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LETTER

Intensified reduction in summertime light rainfall over mountains compared with plains in Eastern China

A letter

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Abstract Based on daily rainfall data from 1960 to 2007, this study investigated the difference in rainfall trends between seven mountain stations and 21 nearby plain stations in eastern China for the months June–August. The amount and frequency of light rain ($\leq$2.5 mm/day) over the mountain areas showed a greater decreasing trend than over the surrounding plain regions. The trend of light-rainfall frequency at mountain stations is −4.8%/decade, approximately double that at plain stations (−2.3%/decade). The trend in light-rainfall amount at mountain stations is −5.0%/decade, approximately three times that at plains station (−1.4%/decade). Reduced wind speed may explain the enhanced decrease in light rainfall over mountain areas through the weakened orographic lifting. Further study is needed to determine whether the precipitation difference between mountain and plain (urban) regions is exacerbated by air pollution in East China through its indirect effects and influence on regional air stability and wind speed.

1 Introduction

Temporal trends in orographic rainfall have received increasing attention in recent years because precipitation over hills and mountains is a major water source for some subtropical continental regions. Many studies have investigated the trend in orographic precipitation over subtropical regions based on analyses of the orographic rainfall ratio. For example, a temporal decrease in the orographic rainfall ratio has been reported for many mountain ranges in the western United States (e.g., Griffith et al. 2005), central Israel (e.g., Givati and Rosenfeld 2004), and at Mountain Huashan in central China (Rosenfeld et al. 2007). Most of these studies attributed the reduction in orographic precipitation to increased pollution (e.g., Givati and

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Rosenfeld 2004; Rosenfeld et al. 2007), based on our understanding of the effect of aerosol pollution on cloud condensation nuclei (CCN) and the development of precipitation (e.g., Gunn and Phillips 1957; Warner and Twomey 1967). However, a recent study that used data from a large number of stations, including both inland and coastal stations throughout Israel, found statistically significant trends in orographic rainfall ratio with positive and negative signs (Alpert et al. 2008), which is somewhat inconsistent with the results of the above studies.

The studies summarized above were largely based on analyses of the orographic rainfall ratio, which is defined as the ratio of mountain rain to plain rain. The limitations of this approach were considered by Alpert et al. (2008). A decrease in the value of a ratio may reflect an increase in the denominator or a decrease in the numerator. In addition, a ratio decreases if a constant is added to both the nominator and the denominator (for a ratio >1). Consequently, a spatially homogeneous increase in rainfall due to a large-scale process could result in a decrease in the orographic rainfall ratio. Therefore, a decline in the orographic rainfall ratio does not necessarily correspond to the reduced precipitation in mountain areas.

Most previous studies on temporal trends in orographic precipitation focused on total rainfall (e.g., Givati and Rosenfeld 2004; Rosenfeld et al. 2007; Alpert et al. 2008). Total orographic rainfall is influenced by various rainfall-forming processes, including large-scale synoptic precipitation (mostly causing moderate to heavy rainfall), uplift-related stable stratiform precipitation (mostly causing light rainfall), and strong small-scale convection related to topography (mostly causing heavy rainfall) (Smith 2003). Therefore, the factors that underlie observed trends in total orographic rainfall are complex and difficult to resolve.

In addition to analyzing the orographic precipitation ratio, this study calculates temporal trends in total rainfall and various rainfall grades (intensities) at seven mountains and surrounding plain regions in Eastern China. The differences in light-rainfall trends between the mountain and plain regions are evaluated, and possible reasons for these differences are discussed.

2 Data and strategy

This analysis is based mainly on daily precipitation data and daily wind speed data from the China National Meteorology Center, covering the period from 1960 to 2007. Based on the results of sensitivity tests, daily rainfall amounts are categorized into four grades: 0.1–2.5, 2.5–10, 10–30, and >30 mm/day. This division best reflects the common features of precipitation trends in each grade, particularly for light rain (0.1–2.5 mm/day). The period June–August (JJA) is chosen for analysis because this is the wet season at most stations in Eastern China and this period has more warm-cloud precipitation than cold-cloud precipitation.

The orographic precipitation ratio, which is the ratio between precipitation amounts in mountain and plain areas, has been used as an analysis tool in many previous studies (e.g., Hill et al. 1981; Rosenfeld et al. 2007; Alpert et al. 2008). In this study, the trend in the orographic precipitation ratio for each mountain station is the average trend obtained in comparing the mountain rainfall with that at three nearby plain stations in urban areas. For each grade of rainfall, the precipitation amount refers to the daily mean precipitation rate (in millimeters per day) during JJA in this

Table 1 Names and altitudes of seven (A–G) selected mountain stations in eastern China

Number	A	B	C	D	E	F	G
Mt.	Tian Chi	Wu Tai	Tai Shan	Hua Shan	Huang Shan	Lu Shan	Jiuxian Shan
Altitude (m)	2,623	2,208.3	1,533.7	2,064.9	1,840.4	1,164.5	1,653.5

grade, and the precipitation frequency represents the total number of rainfall days during JJA in this grade.

A simple linear regression method is used to obtain trends from time series data. The statistical significance of the obtained trends is assessed using the *t* test which has been used in many similar studies (e.g., Givati and Rosenfeld 2004; Alpert et al. 2008), and the Mann–Kendall trend test (e.g., Yue and Pilon 2004) as the data tend to be non-parametric in nature. Given that almost similar results were obtained from the two tests, only the results of the *t* test are provided below. A simple *t* test is also used to assess the statistical significance of differences in trends between groups (e.g., mountain vs. plain stations).

The selection of mountain stations in eastern China was based on three main criteria: (1) station location east of 105° E, (2) historical rainfall record at the station available for the period 1960–2007, and (3) difference in altitude between the mountain and surrounding plain region of at least 1000 m. The nearby urban stations were selected based on their proximity to the mountains and with the aim of roughly representing the plain regions around each mountain. The small distance between each mountain and the adjacent plain region ensured a similar large-scale meteorological background for the two areas. As a result, we chose seven groups of stations [A–G] in eastern China, with each group comprising one mountain station and three stations in urban areas upon the surrounding plain (Tables 1 and 2; Fig. 1).

Table 2 Names and altitudes of 21 plain stations (marked with number "1" to number "21") nearby the above seven mountains

Group	Number	City	Altitude (m)
A	1	Yan ji	176.8
	2	Song jiang	721.4
	3	Dong gang	774.2
B	4	Da tong	1,067
	5	Shijia zhuang	81
	6	Yang quan	741.9
C	7	Ji nan	170.3
	8	Xin yuan	305.1
	9	Lin yi	86.5
D	10	Xi an	397.5
	11	Lu shi	569.9
	12	Zhen an	693.9
E	13	Chao hu	22.4
	14	An qing	19.8
	15	Tun xi	142.7
F	16	Hua shi	19.8
	17	Bo yang	40.1
	18	Nan chang	46.9
G	19	Fu zhou	84
	20	Yong an	206
	21	Xia men	139

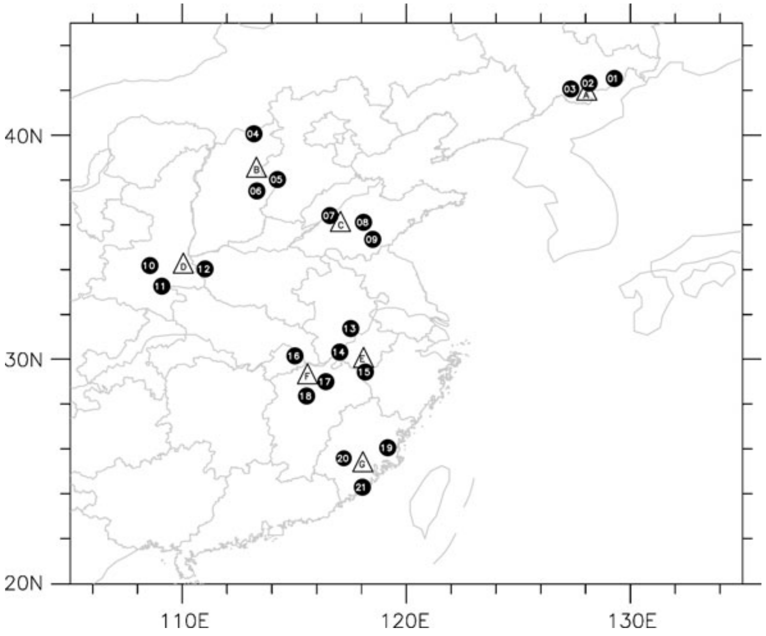

Fig. 1 Locations of seven groups of mountain stations and plain stations in eastern China. Each plain city is denoted by a *circle with a number inside*, and each mountain is signified by a *triangle with a capital letter inside* (the numbers and capital letters are interpreted by Tables 1 and 2)

3 Results and discussion

First, we assessed the trend in orographic rainfall ratios (total rainfall) from 1960 to 2007 for each mountain station (Fig. 2a). Most of the ratios (17 of 21) show decreasing trends, with some exceptions in Groups C and E. The observed temporal reduction in orographic precipitation ratios is consistent with the results of many previous studies (see the Section 1).

Next, we assessed the trends in total rainfall and the four grades of rainfall (see Section 2) for each mountain station and three stations on the surrounding plain (i.e., seven groups of stations) from 1960 to 2007. To more realistically reflect the conditions of the plain region surrounding each mountain, we averaged the rainfall trends for the three plain stations around each mountain station.

The total rainfall shows a trend of typical "north drought and south wet" (Fig. 2b), which is closely related to variations in the East Asian summer monsoon, as reported in many previous studies (e.g., Gong and Ho 2002; Wang et al. 2008; Zhou et al. 2009). Among those stations with negative trends in the total rainfall, the mountain stations have larger decreasing trends than do most of the nearby plain stations. When we divide the total rainfall into four grades and perform the same analysis for both precipitation amount and frequency, we find that the greater reduction over mountain regions compared with plains is found more obviously for light rainfall (Fig. 2c, d) but is less pronounced for other grades of rain (figures not shown). Compared with the other grades of rainfall and total rainfall, another distinctive feature of light rainfall is that a decreasing trend is obtained for most stations in

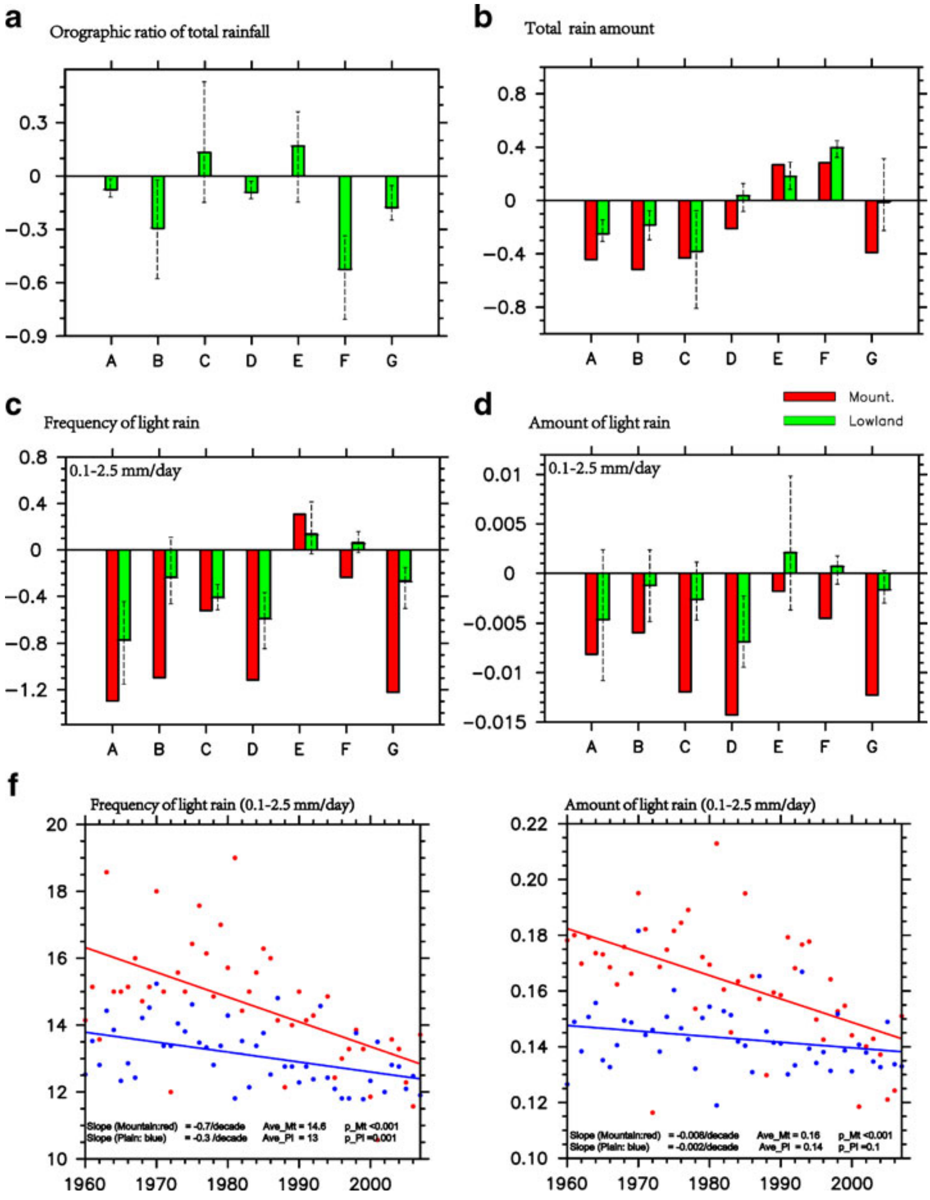

Fig. 2 Slopes of trends respectively for **a** orographic ratio of total rainfall (per decade), **b** the total rainfall (unit: millimeters per day per decade), **c** frequency of light rainfall (unit: days per decade) and **d** amount (unit: millimeters per day per decade) of light rainfall during JJA from 1960 to 2006 in the seven groups of stations. The *red bars* represent mountain stations and the *green bars* denote the average of urban regions. The *dashed error bars* mark the maximum and minimum of the trend slopes among the plain cities. The *capital letters* in *x*-axis are group numbers as listed in Tables 1 and 2. **e** Trends of frequency (days) and amount (millimeters per day) of light rains respectively averaged for seven mountains (*red lines* and *dots*) and 21 plain stations (*blue lines* and *dots*), and "p_mt" (mountain) and "p_pl" (plain) represent the statistical significances that corresponds to the *t* test statistic

both frequency (22 of 28 stations; above the 90% confidence level for 15 stations) and amount (20 of 28 stations; above the 90% confidence level for 14 stations).

To gain greater insight into the difference between mountain and plain regions in terms of trends in light rainfall, we calculated the average trends in light-rainfall change among the seven mountain stations and among the 21 plain stations (Fig. 2e). The results for both precipitation amount and frequency reveal two features that are similar to those shown in Fig. 2c, d. First, both the amount and frequency of light rainfall show a significant decreasing trend during the past 50 years over both mountain and plain regions. Second, the amount and frequency of light rainfall at mountain stations show stronger decreasing trends than at plain stations. The average trend in light-rainfall frequency at mountain stations is −4.8%/decade (0.7/14.6), whereas the trend at plain stations is −2.3%/decade (0.3/13). The trend in precipitation amount at mountain stations is −5%/decade (0.008/0.16), more than three times higher than the trend at plain stations (−1.4%/decade). The differences in the decreasing trends between mountain and plain stations (for both frequency and amount) are above the 99% confidence level (*t* test).

The decrease in light rainfall over eastern China, as reported above, has also been reported in previous studies, which generally attributed the decrease to increasing aerosol concentrations in the atmosphere. For example, Gong et al. (2007) found a weekly cycle in the decreasing frequency of summertime light rainfall in major urban regions in east China that matched the cycle of increasing aerosol pollution. Based on observations and the results of simulations using a cloud-resolving model, Qian et al. (2009) found that increasing concentrations of cloud droplets and reduced droplet numbers in a polluted case could result in reduced raindrop concentration and delayed raindrop formation, causing decreased light rainfall. In addition, the inverse aerosol–rainfall relationship obtained for China is strongest for light rain (Choi et al. 2008; Jin and Shepherd 2008). Regional warming is considered another potential contributor to the observed decreasing trend in light-rainfall events over China (Qian et al. 2007).

Why is the decreasing trend in rainfall over mountainous regions greater than that over nearby plain regions, particularly for light rainfall? To answer this question, we first need to clarify the major difference in the mechanism of precipitation formation over mountains and over plain regions. Orographic rainfall (especially light rainfall) is commonly caused by the forced uplift of moist air as it passes over mountains (Dore et al. 2006), while rainfall over plain regions is generally caused by local convection (Cotton and Yuter 2009). Therefore, compared with rainfall over plain regions, orographic rainfall is more dependent on wind speed (Hill et al. 1981).

We calculated the temporal trends in wind speed (using three measures) for the seven groups of stations (Fig. 3). The maximum wind speed at 10 m has decreased over the past 50 years at 24 of the 27 stations; this decrease is above the 95% confidence level at 22 stations. The prevalence of windy days with a surface daily mean wind speed >5 m/s has decreased at 25 of the 28 stations; this decrease is above the 95% confidence level at 18 stations. Finally, the daily average surface wind speed has declined at 17 of the 28 stations; this decrease is above the 95% confidence level at 13 stations. Previous studies have also reported a general decline in summertime wind speed over China (e.g., Zuo et al. 2005; Xu et al. 2006).

How does the reduction in wind speed influence orographic rainfall? First, it is obvious that the reduced wind speed (particularly over plain regions) may result in reduced uplift of moist air into mountain regions, thereby suppressing the develop-

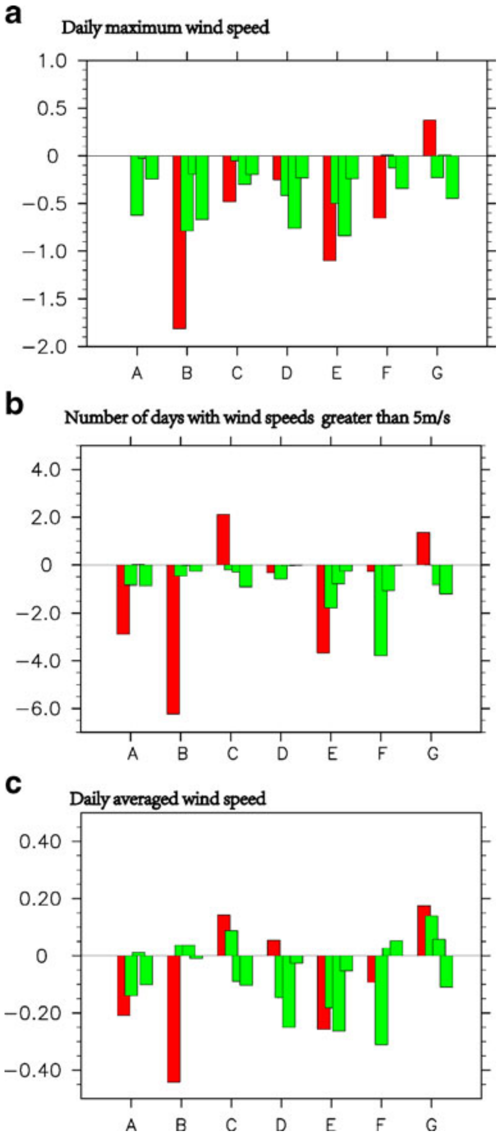

Fig. 3 Slopes of the trends respectively for **a** daily maximum surface wind speed (mountain A has no record), **b** number of days with wind speed >5 m/s, and **c** daily averaged wind speed during JJA from 1960 to 2007. The *capital letters* for the *red bars* represent seven mountains as listed in Table 1; and the *green bars* represent 21 plain cities following the sequence listed in Table 2

ment of stratiform precipitation and reducing the atmospheric water content over mountain regions. Second, the Lagrangian time-scale is a critical parameter in cloud formation (Cotton and Yuter 2009), which directly influences the development of precipitation. For orographic precipitation, the Lagrangian time-scale measures the time required by cloud or an air mass to pass over a mountain. A longer Lagrangian time-scale favors the transition of droplets into rain (Cotton and Yuter 2009). A decrease in wind speed results in a longer Lagrangian time-scale, which would increase the rainfall frequency and amount over mountains (Cotton and Yuter 2009).

The above effects of wind speed on orographic rainfall are contradictory. We assume that the first effect may exceed the second effect. That is, the reduced uplift of large-scale moist air may overcome the increase in rainfall arising from a longer Lagrangian time-scale associated with reduced wind speed; consequently, the frequency and amount of orographic light rainfall are reduced.

We now consider why the surface wind speed has decreased in recent decades. Urbanization has been cited as a reason for reduced surface wind (e.g., Jiang et al. 2009); however, our results show evident decreasing trends in wind speed over both plains and mountain regions (Fig. 3). Therefore, we believe that urbanization has only a negligible effect on reduced surface wind speed over mountain regions. The results of observations and numerical modeling indicate that aerosol particles are an important contributor to reduced wind speed (e.g., Jacobson and Kaufman 2006). Scattering aerosol particles (e.g., sulfate) can increase the atmospheric stability by reducing the amount of solar radiation reaching the ground (e.g., Ackerman 1977). In addition, soot and soil dust in the air may absorb solar radiation, thereby enhancing the atmospheric stability by heating the air aloft. An increase in the stability of air results in reduced vertical turbulence and reduced vertical flux of horizontal momentum (e.g., Archer and Jacobson 2003), resulting in reduced wind speed.

Importantly, none of the above studies focused on East China. Xu et al. (2006) reported that cooling of the ground surface due to the effect of scattering aerosols can result in reduced land–sea thermal contrast in summer, thereby reducing the intensity of the summer monsoon over China. However, it remains unknown if reduced wind speed over East China is related to air pollution.

4 Conclusion

Based on data from seven mountain stations and from 21 urban stations on surrounding plains in eastern China, we calculated the orographic precipitation ratios and compared temporal trends in total rainfall and four grades of rainfall intensity for the period 1960–2007. We found that decreasing trends in the frequency and amount of light rainfall over mountains are greater than those over nearby plain regions. The trend in light-rainfall frequency at mountain stations is −4.8%/decade, approximately double that at plain stations (−2.3%/decade). The trend in light-rainfall amount at mountain stations is −5.0%/dacade, approximately three times larger than that at plain stations (−1.4%/decade). Wind speed has weakened in recent decades at both mountain and nearby urban stations, indicating reduced orographic lifting and consequently suppressed mountain rainfall (especially light rainfall). Many previous studies have found that increased pollution could suppress light rainfall through the so-called secondary indirect aerosol effect (e.g., Gunn and Phillips 1957; Rosenfeld et al. 2008); however, it remains unclear regarding the degree to which orographic rainfall in East China is suppressed in relatively "clear" mountain areas where aerosol concentrations are lower than in nearby urban areas. In addition, further observations and simulation studies are required to determine whether/how decreasing wind speed in East China is related to air pollution, as has been argued in previous studies.

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