Evaluation of the WDM6 scheme in the simulation of number concentrations and drop size distributions of warm-rain hydrometeors: comparisons with the observations and other schemes

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1. Introduction

Instead of only predicting mixing ratios of cloud hydrometeors in single-moment bulk microphysics schemes (Kessler 1969; Tao, Simpson, and McCumber 1989; Chen and Sun 2002), double-moment schemes (Reisner, Rasmussen, and Bruintjes 1998; Cohard and Pinty 2000; Seifert and Beheng 2001) also predict number concentrations of hydrometeors. The prediction of mixing ratios and number concentrations at the same time in double-moment schemes provides flexibility in the description of drop size distribution (DSD) and the ability to reproduce size-sorting (Milbrandt and Yau 2005a). The number concentrations and DSDs of warm-rain particles play an important role in the simulation of microphysical processes and the macrophysical properties of weather systems. Ferrier, Tao, and Simpson (1995) and Li et al. (2009) claimed that the evaporation rate affected by the rain number concentration (N_r) is decisive in the difference in downdraft and storm structure simulation. Lim and Hong (2010) and Morrison, Thompson, and Tatarkii (2009) also found that the simulation of trailing stratiform precipitation was mainly influenced by N_r and the corresponding evaporation rate in an idealized 2D squall line case. The cloud number concentration (N_c) affects both warm-rain and cold-rain microphysical processes. Typically, an increase in N_r leads to a narrower cloud DSD and smaller mean diameter of cloud droplets. This inhibits the autoconversion and delays the onset of precipitation, and meanwhile, more cloud droplets can be transferred to upper levels to intensify cold-rain processes (Rosenfeld et al. 2008; Fan et al. 2016).

Lim and Hong (2010) developed the WDM6 scheme, which was claimed to outperform its single-moment
counterpart (Hong and Lim 2006) in both idealized and real case simulations (Hong et al. 2010; Lim and Hong 2010). Some double-moment schemes, such as the Thompson scheme (Thompson et al. 2008) and the Morrison scheme (Morrison, Thompson, and Tatarskii 2009), set \( N_c \) as a constant. Different from these schemes, WDM6 predicts the \( N_c \) and has been used to study the effects of aerosol on the simulation of weather systems (Lim and Hong 2010; Lim et al. 2011; Dong, Xu, and Luo 2012). Meanwhile, the WDM5 scheme and the newly released WDM7 scheme in the Weather Forecasting and Research (WRF) model are similar to the WDM6 scheme in the calculation of warm-rain hydrometeors. However, little attention has been devoted to the accuracy of \( N_c \) simulation in these schemes.

In this study, the warm-rain hydrometeor number concentrations and DSDs simulated by the WDM6 scheme are compared with airborne observations of a flight trial, as well as the simulations of the widely tested Thompson and Morrison schemes, to evaluate the performance of the WDM6 scheme. The paper is organized as follows: Section 2 describes the flight trial and model configuration. Comparisons of warm-rain hydrometeor number concentrations and DSDs, along with the results of sensitivity tests of initial cloud condensation nuclei (CCN) number concentration (CCN\(_0\)) of the WDM6 scheme, are presented in section 3. A summary of the present findings and suggestions for future work is given in the final section.

### 2. Description of the flight trial and model configuration

#### 2.1 Flight trial description

A flight trial was conducted on 22 May 2017 in Hebei Province, China, with five periods of observation mainly concentrated in the area of 2–7 km in height and −20°C to 10°C in temperature. Three airborne DSD probes (a cloud droplet probe (CDP), cloud imaging probe (CIP) and high-volume precipitation spectrometer (HVPS)), along with an aircraft-integrated meteorological measurement system (AIMMS-20) recording environmental information such as:

**Table 1. Description of instruments used in the flight trial.**

| Instrument                                      | Range       | Bin width | Bin number | Manufacturer |
|-------------------------------------------------|-------------|-----------|------------|-------------|
| Cloud droplet probe                             | 2–50 \(\mu m\) | 1–2 \(\mu m\) | 30         | DMT, USA    |
| Cloud imaging probe                             | 25–1550 \(\mu m\) | 25 \(\mu m\) | 62         | DMT, USA    |
| High-volume precipitation spectrometer           | 150–8700 \(\mu m\) | 150–750 \(\mu m\) | 37       | SPEC, USA   |
| Aircraft integrated meteorological measurement system | Height, temperature, geolocation etc. |          |            | DMT, USA    |

**Figure 1.** Observed radar composite reflectivity and simulated rain rate: (a, b) composite reflectivity, with the red box marking the location of the observation; (c, d) time series of maximum and standard deviation of observed composite reflectivity, in which the dashed red lines represent the start time and end time of the observation; (e, f) time series of the simulated rain rate, in which the dashed blue lines represent the start time and end time of the model output used for comparison. The first and second rows represent the results of the convective cloud and stratiform cloud, respectively.
geolocation, height, temperature, etc., were used during the flight trial. Details of the instruments are shown in Table 1. The locations of the second and fourth periods of observation are presented in Figure 1(a and b), marked by the red boxes along with the radar composite reflectivity. The second period of observation was regarded as the observation of a convective cloud (CC), since the radar composite reflectivity was over 30 dBZ in most parts, with the maximum exceeding 35 dBZ, which could be taken as the threshold of a convective echo. The fourth period of observation, with a uniform reflectivity of 20 dBZ, was regarded as the observation of a stratiform cloud (SC).

Table 2. Model configuration.

|          | D01                  | D02                  | D03                  |
|----------|----------------------|----------------------|----------------------|
| Grids    | 106 × 106, 9 km      | 151 × 151, 3 km      | 190 × 250, 1 km      |
| Center   | 38.0°N, 114.0°E      | 37.72°N, 113.48°E    | 37.08°N, 113.69°E    |
| Model top| 50 hPa               | 50 hPa               | 50 hPa               |
| Vertical layers | 40 layers        | 40 layers            | 40 layers            |
| Cumulus  | Kain-Fritsch         | None                 | None                 |
| Radiation| RRTM longwave, Dudhia shortwave | None               | None                 |
| PBL      | Yonsei University Scheme | None               | None                 |
| Surface layer | Revised MM5 Scheme | Revised MM5 Scheme   | Revised MM5 Scheme   |
| Land surface | Noah–MP Land Surface Model | Noah–MP Land Surface Model | Noah–MP Land Surface Model |
| Microphysics | WDM6, Thompson, Morrison | WDM6, Thompson, Morrison | WDM6, Thompson, Morrison |

Figure 2. Contours of cloud DSD. The first and second rows represent the results of the convective cloud (CC) and stratiform cloud (SC), respectively. Columns 1–4 represent the results based on observation (cloud droplet probe), the WDM6 simulation, the Thompson simulation, and the Morrison simulation, respectively.
2.2 Model configuration

The model used in this study was the WRF model, version 3.6, the model configuration of which is presented in Table 2. The microphysics schemes used in this study included the WDM6 scheme, the Thompson scheme and the Morrison scheme. Detailed description of these schemes can be found in Lim and Hong (2010), Thompson et al. (2008), and Morrison, Thompson, and Tatarskii (2009), respectively. The activation of CCN in the WDM6 scheme follows Twomey (1959):

\[ n_a = C S^k \]  

(1)

Here, \( n_a \) is activated CCN (\( N_{CCN} \)) and \( S \) is supersaturation; \( C \) is the total CCN; \( k \) is a parameter that can be devised from observations and is set to 0.6 in this case (Khairoutdinov and Kogan 2000). The CCN\(_0\) of the WDM6 scheme was set to \( 10^3 \) cm\(^{-3} \) at a supersaturation of 0.48% (\( S_{max} \)), and thus Equation (1) could be written as

\[ n_a = CCN_0 \left( \frac{S}{S_{max}} \right)^k \]  

(2)

at the beginning of the simulation. The \( N_c \) was set to 300 cm\(^{-3} \) in both the Thompson scheme and the Morrison scheme, as recommended for continental systems. The time series of simulated rain rate was compared with that of the reflectivity and model output of 48 min before the convective observation was used for the comparison, since the reflectivity indicated that the CC was in the developing stage.

3. Results and discussion

3.1 Comparisons with observations and other schemes

The observed and simulated cloud DSDs are presented in Figure 2. The plane’s movement during the observation period would have mainly been a spiral pattern while ascending or descending. As a result, the plane could have been outside of the clouds some of the time, leading to discontinuity in the observations, as shown in Figure 2(a and b). Generally, an aerosol-aware scheme should be more sophisticated and do a better job than microphysics schemes with a constant droplet number concentration. However, the results of the WDM6 scheme are distinct from the observations and the other two schemes, especially in the SC. The cloud DSDs of the WDM6 scheme are wider than observed. Most cloud droplets have a

![Figure 3](image-url)  

*Figure 3.* Observed and simulated cloud DSDs and number concentrations: (a, b) cloud DSD of the convective cloud (CC) and stratiform cloud (SC) at 3°C, respectively; (c, d) cloud DSD of the CC and SC at 7°C, respectively; (e, f) cloud number concentration (Nc) of the CC and SC, respectively.
diameter of 10–30 μm in the WDM6 scheme simulation, while most are concentrated within 5–20 μm in the observation. The cloud DSDs of the WDM6 scheme noticeably broaden above 7°C, which is not observed or simulated by the other two schemes in the SC. The relatively poor performance of the WDM6 scheme might be because of the use of the somewhat simplistic Twomey’s CCN activation formula, in which the activated \( N_{CCN} \) is only determined by the supersaturation. In fact, the supersaturation in contact with CCN, which relies on the vertical velocity, temperature, pressure, etc., is usually not well predicted at grid scale in 3D mesoscale models (Cohard and Pinty 2000). Clearer illustrations are shown in Figure 3(a–d). Generally, the Thompson scheme and the Morrison scheme are consistent with each other in both the CC and SC, though the cloud DSDs of the Morrison scheme are slightly narrower. The Thompson (Morrison) scheme compares well with the observation in the CC and is larger in magnitude at upper levels and narrower at lower levels, as shown in Figure 3(b and d), in the SC. Note that this study is mainly focused on the warm parts of clouds, since the DSD probes used on the flight could not distinguish between liquid particles and ice particles.

The \( N_r \) results shown in Figure 3(e and f) provide a similar conclusion as from the cloud DSD results. The WDM6 scheme underestimates \( N_r \), especially in the SC. The extremely low \( N_r \) of the WDM6 scheme in the SC above 7°C corresponds to the extremely wide cloud DSD. The constant \( N_r \) set in the Thompson scheme and the Morrison scheme is reasonable in the CC and approximately five times larger in the SC compared to the observations.

The observed and simulated \( N_r \) and rain DSDs at 7°C are presented in Figure 4. The 7°C level was chosen since the rain DSD observation near the melting layer may be affected by unmelting ice particles, thus becoming less accurate. The WDM6 scheme overestimates, while the other two schemes underestimate, the \( N_r \) compared to the observations. The observations of rain DSDs are composed of the CIP observations of 100–750 μm and the HVPS observations of 750–3000 μm, considering their best measuring ranges. The \( N_r \) of the Thompson (Morrison) scheme is smaller in the SC than the CC, which is consistent with many observations and model simulations (Ferrier, Tao, and Simpson 1995; Tokay and

*Figure 4. Observed and simulated rain number concentration (\( N_r \)) and rain DSD, together with the average autoconversion rate: (a, b) \( N_r \) of the convective cloud (CC) and stratiform cloud (SC), respectively; (c, d) rain DSD at 7°C of the CC and SC, respectively; (e) autoconversion rate of \( N_r \) averaged during the total simulation period in domain 3.*
Short 1996; Gong, Liu, and Li 1997; Morrison, Thompson, and Tatarskii 2009), though the difference between different clouds for this flight trial is small. The Thompson scheme and Morrison scheme underestimate the quantity of small raindrops in both the SC and CC compared to the WDM6 scheme, possibly because of the underestimation of autoconversion processes (shown in Figure 4(e)) owing to the overestimation of $N_c$. On the contrary, the WDM6 scheme produces notably fewer large raindrops in the SC.

### 3.2 Sensitivity tests of the initial CCN$_0$ of the WDM6 scheme

As mentioned by several researchers (Khain, Rosenfeld, and Pokrovsky 2005; Cheng, Wang, and Chen 2010; Fan

![Figure 5. Average cloud number concentration ($N_c$) and rain number concentration ($N_r$) under a differing initial CCN number concentration (CCN$_0$) in different areas. The first and second rows represent $N_c$ and $N_r$, respectively. Columns 1–3 show the average for the convective cloud (CC), stratiform cloud (SC), and domain 3, respectively.](image-url)
et al. 2012), an increase in the \(N_{\text{CCN}}\) will lead to a larger \(N_c\) and a narrower cloud DSD. The \(N_{\text{CCN}}\) observed in North China lies mostly between \(10^3\) and \(10^4\ \text{cm}^{-3}\), with a maximum value exceeding \(4 \times 10^4\ \text{cm}^{-3}\) at a supersaturation of 0.4%–0.6% (Shi and Duan 2007; Wang et al. 2013). Here, four experiments with different \(N_{\text{CCN}}\) values of \(10^3\), \(5 \times 10^3\), \(10^4\), and \(10^5\ \text{cm}^{-3}\) were conducted to examine if the smaller \(N_c\) and narrower cloud DSD produced by the WDM6 scheme is caused by an inappropriate selection of \(N_{\text{CCN}}\).

The average profiles of simulated \(N_c\) and \(N_r\) in the CC, SC, and whole of domain 3 (D03), using the WDM6 scheme with different \(N_{\text{CCN}}\), are shown in Figure 5. The results show that an increase in \(N_{\text{CCN}}\) leads to an increase in the domain-average \(N_c\), while the responses of the \(N_c\) vary with cloud type. At SC upper levels, \(N_c\) is still substantially underestimated, even if the \(N_{\text{CCN}}\) is increased 100-fold, which could also be limited by the prediction of supersaturation. As a result, an increase in the \(N_{\text{CCN}}\) is unable to improve the cloud DSD in the SC. In the CC, both the \(N_c\) and cloud DSDs agree better with the observations when the \(N_{\text{CCN}}\) is set to \(10^4\ \text{cm}^{-3}\), as shown in Figure 6 and, although this value is within the range of \(N_{\text{CCN}}\) observation, more case studies are needed for a more comprehensive evaluation of the best \(N_{\text{CCN}}\) to select. \(N_r\) varies little when the \(N_{\text{CCN}}\) is increased from \(10^3\) to \(10^5\ \text{cm}^{-3}\), which is consistent with the findings of Lim and Hong (2010).

4. Summary and future work

In this study, the performance of the WDM6 scheme in the simulation of warm-rain hydrometeor \(N_c\) and DSD is compared with airborne observations from a flight trial and other two double-moment bulk schemes. The results show that the WDM6 scheme underestimates (overestimates) the cloud (rain) number concentration. The \(N_c\) is predicted in the WDM6 scheme, while it is set as a constant in the Thompson scheme and Morrison scheme. The WDM6 scheme performs worse than the Thompson scheme and Morrison scheme in aspects of \(N_c\) and DSD compared to the airborne observations. Sensitivity tests of the initial \(N_{\text{CCN}}\) in the WDM6 scheme indicate that changing the initial \(N_{\text{CCN}}\) provides a possible way to improve the simulation of \(N_c\) and DSD in CC, whereas it does not help much in SC simulation.

Unfortunately, the observations of this flight trial, covering only a small part of the clouds in both time and space, were discontinuous in height. As a result, our comparisons were restricted to certain specific levels. In future work, more observations from other sources, such as conventional surface observations,

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**Figure 6.** Cloud and rain DSDs of different cloud types and levels: (a, b) cloud DSDs of the convective cloud (CC) and stratiform cloud (SC) at 3°C, respectively; (c, d) cloud DSDs of the CC and SC at 7°C, respectively; (e, f) rain DSDs of the CC and SC at 7°C, respectively.
surface distometers, and dual-polarization radar, should be used to obtain a more comprehensive conclusion. The \( N_a \) simulated by the WDM6 scheme is expected to be more accurate because it is predicted explicitly, but the present results indicate that more efforts are needed to improve its performance. In future work, other aerosol-aware microphysics schemes (i.e. Milbrandt and Yau 2005b; Thompson and Eidhammer 2014) using different CCN activation formula will also be evaluated.

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References

Chen, S.-H., and W.-Y. Sun. 2002. “A One-dimensional Time Dependent Cloud Model.” Journal of the Meteorological Society of Japan. Ser. II. 80 (1): 99–118. doi:10.2151/jmsj.80.99.

Cheng, C.-T., W.-C. Wang, and J.-P. Chen. 2010. “Simulation of the Effects of Increasing Cloud Condensation Nuclei on Mixed-phase Clouds and Precipitation of a Front System.” Atmospheric Research 96 (2): 461–476. doi:10.1016/j.atmosres.2010.02.005.

Cohard, J.-M., and J.-P. Pinty. 2000. “A Comprehensive Two-moment Warm Microphysical Bulk Scheme. I: Description and Tests.” Quarterly Journal of the Royal Meteorological Society 126 (566): 1815–1842. doi:10.1002/qj.49712656613.

Dong, H., H. Xu, and Y. Luo. 2012. “Effects of Cloud Condensation Nuclei Concentration on Precipitation in Convection Permitting Simulations of a Squall Line Using WRF Model: Sensitivity to Cloud Microphysical Schemes.” Chinese Journal of Atmospheric Sciences (in Chinese) 36 (1): 145–169. doi:10.3878/j.issn.1006-9895.2012.01.12.

Fan, J., L. R. Leung, Z. Li, H. Morrison, H. Chen, Y. Zhou, Y. Qian, and Y. Wang. 2012. “Aerosol Impacts on Clouds and Precipitation in Eastern China: Results from Bin and Bulk Microphysics.” Journal of Geophysical Research: Atmospheres 117: D16. doi:10.1029/2011JD016537.

Fan, J., Y. Wang, D. Rosenfeld, and X. Liu. 2016. “Review of Aerosol–Cloud Interactions: Mechanisms, Significance, and Challenges.” Journal of the Atmospheric Sciences 73 (11): 4221–4252. doi:10.1175/JAS-D-16-0037.1.

Ferrier, B. S., W.-K. Tao, and J. Simpson. 1995. “A Double-moment Multiple-phase Four-class Bulk Ice Scheme. Part II: Simulations of Convective Storms in Different Large-scale Environments and Comparisons with Other Bulk Parameterizations.” Journal of the Atmospheric Sciences 52 (8): 1001–1033. doi:10.1175/1520-0469(1995)052<1001:ADMMPF>2.0.CO;2.

Gong, F., J. Liu, and Z. Li. 1997. “Study of the Raindrop Size Distributions for Three Types of Precipitation.” Chinese Journal of Atmospheric Sciences (in Chinese) 21 (5): 607–614. doi:10.3878/j.issn.1006-9895.1997.05.12.

Hong, S.-Y., and J.-O. J. Lim. 2006. “The WRF Single-moment 6-class Microphysics Scheme (WSM6).” Journal of the Korean Meteorological Society 42 (2): 129–151.

Hong, S.-Y., K.-S.-S. Lim, Y.-H. Lee, J.-C. Ha, H.-W. Kim, S.-J. Ham, and J. Dudhia. 2010. “Evaluation of the WRF Double-Moment 6-class Microphysics Scheme for Precipitating Convection.” Advances in Meteorology 2010: 10. doi:10.1155/2010/707253.

Kessler, E. 1969. On the Distribution and Continuity of Water Substance in Atmospheric Circulations, 1–84. Springer. doi:10.1007/978-1-935704-36-2_1.

Khain, A., D. Rosenfeld, and A. Pokrovsky. 2005. “Aerosol Impact on the Dynamics and Microphysics of Deep Convective Clouds.” Quarterly Journal of the Royal Meteorological Society 131 (611): 2639–2663. doi:10.1256/qj.04.62.

Khairoutdinov, M., and Y. Kogan. 2000. “A New Cloud Physics Parameterization in A Large-Eddy Simulation Model of Marine Stratocumulus.” Monthly Weather Review 128 (1): 229–243. doi:10.1175/1520-0493(2000)128<0229:ANCPI>2.0.CO;2.

Li, X., W.-K. Tao, A. P. Khain, and D. E. Johnson. 2009. “Sensitivity of a Cloud-resolving Model to Bulk and Explicit Bin Microphysical Schemes. Part II: Cloud Microphysics and Storm Dynamics Interactions.” Journal of the Atmospheric Sciences 66 (1): 22–40. doi:10.1175/2008JAS2647.1.

Lim, K.-S.-S., and S.-Y. Hong. 2010. “Development of an Effective Double-Moment Cloud Microphysics Scheme with Prognostic Cloud Condensation Nuclei (CCN) for Weather and Climate Models.” Monthly Weather Review 138 (5): 1587–1612. doi:10.1175/2009MWR2968.1.

Lim, K. S. S., S. Y. Hong, S. S. Yum, J. Dudhia, and J. B. Klemp. 2011. “Aerosol Effects on the Development of a Supercell Storm in a Double-moment Bulk-cloud Microphysics Scheme.” Journal of Geophysical Research: Atmospheres 116: D2. doi:10.1029/2010JD014128.

Milbrandt, J. A., and M. K. Yau. 2005a. “A Multimoment Bulk Microphysics Parameterization. Part I: Analysis of the Role of the Spectral Shape Parameter.” Journal of the Atmospheric Sciences 62 (9): 3051–3064. doi:10.1175/JAS3534.1.

Milbrandt, J. A., and M. K. Yau. 2005b. “A Multimoment Bulk Microphysics Parameterization. Part II: A Proposed Three-Moment Closure and Scheme Description.” Journal of the Atmospheric Sciences 62 (9): 3065–3081. doi:10.1175/JAS3535.1.

Morrison, H., G. Thompson, and V. Tatarskii. 2009. “Impact of Cloud Microphysics on the Development of Trailing Stratiform Precipitation in a Simulated Squall Line: Comparison of One-
and Two-Moment Schemes." Monthly Weather Review 137 (3): 991–1007. doi:10.1175/2008MWR2556.1.
Reisner, J., R. M. Rasmussen, and R. T. Bruintjes. 1998. "Explicit Forecasting of Supercooled Liquid Water in Winter Storms Using the MM5 Mesoscale Model." Quarterly Journal of the Royal Meteorological Society 124 (548): 1071–1107. doi:10.1002/qj.49712454804.
Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. Dowd, M. Kulmala, S. Fuzzi, A. Reissell, and M. O. Andreae. 2008. “Flood or Drought: How Do Aerosols Affect Precipitation?” Science 321 (5894): 1309. doi:10.1126/science.1160606.
Seifert, A., and K. D. Beheng. 2001. “A Double-moment Parameterization for Simulating Autoconversion, Accretion and Selfcollection.” Atmospheric Research 59-60: 265–281. doi:10.1016/S0169-8095(01)00126-0.
Shi, L., and Y. Duan. 2007. “Observations of Cloud Condensation Nuclei in North China.” Acta Meteorologica Sinica (in Chinese) 65 (4): 644–652. doi:10.11676/qxxb2007.059.
Tao, W.-K., J. Simpson, and M. McCumber. 1989. “An Ice-water Saturation Adjustment.” Monthly Weather Review 117 (1): 231–235. doi:10.1175/1520-0493(1989)117<0231:AIWSA>2.0.CO;2.
Thompson, G., and T. Eidhammer. 2014. “A Study of Aerosol Impacts on Clouds and Precipitation Development in A Large Winter Cyclone.” Journal of the Atmospheric Sciences 71 (10): 3636–3658. doi:10.1175/JAS-D-13-0305.1.
Thompson, G., P. R. Field, R. M. Rasmussen, and W. D. Hall. 2008. “Explicit Forecasts of Winter Precipitation Using an Improved Bulk Microphysics Scheme. Part II: Implementation of a New Snow Parameterization.” Monthly Weather Review 136 (12): 5095–5115. doi:10.1175/2008MWR2387.1.
Tokay, A., and D. A. Short. 1996. “Evidence from Tropical Raindrop Spectra of the Origin of Rain from Stratiform versus Convective Clouds.” Journal of Applied Meteorology 35 (3): 355–371. doi:10.1175/1520-0450(1996)035<0355:EFTRSO>2.0.CO;2.
Twomey, S. 1959. “The Nuclei of Natural Cloud Formation Part II: The Supersaturation in Natural Clouds and the Variation of Cloud Droplet Concentration.” Geofisica Pura E Applicata 43 (1): 243–249. doi:10.1007/BF01993560.
Wang, Z. B., M. Hu, J. Y. Sun, Z. J. Wu, D. L. Yue, X. J. Shen, and Y. M. Zhang. 2013. “Atmospheric Chemistry and Physics Characteristics of Regional New Particle Formation in Urban and Regional Background Environments in the North China Plain.” Atmospheric Chemistry and Physics 13 (24): 12495–12506. doi:10.5194/acp-13-12495-2013.