Possible impact of aerosols on orographic precipitation in eastern China

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Abstract To analyse the possible suppression by aerosols of orographic precipitation, three catchments were chosen in eastern China. The suppression was quantified as change in the orographic precipitation enhancement factor (*R*o), defined as the ratio between the hilly and the plains precipitation. The results show a significant downward trend of *R*o in the past 50 years, accompanied by a decrease in visibility (indicating an increase in aerosols concentration). During the period from 1980 to 2002, the three catchments had a decrease in *R*o, with a rate of 22–42% and an increase in the aerosols concentration, with a rate of approx. 0.01–0.02 mg/m^3 (10–30%). It is speculated that the possible cause of *R*o decreasing is the increase in aerosols concentration, and this implies the loss of significant water resources in hilly areas, which may be a reason for aggravation of the water resources shortage, especially in north China and northeast China.

Key words orographic precipitation; enhancement factor; aerosols; visibility

INTRODUCTION

It was recognized 50 years ago, through laboratory experiments in a giant expansion chamber (Gunn & Philips, 1957), that air pollution resulted in more and smaller cloud droplets and suppressed precipitation. Recent studies confirmed that a large quantity of aerosol particles from burning biomass and industrialization had been released into the atmosphere, serving as cloud condensation nuclei (CCN) to initiate cloud formation, and hence participate in the precipitation process. More aerosols result in more, but smaller cloud drops (Ackerman *et al.*, 2000), which suppress the drop-coalescence and warm-rain processes as well as ice precipitation (Rosenfeld, 1999, 2000; Borys *et al.*, 2003; Andreae *et al.*, 2004) and so prolong the time required to convert the small drops into large drops that can precipitate. If the time is longer than the lifetime of cloud drops, less precipitation will occur. Short-lived cloud elements typically form as air rises over topographic barriers, and then evaporate when forced down across the ridge line (Rosenfeld *et al.*, 2007).

To quantify the effect of the orographic component of precipitation, the orographic enhancement factor (*R*o) was introduced, where *R*o is defined as the ratio between the precipitation amounts on the hills and on the upwind plains (Givati & Rosenfeld, 2004). Following this, the effect of aerosols on precipitation was quantified in different countries. Givati & Rosenfeld (2005) analysed the rainfall amounts in northern Israel, and their results show that for the whole period of 1980–2002 *R*o decreased by 15%. Jirak & Cotton (2006) found that along the front range of the Rocky Mountains *R*o had decreased by approx. 30% over the past half-century due to the effect of pollution. In China, Rosenfeld *et al.* (2007) examined *R*o in Mt Hua in the centre of China, and suggested that particulate air pollution caused a decreasing trend of 10–25%.

The historical records of aerosols generally have a very short series, especially in China. Rosenfeld *et al.* (2007) hypothesized that reduced visibility indicated the presence of more aerosols. Yang *et al.* (2007) found that the decrease of visibility in Jinan resulted from the combined influence of PM2.5, PM10 and meteorological conditions. Liang & Xia (2005) proposed that the rapid increase in aerosol loading resulted in visibility deteriorating heavily in eastern China. Analysis of the data of visibility and meteorological variables in Chongqing, China, suggested that the decrease of horizontal visible distance was dominated by the increase of airborne pollution (Peng & Chen, 1992). In general, visibility can be a good indicator of the aerosols concentration in the atmosphere.

The impact of air pollution on orographic precipitation can be quantified with the change ratio of *R*o. Three catchments were chosen for this study, and the objectives were: (1) to analyse the change trends in *R*o and the visibility in the three catchments; (2) to examine the relationship of *R*o with the visibility; and (3) to quantify the impact of aerosols on the orographic precipitation, based on the regression equation between the aerosols concentration and the visibility.

STUDY AREAS, DATA AND METHOD

In the eastern part of China, a rapid growth of industrialization and urbanization, accompanied by a large amount of fossil fuel consumption, induces more aerosol release into the atmosphere. To analyse the possible impact of aerosols on precipitation and water resources, following the method proposed by Givati & Rosenfeld (2004, 2005), three catchments with raingauges in hilly and plain areas were chosen, as well as three stations having observations on visibility and concentration of PM10 (the particle diameter <10 μm) (see the locations in Fig. 1). Three catchments were located from the north to the south in the eastern part of China: Catchment 1 belonging to the Heilongjiang River basin in northeast China, Catchment 2 located in the Hai River basin in north China, and Catchment 3 situated in southeast China. Every catchment has raingauges located in both hilly and plain areas; there are 13 raingauges in total (see Table 1 for more details, data released by the National Meteorological Administration of China). These gauges were sorted into hilly and plain raingauges according to the elevation and topography on the basis of DEM (Digital Elevation Model). The daily precipitation at the 13 gauges was collected from 1961 to 2006.

Fig. 1 Locations of the three catchments chosen in the eastern part of China in this study; the stars represent the adjacent stations with the observation of the concentration of PM10 and visibility.

Table 1 Locations and details of the plains and hilly raingauges in the three catchments.

No.	Hilly stations	Latitude (°)	Longitude (°)	Elevation (m)	Plain stations	Latitude (°)	Longitude (°)	Elevation (m)
1	54287	42.02	128.08	2623	54284	42.10	127.57	774
					54285	42.53	128.25	591
					54276	42.35	126.82	549
2	53588	39.03	113.53	2896	53698	38.03	114.42	81
	53673	38.73	112.72	828	53798	37.07	114.50	77
	53782	37.85	113.55	742				
3	58927	25.10	117.03	342	59126	24.50	117.65	29
					59134	24.48	118.07	139
					59321	23.78	117.50	54

This study also used data collected during 6-hours observation of visibility (in kilometres) at 574 stations from 1980 to 2002 over mainland China, as well as the weather phenomena, and both were released by the National Meteorological Administration of China. If there was fog, precipitation or other special weather phenomena during the observations, the visibility data was excluded from the series. Daily and annual mean of visibility were then both calculated for each station.

For each gauge, annual precipitation was obtained as the sum of daily precipitation. Further, the arithmetic mean of annual precipitation was calculated for the hilly and the plains gauges for each catchment. Then *R*o was taken as the ratio between the mean precipitation in the hilly areas and that in the plains. The arithmetic mean of visibility was also calculated for each catchment. The relationship between *R*o and visibility was analysed by linear regression. The relationships of the concentration of PM10 with the visibility in the three stations were also examined by regression analysis on the basis of daily data from 2001 to 2002.

RESULTS AND DISCUSSION

As shown in Fig. 2, all three catchments have significant decrease trends ($p < 0.10$) in annual precipitation in the hilly areas, while Catchments 1 and 2 have slight decreases in annual precipitation and Catchment 3 has a significant increase ($p = 0.01$) in the plains during the period from 1961 to 2006. It shows that annual precipitation in the plains has a downward trend in the northern part, but an upward trend in the southern part; at the same time the precipitation over the hilly areas has a common decrease trend in both northern and southern areas. Additionally, a decrease trend in *R*o has been detected for the two catchments at a level of $p < 0.01$, except

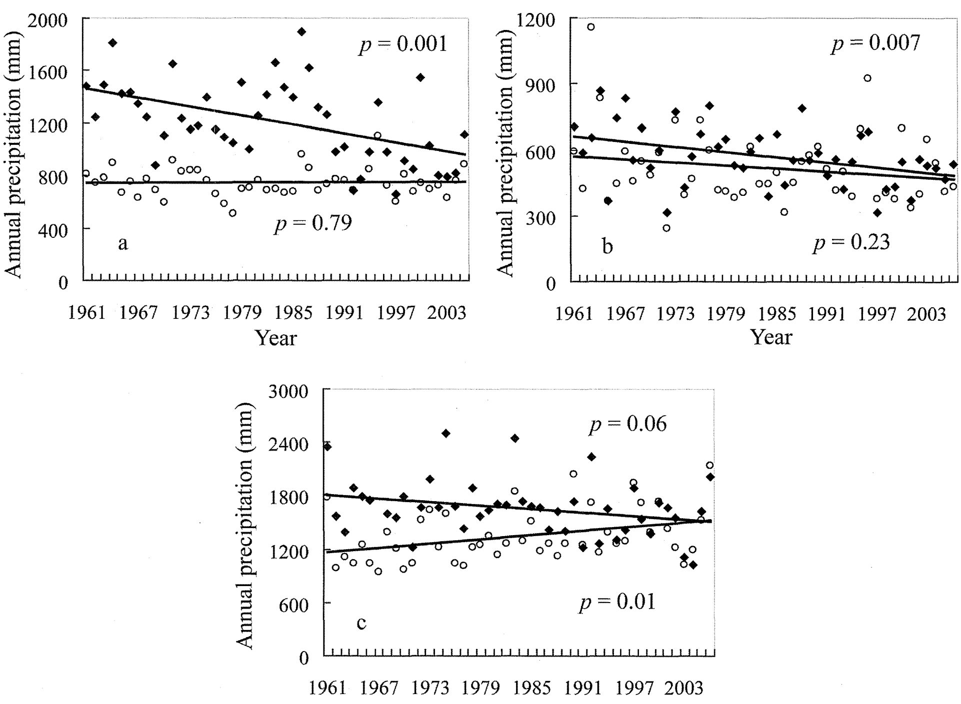

Fig. 2 Trends in annual precipitation of hilly areas and plains in (a) Catchment 1, (b) Catchment 2, and (c) Catchment 3 (○ representing the plains precipitation, and ◆ representing the hills precipitation). The trends are given as two solid lines within each plot. The probability (*p*) for the lines are given for each plot.

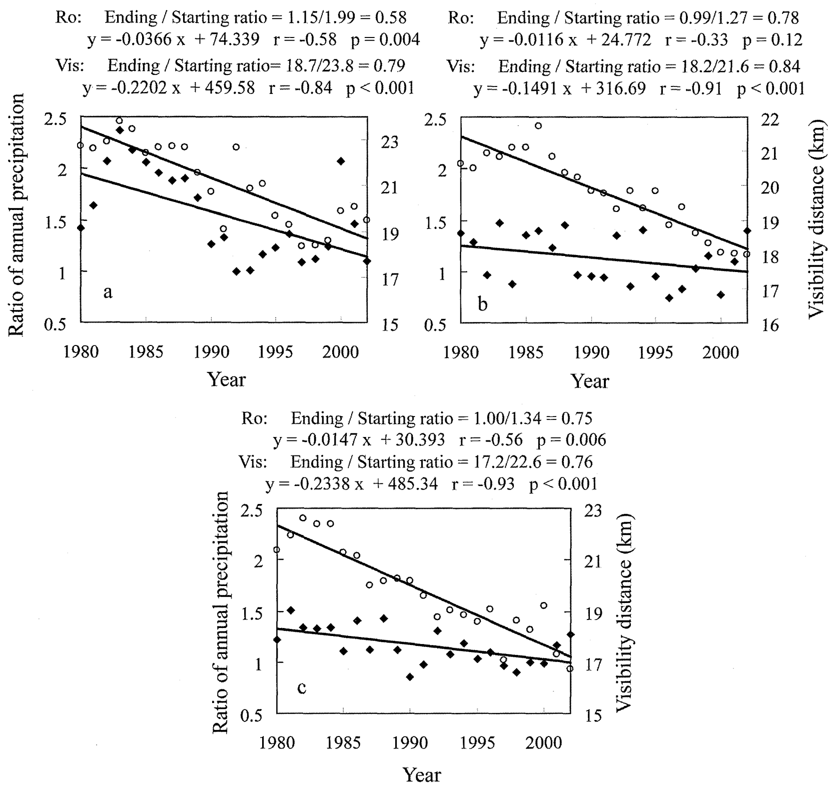

Fig. 3 Trends in *R*o and visibility in (a) Catchment 1, (b) Catchment 2, and (c) Catchment 3 (○ representing the *R*o, and ◆ representing the visibility). The trends are given as solid lines within each plot. The regression equations for the lines are given above the top of each plot, as well as the relation coefficient (r) and probability (p).

Catchment 2 at a significant level of $p = 0.12$ (see Fig. 3). As shown in Fig. 3, during the period from 1980 to 2002, *R*o has an ending/starting ratio of 0.58–0.78; i.e. the hilly areas lost 22–42% precipitation, i.e. 42% in Catchment 1 in northeast China, 22% in Catchment 2 in north China, and 25% in Catchment 3 in southeast China. It implies a loss of water resources, and aggravates the water resources shortage in the arid and semi-arid regions. Similar phenomena were found in the other countries of the world, such as Israel, about 6.5% of the national water consumption was lost due to the suppression of aerosols on orographic precipitation (Givati & Rosenfeld, 2007).

Simultaneously all the catchments have significant decrease trends in visibility at a significance level of $p < 0.001$, with an ending/starting value of 0.76–0.84. The possible cause was speculated to be more aerosols released into the atmosphere due to a rapid growth of industrialization and urbanization in these regions. The relationship between *R*o and visibility was further examined using regression analysis during the period from 1980 to 2002. The results, as listed in Table 2, show a positive correlation with a correlation coefficient of 0.28–0.66 and a significant level of $p < 0.01$ in two of the catchments, and another with a significant level of $p = 0.20$.

Table 2 Correlation between Ro and the visibility.

Catchment	Correlation coefficient (r)	Significance level (p)
1	0.66	<0.001
2	0.28	0.20
3	0.51	0.01

It can be speculated that the increasing aerosols concentration leads to the decline in visibility, and induces the downward trend in *R*o. The relationship of aerosols concentration with visibility is shown in Fig. 4. A significant linear correlation ($p < 0.001$) can be found between the concentration of PM10 and the logarithm of the visibility in the three stations. We also assumed that the relationship in the stations can represent the relationship in the adjacent catchment (see Fig. 1). According to the linear regression equation of the concentration of PM10 with the visibility, we can estimate the aerosols concentration in every catchment (see Table 3). The results show that the increase of PM10 concentration is 0.018 mg/m^3 (26.9%) in Catchment 1, 0.016 mg/m^3 (10.1%) in Catchment 2, and 0.011 mg/m^3 (14.1%) in Catchment 3 during the period from 1980 to 2002, corresponding to the decrease rates of *R*o being 42%, 22% and 25%, respectively. It suggests that *R*o is sensitive to the aerosols concentration. This was also found by Borys *et al.* (2003), that an addition of 0.001 mg/m^3 of sulphate aerosols to a clean background can decrease the orographic snowfall rate by up to 50% in the Colorado Rocky Mountains.

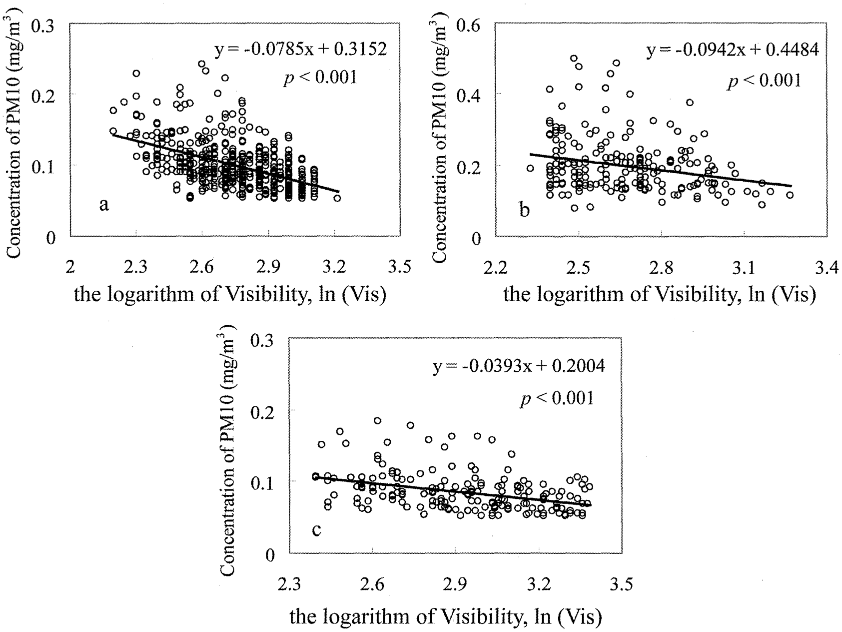

Fig. 4 Relationship between the concentration of PM10 and the logarithm of the visibility. The regression equations for the lines are given, as well as the probability (p).

Table 3 Changes in aerosols (PM10) concentration estimated by regression equation in Fig. 4 for each catchment (the visibility calculated by the regression equation in Fig. 3).

Catchment	PM10 in 1980 (mg/m^3)	PM10 in 2002 (mg/m^3)
1	0.067	0.085
2	0.159	0.175
3	0.078	0.089

Besides the impact on the orographic precipitation, aerosols absorb sunlight and heat air, which lead to higher atmospheric stability (Ramanathan *et al.*, 2005). This results in the depression of the upward motions of the atmosphere, which can reduce cloud formation, and further suppress precipitation and it has been shown in eastern central China (Zhao *et al.*, 2006).

CONCLUSION

In the eastern part of China, the decreasing visibility is possibly as a result of many aerosols released into the atmosphere due to a rapid growth in industrialization and urbanization, accompanied by a large amount of fossil fuel consumption. It was estimated that the increase in aerosols (PM10) concentration was approx. 0.01–0.02 mg/m^3 (10–30%) during the period from 1980 to 2002.

Precipitation in the hilly areas mainly transforms into runoff, supplied to agriculture, cities, and the ecological system in the plains, especially in northeast China and north China. The precipitation enhancement by uplifting on topographic barriers is sensitive to aerosols concentration. This study found that the concentration of PM10 increased by 10–27% in the three catchments, and *R*o decreased by about 22–42% from 1980 to 2002 due to the possible suppression of air pollution on orographic precipitation. It shows a significant loss of water resources in hilly areas, and implies the water resources shortage is aggravated in the plains.

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REFERENCES

Ackerman, A. S., Toon, O. B., Taylor, J. P., Johnson, D. W., Hobbs, P. V. & Ferek, R. J. (2000) Effects of aerosols on cloud albedo: Evaluation of Twomey's parameterization of cloud susceptibility using measurements of ship tracks. *J. Atmos. Sci.* **57**, 2684–2695.

Andreae, M. O., Rosenfeld, D., Artaxo, P., Costa, A. A., Frank, G. P., Longo, K. M. & Silva-Dias, M. A. F. (2004) Smoking rain clouds over the Amazon. *Science* **303**, 1337–1342.

Borys, R. D., Lowenthal, D. H., Cohn, S. A. & Brown, W. O. (2003) Mountaintop and radar measurements of anthropogenic aerosol effects on snow growth and snowfall rate. *Geophys. Res. Lett.* **30**(10), 1538, doi:10.1029/2002GL016855.

Givati. A. & Rosenfeld, D. (2004) Quantifying precipitation suppression due to air pollution. *J. Appl. Met.* **43**, 1038–1056.

Givati, A. & Rosenfeld, D. (2005) Separation between cloud-seeding and air-pollution effects. *J. Appl. Met.* **44**, 1298–1314.

Givati, A. & Rosenfeld, D. (2007) Possible impacts of anthropogenic aerosols on water resources of the Jordan River and the Sea of Galilee. *Water Resour. Res.* **43**, W10419, doi:10.1029/2006WR005771.

Gunn, R. & Phillips, B. B. (1957) An experimental investigation of the effect of air pollution on the initiation of rain. *J. Met.* **14**, 272–280.

Jirak, I. L. & Cotton, W. R. (2006) Effect of air pollution on precipitation along the front range of the Rocky Mountains. *J. Appl. Met. & Climatol.* **45**(1), 236–245.

Liang, F. & Xia, X. A. (2005) Long-term trends in solar radiation and the associated climatic factors over China for 1961–2000. *Ann. Geophys-Germany* **23**, 2425–2432.

Peng, Z. G. & Chen, J. (1992) Relation of visibility to air pollution. *Chongqing Environ. Sci.* **14**(3), 16–21 (in Chinese).

Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, T., Washington, W. M., Fu, Q., Sikka, D. R. & Wild, M. (2005) Atmospheric brown clouds: impact on South Asian climate and hydrologic cycle. *Proc. Natl. Acad. Sci.* **102**, 5326–5333.

Rosenfeld, D. (1999) TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophys. Res. Lett.* **26**, 3105–3108.

Rosenfeld, D. (2000) Suppression of rain and snow by urban and industrial air pollution. *Science* **287**, 1793–1796.

Rosenfeld, D., Dai, J., Yu, X., Yao, Z. Y., Xu, X. H., Yang, X. & Du, C. L. (2007) Inverse relations between amounts of air pollution and orographic precipitation. *Science* **315**, 1396–1398.

Yang, D. Z., Fang, X. M. & Li, X. S. (1998) Analysis on the variation of sandstorm in northern China. *Q. J. Appl. Met.* **9**(3), 352–358.

Yang, L. X., Wang, D. C., Cheng, S. H., Wang, Z., Zhou, Y. H. & Wang, W. X. (2007) Influence of meteorological conditions and particulate matter on visual range impairment in Jinan, China. *Sci. Total Environ.* **383**, 164–173.

Zhao, C. S., Tie, X. X. & Lin, Y. P. (2006) A possible positive feedback of reduction of precipitation and increase in aerosols over eastern central China. *Geophys. Res. Lett.* **33**, L11814, doi:10.1029/2006GL025959.