**Response to comments by referee 1**

We would like to thank you for your comments and helpful suggestions. We revised our manuscript according to these comments and suggestions.

**Specific comments:**

This paper characterizes mixing layer height (MLH) over the major cities in the North China Plain based on the two-year surface observations. The relationship between MLH and regional air pollution is explored using concurrent PM, MLH, surface radiation, and meteorological parameters in the same cities. Overall, the paper is well written and the finding about the low MLH in southern Hebei is valuable to develop an efficient air pollution mitigation strategy in North China. I suggest the paper should be accepted by ACP after the authors address my comments below.

**Comment 1:**

It is not clear what is the difference between the MLH discussed here and the traditional defined planetary boundary layer height (PBLH). It would be interesting to see if the MLH obtained from surface can be inter-compared with PBLH from soundings like Guo J. et al. (2016).

**Response 1:**

Thank you for your helpful suggestion. Actually, we have already made comparisons between the MLH obtained from ceilometers and sounding data in Tang et al. (2016). The comparison results found that the ceilometers underestimate the MLH under conditions of neutral stratification caused by strong winds, whereas it overestimates MLH when sand-dust is crossing. When we excluded these two special weather conditions, the ceilometers observation results were fairly consistent with those retrieved from the sounding data. Besides, since the ceilometers can reflect the rainy conditions and the precipitation will influence the MLH retrieval, data for precipitation were also excluded. In our study, data rectifications were made at the BJ, SJZ, TJ and QHD stations. The criterion to exclude the data points with (a) precipitation, i.e. cloud base lower than 4000 m and the attenuated backscattering coefficient of at least $2\times10^{-6}$ $m^{-1}sr^{-1}$ within 0 m and the cloud base, (b) sandstorm, i.e. the ratio of $PM_{2.5}$ to $PM_{10}$ suddenly decreased to 30 % or lower and the $PM_{10}$ concentration was higher than 500 μg $m^{-3}$, and (c) strong winds, i.e. a sudden change in temperature and wind speed when cold fronts passed by (Muñoz and Undurraga, 2010; Tang et al., 2016; van der Kamp and McKendry, 2010). Relevant contents were modified in section 2.2 in the revised manuscript.

**Comment 2:**

L266, the authors attribute the lower summertime MLH in QHD to the higher frequency of sea breeze. However, the underlying physical mechanism is not fully explained. Intuitively, the active sea breezes should come with more unstable atmosphere over the land. Figure 5 about prevailing wind directions in different seasons is referred, but it is still unclear to me how this figure supports the hypothesis above. Some detailed discussions are needed to better describe the formation and characteristics of the sea breeze in the coastal regions.

**Response 2:**

Thank you for your helpful suggestion. We are sorry for the unclear illustration about the impact of sea breezes. Here, we remade the monthly diurnal wind vectors and shown below in Fig.1. We can see that the sea breeze usually started at midday (approximately 11:00 LT) and prevailed during daytime at the QHD station in spring and summer (Fig. 1d). The sea breeze usually brings cold and stable air mass from the sea to the coastal region. Under the influence of the abrupt change of aerodynamic roughness and temperature between the land and sea surfaces, a thermal internal boundary layer (TIBL) will form in the coastal areas. Then the local mixing layer will be replaced by the TIBL. Under the influence of warm air on the land, the sea air advects downwind and warms, leading to a weak temperature difference between the air and the ground. In consequence, the TIBL warms less rapidly due to the decreased heat flux at the ground, and the rise rate reduced. Besides, since the TIBL deepens with distance downwind and usually can not extend all the way to the top of the intruding marine air, the remaining of the cool marine air above the TIBL will hinder the TIBL vertical development (Stull, 1988; Sicard et al., 2006). As a result, the MLH at the QHD station was lower than other stations from April to September. Since this south-southwesterly wind impacts enhanced in summer due to the weak synoptic systems, frequent occurrence of the TIBL resulted in the lowest MLH at the QHD station in summer. To better illustrate the sea breezes impacts, we also made relevant modifications in section 3.2.2 in the revised manuscript.

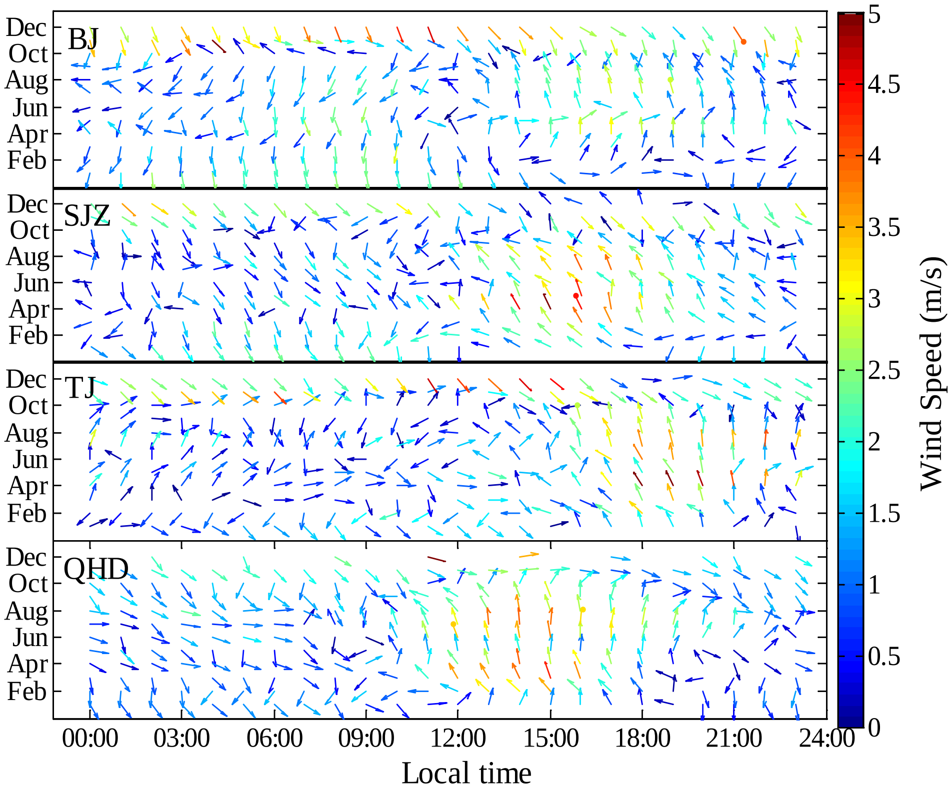


Fig. 1 Monthly variations of diurnal wind vectors at the BJ, SJZ, TJ and QHD stations from December 2013 to November 2014.

**Comment 3:**

L372, to overcome the lack of radio sounding in SJZ, how about directly using the reanalysis data? The quality of reanalysis can be evaluated by radio-sound at XT.

**Response 3:**

Thank you for your suggestion. We have made comparisons between reanalysis data and observation data at the Xingtai (XT) and Laoting (LT) stations, respectively. The reanalysis data were downloaded from the ECMWF website (http://apps.ecmwf.int/datasets/data/interim-full-mnth/levtype=pl/). As shown in Fig.2, there were large discrepancies between the two data sets. Meanwhile, the vertical resolution of reanalysis data was too low to calculate the wind shear profile. Therefore, the reanalysis data could not be used to describe the meteorological parameters variations in this study. Considering the absence of vertical meteorological observations in other stations, comparisons of wind speed between the XT and Shijiazhuang (SJZ) stations, as well as LT and Qinhuangdao (QHD) stations were also made with the reanalysis data (Fig. 3). Wind speed between the XT and SJZ stations, LT and QHD stations were highly correlated, respectively, which indicated that the wind speed in SJZ and QHD could be replaced by data in the XT and LT stations, respectively.

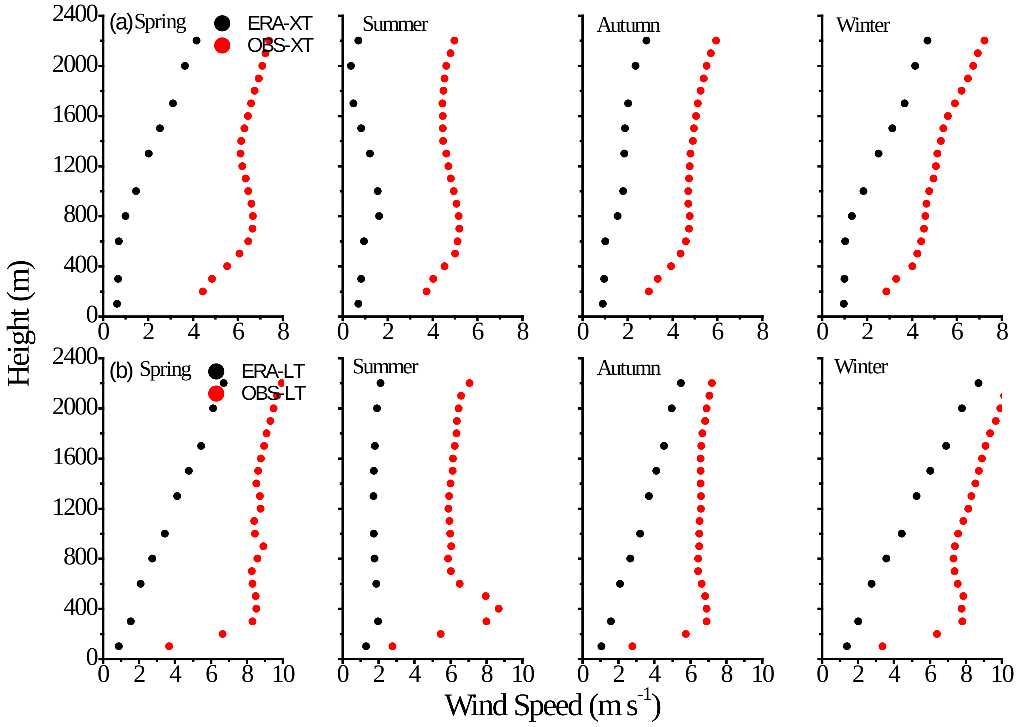


Fig. 2 Comparisons of seasonal wind speed profiles between the reanalysis and observation data at (a) the XT stations and (b) the LT stations.

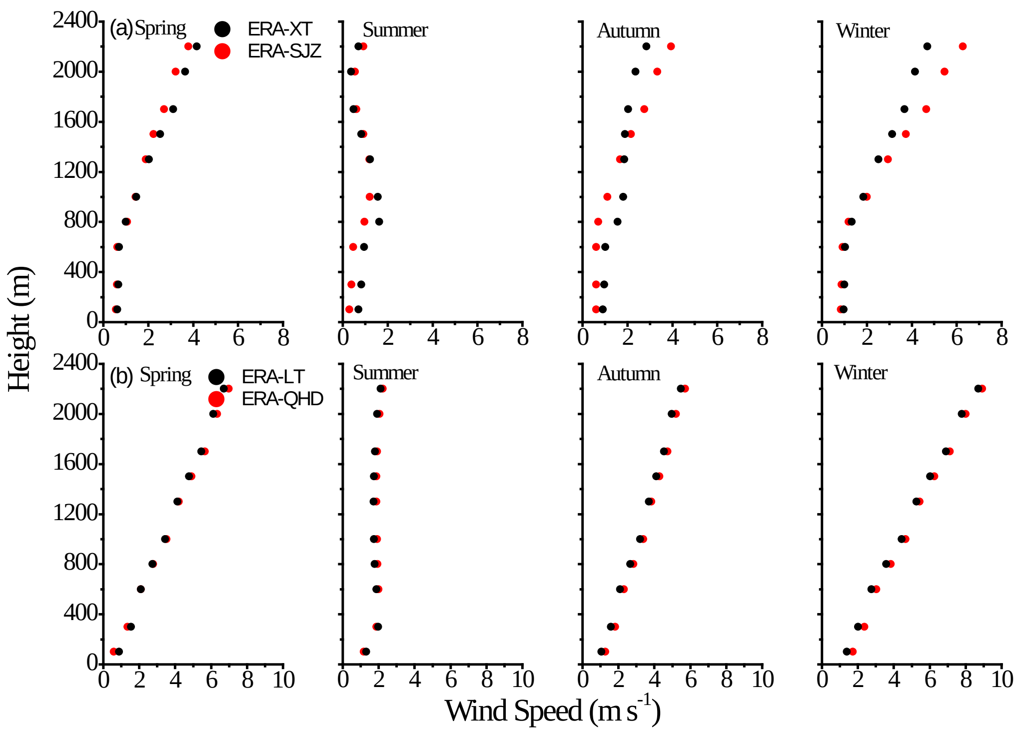


Fig. 3 Comparisons of seasonal wind speed profiles between the (a) XT and SJZ stations and the (b) LT and QHD stations with reanalysis data.

**Comment 4:**

Section 4.1, could absorbing aerosols be another factor to explain the reason of the low MLH in southern Hebei? Observations have revealed that the ambient aerosols can become highly absorptive in the urban conditions in China [Peng J. et al., 2016, PNAS]. The strong solar absorption near the top of PBL can increase the atmospheric stability and convective inhibition energy [Wang Y. et al., 2013, AE; Li Z. et al., 2016, Rev. Geos.]. Those possible influences from the feedback of air pollution should be discussed and quantified if possible.

**Response 4:**

Thank you for your constructive suggestion very much. We have read your mentioned papers and some other relevant researches. Absorbing aerosols above the MLH can be another factor affecting the MLH, it give rise to an increasing temperature aloft but a decreasing temperature at the surface, which will enhance the strength of capping inversion and inhibit the convective ability (Peng et al., 2016; Wang et al., 2013b; Li et al., 2016). On the contrary, absorbing aerosols within the mixing layer could reduce the capping inversion intensity despite the reduction in the surface buoyancy flux and raise the MLH (Yu et al., 2002). Considering the higher concentrations of surface $PM_{2.5}$ in southern Hebei, absorbing aerosols could be likely to have some impacts on MLH development. However, the comprehensive influences from the feedback of absorbing aerosols above and below the MLH are hard to explain without sufficient knowledge of vertical variations in absorbing aerosols. Although the near-ground absorbing aerosol concentration (such as black carbon) has regional differences (Zhao et al., 2013), the absorbing aerosol column concentrations could be consistent (Gong et al., 2017) with little difference in absorptive aerosol optical depths (AAOD). Besides, the mixed state and morphology of absorbing aerosols also dominate the absorption effects (Jacobson, 2001; Bond et al., 2013). Therefore, without sufficient observation data, it is hardly to discuss and quantify the possible influences from the feedback of air pollution on MLH development at present. Some elaborate experiments of vertical profiles and morphology need to be implemented in future studies. To compensate for this deficiency and let readers know the uncertainties, the relevant contents were modified in section 4.1 in the revised manuscript.

**Comment 5:**

L437, what makes the RH at SJZ is higher than that in BJ and TJ? SJZ is more inland than those two cities.

**Response 5:**

Thank you for your suggestion. As shown in Fig. 4, seasonal distributions of near-ground RH from December 2013 to November 2014 in the NCP were depicted below. It was obvious that the southern Hebei had higher RH than that in the northern NCP. The RH distribution was not only related to the distance from the sea, but also to the flow fields and synoptic systems. This might be resulted from the frequent passage of Siberian high in the northern NCP, especially in spring and winter. In spring, when frequent sand storm happens, it brings dry air mass to the northern NCP, thus the RH in northern NCP was far less than that in southern Hebei (Fig. 4a). Meanwhile, under the impact of Siberian High, frequent weak northwest flow from the Inner Mongolia will bring cold and dry air to the northern NCP in winter and autumn, and such north flow was too weak to reach southern Hebei (Su et al., 2004), which will lead to lower RH in the northern NCP (Fig. 4c and 4d). Besides, the higher RH in the southern Hebei could also be affected by the subtropical high (wet southeast flow) from the yellow sea.

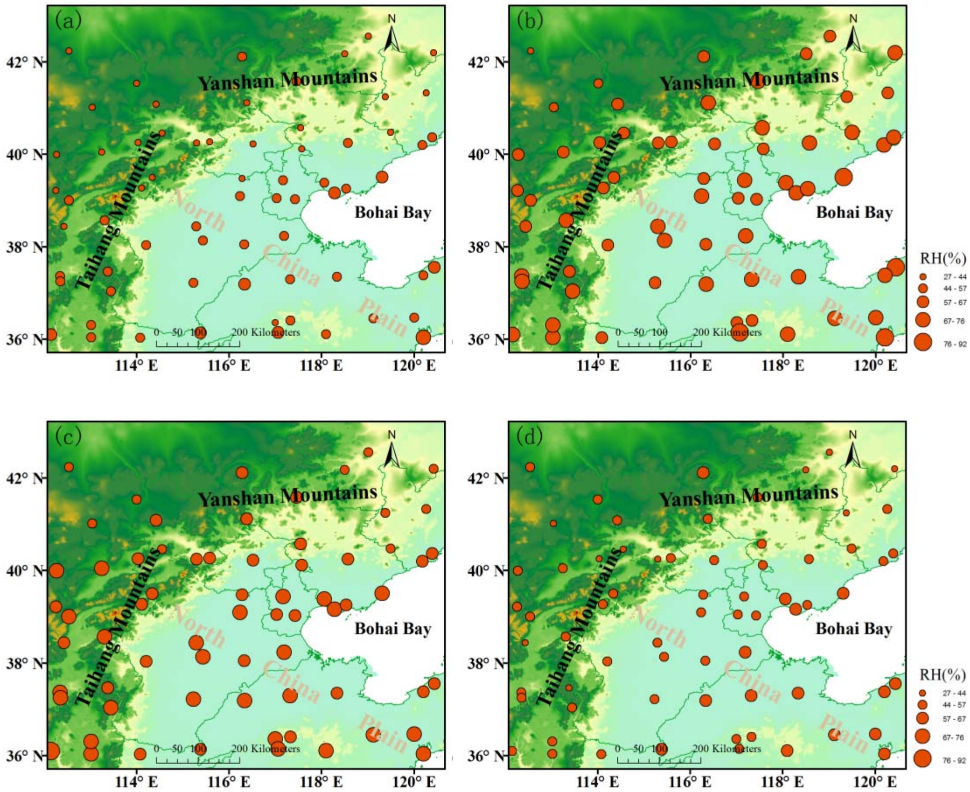


Fig. 4 Distributions of seasonal averaged RH in the NCP from December 2013 to November 2014: (a) spring, (b) summer, (c) autumn and (d) winter.

**Comment 6:**

L432-445, some basics of new particle formation in urban condition should be thoroughly reviewed. Please refer to Zhang, R. 2010, Science and 2015, Rev. Chem.

**Response 6:**

Thank you for your helpful suggestion. We are sorry for our superficial cognition about the new particle formation and growth processes. We remade some figures to illustrate the annual means of RH and T distributions over north China (Fig. 5). The T value in the southern Hebei was similar to that in the northern NCP (Fig. 5a), which indicated an almost consistent temperature condition for atmospheric chemical reaction between these two areas (Seinfeld., 1998; Zhang et al., 2010; Zhang et al., 2015). However, differences existed in RH between southern Hebei and the northern NCP. The RH in the southern Hebei was always higher than that in the northern NCP (Fig. 5b). As our response to your comment 5, the Siberian and the subtropical high will be responsible for such RH distribution in the NCP region. Since the RH is a key factor for haze development, higher RH is beneficial to fine particles growth through hygroscopic growth process and heterogeneous reactions. Relevant contents were modified in section 4.2.1 in the revised manuscript.

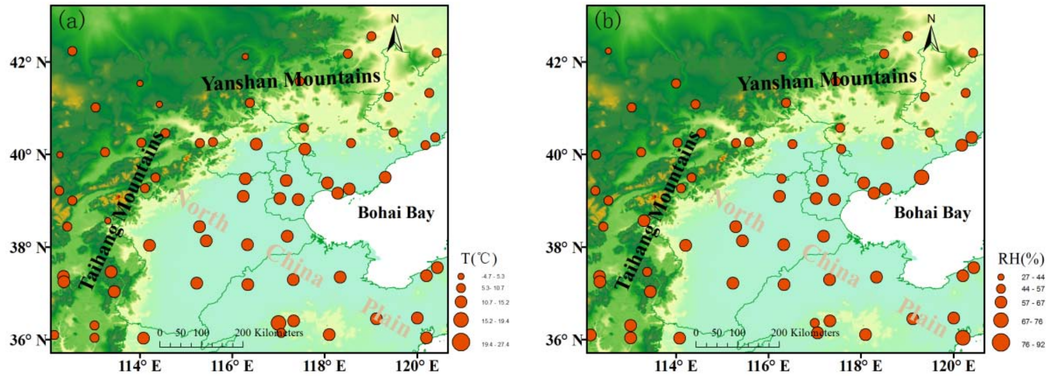


Fig. 5 Distributions of annual means of (a) T and (b) RH over the NCP region from December 2013 to November 2014.

**Comment 7:**

Fig. 8. Define $V_c$ in the figure caption.

**Response 7:**

Thank you for your suggestion. We have already added the definition for $V_c$ in the figure caption of Fig. 9 in the revised manuscript.

**References:**

Bond, T., et al.: Bounding the role of black carbon in the climate system: a scientific assessment, J. Geophys. Res., 118, 1-173, doi:10.1002/jgrd.50171, 2013.

Gong, C., J. X., S. Wang, Y. Wang, T. Zhang: Anthropogenic aerosol optical and radiative properties in the typical urban/suburban regions in China, Atmos. Res., doi:10.1016/j.atmosres.2017.07.002, 2017.

Jacobson, M.: Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols, Nature, 409,695-697, 2001.

Li, Z., et al.: Aeosol and monsoon climate interactions over Asia, Rev. Geophys., 54, 886-929, doi:10.1002/2015RG000500, 2016.

Muñoz, R. and A. Undurraga: Daytime Mixing layer over the Santiago Basin: Description of Two Years of Observations with a Lidar Ceilometer, J. Appl. Meteorol. Clim., 49(8), 1728-1741, doi:10.1175/2010jamc2347.1, 2010.

Peng, J., M. Hu, S. Guo, Z. Du, J. Zheng, D. Shang, M. L. Zamora, L. Zeng, M. Shao, Y. Wu, J. Zheng, Y. Wang, C. R. Glen, D. R. Collins, M. J. Molina, and R. Zhang: Markedly enhanced absorption and direct radiative forcing of black carbon under polluted urban environments, P. Natl. Acad. Sci. Usa., 113(4266-4271), doi:10.1073/pnas.1602310113, 2016.

Sicard, M., Pérez, C., Rocadenbosch, F., Baldasano, J.M. and García-Vizcaino, D.: 2006. Mixed-Layer Depth Determination in the Barcelona Coastal Area From Regular Lidar Measurements: Methods, Results and Limitations. Boundary-Layer Meteorology 119, 135-157.

Stull, R.B.: An Introduction to Boundary Layer Meteorology, Kluwer Academic

Publishers, Dordrecht, 1988.
Su F. Q., M. Z. Yang, J. H. Zhong and Z. G. Zhang: The effects of synoptic type on regional atmospheric contamination in North Chian, Res. Of Environ. Sci., 17(3), doi:10.13198/j.res.2004.03.18.sufq.006, 2004.
Seinfeld J. H. and S.N. Pandis: Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, New York: John Wiley and Sons, 1998.
Tang, G., J. Zhang, X. Zhu, T. Song, C. Münkel, B. Hu, K. Schäfer, Z. Liu, J. Zhang, L. Wang, J. Xin, P. Suppan, and Y. Wang, Mixing layer height and its implications for air pollution over Beijing, China, Atmospheric Chemistry and Physics, 16, 2459-2475, doi:10.5194/acp-16-2459-2016, 2016.
Van der Kamp, D., and I. McKendry: Diurnal and Seasonal Trends in Convective Mixed-Layer Heights Estimated from Two Years of Continuous Ceilometer Observations in Vancouver, BC, Bound.-Lay. Meteorol., 137(3), 459-475, doi:10.1007/s10546-010-9535-7, 2010.
Wang, Y., M. L. Zamora, and R. Zhang: New Directions: Light absorbing aersols and their atmospheric impacts, Atmos. Environ., 81, 713-715, doi: 10.1016/j.atmosenv.2013.09.034, 2013b.
Wei J., G. Tang, X. Zhu, L. Wang, Z. Liu, M. Cheng, C. Münkel, X. Li and Y. Wang: Thermal internal boundary layer and its effects on air pollutants during summer in a coastal city in North China, Journal of Environmental Sciences, 1001-0742, doi:10.1016/j.jes.2017.11.006, 2017.
Yu, H., S. Liu, and R. Dickinson: Radiative effects of aerosols on the evolution of the atmospheric boundary layer, J. Geo. Res.: Atmos., 107, D12(4142), doi:10.1029/2001JD000754, 2002.
Zhao, P., F. Dong, Y. Yang, D. He, X. Zhao, W. Zhang, Q. Yao, H. Liu: Characteristics of carbonaceous aerosol in the region of Beijing, Tianjin, and Hebei, China, Atmos. Environ., 71, 389-398, doi: 10.1016/j.atmosenv.2013.02.010, 2013.
Zhang, R.: Getting to the Critical Nucleus of Aerosol Formation, Science, 328(5984), 1366-1367, doi: 10.1126/science.1189732, 2010.
Zhang, R., G. Hui, S. Guo, M. L. Zamora, Q. Ying, Y. Lin, W. Wang, M. Hu, and Y. Wang: Formation of Urban Fine Particulate Matter, Chem. Rev., 115, 3803-3855, doi: 10.1021/acs.chemrev.5b00067, 2015.