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Simulation of aerosol effects on orographic clouds and precipitation using WRF model with a detailed bin microphysics scheme

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Abstract

The effects on orographic clouds and precipitation of aerosol loading have been investigated by simulating an idealized mixed-phase orographic cloud using the Weather Research Forecast (WRF) mesoscale model coupled with a detailed bin microphysics scheme. The results show that the total precipitation amount is reduced by 23.4% with increasing aerosol loading on the orographic clouds. Moreover, increasing aerosol loading will increase the number concentration of cloud droplets in small size range (<19.84 μm in diameter) and lead to a decrease in the peak diameter from 12.5 to 9.92 μm.

Keywords: **orographic cloud; aerosol; precipitation; spillover factor**

1. Introduction

Aerosol can act as cloud condensation nuclei (CCN) and ice nuclei (IN) to affect the cloud microphysical structure, therefore, change the precipitation. As one of the main precipitation systems, orographic clouds and their response to changes in aerosol loading have attracted much attention in recent years (e.g. Givati and Rosenfeld, 2004; Jirak and Cotton, 2006; Lynn *et al.*, 2007; Saleeby *et al.*, 2011). Terrain is considered as one of the major factors in affecting precipitation. When moist air flow impinges on a mountain range, the lifting of an air stream can form clouds and precipitation. In this process, aerosol can impact on the development of orographic clouds and precipitation by microphysical processes.

The effect of aerosol on orographic cloud and precipitation formation remains an open question. Statistical approaches based on records of rain gauge measurements by Givati and Rosenfeld (2004), and Jirak and Cotton (2006) suggest that urban polluted air lead to downwind precipitation losses over mountain range. Some studies support a decrease in orographic precipitation in polluted condition (Rosenfeld and Givati, 2006; Rosenfeld *et al.*, 2007, 2008). In contrast, Alpert *et al.* (2008) and Halfon *et al.* (2009) argued that there is no marked change in the ratio between rainfall amounts on the elevated sites to that over the coastal region, with a slight increase in the middle of Israel.

Many of previous studies have concentrated on the effect of aerosols on orographic cloud. Increasing the number concentration of aerosol particles in the environment leads to suppression of warm-phase microphysical processes (Lynn *et al.*, 2007; Muhlbauer and Lohmann, 2008; Zubler *et al.*, 2011). The precipitation distribution tends to move toward the leeward side of mountain ranges. In addition, an increase in aerosol loading leads to a decrease of cloud droplet sizes and a reduction in the riming efficiency (Borys *et al.*, 2003; Saleeby *et al.*, 2011, 2013). However, the Wegener–Bergeron–Findeisen snow growth is enhanced with increasing aerosol loading (Saleeby *et al.*, 2013). Saleeby *et al.* (2011) simulated winter weather events over the Colorado Rocky Mountains using the Regional Atmospheric Modeling System coupled with size-dependent riming schemes. In their results, anthropogenic pollutants reduced the amount of precipitation and affected the hydrological cycle on the local scale. Furthermore, it was shown that the mixing state and solubility of aerosol particles exerted a great influence on the aerosol microphysical effect on the orographic cloud and precipitation (Muhlbauer and Lohmann, 2009; Xue *et al.*, 2012).

The main goal of this article is to investigate that to what extent urban aerosols may affect orographic cloud and precipitation if other urban effects (such as urban heat island) are not considered. In this article, we attempt to shed some light on the questions that to what extent is orographic precipitation affected by aerosol loading. For this purpose, this article uses Weather Research and Forecast (WRF) mesoscale model coupled with a detailed bin microphysics schemes to reveal the above-mentioned problems.

2. A brief description of the model

In order to investigate the effect of aerosol on orographic cloud, a detail spectral bin microphysical scheme of both warm and cold cloud processes have been implemented in WRF version 3.1. The microphysical processes are formulated and solved using the method of multi-moments (Tzivion *et al.*, 1987; Reisin *et al.*, 1996; Yin *et al.*, 2000). Four hydrometeor species are considered: droplets, ice crystals, snowflakes (aggregates of ice crystals) and graupel. Each hydrometeor particles are divided into 34 bins with mass doubling for adjacent bins. The masses of the first bin and the last bin for both liquid and solid phases are 0.1598×10^{-13} and 0.17468×10^{-3} kg, which correspond to ice particles with equivalent melted diameters of 3.125 and 8063 µm, respectively. The liquid drops contain cloud water and rain water with a minimum diameter of 3.125 µm and a maximum diameter of 8063 µm. The microphysical processes in the scheme included are CCN nucleation, condensation and evaporation, stochastic collision–coalescence, binary breakup, droplet freezing, ice nucleation, sublimation and deposition of ice, ice multiplication, interactions between ice and ice, and between ice and drops, melting, and sedimentation of both drops and ice particles. The aerosol distribution is represented by 43 bins with radii ranging from 0.001 to 15.75 µm. In this study, we only consider the activation of aerosol according to Yin *et al.* (2000). The chemical composition of aerosols is assumed to be composed of ammonium sulphate [see Yin *et al.* (2000) for more description].

3. Initial conditions and experimental design

3.1. Topography

Numerical experiments of moist flow over a bell-shaped mountain are conducted by idealized two-dimensional version of the above-mentioned WRF

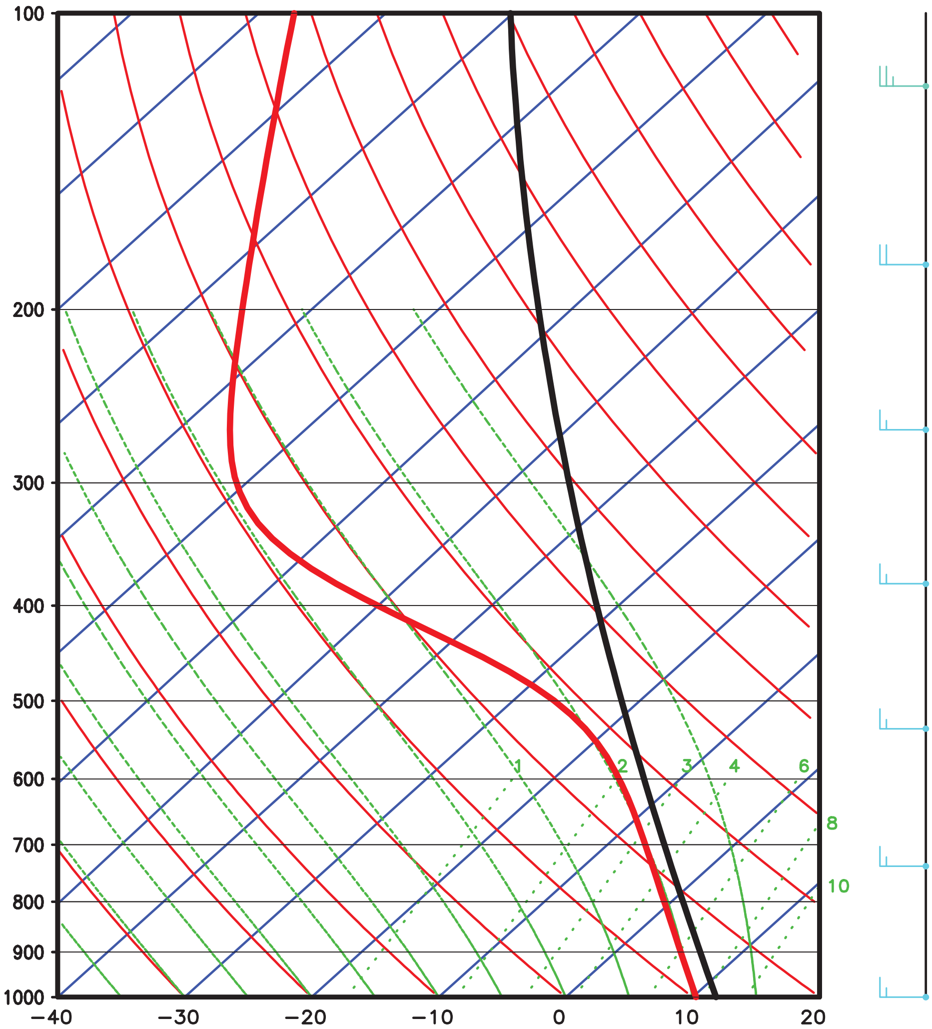

Figure 1. Initial vertical profiles of temperature (solid black line) and dewpoint temperature (solid red line) for idealized simulation.

model system. The two-dimensional model contains 400 grid points in the horizontal direction with a grid resolution of 2 km. The vertical dimension of the model is 25 km from the surface to the top of model with 58 layers. The model is run at 5 s time steps for all the processes except for the processes of diffusive growth/evaporation using 2.5 s time steps. The model simulated time is 10 h. The idealized bell-shaped topography is located at 400 km from left boundary (or at the center of simulated region). The terrain height, h, is given by Equation (1), where $h_0 = 1000$ m is peak mountain height, $x_0 = 400$ km is mountain location and $w = 20$ km is half-width, respectively.

$$h\left(x\right) = \frac{h_0}{\left(\frac{x-x_0}{w}\right)} \quad (1)$$

3.2. The initialization of dynamic and thermodynamic parameters

The profile of the relative humidity is calculated as

$$\mathrm{RH}\left(z\right) = a + \frac{b-a}{1+\exp\left[-c\left(z-z_0\right)\right]} \quad (2)$$

with $a = 0.9$ (surface relative humidity), $b = 0.03$, $c = 0.0015\ \mathrm{m}^{-1}$ and $z_0 = 6000$ m. The surface pressure and temperature are 1000 hPa and 285 K, respectively. A constant value of the dry Brunt–Väisää frequency, $N_\mathrm{d} = 0.0115\ \mathrm{s}^{-1}$, is used. The horizontal wind is $15\ \mathrm{m\,s}^{-1}$ below 10 km and increases linearly above by $1.84\ \mathrm{m\,s}^{-1}$ per km. Figure 1 shows the vertical profile of temperature and dew point temperature.

3.3. Initialization of aerosol distributions and experimental design

The initial aerosol distribution is prescribed by a lognormal distribution of third mode

$$\frac{dN}{d\ln r} = \sum_{i=1}^{3} \frac{N_i}{\sqrt{2\pi}\ln\sigma_i} \exp\left[-\frac{1}{2}\frac{\ln^2\left(r/r_{\mathrm{m}i}\right)}{\ln^2\sigma_i}\right] \quad (3)$$

where i is the aerosol mode number, N_i is the number concentration of aerosol particles, $r_{\mathrm{m}i}$ is the median radius and σ_i is the geometric standard deviation of the ith aerosol mode, respectively. In order to compare the sensitivities of orographic cloud and precipitation to the changes of aerosol concentration because of urban pollution, two scenarios are studied in this study for different background aerosol loading (Figure 2). Experiment Clean and experiment Polluted represent clean continental background condition and polluted urban background condition. The aerosol distributions of continental background condition and urban background condition are based on the field measurements in Huangshan Mountain (Qin et al., 2012) and Nanjing city (Tan et al., 2010), China. The fractions of water-soluble material in these two background conditions are assumed to be 34% (Wen, 2013) and 34.28% (Wang et al., 2003) of total mass, respectively. The soluble aerosols are assumed to be composed of ammonium sulphate, regardless of size (Yin et al., 2005). The initial aerosol number concentration is assumed to decrease exponentially with altitude with a scale height of 2 km according to Yin et al. (2000). These tests can simulate the effect of high concentration of aerosol from urban on topographic cloud without the disturbance of other urban effect such as urban heat island.

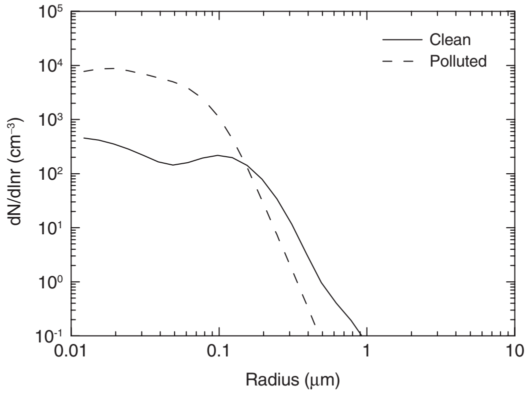

Figure 2. Initial aerosol number density distribution (only the soluble aerosols are shown) for experiment Clean (solid line) and experiment Polluted (dashed line).

4. Results

4.1. Cloud microphysics

The liquid water mixing ratio of experiment Clean and experiment Polluted at 10 h of simulation is shown in Figure 3. When the moist flow impinges on the mountain range, there are no significant differences in cloud spatial distribution between the two cases with different aerosol background conditions. The orographic cloud is mainly formed due to the flow dynamic while aerosols mainly affect the microphysical processes. The liquid water in experiment Polluted can reach up to $0.88\ \mathrm{g\,kg}^{-1}$ that is significantly higher than that in experiment Clean. The results indicate that increasing in aerosol loading leads to a higher number concentration of cloud droplets, and hence a decrease in cloud droplet size and an increase in condensation growth (Yin et al., 2000; Lynn et al., 2007; Muhlbauer and Lohmann, 2008). Precipitation is mainly attributed to the warm cloud process because of low concentration of ice particles. In other situations, when ice particles are present in cloud, cold microphysical processes become active and affect the development of cloud. For example, the seeder-feeder process can enhance precipitation over hills (Passarelli and Boehme, 1983). In this study, the ice particles are too little to affect cloud development and precipitation, but we can concern on the impact of aerosol on precipitation included cold microphysical processes. The maximum mixing ratios of graupel in experiment Clean and experiment Polluted are 0.0018 and

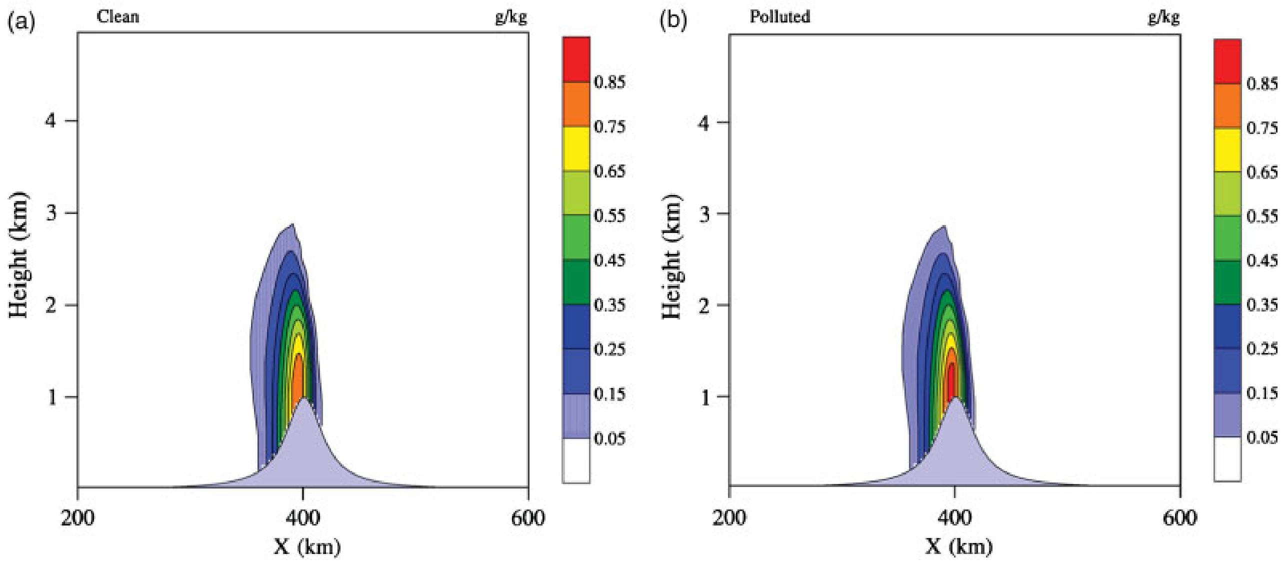

Figure 3. The liquid water mixing ratio of experiment Clean (a) and experiment Polluted (b) at 10 h (Unit: g kg^{-1}).

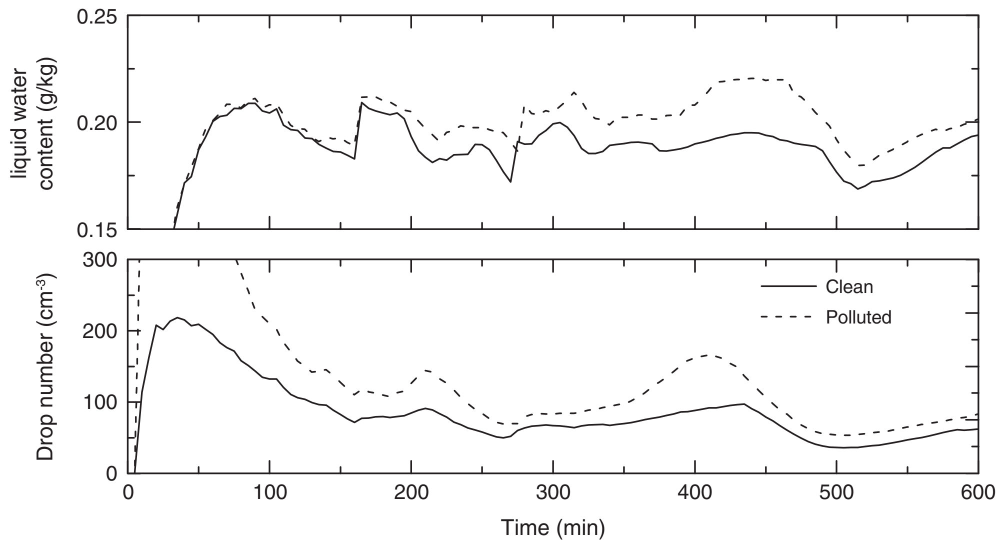

Figure 4. The time series of averaged mixing ratio (upper) and number concentration (lower) of liquid water.

0.0012 g kg^{-1}, respectively, implying that increasing the aerosol loading reduces the size of cloud droplets and mass concentration of graupel particles, the latter is mainly caused by decreasing frozen and riming efficiency in high-aerosol loading condition (Cui *et al.*, 2011). Large concentration of aerosol will result in a large concentration of smaller drops and the suppression of graupel particle through freezing.

Figure 4 illustrates the time series of grid averaged (arithmetic average of all grid point value) mixing ratio and number concentration of liquid water. The liquid water mixing ratio in experiment Polluted is higher than that in experiment Clean. On the contrary, the number concentration of drops increases with increasing aerosol loading. The maximum difference of the grid averaged liquid water mixing ratio between experiment Clean and experiment Polluted is 0.02 g kg^{-1}. And the maximum value of grid averaged number concentrations of drops in experiment Clean and experiment Polluted is 218.3 and 756.2 cm^{-3} at the early stage. It is obvious from this figure that the number concentration and mixing ratio of drops increase with increasing concentration of aerosol.

Figure 5(a) shows the averaged drop spectra over space and time for two experiments. It is found that the drop size distribution of experiment Clean is broader than that of experiment Polluted. The number concentration of experiment Polluted is higher than that of experiment Clean when the drop diameter is less than 19.84 μm, whereas they are completely opposite when the drop diameter is larger than 19.84 μm. The maximum number density of experiment Clean and experiment Polluted is 9.79 and 15.87 cm^{-3} corresponding to peak diameters, respectively. The whole drop size distribution shifts to smaller sizes and the peak diameter is 12.5 μm in experiment Clean whereas it is 9.92 μm in experiment Polluted. In warm-phase cloud, collection and coalescence of drops are the main processes

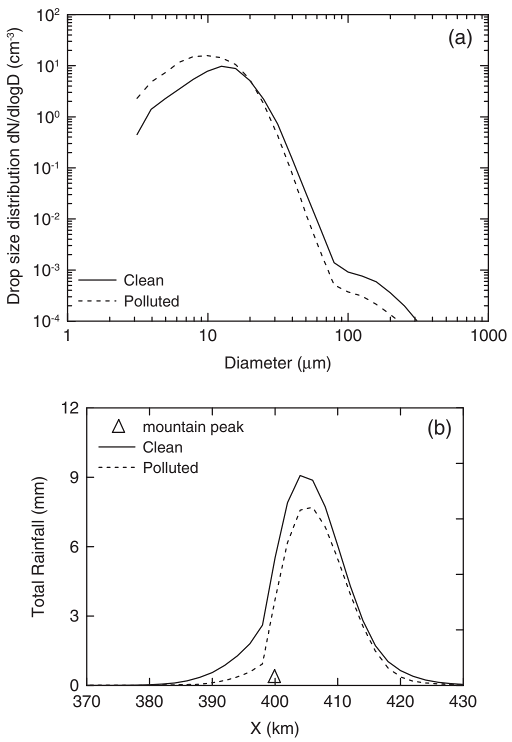

Figure 5. (a) Space-time averaged drop spectra of five experiments. (b) The surface accumulated precipitation distribution after 10 h.

for rain formation. The large drops accelerate the conversion from cloud droplets to rain drops leading to an early development of precipitation.

4.2. Precipitation budgets

Figure 5(b) illustrates the surface accumulated precipitation distribution after 10 h of simulation. The precipitation of experiment Polluted is significantly smaller than that of experiment Clean on the windward side of the mountain and at the mountain crest. The results are consistent with the conclusions of Givati and Rosenfeld (2004) that high concentration of aerosols reduce the size of droplets and then delay the formation of precipitation. The main difference in precipitation distribution between these experiments is on the windward side of the mountain and at the mountain crest.

To investigate the difference of orographic precipitation distributions under different aerosol concentrations, further works are conducted. Table I shows the local budgets of upslope, crest, downslope and the spillover factor under different aerosol background conditions after 10 h. The spillover factor is the fraction of the accumulated precipitation of leeward side to the total accumulated precipitation of the mountain (Jiang, 2003). Compared to the experiment Clean, the experiment Polluted shows a suppression of the upslope precipitation with 87% spillover factor. The precipitation of experiment Polluted tends to move downstream with a higher spillover factor. As increasing aerosol load increases the number concentration of cloud drop leads to the suppression of warm-phase process. The total precipitations of experiment Clean and experiment Polluted are 64.4 and 49.3 mm, respectively. Compared with experiment Clean, the total rainfall amount and upslope precipitation are reduced by about 23.4 and 70.8% in experiment Polluted. More precipitation move to downwind side of the mountain and the spillover factor is increased with the suppression of warm-phase processes of cloud.

5. Summary and conclusions

The effects of the aerosol loading have been investigated by simulating an idealized mixed-phase orographic cloud using Weather Research Forecast (WRF) mesoscale model coupled with a detailed bin microphysics scheme.

Numerical experiments are conducted and compared with different aerosol background conditions to understand the response of cloud microphysical processes and precipitation to changes in concentrations of aerosol particles. The simulations suggest that the total rainfall amount can be reduced up to 23% in the polluted case (experiment Polluted) as compared with the clean case (experiment Clean), but the spillover factor of experiment Polluted is about 0.08 larger than that of experiment Clean. It is shown that aerosol suppresses the development of upslope orographic rain and enhances the advection of rain to the downslope side. Warm-phase processes are the main sources of precipitation in this study. In the experiment Polluted, higher concentration of aerosol particles increases the number concentration of cloud droplets, leading to decrease of drop size and suppression of rain formation. An increase in the aerosol loading shifts the drops size distribution toward smaller diameter. Compared with other simulation studies, this study presents the change of the hydrometeor size distributions. The number concentration of experiment Polluted is more than that of experiment Clean when the cloud droplet diameter is less than 19.84 μm due to the increase of aerosol, whereas they are diametrically opposed when the drop diameter is larger than 19.84 μm. The drop diameter of 19.84 μm is a turning point. When the

Table I. The local budgets of upslope, crest, downslope and the spillover factor under different experiments after 10 h (Unit: mm).

Experiment	Upslope precipitation	Crest precipitation	Downslope precipitation	Total precipitation	Spillover
Clean	7.86	5.52	51.04	64.4	0.79
Polluted	2.29	3.72	43.33	49.3	0.87

drop diameter is less than 19.84 μm, the collision efficiency of spherical water drops decreases significantly (Pruppacher and Klett, 1997). The maximum number density in the experiment Polluted is 62% more than that in experiment Clean. Increasing the aerosol loading leads to a decrease in the peak diameter from 12.5 to 9.92 μm and an increase in the maximum number density. The change in drops spectrum may alter the clouds microphysical properties and the cloud albedo.

In this study, the orographic precipitation is suppressed with increasing aerosol loading without considering other urban effect. But the impact of IN on precipitation from orographic clouds still remains a challenging problem. Future studies will try to investigate the effect of high concentration of aerosol not only serving as CCN, but also acting as IN on the microphysical processes and precipitation in orographic clouds.

Acknowledgements

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