

1 *Supporting Information for*

2 **Declining summertime local-scale precipitation frequency over China and**
3 **the United States, 1981–2012: The disparate roles of aerosols**

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24 1. Calculation of the Trends

25 The trends are estimated of LSP for 1981–2012 based on two independent methods: least
26 square regression and Mann Kendell test with Sen’s slope, which are described in more details
27 in the following two subsections.

28 1.1. Least Square Regression

29 Linear trends and their attendant significance levels are estimated using the same methods
30 as Weatherhead et al. (1998). The time series of observations are modeled by fitting the
31 following relationship with the least square approximation:

$$32 \quad Y_t = Y_0 + bt + N_t \quad (1)$$

33 where Y_t denotes the time series of variable, Y_0 denotes the offset at the start of the time
34 series, N_t is the noise term, and b is the linear trend. N_t is further modeled as an AR (1)
35 (first order of autoregressive model) process:

$$36 \quad N_t = \phi N_{t-1} + \varepsilon_t \quad (2)$$

37 Weatherhead et al. (1998) suggested that the standard deviation of the yearly trend σ_b
38 can be estimated as

$$39 \quad \sigma_b \approx \frac{\sigma_N}{n^{3/2}} \sqrt{\frac{1+\phi}{1-\phi}} \quad (3)$$

40 where σ_N is the standard deviation of N_t , and n equals the total number of years in the
41 series. If $|b/\sigma_b| > 2$, the trend is significant at 95% confidence level. The least-squares
42 approach assumes the dataset following Gaussian distribution, which may be not applicable for
43 many situations. Thus, we jointly use a non-parametric method, namely Mann-Kendall Test.

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45 1.2. Mann-Kendall Test with Sen’s Slope

46 First of all, we use the non-parametric procedure developed by Sen (1968) to estimate the
 47 true slope b of the trend:

$$48 \quad b = \text{Median}\left(\frac{X_i - X_j}{i - j}\right) \forall j < i \quad (4)$$

49 where X_i and X_j denote the i th and j th value respectively in the time series of X . Compared to
 50 other slope estimators such as the linear regression coefficient, Sen's slope is much less
 51 sensitive to outliers.

52 Then the Mann-Kendall statistical test (Kendall, 1975; Mann, 1945) is applied to test
 53 whether the trend is significant or not at 95% confidence level. The test statistic is expressed
 54 as:

$$55 \quad S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(X_j - X_i) \quad (5)$$

56 where n is the number of data points, and sgn is the sign function:

$$57 \quad \text{sgn}(X_j - X_i) = \begin{cases} +1 & \text{if } X_j > X_i \\ 0 & \text{if } X_j = X_i \\ -1 & \text{if } X_j < X_i \end{cases} \quad (6)$$

58 The variance of S is given by

$$59 \quad \text{Var}(S) = \frac{1}{18} n(n-1)(2n+5) \quad (7)$$

60 If the sample size $n > 30$, which is well satisfied in our case, the standard normal test
 61 statistic ZS is computed using:

$$62 \quad ZS = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (8)$$

63 According to the normal distribution table, the 5% significance level is satisfied if
 64 $|ZS| > 1.96$.

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66 2. Calculation of the lower tropospheric stability and precipitable water

67 Klein and Hartmann (1993) defined the lower-tropospheric stability (LTS) as the potential
68 temperature difference between 700 hPa and 1000 hPa. LTS provides a remarkable indicator
69 for convections and low-cloud fraction on seasonal time scales.

70 Following Zhai and Eskridge (1997), the Column total water vapor, or precipitable water
71 (PW), in the atmosphere is defined as follows:

$$72 \quad \text{PW} = \frac{1}{g} \int_{100\text{hpa}}^{1000\text{hpa}} q dp \quad (9)$$

73 where g is the acceleration of gravity, q is the specific humidity, p is the pressure.

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75 3. Standardized multiple linear regression

76 We use a standardized multiple linear regression method following previous studies (Igel
77 and van den Heever, 2015; Stolz et al., 2017). Here we use monthly mean data to establish the
78 standardized regression equation. The standardized regression equation with seven predictor
79 variables x_1, x_2, x_3, x_4 (AOD, temperature, LTS, and PW) and the response y (LSP occurrence
80 hours) can be written as:

$$81 \quad y = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 \quad (10)$$

82 where y and x_i are standardized variables derived from the raw variables Y and X_i by
83 subtracting the sample means (Y, X_i) and dividing by the sample standard deviations (δ_Y, δ_i):

$$84 \quad y = \frac{Y - \bar{Y}}{\delta_Y}, \quad x_i = \frac{X_i - \bar{X}_i}{\delta_i}, \quad i = 1, 2, 3, 4 \quad (11)$$

85 Standardized regression coefficients ignore the independent variables' scale of units,
86 which makes the slope estimates comparable and shows the relative weights to the changes in

87 LSP occurrence hours. A partial correlation is done to control the other predictors and to study
88 the effect of each predictor separately.

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90 **4. Rainfall dataset**

91 Precipitation data employed in this study are hourly rain gauge measurements made at 776
92 stations across China and 693 stations across the U.S. in summer (May to September) for the
93 period 1981–2012 that are quality-controlled. These data are archived by the China
94 Meteorological Administration and National Oceanic and Atmospheric Administration
95 respectively. The hourly rainfall data for China can be found in China Meteorological Data
96 Service Center (<http://data.cma.cn/en>), while the hourly precipitation data over the U.S. can be
97 found in NCDC/NOAA (<https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C01032>).

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99 **References**

- 100 Igel, M. R. and van den Heever, S. C.: The relative influence of environmental characteristics
101 on tropical deep convective morphology as observed by CloudSat, *J. Geophys. Res.-*
102 *Atmos.*, 120, 4304–4322, <https://doi.org/10.1002/2014JD022690>, 2015.
- 103 Kendall MG (1975) Rank Correlation Methods (Griffin, London).
- 104 Klein SA & Hartmann DL (1993) The Seasonal Cycle of Low Stratiform Clouds. *J Climate*
105 6(8):1587–1606.
- 106 Mann HB (1945) Nonparametric Tests against Trend. *Econometrica* 13(3):245-259.
- 107 Sen PK (1968) Estimates of the regression coefficient based on Kendall's Tau. *J. Am. Stat.*
108 *Assoc.* (63):1379–1389.
- 109 Stolz, D. C., Rutledge, S. A., Pierce, J. R., and van den Heever, S. C.: A global lightning
110 parameterization based on statistical relationships among environmental factors, aerosols,
111 and convective clouds in the TRMM climatology, *J. Geophys. Res.-Atmos.*, 122, 7461–
112 7492, <https://doi.org/10.1002/2016JD026220>, 2017.

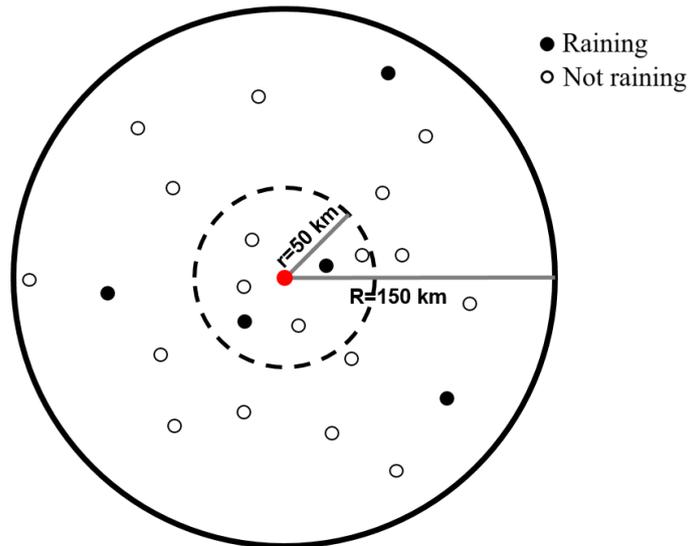
113 Weatherhead, E. C., Reinsel, G. C., Tiao, G. C., Meng, X.-L., Choi, D., Cheang, W.-K., Keller,
114 T., DeLuisi, J., Wuebbles, D. J., Kerr, J. B., Miller, A. J., Oltmans, S. J., and Frederick, J.
115 E. (1998), Factors affecting the detection of trends: Statistical considerations and
116 applications to environmental data, *J. Geophys. Res.*, 103, 17149– 17161,
117 doi:10.1029/98JD00995.

118 Zhai, P. & Eskridge, R. (1997) Atmospheric water vapor over China. *J Climate* 10(10):2643–
119 2652.

120 **Table S1.** Statistics of the partial correlation coefficients of the relationships between the
 121 monthly means of LSP occurrence hours and potential influential factors (AOD, temperature,
 122 LTS, and PW). Also shown are standardized multiple regression equations of the LSP
 123 occurrence hours onto the AOD and three meteorological variables (temperature, LTS, and PW).
 124 Technique details are described in Section 3 of Supporting Information.

Nation/Region	Partial Correlation Coefficients with LSP (y)			
	AOD (x_1)	Temp (x_2)	LTS (x_3)	PW (x_4)
China	-0.29	-0.06	-0.14	0.2
	Standardized multiple regression: $y = -0.27x_1 - 0.02x_2 - 0.16x_3 + 0.35x_4$			
ROI 1	-0.04	-0.25	-0.18	0.25
	Standardized multiple regression: $y = -0.04x_1 - 0.59x_2 - 0.17x_3 + 0.65x_4$			
U.S. ROI 2	0.15	-0.16	0.01	0.17
	Standardized multiple regression: $y = 0.13x_1 - 0.25x_2 + 0.03x_3 + 0.65x_4$			
Other	0.08	-0.31	-0.15	0.4
	Standardized multiple regression: $y = 0.07x_1 - 0.66x_2 - 0.13x_3 + 0.88x_4$			

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134 **Figure S1.** (a) Schematic showing how an LSP event is determined. The precipitation event at
 135 the central station is defined as an LSP event if it satisfies following conditions: the proportion
 136 of rainy sites within the radius of 150 km (not including the central site) is less than or equal to
 137 25%, and the proportion of rainy sites within the radius of 50 km (not including the central site)
 138 is less than or equal to 50%.

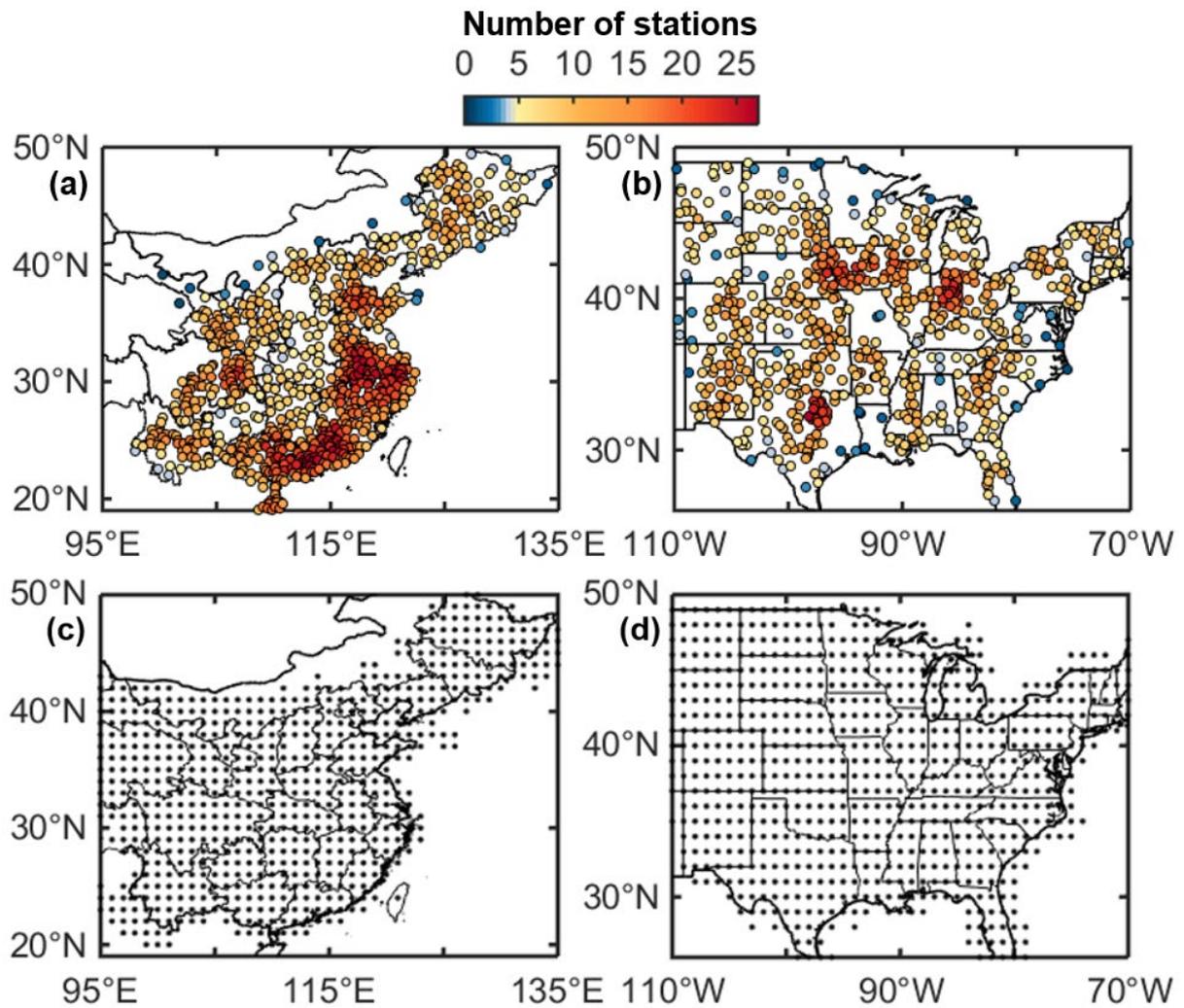


Figure S2. The spatial distribution of weather stations with continuous precipitation records for the period 1981–2012 over (a) China and (b) the US. Colors represent the number of stations within 150 km of a given station (N_{150}). The grids used for the analysis of meteorology are obtained from ERA-Interim reanalysis data over (c) China and (d) the U.S.

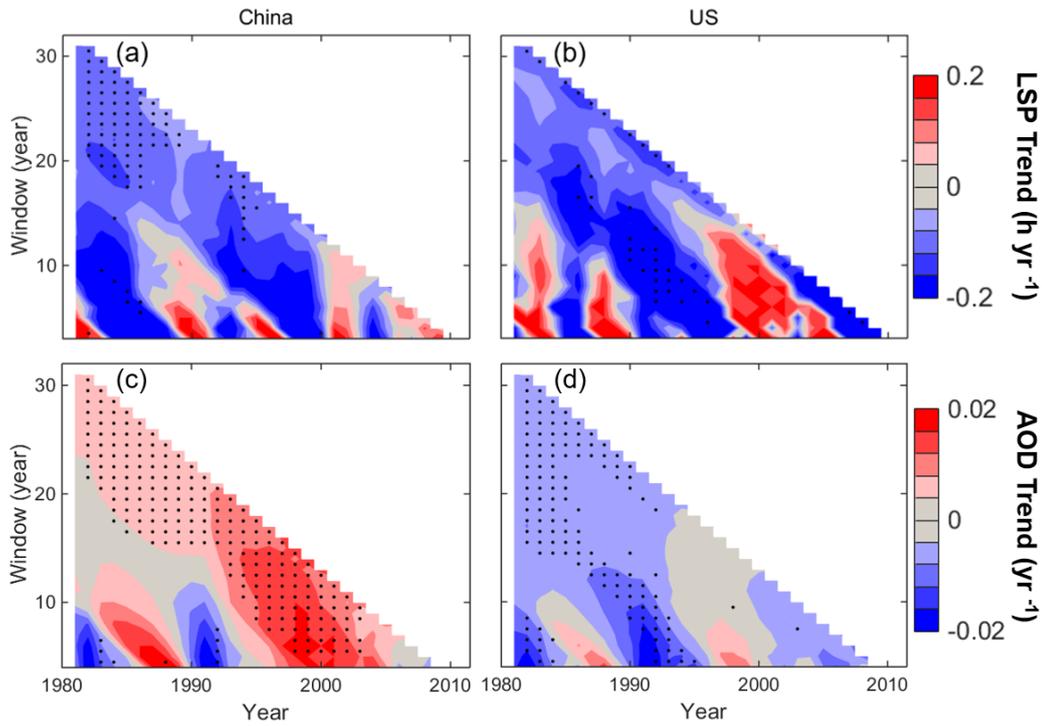


Figure S3. The running trend analysis (color shading in h yr^{-1}) for annual mean LSP in the summer from 1981 to 2012 over (a) eastern China and (b) the US. The running trend analysis (color shading in yr^{-1}) for the annual mean MERRA-2 AOD in the summer from 1981 to 2012 over (c) eastern China and (d) the US. 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.

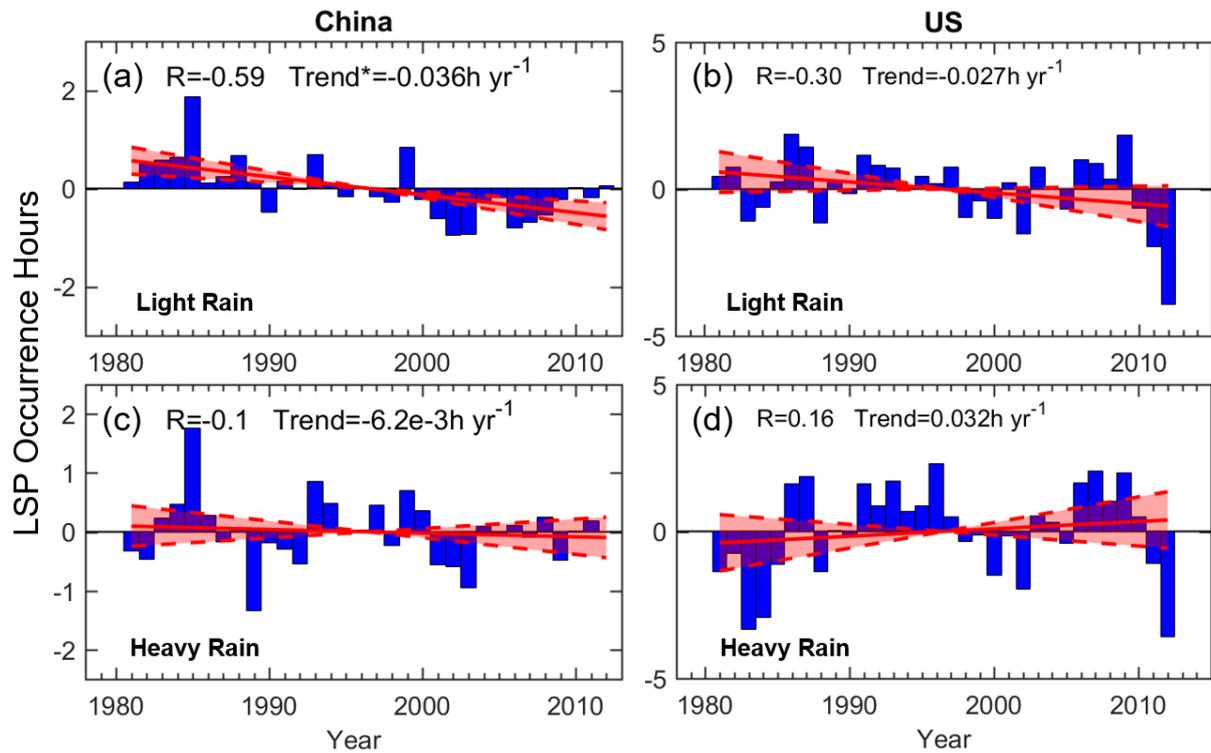


Figure S4. Time series of the annual mean anomalies of occurrence hours of summertime daily LSP for (a) the light rain and (c) heavy rain over China. Time series of the annual mean anomalies of occurrence hours of summertime daily LSP for (b) the light rain and (d) heavy rain over the US. The light rain defines as the rain rates less than or equal to 30% percentile, and heavy rain defines as the rain rates greater than or equal to 30% percentile. Shading and dotted lines indicate 95% confidence intervals on the trends in these time series. Trends with asterisks indicate statistically significant trends at the 95% confidence level.

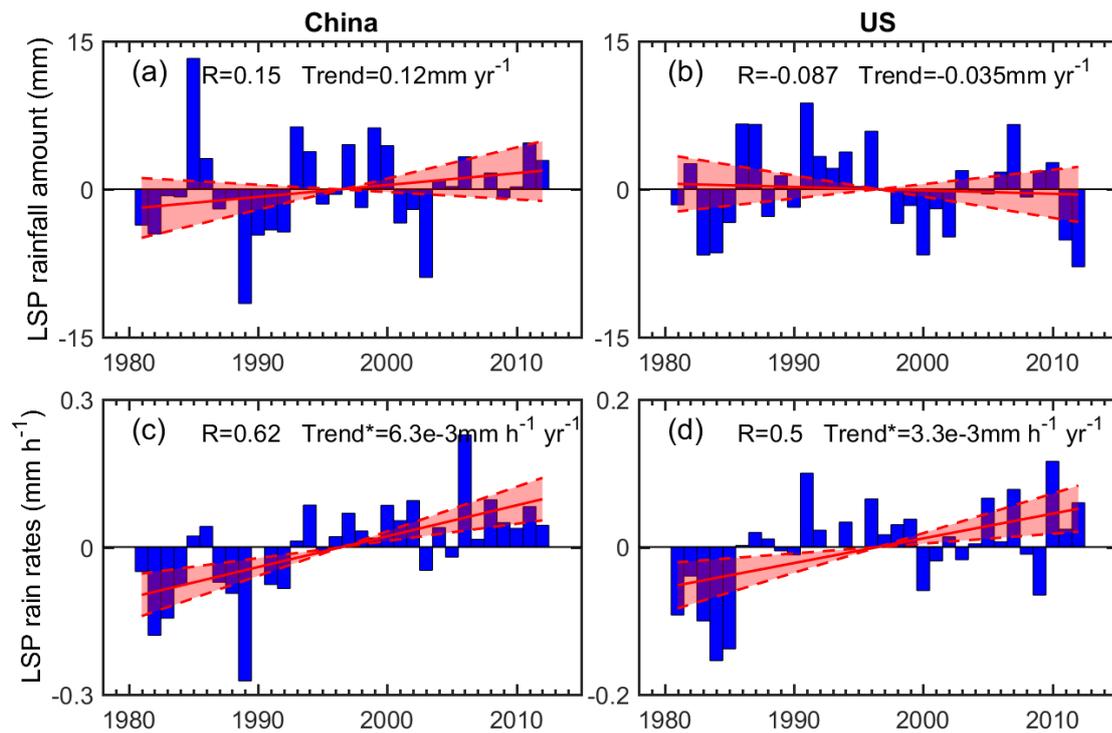


Figure S5. (a, b) Time series of the rainfall amount anomalies of summer LSP for China and the US from 1981 to 2012. (c, d) Time series of the rain rates anomalies of summertime LSP during the same period. Shading and dotted lines indicate 95% confidence intervals on the trends in these time series. Trends with asterisks indicate statistically significant trends at the 95% confidence level.

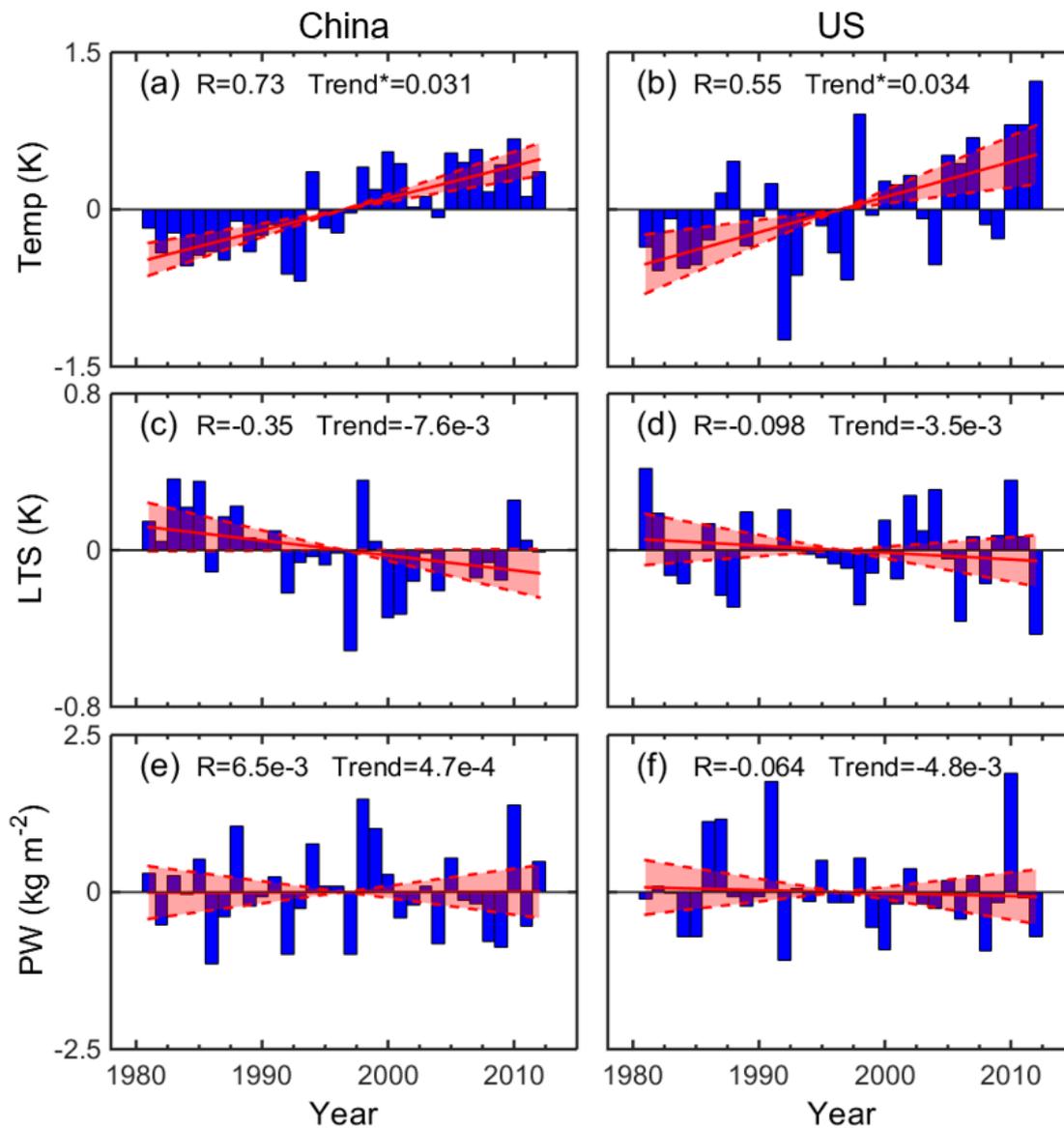


Figure S6. Time series of annual mean anomalies of (a-b) surface temperature, (c-d) LTS, and (e-f) PW derived from ERA-Interim over China and the US from 1981 to 2012. The correlation coefficient R and the trend are shown at the top of each panel. Shading and dotted lines indicate 95% confidence intervals on the trends in these time series. Trends with asterisks indicate statistically significant trends at the 95% confidence level.

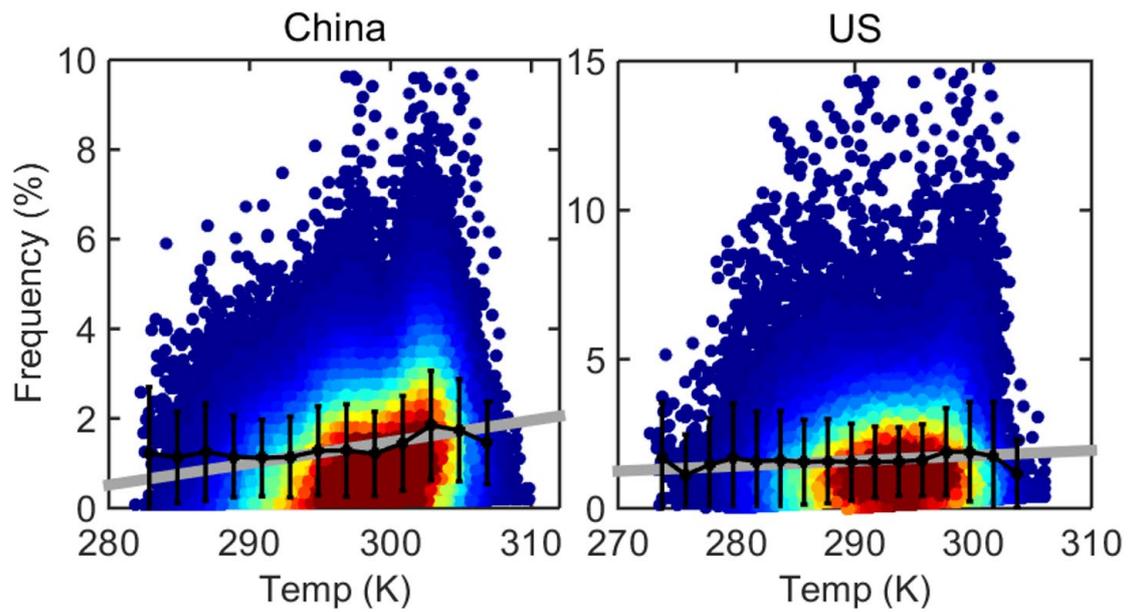


Figure S7. Scatter plots showing the monthly mean LSP frequency as a function of surface temperature for all stations in (a) eastern China and (b) the US. The black dots and whiskers represent the average values and standard deviation for each bin. The grey lines indicate the regressions between surface temperature and LSP frequency in eastern China and the US.

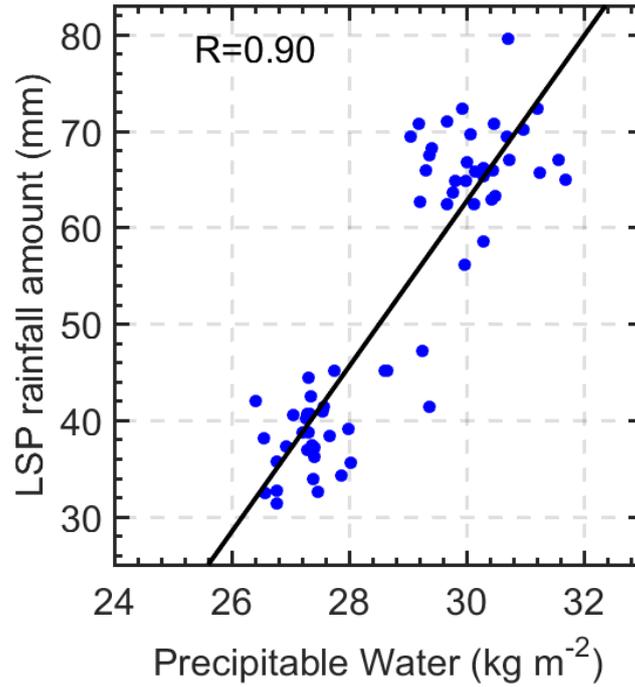


Figure S8. The relationships of annual means between PW and LSP rainfall amount. LSP rainfall amount is calculated from the rain gauge data over China and the US. Precipitable water is obtained from ECMWF reanalysis data. We only use the data during summer (May–September). The high correlations suggest that the LSP rainfall amount may be largely determined by the PW.