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Key Points:
- The summer LSP hours have significantly declined in the United States and China over the past three decades
- The boomerang shape revealing the response of LSP frequency to aerosols points to the importance of aerosol loading rather than AOD trend
- This disparate role of aerosols in the rainfall process requires holistic thinking about air pollution and climate change

Supporting Information:
- Supporting Information S1

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Declining Summertime Local-Scale Precipitation Frequency Over China and the United States, 1981–2012: The Disparate Roles of Aerosols

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Abstract The local-scale precipitation (LSP) is mainly driven by thermal convection. Here we reveal a decreasing trend in the summertime LSP frequency over both China and the United States by utilizing the hourly rain gauge data from 1981 to 2012. The contrasting aerosol trend likely contributes to this same declining trend of LSP in both countries. As aerosol optical depth (AOD) goes beyond the turning zone of 0.25–0.30, the impact of aerosol on precipitation changes from invigoration to suppression. The mean AOD is generally less and larger than this range and of opposite trends in China and United States, respectively, which likely accounts for the same declining trend of LSP hours in the two countries. The observed boomerang shape points to the importance of aerosol loading, which matters as much as, if not more than the AOD trend, thereby potentially serving as a constraint for climate model evaluation.

Plain Language Summary Local-scale precipitation (LSP) is an integral part of the freshwater cycle. Here, we show that summer LSP hours have significantly declined in the United States and China over the past three decades, a phenomenon that cannot be well explained by global warming. The relationship between LSP hours and aerosol loading is a boomerang shape; a turning zone exists for the shifting effect of aerosols from enhancing to suppressing rainfall as aerosol loading increases. China is above this zone with an increasing aerosol trend, and the United States is below it with a decreasing trend, but they have similar reductions in LSP hours. This disparate role of aerosols in the rainfall process requires holistic thinking about air pollution and climate change.

1. Introduction

Cloud and precipitation systems play crucial roles in the modulation of the energy budget and the availability of freshwater (Boucher et al., 2013; Houze, 2018). As a major component of climate change, rainfall variability and trends have attracted considerable attention in recent years because they exhibit large temporal and spatial dependences due to changes in climate modes, meteorology, aerosols, and greenhouse gases (Guo et al., 2016; Koren et al., 2012; Qian et al., 2009). The rainfall trends in different regions of the world, especially China (Day et al., 2018; Zhai et al., 2005) and the United States (Easterling et al., 2000; Feng et al., 2016), have been well documented. Although they vary significantly by region and period analyzed, the rainfall trends in China and the United States have similar general features. Heavy or extreme rainfall has an increasing trend, while light rainfall has a decreasing trend in China during the period 1956 to 2005 (Qian et al., 2009) and the United States from 1960 to 2010 (Karl & Knight, 1998; Wang et al., 2010). The aerosol effects have been considered to be one of the factors contributing to these trends, especially in eastern China (Fan et al., 2018; Li et al., 2011; Li et al., 2016; Qian et al., 2009).

Aerosol effects on precipitation are largely due to aerosol-radiation interactions and aerosol-cloud interactions (ACIs; Boucher et al., 2013; Li et al., 2017). Both enhancement (Fan et al., 2018; Khain et al., 2005) and suppression (Guo et al., 2016; Qian et al., 2009; Rosenfeld et al., 2001) of rainfall by aerosols have been observed. The net effects are still debated and depend on atmospheric conditions (Fan et al., 2009) and aerosol loading (Koren et al., 2014; Rosenfeld et al., 2008; Wang et al., 2014). The complex buffering effect makes the disentangling of aerosol and meteorology effects on precipitation challenging (Stevens & Feingold, 2009) and merits more insightful and rigorous investigations.

In a globally averaged sense, the oceans provide an unlimited supply of moisture, so precipitation formation is energetically unlimited (Mitchell & Finnegan, 2009). By contrast, localized precipitation over land is subject to moisture available (Dong et al., 2018), although it is also limited by local energetic constraints (Raymond et al., 2009). The aerosol effect influences the vertical structures of cloud microphysical properties and atmospheric heating rates, which in turn affects the transport and transformation of moisture and energy (Boucher et al., 2013; Guo et al., 2018). Through the radiative effects and microphysical effects, aerosol can further change the rain rate and frequency (Boucher et al., 2013). This study is primarily focused on local-scale precipitation (LSP). LSP is mainly driven by thermal convection during the daytime, on which the aerosol effects can be more readily discerned from other factors such as large-scale dynamics (Guo et al., 2017).

As a result of rapid industrialization and urbanization over the past few decades, China has become a dominant source region of anthropogenic emissions in both gaseous and particulate matters, although some gas emitters such as SO_2 have reserved their trends in recent decade (C. Li, et al., 2017). Atmospheric pollution over the United States has been steadily declined due to strict emission control policies (Lin et al., 2014). The mean state and long-term trends in aerosols thus differ considerably between China and the United States, even though air quality improvement in the United States has slowed down in recent years (Jiang et al., 2018). It is intriguing and imperative to examine if any changes in LSP frequency in the United States and China have anything to do with the opposite trends in aerosol loading, for which we are examining the role of aerosols in the long-term trends of LSP over eastern China and the United States.

2. Data and Methods

2.1. Data Set

In this study, hourly rain gauge measurements collected across eastern China and the United States during the summer (defined as May to September) for the period 1981–2012, archived by the China Meteorological Administration and the U.S. National Oceanic and Atmospheric Administration, are used. Both data sets have undergone quality-control and homogenization tests (Easterling & Peterson, 1995; Guo et al., 2017).

The AOD is retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Aqua, based on the dark target-deep blue combined algorithm that is suitable for large-scale regions with different underlying surfaces (Levy et al., 2013). The Level-3 MODIS atmosphere monthly global product (MYD08_M3) on a 1° × 1° grid is used. Given the limited temporal coverage of MODIS AODs, the AOD product from Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) is also used with a spatial resolution of 2/3° longitude by 1/2° latitude (Rienecker et al., 2011). MODIS AOD (2002–2012) and MERRA-2 AOD (1981–2012) are both used in this study.

Additional meteorological data are obtained from the European Centre for Medium-Range Weather Forecast ERA-Interim (Dee et al., 2011) reanalysis data sets on a 1° × 1° grid, including surface temperature at 2 m (T_{2m}), lower troposphere stability (LTS), and precipitable water (PW). Annual means can then be calculated for May through September of each year. The grids of ERA-Interim used for the analysis are shown in supporting information Figure S2.

2.2. Determination of LSP Episode

In this study, hourly rain gauge measurements collected across eastern China and the United States during the summer (May to September) for the period 1981–2012, archived by the China Meteorological Administration and the U.S. National Oceanic and Atmospheric Administration, are used. Both data sets have undergone quality-control and homogenization tests (Dai et al., 1999; Easterling & Peterson, 1995; Guo et al., 2017). Based on data availability and quality, 776 stations in eastern China and 693 stations in the United States were used in our study. The rare rainfall and sparse rain-gauge network in the western United States (Jong et al., 2016; Lanzante & Harnack, 1982) leads to so few LSP events that our study region is confined to the central and eastern United States.

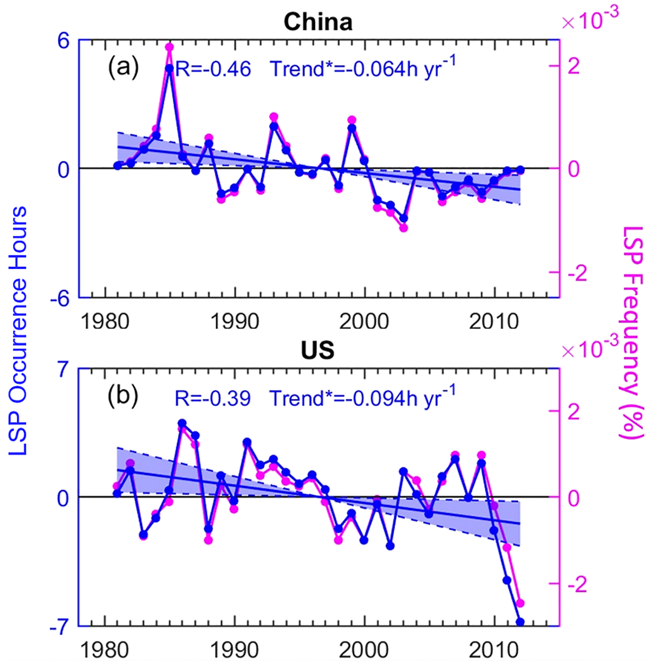

Figure 1. Time series of the annual mean anomalies of occurrence hours (blue lines) and frequency (pink lines) of summertime daily local-scale precipitation (LSP) for (a) China and (b) the United States from 1981 to 2012. The correlation coefficient between LSP hours anomalies and year (R) and its trend are shown at the top of each panel. Shading and dotted lines (blue) indicate 95% confidence intervals on the trends of LSP hours in these time series. Trends with asterisks indicate statistically significant trends at the 95% confidence level.

Jointly driven by thermal convection and dynamic processes, the LSP generally occurs during daytime. To identify an LSP event (measurable rain rate > 0.1 mm/hr) at a given station (target station), we made the following modification to our previous method (Guo et al., 2017). Initially, summertime LSP events were limited to 0700 local time (LT) to 1900 LT. Then, the following two criteria have to be met for determining an LSP event: (1) The proportion of rainy sites within a 150-km radius around the target station had to be equal or less than 25%; and (2) the proportion of rainy sites within a 50-km radius had to be equal or less than 50%. Figure S1 shows a schematic diagram of this. To exclude the residuals resulting from synoptic-scale precipitating systems, only those gauge stations with no rainfall occurring between 0000 and 0700 LT were considered. We defined N_{150} as the number of stations within 150 km of the target station. Figure S2 shows the spatial distribution of weather stations over eastern China and the United States along with the values of N_{150}. To ensure spatial representativeness, only those stations with $N_{150} > 5$ were chosen. Note that stations are unevenly distributed across eastern China and relatively evenly distributed across the United States. Note that the trend analysis methods and standardized multiple linear regressions method are detailed in Supporting Information S1.

3. Results and Discussion

3.1. Summertime LSP Trends

Figure 1 shows the time series of anomalies in the occurrence hours and frequency of daytime LSP for the period 1981–2012 calculated over eastern China and the United States. Note that LSP frequency indicates the LSP occurrence hours divided by the total number of hours, and thus, there are no fundamental differences between annual occurrence hours and frequency of LSP. Even though large interannual variations are evident, declining trends, in general, are seen in both countries. Their negative trends are statistically significant at the 95% confidence level. The declining trend in LSP frequency is rather notable over the United States after 2010, which is partially associated with the widespread drought condition in the Texas and the Great Plains (Nielsen-Gammon, 2012). To corroborate the trends in LSP events, a running window trend analysis with respect to the number of hours with LSP events was done using the robust Sen's slope with different starting and ending years (Figures S3a and S3b). Significant negative trends in LSP occurrence hours over eastern China and the United States are seen, especially for time windows longer than 15 years, regardless of the starting year. By contrast, the trends for time windows of less than 15 years are more reflective of the small-scale fluctuations connected to interannual variability. We further present the trends of LSP for light rain and heavy rain in Figure S4. During this period, the light rain reduced more significantly than heavy LSP did. This is consistent with previous studies (Karl & Knight, 1998; Qian et al., 2009), which show a widespread reduction in the frequency of light rain. In contrast to the declining LSP occurrence hours, the rainfall amounts for LSP events show no significant tendencies in either China or the United States, while significant increasing trends can be seen for the rain rates of LSP over both China and the United States as a possible consequence of the decreasing LSP frequencies (Figure S5).

In terms of the spatial pattern of LSP annual occurrence hours, LSP events have experienced widespread decreasing trends throughout eastern China (Figure 2a), while the LSP trends over the United States are heterogeneous (Figure 2b). To further elucidate the discrepancy, we define the region of interest (ROI) 1 and ROI 2 over the United States, as shown in Figure 2b. These two ROIs are roughly located in the northeast and southwest parts of the Unites States, respectively. A closer look at Figure 2b reveals that some stations in ROI 1 have significantly increasing tendencies in LSP, whereas declining tendencies dominate in ROI 2.

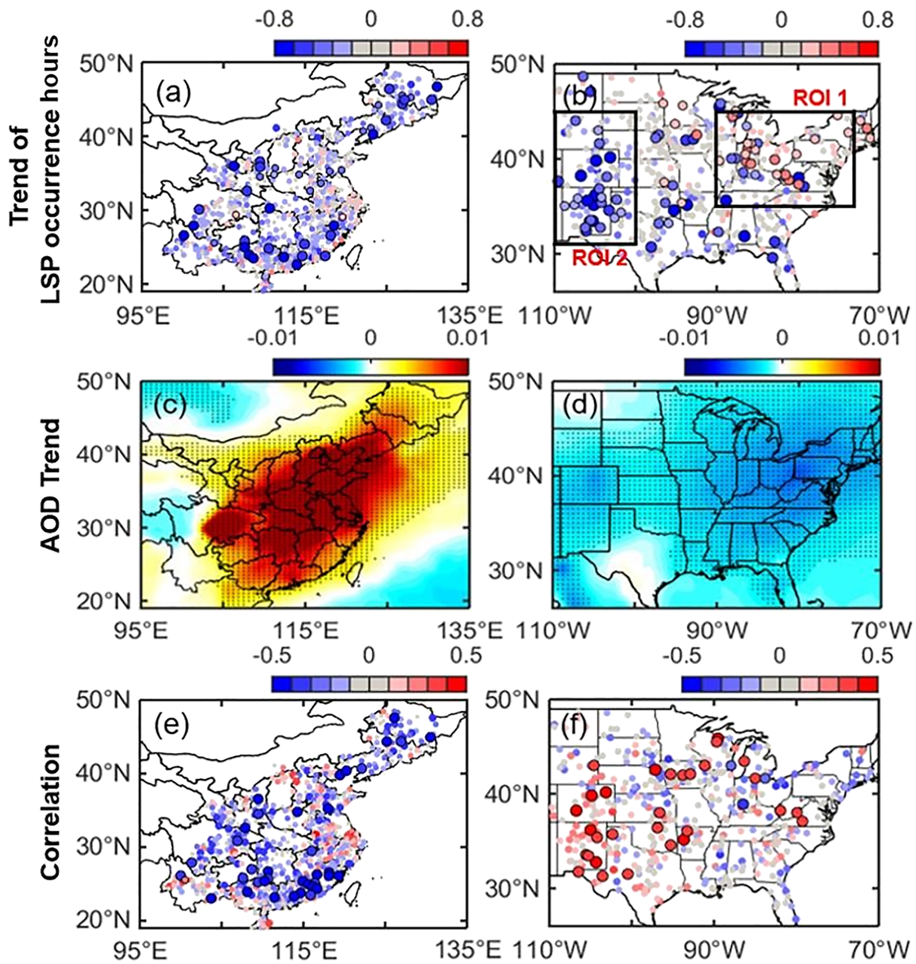

Figure 2. Spatial distributions of the annual summer trends (unit: hr/year) in occurrence hours of local-scale precipitation (LSP) for (a) China and (b) the United States and spatial distributions of Modern-Era Retrospective analysis for Research and Applications, Version 2 aerosol optical depth (AOD) trends (unit: $year^{-1}$) for (c) China and (d) the United States from 1981 to 2012. Also shown are the corresponding spatial distributions of linear correlations between annual AOD and the occurrence hours of LSP for (e) China and (f) the United States. Dots marked with black circles indicate trends that are statistically significant at the 95% confidence level. ROI = region of interest.

3.2. The Relative Contribution by Aerosol and Meteorology

Long-term trend analyses using MERRA-2 AOD indicate a significant rising trend over eastern China (Figure 2c), in sharp contrast to a steady declining trend revealed in the United States (Figure 2d), due to the large differences in emission tendencies (Wang et al., 2018). Contrasting trends in AOD stand out between eastern China and the United States. AOD shows a positive trend over eastern China, as opposed to the negative trend observed over the United States for time windows longer than 15 years (Figures S3c and S3d).

Figures 2e and 2f compare the spatial patterns of correlation coefficients between the annual MERRA-2 AOD time series and LSP anomalies over China and the United States. By large, the LSP events are negatively associated with AOD at most sites in China, and the relationship in the United States is more complex where positive correlations dominate ROI 2 but negative correlations dominate ROI 1.

To gain further insight into a possible link between LSP and aerosols, we matched the monthly mean LSP frequency with MODIS AOD and then examined the changes in LSP frequency as a function of AOD (Figures 3a and 3b). Boomerang-shaped trends are found in both countries for the variation in LSP frequency with aerosol loading. Since an ideal turning point would differ vastly by region, depending on various factors

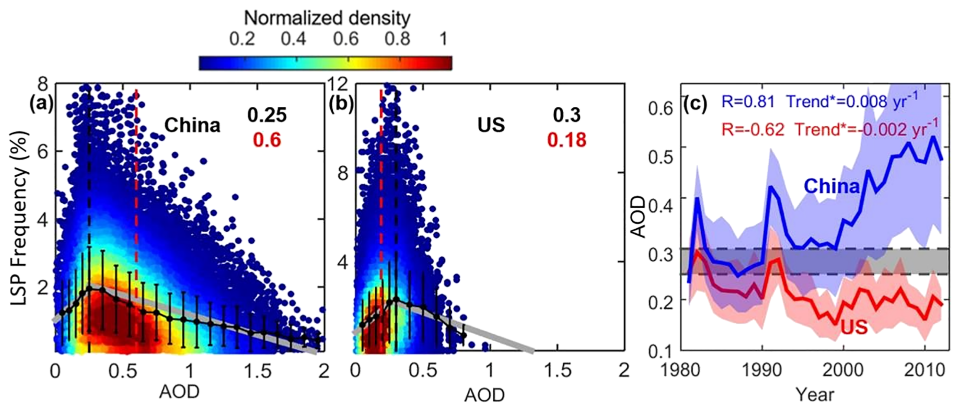

Figure 3. Scatter plots showing the monthly mean local-scale precipitation (LSP) frequency as a function of Moderate Resolution Imaging Spectroradiometer aerosol optical depth (AOD) for all stations in (a) China and (b) the United States. The responses of the LSP frequency to aerosol loading are boomerang shapes in eastern China and the United States (black solid lines). In (a) and (b), the AOD turning points are between 0.25 and 0.3. The black dots and whiskers represent the average values and standard deviation for each bin. The gray lines indicate the regressions before and after the turning points. Red dashed lines (and numbers in red) show the mean Moderate Resolution Imaging Spectroradiometer AOD values. The vertical black (red) dashed lines show the turning points of mean AOD. (c) Time series of annual mean Modern-Era Retrospective analysis for Research and Applications, Version 2 AOD in China (blue) and the United States (red). The gray area delineates the turning zone. To match the LSP trends, we only analyzed those Modern-Era Retrospective analysis for Research and Applications, Version 2 AOD grids containing weather stations.

such as aerosol properties and convection strength (Wang et al., 2018), we used a turning zone (AOD: 0.25–0.3) rather than a turning point to illustrate the shift in potential aerosol effects from invigoration to suppression with increases in AOD. This well agrees with previous studies (Chakraborty et al., 2018; Rosenfeld et al., 2008).

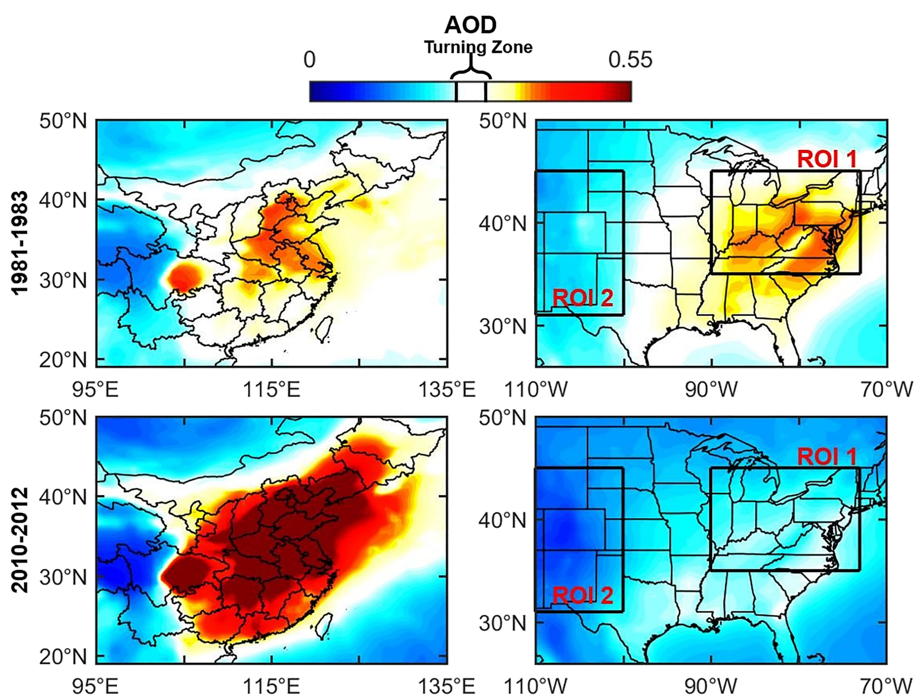

Figure 4. Spatial distributions of mean Modern-Era Retrospective analysis for Research and Applications, Version 2 aerosol optical depth (AOD) in summer from 1981 to 1983 for (a) China and (b) the United States and from 2010 to 2012 for (c) China and (d) the United States. Areas in white denote AODs within the turning zone. ROI = region of interest.

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Figures 3a and 3b illustrate that the majority of monthly AOD means in eastern China are beyond the turning zone (~0.3), in contrast to that in the United States. This is further corroborated by the time series of the annual mean AOD illustrated in Figure 3c. Figure 4 shows the spatial distributions of summertime AOD over eastern China and the United States for two time periods: 1981–1983 and 2012–2012. During 1981–1983, both eastern China and the United States had similar AOD patterns, with much higher aerosol loadings in the eastern coastal regions in the United States. AODs in eastern China rose rapidly afterward, opposite to the steady decline in AODs in the United States. During 2010–2012, AOD values in eastern China became much higher than those in the United States. The AOD values over eastern China were typically greater than the maximum value of the turning zone during the full study period (1981–2012), with a significant increasing trend.

Regarding the long-term trend, sharp discrepancies exist between the increasing trend in eastern China and the decreasing trend in the United States. Because the majority of AODs lie beyond the turning zone and because an increasing trend in AOD is observed during the period investigated here, the aerosol suppression effect dominates over eastern China. This may partly explain the declining trend in LSP occurrence hours. The majority of AODs in the United States lie below the turning zone (Figure 3b). This may, to some extent, account for the declining trend at most stations (Figure 2b) due to the decreasing trend in AOD in recent decades. This decrease in AOD leads to a dearth of aerosol particles suspended in the atmosphere, thus inhibiting LSP because the aerosol loading in the United States is well below the turning zone.

The physical principle behind this phenomenon may be closely associated with the disparate roles of aerosols in LSP events. At the beginning of an LSP event, aerosols in the boundary layer are lifted into the free atmosphere by local thermal convection, leading to an increase in cloud condensation nuclei. This increase facilitates the cloud-to-precipitation conversion process as the atmosphere shifts from pristine to slightly polluted (Fan et al., 2018; Rosenfeld et al., 2008), leading to a positive correlation between AOD and LSP occurrence hours in the United States. Under light pollution condition, ACI plays an important role in LSP events, while aerosol-radiation interaction (ARI) is relatively weak. As AOD approaches the turning zone, aerosol radiative effect exerts higher impacts and partly compensates for the ACI effects due to the opposite signs (Koren et al., 2008; Rosenfeld et al., 2008), which generally corresponds to the situation in the northeast United States (ROI 1). However, when aerosol loading exceeds the turning zone (i.e., the situation in eastern China), cloud condensation nuclei in the atmosphere tend to be saturated. Therefore, an increase in aerosols will instead lead to a decrease in cloud droplet radii (Twomey, 1977). This tends to inhibit the collision-coalescence process and further reduces LSP reaching the surface (Albrecht, 1989). The radiative effect of aerosols is generally negligible when the aerosol loading is low but can become an important factor to stabilize atmosphere and suppress LSP as the aerosol loading becomes heavier. Thus, the disparate effects of ACI and aerosol-radiation interaction lead to the nonlinear response of LSP frequency to aerosol loading.

The confounding meteorological factors may also modulate the LSP trends. The T_{2m} over both countries exhibits an upward tendency during the study period (Figures S6a and S6b). The LSP occurrence hours seem to increase as T_{2m} rises, but the correlation is weak (Figure S7). Figures S6c–S6f shows that LTS was slightly declining as well, indicating an increasingly unstable lower atmosphere and more frequent LSP. However, the overall trends are not significant. Meanwhile, despite the high correlation between PW and LSP rainfall amount (Figure S8), there is no detectable trend for PW. To investigate the relative roles of these variables, the standardized multiple regression equations with partial correlations between LSP occurrence hours, AOD, and meteorological variables were examined in different regions over China and United States, where the coefficients represent the relative importance of individual factors (Table S1). As a net effect, aerosol may suppress the LSP frequency over China and enhance the LSP frequency in the ROI 2 of United States. While aerosol seems to play a neutral role in LSP frequency in the ROI 1. The weak partial correlation of the AOD-LSP relationship also suggests that the LSP is not controlled by aerosol, but aerosol can affect convection and LSP through modulating the thermodynamic variables that affect the ACI. We cannot totally rule out the influences of other dynamic factors on the observed LSP events, such as jet stream position, soil moisture, and convective available potential energy (Fernando et al., 2016).

3.3. LSP and AOD Trends Over Different Regions

As discussed in section 3.1, there are large regional disparities in the trends in LSP over ROI 1 and ROI 2 in the United States (Figure 2b). Meanwhile, the AOD has a decreasing trend over both ROI 1 and ROI 2, albeit with different rates. Figures 4b–4d compares the spatial distributions of summertime AOD over the United

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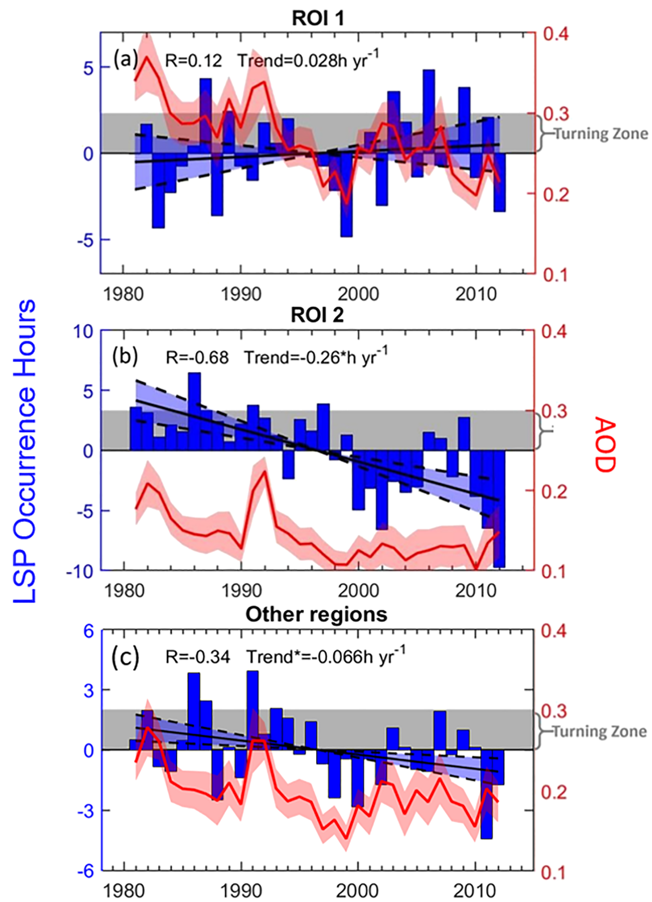

Figure 5. Time series of the annual mean anomalies of occurrence hours with daytime local-scale precipitation (LSP) over (a) region of interest (ROI) 1, (b) ROI 2, and (c) the other regions of United States in the summers of 1981 through 2012. The correlation coefficient between LSP anomalies and year (R) and the trend are shown at the top of each panel. The blue shaded areas indicate 95% confidence intervals on the trends in these time series. The asterisks indicate statistically significant trends at the 95% confidence level. The red line shows annual mean Modern-Era Retrospective analysis for Research and Applications, Version 2 aerosol optical depth (AODs). The gray area delineates the turning zone of 0.25–0.3.

States between 1981–1983 and 2010– 2012. The AOD over ROI 1 was greater than the maximum value of the turning zone at the beginning (1981–1983) and then dropped steadily until 2010–2012, when the AOD values were slightly below the turning zone. AOD values over ROI 2 were below the minimum value of the turning zone (~0.25) throughout the period.

Figure 5 shows similar significant decreasing trends in AOD over both ROIs. Coincident with the decreasing AOD, a slight increasing trend in LSP over ROI 1 is seen (Figure 5a). This increasing trend in LSP, however, is not statistically significant at the 95% confidence level and has a large spread ranging from negative to positive values. This means that there is no apparent negative or positive trend in LSP for ROI 1. This is likely due to the noise caused by the complex AOD variability crossing the turning zone. The occurrence hours of LSP events tend to be enhanced at the beginning until the AOD turning zone is reached, followed by the suppression of LSP events with the AOD dropping well below the turning zone due to the scarcity of aerosol particles. This combined effect tends to obscure the correlation between aerosols and LSP in ROI 1.

Interestingly, the LSP occurrence hours over ROI 2 significantly decreases as AOD decreases (Figure 5b). This is most likely due to the much lower AOD over ROI 2 (it stayed below the turning zone throughout the period), leading to the monotonic inhibition effect observed here for the response of LSP to aerosols in ROI 2. Also, the LSP occurrence hours show pronounced declining signal for other regions in the United States (Figure 5c), even though both AOD and LSP trends are weaker over other regions of United States compared with that over ROI 2.

4. Conclusions

Using long-term hourly gauge measurements, a gross decreasing trend in LSP frequency was found over China and the United States for the period 1981–2012, even though the aerosol loading had shown an opposite trend. Particularly, spatially inhomogeneous declining frequency in LSP events was observed in the United States, as compared with the widespread decreasing LSP trends seen in eastern China.

In eastern China, an increasing trend in AOD during the period 1981–2012 was seen, and most of the AOD values were above the turning zone, which suppressed the LSP. In the United States, the decreasing trend in LSP occurrence hours was due to the decreasing trend in AOD that was well below the turning zone. The insufficient supply of aerosols would suppress the formation of LSP, keeping related meteorological factors constant. Furthermore, the potential meteorological factors were analyzed that could cause the trends in LSP frequency over eastern China and the United States. Thermodynamic factors and water vapor cannot explain the declining LSP trends, and the microphysical process associated with aerosols is more likely to contribute to the declining LSP trends over China and the United States despite the contrasting aerosol trends.

Overall, the boomerang shape revealing the response of LSP frequency to aerosols points to the importance of aerosol loading, which matters as much as, if not more than, the AOD trend. Although the unexpected disparate response of LSP could be in part attributed to aerosols, our understanding of how aerosols affect cloud and precipitation at various spatial scales needs to be improved. This calls for further explicit observational analyses and model simulations.

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Erratum

In the originally published version of this article, the affiliation for author Zhanqing Li was published incorrectly. This error has since been corrected, and the present version may be considered the authoritative version of record.