AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL073533

Key Points:
- A novel method developed to identify a local-scale precipitation event based on hourly rain gauge data
- A widespread declining trend of daytime local-scale precipitation events was observed in eastern China in summer for 1970 to 2010
- Coincident increase in aerosol could partly account for the decreasing trend of local-scale precipitation

Supporting Information:
- Supporting Information S1

Correspondence to:
J. Guo, T. Su, and Z. Li,
jpguocams@gmail.com;
tianning@umd.edu;
zli@atmos.umd.edu

Citation:
Guo, J., T. Su, Z. Li, Y. Miao, J. Li, H. Liu, H. Xu, M. Cribb, and P. Zhai (2017), Declining frequency of summertime local-scale precipitation over eastern China from 1970 to 2010 and its potential link to aerosols, *Geophys. Res. Lett.*, *44*, doi:10.1002/2017GL073533.

Received 22 MAR 2017
Accepted 18 MAY 2017
Accepted article online 31 MAY 2017

Declining frequency of summertime local-scale precipitation over eastern China from 1970 to 2010 and its potential link to aerosols

Jianping Guo[1], Tianning Su[2], Zhanqing Li[2,3], Yucong Miao[1], Jing Li[4], Huan Liu[1], Hui Xu[1], Maureen Cribb[2], and Panmao Zhai[1]

[1]State Key Laboratory of Severe Weather and Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, Beijing, China, [2]Department of Atmospheric and Oceanic Sciences and ESSIC, University of Maryland, College Park, Maryland, USA, [3]State Key Laboratory of Earth Surface Processes and Resource Ecology and College of Global Change and Earth System Science, Beijing Normal University, Beijing, China, [4]Department of Atmospheric and Oceanic Sciences, Peking University, Beijing, China

Abstract Summer precipitation plays critical roles in the energy balance and the availability of fresh water over eastern China. However, little is known regarding the trend in local-scale precipitation (LSP). Here we developed a novel method to determine LSP events in the summer afternoon throughout eastern China from 1970 to 2010 based on hourly gauge measurements. The LSP occurrence hours decrease at an annual rate of 0.25%, which varies considerably by region, ranging from 0.14% over the Yangtze River Delta to 0.56% over the Pearl River Delta. This declining frequency of LSP is generally accompanied by an increase in rain rate of LSP but a decrease in visibility, whose linkage to LSP events was investigated. In particular, more LSP events tended to form when the atmosphere was slightly polluted. Afterward, LSP was suppressed. These findings have important implications for improving our understanding of the climatology of daytime precipitation at local scales.

Plain Language Summary Summer precipitation plays critical roles in the energy balance and the availability of fresh water over eastern China. However, the knowledge remains poorly understood regarding the trend of local-scale precipitation (LSP). Long-term hourly gauge data in the summer afternoon throughout eastern China for 1970 to 2010 reveal that LSP occurrence hours decrease at an annual rate of 0.25%, which differs greatly by region, ranging from 0.14% over the Yangtze River Delta to 0.56% over the Pearl River Delta. In contrast, large-scale precipitation events do not show significant increasing/decreasing trends over most regions. Further, concurrent visibility observations exhibit a decreasing trend, whose linkage to declining LSP is investigated. In particular, more LSP events tend to form as the atmosphere is slightly polluted. Afterward, LSP is suppressed. The findings provide deep insight into how precipitation changes over long term from a perspective of smaller spatial scale rainfall.

1. Introduction

Cloud and precipitation systems in the summer play crucial roles in the modulation of the energy budget and the availability of fresh water in eastern China, a region under the influence of the East Asian summer monsoon (EASM) [*Ding*, 1994]. Recently, changes in total precipitation have been attracting increasing attention. *Zhai et al.* [2005] revealed a dipole pattern with drought in north China and flooding in south China based on long-term rain gauge data. *Ding et al.* [2008] found that there exists a large interdecadal variation of summer precipitation in East China due to its strong association with the weakening Asian summer monsoon. Precipitation events with various intensities can exhibit different variational trends. For example, both observation and modeling studies focused on this region suggest that light rain has decreased, whereas heavy rain has increased [*Qian et al.*, 2009; *Guo et al.*, 2014]. In a comprehensive review of Asian monsoon and aerosol interaction, *Z. Li et al.* [2016] presented ample evidences of the connections between climate changes and air pollution in Asia.

The rainfall changes vary considerably both spatially and temporally with the most significant drop in light rain occuring in northern and central-western China [*Guo et al.*, 2014] and more dramatic increases in heavy rains and thunderstorms occurring in south and southeast China [*Yang and Li*, 2014; *Guo et al.*, 2016]. Most previous studies have been based on daily precipitation data, and few have explicitly dealt with how the precipitation varies from a spatial-scale perspective based on one-hourly precipitation records, which remains poorly understood.

Regarding the causes underlying the observed decrease/increase of light/heavy precipitation in eastern China, both natural variability and the anthropogenic effects of either greenhouse gases [e.g., *Liu et al.*, 2015] or aerosol particles [*Rosenfeld et al.*, 2007; *Song et al.*, 2014; *Wang et al.*, 2016; *Z. Li et al.*, 2016] have been proposed to be potential factors. However, great uncertainties remain in attributing to any of these quantities due to the complicated tangling effects between meteorology and aerosols [*Stevens and Feingold*, 2009; *Boucher et al.*, 2013].

Local-scale precipitation (LSP) is generally associated with local convection, while synoptic precipitation is caused by large-scale uplift such as that from frontal systems and extratropical cyclones [*Houze*, 2014], which occur frequently in summer in eastern China due to the EASM that may interact with aerosol to affect precipitation [*Z. Li et al.*, 2016]. To exclude the latter type of precipitation, this study extends upon previous ones by developing an original method to identify LSP events aimed at examining the trends in LSP in eastern China during the summertime and its potential causes.

2. Data and Methods

2.1. Determination of Local-Scale Precipitation

Precipitation data employed in this study are hourly rain gauge measurements made at 2420 weather stations across China in summer (May to September) for the period 1970–2010 that are quality-controlled and archived by the China Meteorological Administration.

Being a thermally driven precipitation, LSP generally occurs in the afternoon. As such, we only choose rainfalls from 1200 Beijing time (BJT) to 1800 BJT, a period when convective precipitation usually peaks [*Yu et al.*, 2007; *Guo et al.*, 2016; *Lee et al.*, 2016]. Given the fact that large-scale precipitation is generally driven by synoptic-scale systems, which range from a few hundreds to thousands of kilometers in length, the rainfall amount and frequency of large-scale precipitation show large interannual variability and oscillation.

To determine if a precipitation event (rainfall $>$0.1 mm h^{-1}) at a given station at a given hour is a LSP event, we counted the proportion of rainy sites within a 150 km radius around the station. To be a LSP event, the proportion of rainy sites must be less than or equal to 20% (Figure 1a). To exclude the residuals from synoptic-scale precipitating systems, only those gauge stations with no rainfall occurring between 0000 BJT and 0800 BJT are chosen. The rest of the raining events are considered to be nonlocal-scale precipitation (NLSP) events. We define N_{150} as the number of stations within 150 km of a given station. To ensure spatial representativeness, only those stations with $N_{150} > 5$ are chosen. Six hundred and ninety-six stations out of the 748 stations in eastern China (Figure 1b) met this requirement and were selected for the analysis. Missing or inaccurate data at these stations accounted for less than 1% of all data during the study period.

2.2. Visibility Data

To help understand the potential causes of the long-term trend in precipitation, visibility data are employed as a gross measure of air quality, which has undergone dramatic changes in China over the past few decades [*Chang et al.*, 2009]. This is regarded as an important factor affecting precipitation in China [e.g., *Rosenfeld et al.*, 2007; *Guo et al.*, 2014; *Z. Li et al.*, 2016]. Visibility is routinely measured at 0200, 0800, 1400, and 2000 BJT under all-sky conditions at all weather stations. Note that only 1400 BJT visibility data are used here to better match the afternoon LSP events during May–September for the period 1970 to 2010. A series of quality control measures were implemented to improve the consistency and accuracy of the visibility data. Details can be found in the supporting information. Then, visibility with humidity correction was converted to dry extinction using the following formula: 3.912/visibility [*Koschmieder*, 1926]. Among the 748 meteorological stations in eastern China, a total of 442 stations had valid visibility observations according to the criteria described in the supporting information. The trend in dry extinction anomalies was calculated accordingly (cf. Figure S2 in the supporting information).

2.3. European Centre for Medium-Range Weather Forecast Reanalysis

Additional meteorological data are obtained from the European Centre for Medium-Range Weather Forecast ERA-40 and ERA-Interim reanalysis data sets on a 1° × 1° longitude-latitude grid [*Uppala et al.*, 2005]. They

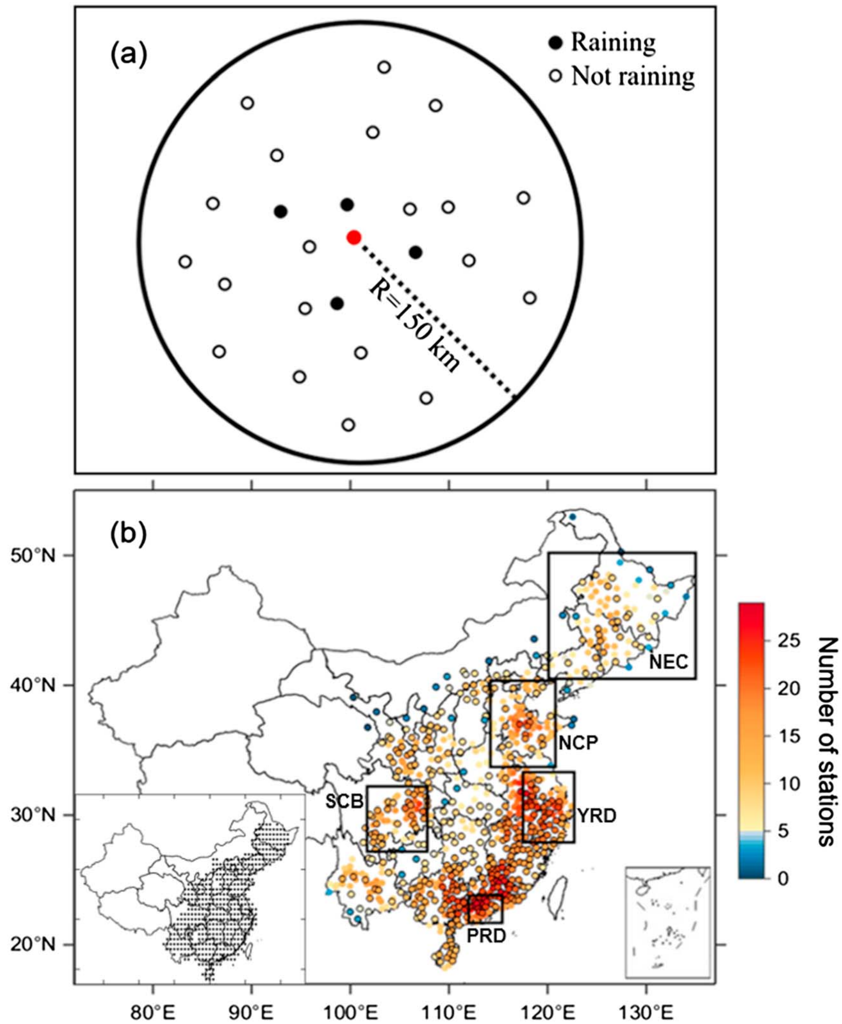

Figure 1. (a) Schematic showing how a local-scale precipitation (LSP) event is determined. If the proportion of rainy sites within this circle is less than 20%, the precipitation event at the central station is defined as a LSP event. (b) The spatial distribution of weather stations with continuous precipitation records for the period 1970–2010. Colors represent the number of stations within 150 km of a given station (N_{150}). Note that the stations shown as black circles are stations with valid visibility observations according to the criteria shown in the supporting information. The black rectangles outline the five regions of interest defined in Table S1. The dots in the left bottom inset represent the grids used for the trend analysis of meteorology obtained from ERA-40 and ERA-Interim reanalysis data.

include surface temperature, lower tropospheric stability (LTS), and precipitable water (PW) at 1400 BJT. Annual means can then be calculated from May to September. Note that ERA-40 data are available from 1970 to 2002 and ERA-Interim data are available from 1979 to 2010. Both data sets are jointly used in the following trend analysis.

2.4. Trend Analysis Methods

Two independent statistical methods, namely the least squares regression and the Mann-Kendall (MK) test [*Mann*, 1945; *Kendall*, 1975], are used to determine the annual trends at each site shown in Figure 1b. Least squares regression typically assumes a Gaussian data distribution in the trend analysis. The MK test is a nonparametric test used to identify whether monotonic trends exist in a time series and is more suitable for data that are not normally distributed. To improve the robustness of the trend, these two methods have been jointly applied, consistent with the methods used in *J. Li et al.* [2016]. More details are given in section 2 in the supporting information. Trends in LSP and NLSP events, in combination with dry extinction, are calculated as the Sen's slope [*Sen*, 1968], which is a robust estimator based on Kendall rank correlation. A trend is

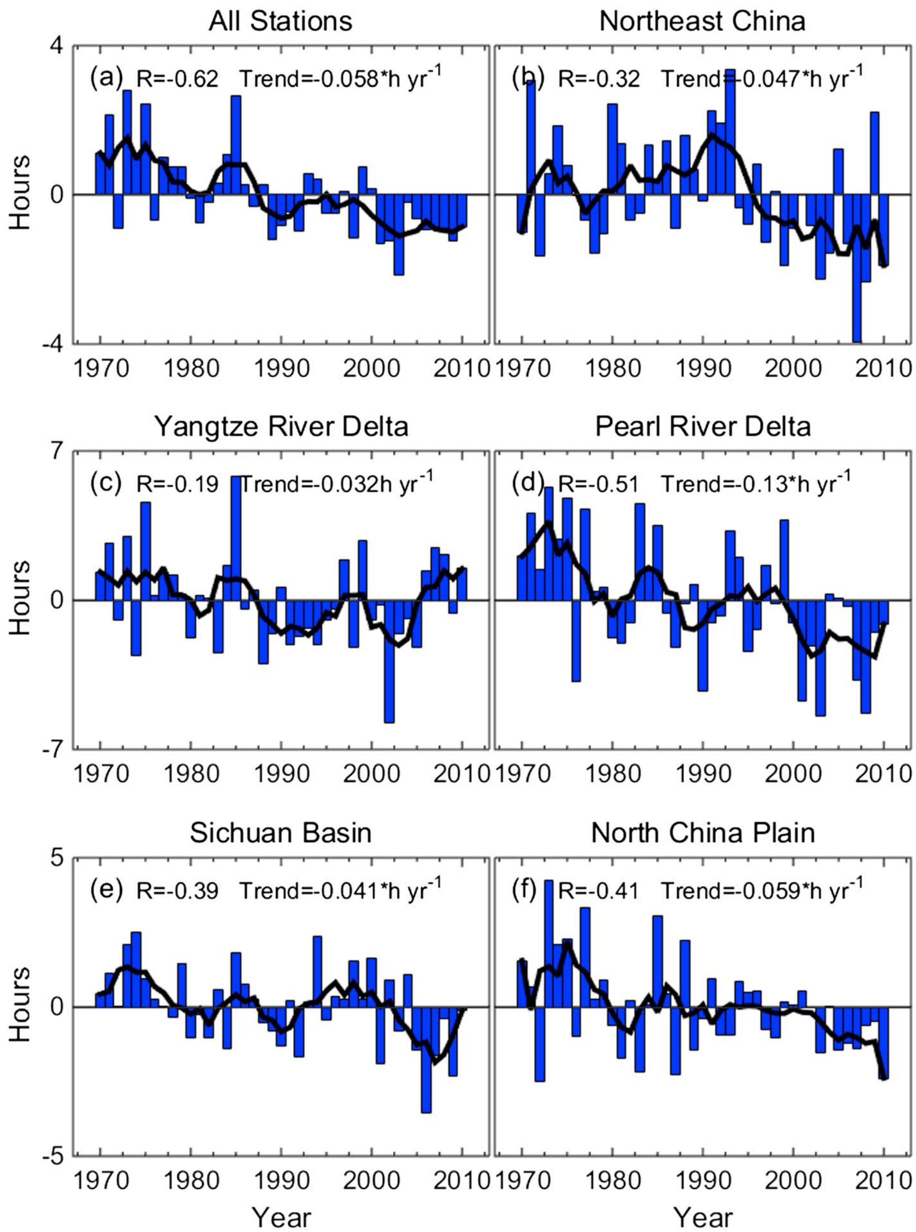

Figure 2. Time series of the annual mean anomalies of hours with local-scale precipitation (LSP) averaged (a) for all stations in eastern China and (b–f) for those in the five regions of interest defined in Table S1. The black lines indicate 5 year running means of the LSP anomalies. The correlation coefficient between LSP anomalies and year (*R*) and the trend are shown at the top of each panel. Trends with asterisks indicate statistically significant trends at a 95% confidence level.

considered to be significant when the confidence level is above 95% for both least squares regression and the MK test.

3. Results and Discussion

3.1. Trend in Summertime LSP

Figure 2 shows anomalies and their trends regarding afternoon LSP events in summer calculated for all stations and for the five regions of interest (ROIs): Northeast China (NEC), Yangtze River Delta (YRD), Pearl River Delta (PRD), Sichuan Basin (SCB), and North China Plain (NCP), as defined in Table S1. Although there exist large interannual variations, general declining trends are seen in all ROIs. Overall, the number of LSP hours throughout eastern China decreased at an annual rate of 0.25%, amounting up to 2.3 h (40 yr)$^{-1}$

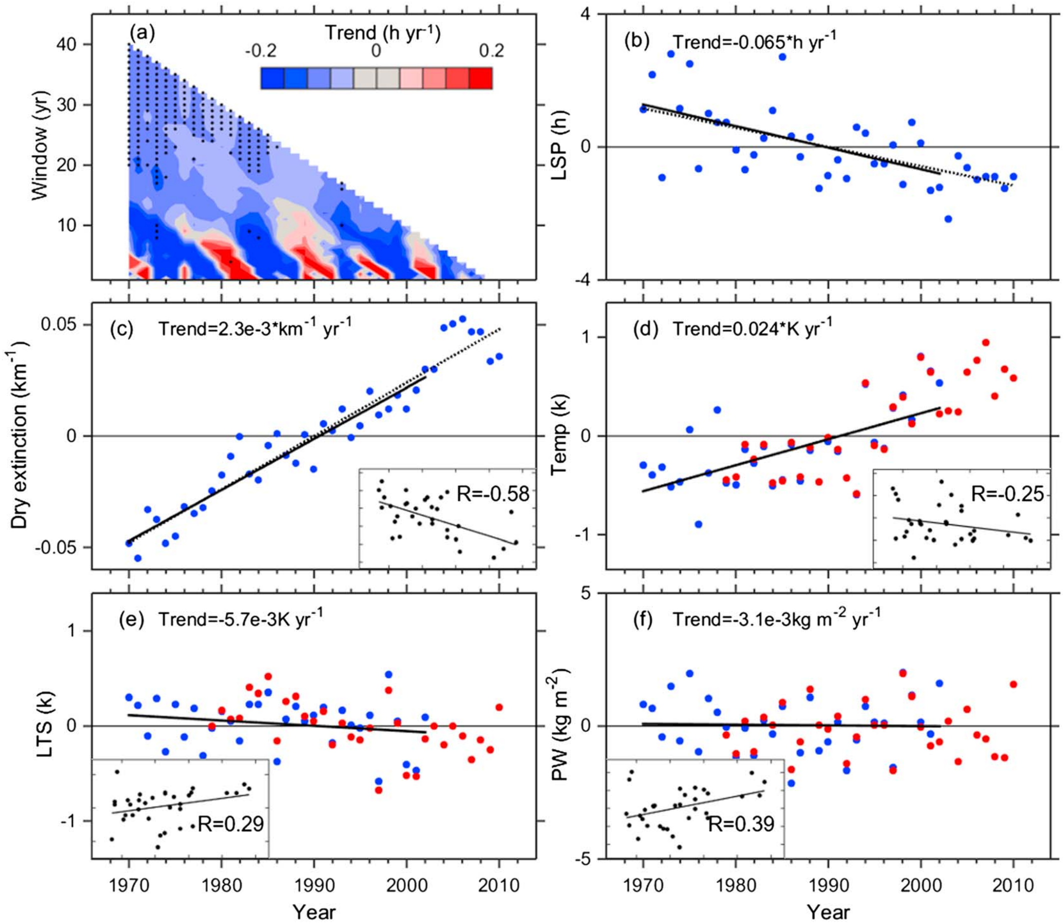

Figure 3. (a) The running trend analysis (color shading in h yr^{-1}) for annual mean LSP at all stations from 1970 to 2010. The *x* axis and *y* axis denote the start year and the length of the period under analysis, respectively. The black dots indicate statistically significant trends at the 95% confidence level. Time series of annual mean anomalies of (b) LSP, (c) dry extinction, (d) surface temperature, (e) lower tropospheric stability (LTS), and (f) precipitable water (PW). In Figures 3d–3f, the blue and red dots indicate data derived from ERA-40 and ERA-Interim, respectively. The systematic biases between ERA-40 and ERA-Interim have been removed. Trends for the period 1970–2002 are given at the top of Figures 3b–3f. The inset scatter plots in Figures 3c–3f show the correlations between different meteorological parameters and LSP during 1970–2002. Note that only ERA-40 reanalysis is used to calculate *R*.

depending on the ROI. For instance, LSP events decreased at an annual rate of 0.14% (1.28 h (40 yr)$^{-1}$) in summer over the YRD (Figure 2c), which is not statistically significant. In contrast, an annual decreasing rate of 0.56% (5.2 h (40 yr)$^{-1}$) was observed over the PRD (Figure 2d), which is statistically significant. Even for the trend in daytime (0800–1800 BJT) LSP events, a significant declining trend can be seen, but with a larger magnitude, irrespective of the ROI under investigation (Figure S1).

To better characterize the trend in LSP events, a running window trend analysis with respect to the number of hours with LSP events was done for the period 1970–2010 for all stations in eastern China (Figure 3a). Broadly speaking, Figure 3a shows that LSP has a significant decreasing trend, especially for the time window longer than 15 years, regardless of the starting year. Concerning trends in rainfall amount, the amounts for both total rainfall and LSP events show no significant increasing or decreasing tendencies at any ROI (Figures S3-S4).

3.2. The Potential Link Between LSP Trends and Aerosol Pollution

Figures 3a and 3b show a significant declining trend for LSP events during the period 1970–2010, in contrast to a dramatic increasing trend observed in the dry extinction of aerosols (Figure 3c). Surface temperature in the region under investigation exhibits an increasing trend (Figure 3d). It is well known that increased surface

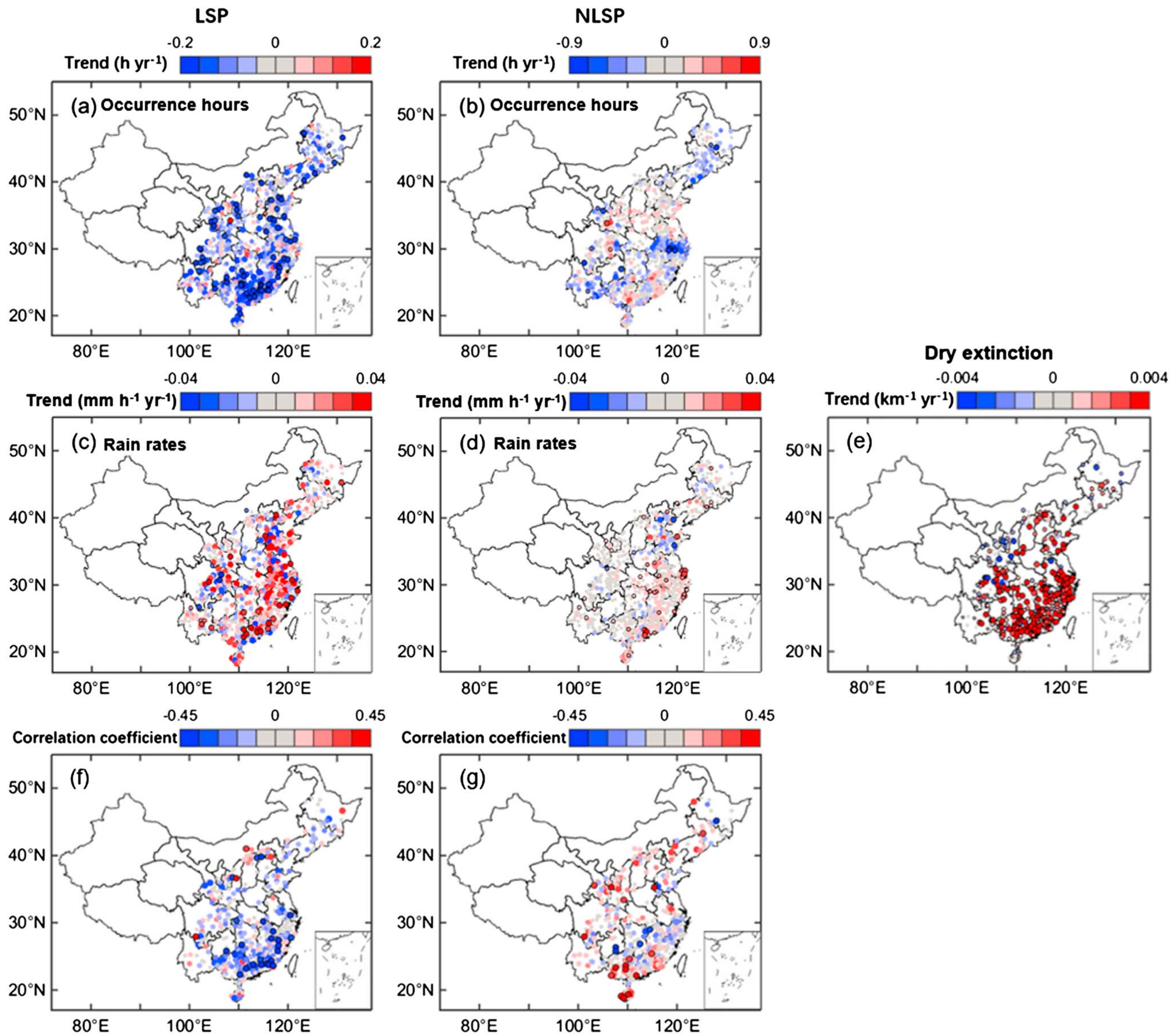

Figure 4. Spatial distributions of the annual summertime trends in (a) occurrence hours of LSP, (b) occurrence hours of NLSP, (c) rain rates of LSP, (d) rain rates of NLSP, and (e) dry extinction for the period 1970–2010. Also shown are the corresponding spatial distributions of linear correlations (f) between annual mean dry extinction and the frequency of LSP and (g) between annual mean dry extinction and the frequency of NLSP. Dots marked with black circles indicate trends that are statistically significant at the 95% confidence level.

temperatures likely strengthen convection, leading to an enhanced frequency of LSP events, which is contradictory to the declining trends in the observations seen here. LSP is typically associated with local thermodynamic conditions and humidity, so the time series of and corresponding trends in LTS and PW are shown in Figures 3e and 3f. During the study period, there is a slight downward, but not significant, trend in LTS and PW. Therefore, the evolution of thermodynamics and water vapor likely does not explain the declining trend in LSP. We further calculated the correlation coefficients between LSP and related variables during 1970–2002. The dry extinction of aerosols is more associated with LSP ($R = -0.58$) as compared with surface temperature ($R = -0.25$), PW ($R = 0.39$), and LTS ($R = 0.29$). As thermodynamic processes are both engaged in local thermal convection and synoptic systems, these meteorological factors do not exhibit strong correlation with LSP events. The declining trend in LSP frequency may be attributed to microphysical process, which is potentially linked to the increasing aerosol pollution during the recent past 40 years.

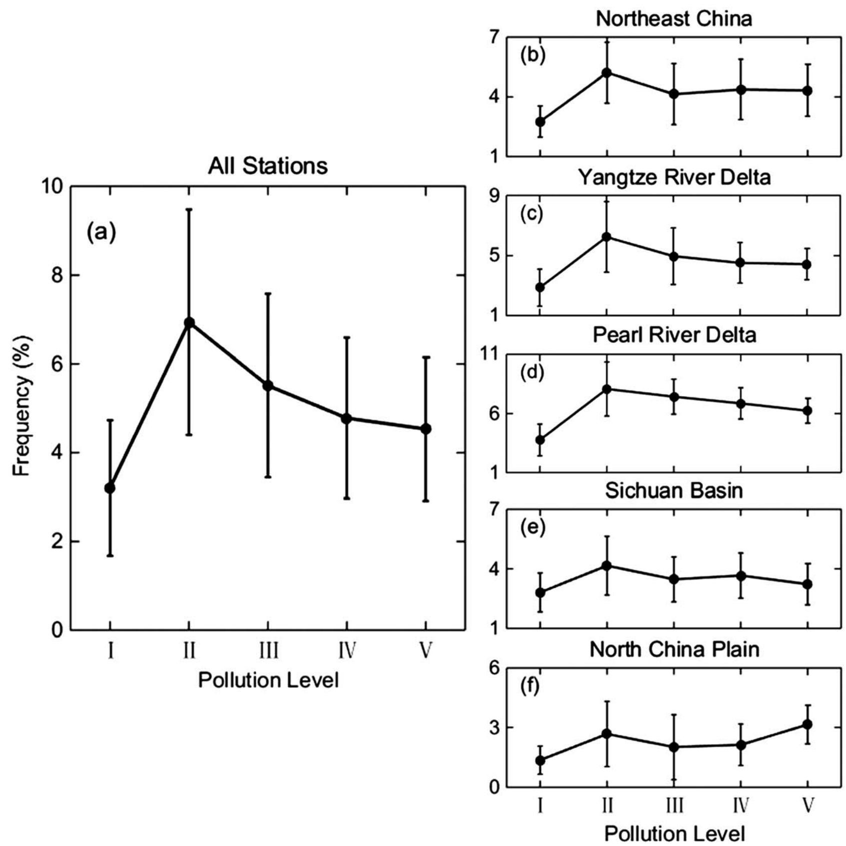

Figure 5. (a) Mean frequencies of occurrence of summertime LSP events at all stations in eastern China and (b–f) at those stations in the five ROIs defined in Table S1 for the period 1970–2010 as a function of pollution level. The error bars represent one standard deviation.

Interestingly, LSP events experienced widespread decreasing trends at most of the weather stations in eastern China (Figure 4a), in sharp contrast to the trends in NLSP that are mostly trivial and insignificant (Figure 4b). It is worth noting that the economic activities have been most intensive and developed most rapidly in eastern China where visibility also declined most significantly [*Niu et al*., 2010]. A closer look at Figure 4b reveals that quite a few stations in NCP and PRD exhibit markedly increased tendency. The enhanced NLSP events in these ROIs likely occur at the expense of suppressed LSP events. As shown in Figure 4c, an increasing trend can be seen for the rain rates of LSP at most sites of eastern China, most likely as a result of a prevailing decrease in the frequency of LSP. In contrast to the increasing rain rate of LSP, the trends in NLSP rain rates are much weaker (Figure 4d), while several sporadic sites in coastal areas exhibit significantly upward trends. Meanwhile, significant increasing trends in dry extinction are found over most of eastern China (Figure 4e). As illustrated in Figure 4f, the frequency of LSP events is negatively associated with dry extinction at most sites, spreading widely from northern China to southern China. Most of the sites with statistically significant trends, however, are limited to the PRD region. Contrary to LSP, the spatial distribution of the association between NLSP occurrence and dry extinction seems more complex and vague (Figure 4g). A large number of sites show a positive correlation between NLSP occurrence and dry extinction, whereas sporadic sites show a negative correlation.

To gain a further insight of a possible link between LSP and aerosols, the frequency of LSP occurring during 1500–1800 BJT at five aerosol pollution levels is examined (Figure 5). The five pollution levels are defined in Figure S5. To avoid contamination of visibility data caused by precipitation, cases with precipitation recorded between 1200 and 1400 BJT were excluded. Intriguingly, there exhibits a boomerang pattern for the variation of the LSP frequency with aerosol loading, indicative of a nonlinear relationship between LSP and aerosols: positive first and negative after. This phenomenon is consistent with the boomerang shape revealed by satellite observations [*Koren et al*., 2014; *Wang et al*., 2015], surface observations [*Jiang et al*., 2016], and theoretical calculations [e.g., *Feingold et al*., 2001; *Rosenfeld et al*., 2008].

Atmospheric dynamics and cloud microphysical processes jointly control the precipitation. Rainfalls produced by synoptic-scale systems are typically associated with strong dynamics forcing; the microphysical processes, however, play a more important role in the formation and development of LSP. At the beginning of LSP, the aerosol particles in boundary layer would be uplifted to free atmosphere by local thermal convection, which are activated as cloud condensation nuclei (CCN) to be engaged in cloud process and precipitation. Increase in CCN concentrations facilitates the cloud-to-precipitation conversion process when the atmosphere lacks CCN. As the CCN in the atmosphere becomes saturated, a further increase in aerosols will instead lead to a decrease in cloud droplet radius [*Twomey*, 1977]. The collision-coalescence process is thus inhibited, leading to longer cloud lifetimes and less precipitation reaching the surface [*Albrecht*, 1989]. Besides, the aerosol radiative effect is negligible for low aerosol loading but can become an important suppressing factor for convection as the aerosol loading becomes heavier.

4. Conclusions

Based on long-term measurements of hourly rainfall at 748 stations located throughout China during the period 1970–2010, concurrent with measurements of visibility at 1400 Beijing time, we developed a novel method to identify local-scale precipitation events based on the fraction of raining stations within a 150 km radius around a target station. Long-term trend analyses show that afternoon LSP events decreased at a rate of 0.58 h $(\text{decade})^{-1}$ during the period 1970–2010 over eastern China, as opposed to the slightly increasing trend found for NLSP events. The trend in LSP frequency varies from region to region, ranging from a minimum of 0.32 h $(\text{decade})^{-1}$ over the YRD to a maximum of 1.3 h $(\text{decade})^{-1}$ over the PRD. Conversely, markedly increasing trend in LSP rain rates over most sites of eastern China is found, which matches well with the declining frequency in LSP events.

During the study period, air quality has deteriorated in China with the most severe deterioration occurred in eastern China, as indicated by an increase in dry extinction derived from surface visibility data. The frequency of LSP events was shown to be negatively associated with dry extinction, compared with the positive association between NLSP events and dry extinction. Afternoon LSP events are closely related to thermal convection, resulting in a high susceptibility of LSP to aerosol pollution. Trends in surface temperature, LTS, and PW were calculated, as well as their correlations with the occurrence of LSP. These atmospheric properties cannot explain the decreasing trend in LSP events. Aerosol pollution is therefore hypothesized to be a possible cause for suppressing LSP events. The responses of LSP events to various aerosol loadings were also examined. A boomerang shape describing how LSP events vary with aerosol pollution, regardless of the ROI location, was revealed. Despite the inverse correlation seen between the decrease in LSP events and the increase in aerosol loading, it is still elusive to identify the causal relationship between them due to the confounding effect induced by meteorology. This merits further analysis using more comprehensive measurements from field experiments for well-defined and constrained LSP events together with model simulations that account for aerosol-cloud-precipitation interactions while controlling all other variables.

Acknowledgments
This work was supported by the National Natural Science Foundation of China under grants 91544217 and 41405006, the Ministry of Science and Technology of China under grants 2015DFA20870 and 2013CB955804, and the Natural Science Foundation of China under grants 41471301, and Chinese Academy of Meteorological Sciences under grant 2015Z003. The authors thank the European Centre for Medium-Range Weather Forecasts for making the reanalysis data publicly accessible and the China Meteorological Data Service Center (http://data.cma.cn/en) for providing hourly rainfall and visibility data used in this work. Fruitful discussions with Dr. Yun Qian of the Pacific Northwest National Laboratory are appreciated as well. Last but not least, the authors are grateful to the Editor and anonymous reviewers for their constructive comments, which helped to improve the quality of this manuscript.

References

Albrecht, B. (1989), Aerosols, cloud microphysics, and fractional cloudiness, *Science*, *245*, 1227–1230.

Boucher, O., et al. (2013), Clouds and aerosols, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 571–657, Cambridge Univ. Press, Cambridge, U. K.

Chang, D., Y. Song, and B. Liu (2009), Visibility trends in six megacities in China 1973–2007, *Atmos. Res.*, *94*(2), 161–167, doi:10.1016/j.atmosres.2009.05.006.

Ding, Y. (1994), *Monsoons Over China*, pp. 1–419, Kluwer Acad., Netherlands.

Ding, Y., Z. Wang, and Y. Sun (2008), Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences, *Int. J. Climat.*, *28*, 1139–1161.

Feingold, G., L. A. Remer, J. Ramaprasad, and Y. J. Kaufman (2001), Analysis of smoke impact on clouds in Brazilian biomass burning regions: An extension of Twomey's approach, *J. Geophys. Res.*, *106*(D19), 22,907–22,922, doi:10.1029/2001JD000732.

Guo, J., M. Deng, J. Fan, Z. Li, Q. Chen, P. Zhai, Z. Dai, and X. Li (2014), Precipitation and air pollution at mountain and plain stations in northern China: Insights gained from observations and modeling, *J. Geophys. Res. Atmos.*, *119*, 4793–4807, doi:10.1002/2013JD021161.

Guo, J., M. Deng, S. S. Lee, F. Wang, Z. Li, P. Zhai, H. Liu, W. Lv, W. Yao, and X. Li (2016), Delaying precipitation and lightning by air pollution over the Pearl River Delta. Part I: Observational analyses, *J. Geophys. Res. Atmos.*, *121*, 6472–6488, doi:10.1002/2015JD023257.

Houze, R. A., Jr. (2014), *Cloud Dynamics*, vol. 104, pp. 1–496, Academic Press, Chicago.

Jiang, M., Z. Li, B. Wan, and M. Cribb (2016), Impact of aerosols on precipitation from deep convective clouds in eastern China, *J. Geophys. Res. Atmos.*, *121*, 9607–9620, doi:10.1002/2015JD024246.

Kendall, M. G. (1975), *Rank Correlation Methods*, pp. 1–202, Griffin, London.

Koren, I., G. Dagan, and O. Altaratz (2014), From aerosol-limited to invigoration of warm convective clouds, *Science*, *344*(6188), 1143–1146, doi:10.1126/science.1252595.

Koschmieder, H. (1926), Theorie der horizontalen Sichtweite, *Beitsaege Phys. Atmos.*, *12*, 33–55.

Lee, S.-S., J. Guo, and Z. Li (2016), Delaying precipitation by air pollution over the Pearl River Delta. Part II: Model simulations, *J. Geophys. Res. Atmos.*, *121*, 11,739–11,760, doi:10.1002/2015JD024362.

Li, J., C. Li, C. Zhao, and T. Su (2016), Changes in surface aerosol extinction trends over China during 1980–2013 inferred from quality-controlled visibility data, *Geophys. Res. Lett.*, *43*, 8713–8719, doi:10.1002/2016GL070201.

Li, Z., et al. (2016), Aerosol and monsoon climate interactions over Asia, *Rev. Geophys.*, *54*, 866–929, doi:10.1002/2015RG000500.

Liu, R., S. C. Liu, R. J. Cicerone, C.-J. Shiu, J. Li, J. Wang, and Y. Zhang (2015), 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.

Mann, H. B. (1945), Nonparametric tests against trend, *Econometrica*, *13*, 245–259.

Niu, F., Z. Li, C. Li, K.-H. Lee, and M. Wang (2010), Increase of wintertime fog in China: Potential impacts of weakening of the eastern Asian monsoon circulation and increasing aerosol loading, *J. Geophys. Res.*, *115*, D00K20, doi:10.1029/2009JD013484.

Qian, Y., D. Gong, J. Fan, L. R. Leung, R. Bennartz, D. Chen, and W. Wang (2009), Heavy pollution suppresses light rain in China: Observations and modeling, *J. Geophys. Res.*, *114*, D00K02, doi:10.1029/2008JD011575.

Rosenfeld, D., J. Dai, X. Yu, Z. Yao, X. Xu, X. Yang, and C. Du (2007), Inverse relations between amounts of air pollution and orographic precipitation, *Science*, *315*(5817), 1396–1398, doi:10.1126/science.1137949.

Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell, and M. O. Andreae (2008), Flood or drought: How do aerosols affect precipitation?, *Science*, *321*, 1309–1313, doi:10.1126/science.1160606.

Sen, P. K. (1968), Estimates of the regression coefficient based on Kendall's Tau, *J. Am. Stat. Assoc.*, *63*, 1379–1389, doi:10.1080/01621459.1968.10480934.

Song, F., T. Zhou, and Y. Qian (2014), Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models, *Geophys. Res. Lett.*, *41*, 596–603, doi:10.1002/2013GL058705.

Stevens, B., and G. Feingold (2009), Untangling aerosol effects on clouds and precipitation in a buffered system, *Nature*, *461*, 607–613, doi:10.1038/nature08281.

Twomey, S. (1977), The influence of pollution on the shortwave albedo of clouds, *J. Atmos. Sci.*, *34*(7), 1149–1152, doi:10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2.

Uppala, S. M., et al. (2005), The ERA-40 re-analysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012, doi:10.1256/qj.04.176.

Wang, F., J. Guo, J. Zhang, J. Huang, M. Min, T. Chen, H. Liu, M. Deng, and X. Li (2015), Multi-sensor quantification of aerosol-induced variability in warm cloud properties over eastern China, *Atmos. Environ.*, *113*, 1–9, doi:10.1016/j.atmosenv.2015.04.063.

Wang, Y., P.-L. Ma, J. Jiang, H. Su, and P. Rasch (2016), Towards reconciling the influence of atmospheric aerosols and greenhouse gases on light precipitation changes in eastern China, *J. Geophys. Res. Atmos.*, *121*, 5878–5887, doi:10.1002/2016JD024845.

Yang, X., and Z. Li (2014), Increases in thunderstorm activity and relationships with air pollution in southeast China, *J. Geophys. Res. Atmos.*, *119*, 1835–1844, doi:10.1002/2013JD021224.

Yu, R., T. Zhou, A. Xiong, Y. Zhu, and J. Li (2007), Diurnal variations of summer precipitation over contiguous China, *Geophys. Res. Lett.*, *34*, L01704, doi:10.1029/2006GL028129.

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