$  | $-0.22$                    | 0.37$^a$ | 0.29                 |

The period of available daily visibility data is 1951–2011, RH refers to the air mass-weight RH from 850 to 500 hPa during 1984–2011, and AOD data are available only for 2001–2011. Superscripts $a$ and $b$ refer to the correlation coefficients and the differences of composite analysis statistically significant at the 90% and 99% levels, respectively.
Table 2. Composite analysis results between light rainfall amount and visibility, AOD, and RH in Tengchong city.

| Light rainfall amount | Visibility | Sunny visibility | Visibility on light rain days | MODIS AOD | MODIS AOD on light rain days | RH | RH on light rain days |
|-----------------------|------------|------------------|-------------------------------|-----------|-------------------------------|----|-----------------------|
| Correlation coefficient | \(-0.34^b\) | 0.02             | 0.00                          | \(-0.24\) | \(-0.22\)                   | 0.37^h | 0.29                  |
| Results of composite analysis-1 | \(-0.72\) km | 0.35 km          | 0.73 km                       | 0.00      | \(-0.01\)                   | 6.02%^a | 2.20%                 |
| Results of composite analysis-2 | 30.93 mm   | 23.75 mm         | 2.16 mm                       | \(-10.60\) mm | \(-4.42\) mm                | 47.50 mm | 52.11 mm              |

The period of available daily visibility data is 1951–2011, RH refers to the air mass-weight RH from 850 to 500hPa during 1984–2011, and AOD data are available only for 2001–2011. Results of composite analysis-1 indicate the differences of each factor in the first line between the positive and negative years of abnormal amounts of light rain, and results of composite analysis-2 indicate the differences in light rainfall amounts between the positive and negative abnormal years for each factor in the first line. Superscripts ^a and ^b refer to the correlation coefficients and the differences of composite analysis statistically significant at the 90% and 99% levels, respectively.

Figure 3. Temporal changes of air mass-weighted temperature and column water vapor (a) and air mass-weighted RH between 850 to 500hPa, as well as relative contributions from changes in temperature (RH\(_t\)) and water vapor (RH\(_q\)) to the long-term change of RH in Tengchong city (b). T and Rst stand for the climatic tendency and the linear trend coefficient, respectively. Superscript ^a refers to the correlation coefficients statistically significant at the 99% levels.

The effects of warming and the change of water vapor content on the long-term changes of mass-weighted RH are shown in Figure 3. The air mass-weighted temperature between 850 to 500hPa increased from 4.5 to 5.0°C during 1984–2013, which included a rapid increase after the middle of the 1990s. Meanwhile, the column water vapor content in the same vertical range decreased from 22 to 21.5kgm\(^{-2}\), which included a rapid decrease after 2000 (Figure 3(a)). These two changes could affect the mass-weighted RH distinctly. Figure 3(b) shows the long-term changes of mass-weighted RH and the individual contributions from the warming (RH\(_t\)) and from the changes of water vapor content (RH\(_q\)), calculated using the Clausius–Clapeyron equation by constraining the column water vapor content and the temperature at their 1984 values, respectively. RH decreased from 68% in 1984 to 62% in 2013 with a decreasing rate of \(-0.28\) %a\(^{-1}\), which was statistically significant at the 99% level. A fluctuation in RH was observed during 1984–1993, and the most distinct decrease was found after 2004. RH showed a constant decreasing trend.
during 1984–2013 with a linear trend of \(-0.15\%a^{-1}\). At the same time, RH\(_t\) fluctuated during 1984–1998, followed by a distinct decrease after 1999, especially after 2004, and the linear trend of RH\(_t\) reached \(-0.2\%a^{-1}\) during 1984–2013. The contribution from the linear trend of RH\(_t\) to RH was more significant than that of RH\(_g\), and the decrease of RH during 1984–2013 was 5.97\%, for which RH\(_t\) and RH\(_g\) accounted for 0.9 and 4.06\%, respectively. In addition, the large decrease of RH after 2004 was mainly caused by the corresponding decrease of RH\(_g\), and the constant decreasing trend of RH, especially during 1984–1999, can be explained by the steady reduction of RH, because RH\(_g\) fluctuated during the same period. Thus, the warming and the reduction of column water vapor content are two factors inducing the light rain decrease in Tengchong during 1984–2013.

4. Summary

We examined the light rain reduction in Tengchong city in Southwest China during the period 1951–2011, when the air was consistently clean, as indicated by the weak increase of visibility over 60 years and a steady fluctuation of satellite AOD after 2001. It was obvious that the significant reductions of both the amounts and days of light rain in Tengchong could not be explained by an increase of aerosols, as was reported in other regions with high concentrations of air pollutants. At the same time, the air mass-weighted temperature from 850 to 500 hPa in the city was increasing markedly, whereas the column water vapor content in the same layers was decreasing, so the two factors decreased the air mass-weighted RH, which in turn improved conditions for condensation and thus decreased the occurrences of light rain. In conclusion, the effects of the changes in temperature and water vapor on the changes in light rain should be stressed, especially in clean air regions.

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