Anonymous Referee #2

We greatly appreciate the constructive review from the referee that has improved the quality of our manuscript. We have considered each comment carefully and revised our manuscript accordingly to address the issues raised. Below we address each comment point by point. Reviewer comments are marked as black, our response as blue and changes to the manuscript as red.

The authors present a nice, if perhaps a little over-extensive, study looking at in situ and some satellite measurements in an urban and complex setting. While the analysis presented here in some cases is not new, the data analysis of in situ data is hard and different and the analysis warrants publishing to add to our growing knowledge of aci.

We appreciate the reviewer for recognizing the value of this work. Specific points raised by the reviewer have been carefully considered and addressed in the following replies. In particular, much of the related revisions are focused on aerosol and cloud properties used in ACI and the discussion of the relevant results. We have addressed each comments in the sections below and made revisions to the manuscript accordingly.

I find some of the discussion of adjustments overly assertive of causality, which the authors cannot show empirically. These regions need to be trimmed to report on findings without asserting a causal connection, or the authors should perform modelling of the region where they can make some advances to understanding the direction of causality in what their observations are doing.

We thank the reviewer for pointing out this concern. We also agree that a modeling study may enhance our knowledge of the causality; however, this would extend us beyond our current capacity. Instead of a modeling component, we have revisited our observational data, with particular focus on CER-CTT statistics and raindrop size distribution analysis, allowing us to obtain a process-level insight into aerosol impacts on drizzle and precipitation. In the revised manuscript, we have added two figures about aerosol effects on precipitation. Figure 10 shows the multiyear (2005-2017) JWD sample number (days), mean droplet number per minute and the differences between polluted and clean days of the mean droplet number in each bin. The droplet number in the n2 bin was significantly lower on polluted days, indicating less drizzle in that condition. Fig. 11 shows differences between polluted and clean days in the percentage of the cumulative droplet number distribution for (a) all data and (b) data with precipitation less than or equal to 1 mm h^{-1}. The results using all data are similar with Fig. 10c; the droplet numbers appear lower for the smaller raindrop bins (≤ n5) on polluted days compared to clean days, and higher for the larger raindrop bins (> n5) (Fig. 11a). When precipitation is lower than or equal to 1 mm h^{-1} (i.e. light rain), abundant CCN drives raindrops towards smaller drop sizes, effectively increasing the number of drizzle drops (Fig. 11b).

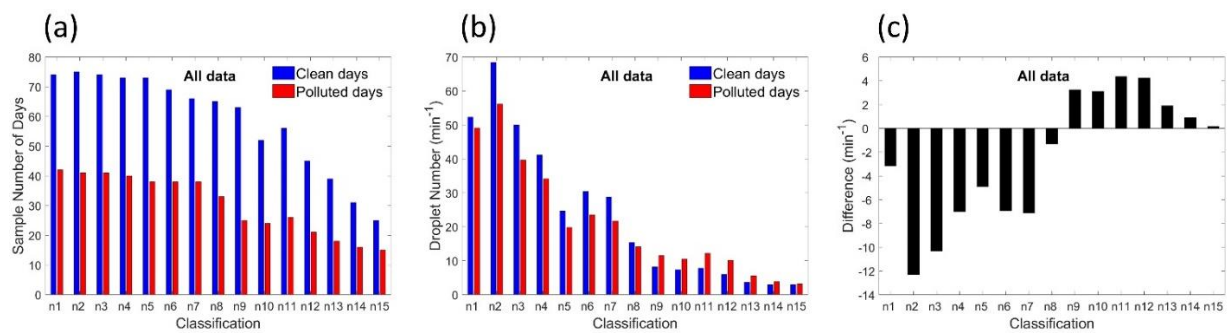

Figure 10: Multiyear (2005-2017) (a) JWD sample number of days in each raindrop size bin, (b) mean droplet number per minute for clean and polluted days and (c) The differences in the mean droplet number between polluted and clean days. nX reflects different raindrop size bins. The mean droplet size for n1 to n15 are, in order, 0.359, 0.455, 0.551, 0.656, 0.771, 0.913, 1.116, 1.331, 1.506, 1.665, 1.912, 2.259, 2.584, 2.869, and 3.198 mm.

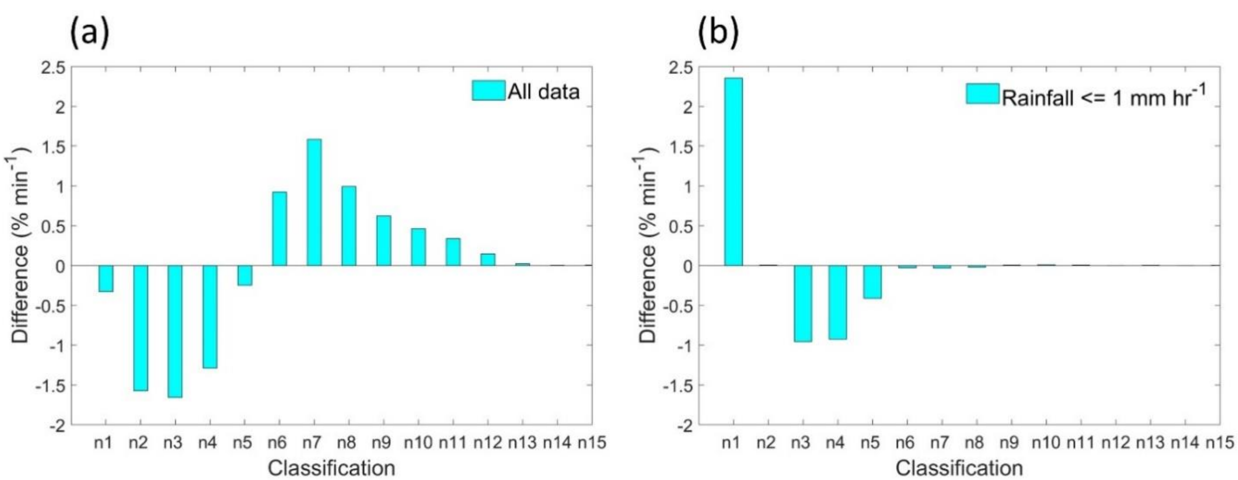

Figure 11: Multiyear (2005-2017) differences between polluted and clean days as percentages of the cumulative droplet number distribution for (a) all data and (b) the data with precipitation less than or equal to 1 mm h^{-1}. nX reflects different raindrop size bins as listed in Fig. 10.

In addition, we rewrote some paragraphs of findings by adding references rather than asserting a causal connection. The summary paragraph in Sect. 3.4 is rephrased as (lines: 297-303):

Although the existence of an aerosol effect on cloud lifetime is still widely disputed (Small et al., 2009; Stocker, 2014), our preliminary results show that precipitation might be suppressed and delayed under high aerosol loading. Combined with the results from Sect. 3.2, the process in the aerosol-cloud-precipitation interactions is consistent with the cloud lifetime effect. The presence of aerosols enhances the concentration of condensation nuclei under a fixed water content, which increases the cloud droplet number, redistributes cloud water to more numerous and smaller droplets, reducing collision–coalescence rates, which in turn suppresses precipitation and delays rainfall occurrence (i.e. the cloud lifetime effect (Albrecht, 1989; Pincus and Baker, 1994; Lohmann and Feichter, 2005)).

And a portion of the conclusions has been rephrased as (lines: 313-331):

We used surface $PM_{2.5}$ mass concentration data as aerosol proxy to study the aerosol impacts on clouds and precipitation. According to $PM_{2.5}$ concentration level, the data was split into clean and polluted days. The analysis of aerosol effects on clouds indicated that in CWP group 9 ($150 \leq CWP < 297$), the average COT in the main research area increased by 9.53, CER decreased by 2.77 μm, CF increased by 0.07, and CTT decreased by 1.28 K on polluted days compared with clean days. According to the aerosol indirect effect, polluted atmospheric conditions are connected with clouds characterized by lower CER, CTP, and larger CF and COT, which our results further support. Regarding the vertical distribution, our evidence shows that excess aerosols produced more liquid particles at lower altitude and inhibited the cloud droplet size under polluted conditions. Moreover, the effects of aerosol on cloud microphysics in polluted (i.e. land) and remote (i.e. ocean, less polluted) areas were investigated in CWP group 9, the ACI value of the remote area was 0.09, and the polluted area was 0.06. The ACI value in the remote area was larger than in the polluted area, indicating that clouds in the remote area were more sensitive to aerosol indirect effects.

Our analysis shows that precipitation might be suppressed and delayed under high aerosol loading. The observational data shows higher aerosol concentration redistributed cloud water to more numerous and smaller droplets under a constant liquid water content, reducing collision–coalescence rates, which further suppressed the precipitation and delayed rainfall duration. Our results are consistent with the cloud lifetime effect. Finally, we combined the observation of raindrop size distribution to complete the story of aerosol-cloud-precipitation interactions. As a result, on polluted days compared to clean days, droplet numbers decreased for smaller droplets bins but increased for larger droplets. However, when we looked into the light rain ($\leq$ 1 mm h^{-1}) category, high concentration of aerosols drove raindrops towards smaller droplet sizes and increased the appearance of drizzle drops.

While I acknowledge that many studies utilize CER to calculate aci, I would suggest using N_d, which the authors have already calculated to provide a complimentary calculation that may be more relevant to more recent studies.

Thank you for the suggestion. We agree with the reviewer's insight that cloud droplet number concentration (N_d) calculation may be more relevant. Grosvenor et al. (2018) indicated that N_d is of central interest to improve the understanding of cloud microphysics and for quantifying the effective radiative forcing by aerosol-cloud interactions. However, current standard satellite retrievals do not operationally provide N_d. It can be inferred from retrievals of cloud optical depth (COD), cloud droplet effective radius (CER) and cloud top temperature, but errors propagated from passive retrievals of COD and CER will generate uncertainties in the subsequently derived N_d (Grosvenor et al., 2018); thus, we currently retain the calculation of ACI by using CER.

The authors may also wish to say a few words about why $PM_{2.5}$ may be a good CCN and need to address near-cloud aerosol swelling in the text, which makes the direction of causality even more difficult to infer. The use of the rain size distribution is a good way to approach this problem.

Thank you for the suggestion. In the revised manuscript, we have added a relevant sentence to specify the $PM_{2.5}$ characteristics that we considered for using it as a suitable proxy of CCN (lines: 110-113):

The composition of $PM_{2.5}$ in East Asia is usually dominated by carbonaceous species and water soluble ions, including SO_4^{2-}, NH_4^+, and NO_3^- (Xu et al., 2012), which are important in determining the hygroscopicity of aerosols (Shen et al., 2009). Thus, based on these suitable characteristics and the lack of measured CCN in this study, we used $PM_{2.5}$ as a proxy for CCN concentrations.

Li et al. (2017) used $PM_{2.5}$ measurements to represent aerosol loading under cloudy conditions and showed significant negative relationships between cloud droplet effective radius (CER) and $PM_{2.5}$. Large-scale measurements of cloud condensation nuclei (CCN) are difficult to obtain on a routine basis, whereas aerosol optical quantities are more readily available (Liu and Li, 2014). However, AOD is not available under cloudy conditions, and AOD cannot represent the aerosol concentrations at the bottom of the cloud, leading to uncertainties in aerosol-cloud-precipitation interaction studies (Liu et al., 2020). Thus, hourly in-situ measurements, such as $PM_{2.5}$, are an alternative choice to estimate aerosol loading under cloudy conditions.

Aerosol swelling in high humidity cloudy environments (Clarke et al., 2002) is a possible reason behind the large uncertainties in aerosol-cloud interaction (ACI) studies using satellite retrievals (Liu et al., 2018). To address the near-cloud aerosol swelling in the text, we now reference the analysis methodology of Rosenfeld (2000), and have replotted the mean and one standard deviation of CER at each CTT bin in Fig. 8 as below. We defined the clean/polluted days by using surface $PM_{2.5}$ data, and then displayed the CTT-CER relationship and the occurrence frequency (%) of the CTT in CWP group 9 on clean and polluted days. This avoids the effect of near-cloud aerosol swelling, because $PM_{2.5}$ observations were at the surface. Figure 8 showed that CTT between 285 and 288 K exhibited a higher occurrence frequency during polluted days, whereas clean days had a higher frequency of CTT between 282 and 285 K. These results suggest that abundant aerosols activated higher concentrations of CCN near surface, thus forming more low-level clouds with smaller cloud droplet size.

In the revised manuscript, we are able provide insights to our research questions, but there are still many uncertainties. For example, $PM_{2.5}$ is not equal to CCN, satellites cannot observe particle size distribution, and it is difficult ensure our representative aerosols concentrations are present in the cloud. We appreciate that the reviewer suggested such a helpful addition; analysis of rain droplet size distribution provided us another independent verification, which made us more confident in our results.

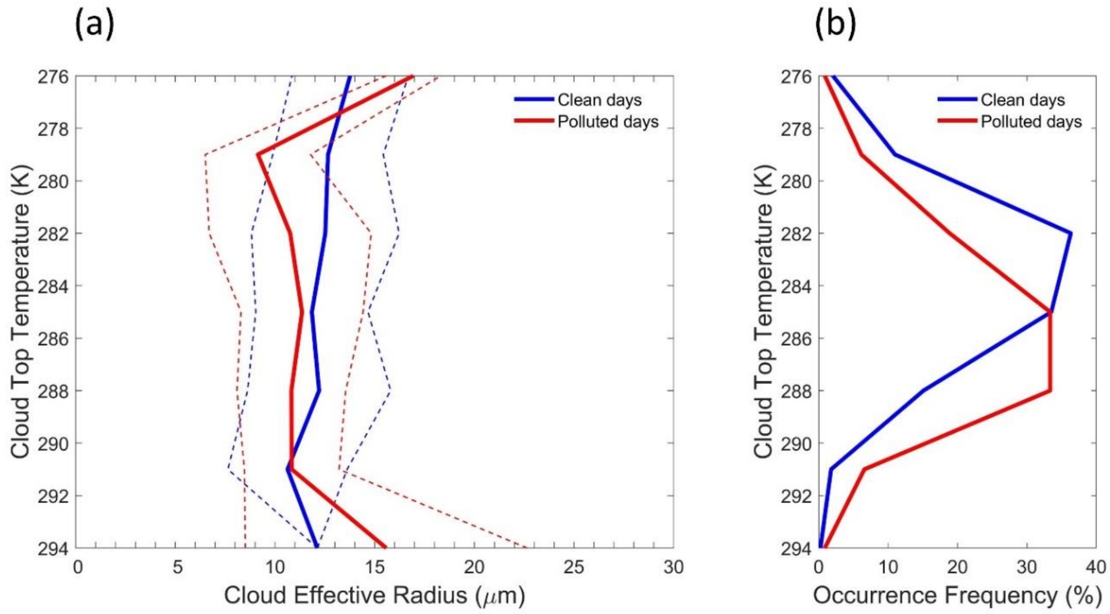

Figure 8: Multiyear (2005–2017) (a) cloud top temperature (CTT)-cloud effective radius (CER) relationship. Plotted are the mean (solid line) and one standard deviation (dashed line) of the CER for each 3 K interval, and (b) Frequency of occurrence of the CTT. Clean and polluted days are depicted with blue and red lines, respectively. Both (a) and (b) are constrained to CWP group 9 ($150 \leq CWP < 297$).

Another way the authors might want to consider looking at this is performing the same analysis in their paper, but instead of sorting clean/polluted sorting by atmospheric advection from the east or west. This might reveal the underlying meteorological signal that will covary with aerosol. This result can be used to say 'on days when the dominant weather pattern is such, but there is unusually little aerosol then the clouds do this'.

We plotted the wind rose diagrams of wind speed, relative humidity, and $PM_{2.5}$ concentration at Pingzhen station from Oct.15 to Nov. 30, 2005-2017 (Fig. R1). The prevailing wind was northeast, the highest occurrence frequency for wind speed was about 4 m s^{-1}, relative humidity was between 70% and 90%, and the $PM_{2.5}$ concentration was below 50 μg m^{-3}.

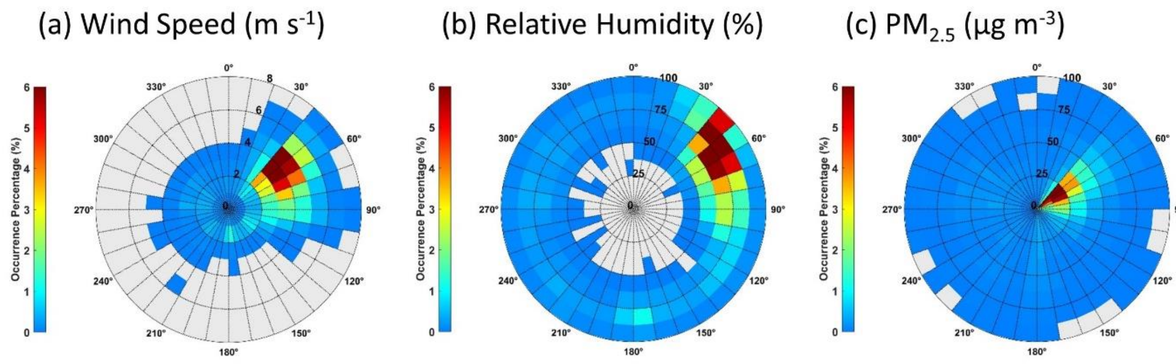

Figure R1: Multi-year (2005-2017) wind rose diagrams of (a) wind speed, (b) relative humidity, and (c) $PM_{2.5}$ concentration at Pingzhen station during Oct. 15 to Nov. 30.

To discuss the effect of atmospheric advection, we replotted Fig. 7 from the manuscript, but sorted by east wind and west wind (Fig. R2). If the most frequently occurring daily wind direction was between 0°-180°, it was defined as east wind; vice versa, it was defined as west wind when it was between 180°-360°. The difference in cloud microphysical parameters between east wind and west wind over the main research area (24.6°–25.2° N, 120.9°–121.5° E) was then calculated (Fig. R2). The East-West difference in COT, CER, CF, and CTT was -3.02, +0.47 μm, +0.01, and −1.50 K, respectively. Overall, the samples on west wind days were less available, although 13-years data were included. Thus, for the current manuscript, we decided to retain the analysis of clean vs. polluted days, but will consider a comprehensive analysis separating east vs. west air mass origins for a future work.

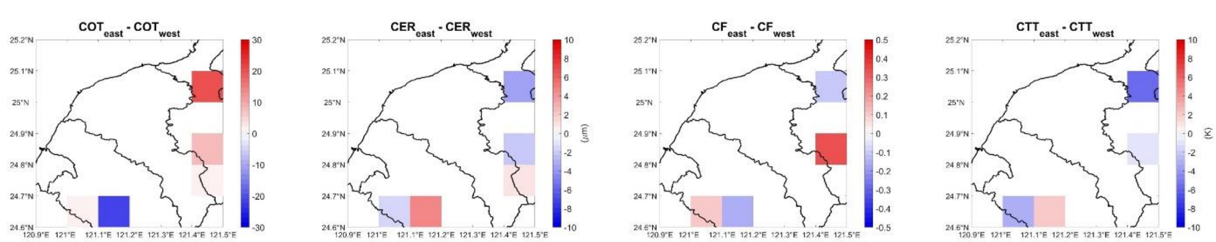

Figure R2: Multiyear (2005-2017) difference in (a) COT, (b) CER, (c) CF, and (d) CTT between east wind and west wind when considering only CWP group 9 ($150 \leq CWP < 297$). White parts are missing values.

Regarding meteorological parameters and $PM_{2.5}$ concentrations at Pingzhen station (Fig. 4), lower relative humidity, less rainfall, higher frequency of northeast wind, and lower wind speed were associated with polluted days compared with clean days. A weaker and more disorderly direction of the wind was observed on polluted days, which suggests that pollution may be associated with more stagnant conditions. However, on polluted days, the prevailing wind direction was still northeast, indicating although differences in the meteorological condition were evident between clean and polluted days, the predominant wind direction was the same. Due to the difference in meteorological conditions were between clean and polluted days, we tried to avoid any consequent impact by constraining the key cloud microphysical parameter CWP (i.e. performed analysis only on CWP group 9). We indeed understand the reviewer's concern, so we plotted Fig. R2 and attempted to clarify the effect of meteorology. However, due to a prevailing northeast wind throughout the sampling period, the samples associated with west wind days were not sufficient to represent a robust result.

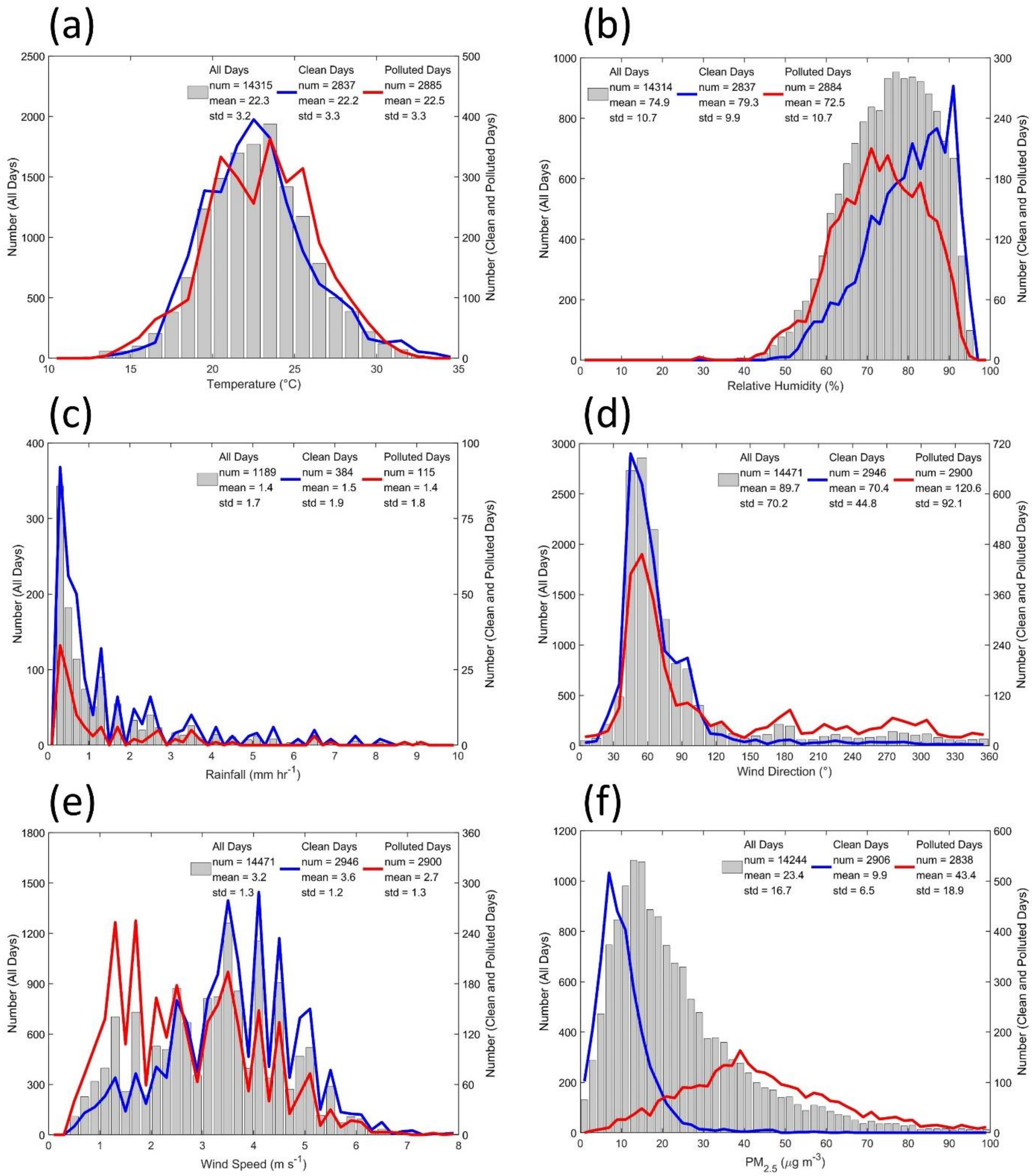

Figure 4: The distribution of (a) temperature, (b) relative humidity, (c) rainfall, (d) wind direction, (e) wind speed, and (f) $PM_{2.5}$ hourly data from Pingzhen station from Oct. 15 to Nov. 30, 2005–2017. The gray bars are the distribution of all valid observations, the blue lines represent the clean days and the red lines represent the polluted days.

P1 L15: I am not sure what this sentence is getting at- is the human activity causing low cloud?

Thank you for pointing out the confusion. We want to describe, based on a long-term analysis, that there are more low-level clouds and high AOD in northwestern Taiwan than northeastern Taiwan. In the revised manuscript, the sentence has been corrected as (lines 15-17):

Our results indicated that northwestern Taiwan, which has several densely populated cities, is dominated by low-level clouds (e.g. warm, thin, and broken clouds) during the fall season.

P2 L17: You should discuss spurious correlation between AOD and cloud properties as shown in (Christensen et al. 2017; Twohy et al. 2009).

Thank you for the suggestion. We have added discussion of spurious correlation in the text at (lines: 46-49):

Likewise, Twohy et al. (2009) and Christensen et al. (2017) reported spurious correlations between AOD and cloud properties using in-situ aircraft and satellite data. Despite advances in satellite-based retrievals in recent decades, obtaining robust statistical relationships between aerosols and clouds is difficult using only satellite-based observations (Christensen et al., 2017).

P2 L31: I might say weakly constrained (Bellouin et al. 2020).

The sentence has been rephrased as (lines: 60-62):

Although numerous studies have used observations and model simulations to discuss the indirect effects of aerosols, the interaction mechanism between aerosols and clouds remains weakly constrained (Bellouin et al., 2020) in the global climate system.

P3 L3: What does largely dominant mean? Relative to what?

Thank you for pointing out the confusion. In the revised manuscript, the sentence has been revised as (lines: 66-68):

Furthermore, Giorgi et al. (2003), using a coupled regional chemistry–climate model, found that **aerosol indirect effects were largely dominant over direct effects** in inhibiting precipitation in East Asian climates.

P3 L6: It seems like it might be good to discuss this in the context of the current synthesis report on aci (Bellouin et al. 2020).

Thank you for the suggestion. We have added discussion referencing the suggested reference as (lines: 71-74):

These studies have demonstrated a significant correlation between aerosols and cloud microphysics and the indirect effect of aerosols on regional precipitation. However, the aerosol type, concentration, and characteristics vary by region. **Moreover, the uncertainty on radiative forcing, especially via the impact from clouds remains large in Earth's radiation budget (Bellouin et al., 2020).**

P4 L13: So AOD was only retrieved when AOD was visible? It seems like all periods with cloud should be zeroed out since there might be AOD below cloud that is not being counted.

AOD is not available under cloudy conditions, and AOD cannot represent the aerosol concentrations at the bottom of the cloud. To compensate for this limitation, densely available surface $PM_{2.5}$ data in the study domain was used to resolve this condition, although this assumes that the measured $PM_{2.5}$ concentrations are representative of that within the cloud. While we have $PM_{2.5}$ observations from land-based stations, we relied solely on satellite data for aerosol proxy (i.e. AOD) levels within grid cells over the sea. In this research, to ensure the integrity of the data, satellite data, with a resolution of cloud properties at 1 and 5 km and aerosol properties at 10 km, were interpolated to a coarse resolution of $0.1° \times 0.1°$. These limitations lead to uncertainties in the study of aerosol-cloud-precipitation interaction that we are currently unable to improve; thus, there is room for improvement in future works.

P4 L19: What is this based on? Afternoon aerosol should be able to affect afternoon clouds.

Thank you for pointing out the confusion. In the revised manuscript, the sentence has been corrected as (lines: 119-121):

Fine particles were assumed well-mixed throughout the PBL during daytime (Maletto et al., 2003). $PM_{2.5}$ data between 10:00 and 14:00 were averaged as a measure of daily $PM_{2.5}$ concentrations for comparison with Aqua satellite data (overpass time is approximately 13:30 local time).

P5 L1: This would be more reliably at a constant CWP if cloud droplet number concentration (N_d) was used instead of CER and binning by CWP (Grosvenor et al. 2018). Any inferred aci will be a function of binning decisions.

We agree with the reviewer's insight that a constant CWP would be more reliable if we used cloud droplet number concentration (N_d) instead of CER. Grosvenor et al. (2018) indicated that N_d is of central interest to improve the understanding of cloud physics and for quantifying the effective radiative forcing by aerosol-cloud interactions. Current standard satellite retrievals do not operationally provide N_d, but it can be inferred from retrievals of cloud optical depth (COD) cloud droplet effective radius (CER) and cloud top temperature.

However, errors propagated from passive retrievals of COD and CER will generate uncertainties in the subsequently derived N_d. The CER uncertainties are likely to have a larger impact than COD errors due to the larger sensitivity of N_d to CER. Retrievals based on MODIS and other instruments employ bispectral algorithms for retrieving COD and CER (Nakajima & King, 1990), whereby these quantities are estimated using reflectances from both a nonabsorbing visible wavelength (denoted here as R_{vis}) and an absorbing shortwave infrared wavelength (R_{SWIR}). To observe R_{vis}, the instrument uses the 0.65-μm channel over land and the 0.86-μm channel over the ocean. Since surface albedo errors can be large, it is worth discussing them further, although we note that the uncertainties examined above in Platnick et al. (2017) were over the land, where MODIS surface albedo uncertainties are likely to be much higher than over the oceans (Bréon &

Doutriaux-Boucher, 2005; King et al., 2004; Rosenfeld et al., 2004) since the surface albedo over land is much more variable than over the ocean (Grosvenor et al., 2018).

In summary, we agree with the reviewer's insight that it may be more reliable if cloud droplet number concentration (N_d) was used instead of CER, but to avoid the large uncertainties associated with derived N_d, we currently maintain the calculation of ACI by using CER.

P7 L7: This is a nice comparison to previous studies. Please consider summarizing in a figure.

Thank you for the suggestion. We have collected this information in Table 2 as below:

Table 2: ACI values from the literature in comparison to this study.

Study	**ACI values**	**Sources**	**Region**
Feingold et al., 2003	0.02-0.16	ground-based remote sensors	Oklahoma, United States
Kim et al., 2008	0.04-0.17	ground-based remote sensors	Oklahoma, United States
McComiskey et al., 2009	0.04-0.15	ground-based remote sensors	California, United States
This study	0.07 in CWP group 9 ($150 \leq CWP < 297$)	satellite and surface observations	Northern Taiwan

P7 L13: This is not a robust piece of analysis. Differing $PM_{2.5}$ is likely a function of atmospheric state (air masses moving from the west for instance) and this is likely to do more to CF and COT than aci.

Thank you for pointing this out. We agree with the reviewer's insight of impact from atmospheric state. As discussed above for Fig. R2, the difference in cloud microphysical parameters between east wind and west winds affecting the main research area were calculated. The samples on west wind days were too few even though 13 years of data were included. Although meteorological conditions were different between clean and polluted days, we attempted to avoid an effect from meteorology by constraining the key cloud microphysical parameter CWP (i.e. performed analysis on CWP group 9 only). We indeed understand the reviewer's concern, and tried to clarify the effect from meteorology. Owing to the prevailing northeast wind, the samples on west wind days were not sufficient to represent a robust result. Currently, in the revised manuscript, we added a reference to discuss the meteorological impact, and the paragraph has been revised as (lines: 201-203):

While the positive CF value difference may have been due to higher aerosol loading, the atmospheric condition may have contributed as well. For instance, Saponaro et al. (2017) showed that CF is more sensitive to lower troposphere stability (LTS) than other cloud variables (i.e. CER, CTT, and COT).

P8 L6: Please comment on the unintuitive diagnosed stronger aci in more polluted clouds. A lot of studies point to stronger aci in more pristine clouds (Carslaw et al. 2013). Again, this may be a function of binning, which is also going to select for clouds in an atmospheric regime.

Thank you for the comment. The ACI calculation is dependent on how the environmental factors are constrained (i.e., fixed CWP) and on the data binning. In our results, the differences across three polluted levels are relatively small; ACI values were 0.08, 0.07, and 0.06 for heavily, moderately, and slightly, respectively, when considering only CWP group 9 ($150 \leq CWP < 297$) data. This implies that ACI changes between different polluted levels may not have been significant as long as the clouds contained a certain amount of CCN. Without in-situ measurement, we are not able to definitively verify our results. We are planning a more comprehensive measurement study to quantify the ACI index in our future works.

P9 L4: Or the cleaner days could be occurring because of rain scavenging aerosol. Unfortunately, in an empirical study such as this you can't make causal statements. However, the high temporal resolution of ground data used here might allow for some sort of time evolution analysis that could show causality.

Thanks for the comments. We agree with the reviewer's insight and have avoided an overly assertive statement of causality by rephrasing the sentence as (lines: 257-259):

Figure 10a shows the number of sample occurrences under different raindrop size classifications for clean and polluted days. **The sample number (days) was significantly higher for clean conditions, suggesting rainfall was more common on clean days than on polluted days.**

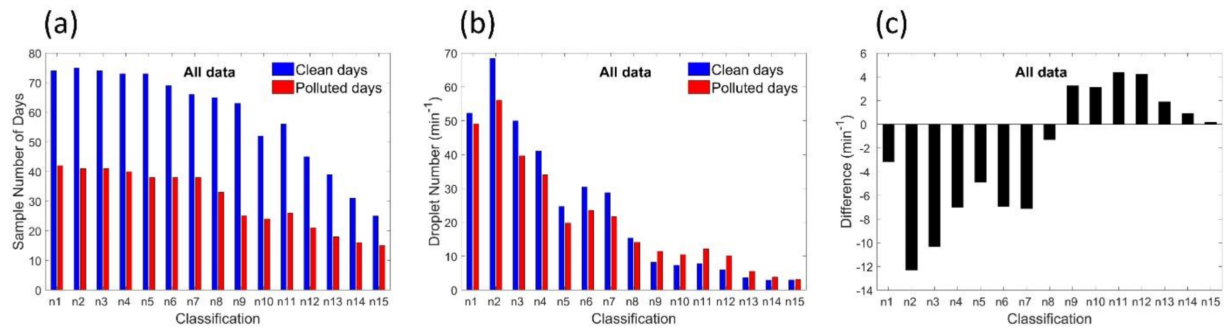

Figure 10: Multiyear (2005-2017) (a) JWD sample number of days in each raindrop size bin, (b) mean droplet number per minute for clean and polluted days and (c) The differences in the mean droplet number between polluted and clean days. nX reflects different raindrop size bins. The mean droplet size for n1 to n15 are, in order, 0.359, 0.455, 0.551, 0.656, 0.771, 0.913, 1.116, 1.331, 1.506, 1.665, 1.912, 2.259, 2.584, 2.869, and 3.198 mm.

As the reviewer pointed out, it is overly assertive to make causal statements in an empirical study. To further improve this part of the analysis, we traced back the timeframe to 00:00 as shown in Fig. R3. $PM_{2.5}$ data were averaged from 10:00 to 14:00 as daily $PM_{2.5}$ (orange box). Therefore, the rainfall data from 00:00 to 10:00 represents the pre-setting period of clean/polluted days. For the clean days, rain scavenging occurred in the morning, especially during the period of 05:00-10:00. The rainfall and $PM_{2.5}$ concentrations were both at low values from 10:00-14:00. The rainfall variability during clean days can be considered as the typical pattern without aerosol effects. For polluted days, there was scarcely rainfall occurring before 10:00. After 10:00, when daily $PM_{2.5}$ was higher, high aerosol concentrations led to higher concentrations of CCN, produced more liquid particles and inhibited the cloud droplet size (as the Sect. 3.2 shown). Precipitation started early in the night (i.e. 12-16 hrs after the $PM_{2.5}$ averaging period). Synthesizing the results mentioned above, under a fixed CWP ($150 \leq CWP < 297$), a higher aerosol concentration redistributes cloud water to more numerous and smaller droplets, reducing collision–coalescence rates, which in turn suppress precipitation and constrain the time of rainfall occurrence.

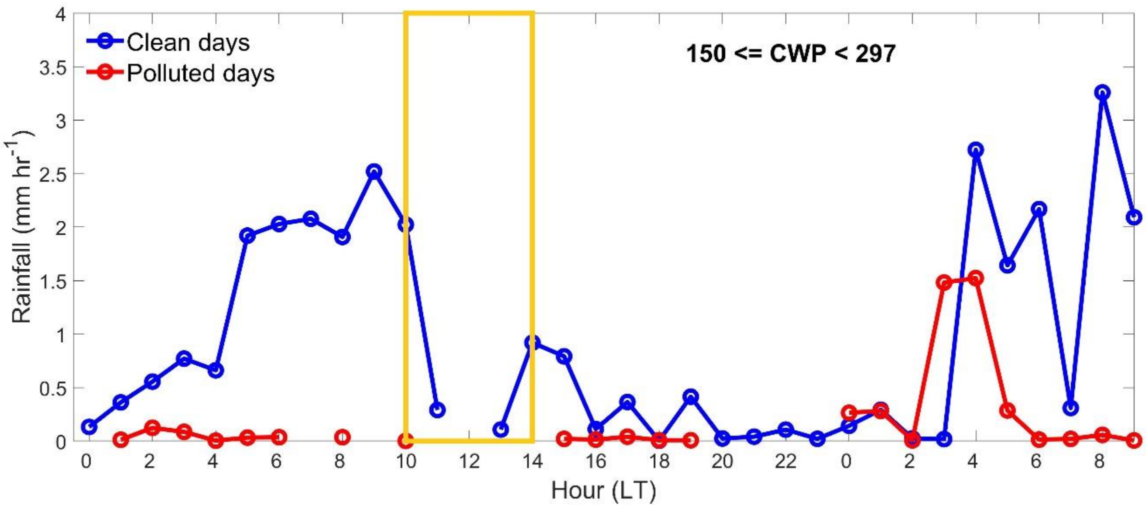

Figure R3: Time series of average hourly-rainfall rate calculated for clean and polluted days when considering CWP group 9 ($150 \leq CWP < 297$) only. $PM_{2.5}$ data were averaged from 10:00 to 14:00 as daily $PM_{2.5}$ (orange box) and rainfall analyses were performed from 00:00 of that day (i.e. before the $PM_{2.5}$ averaging period) to 10:00 of the following day.

P9 L22: Please note that precipitation reduction is often a function of model parameterization.

The sentence has been rephrased as (lines: 284-286):

A modeling study (Huang et al., 2007) revealed that the second indirect effect of aerosols (a large number of small droplets are generated by enhanced aerosols and reduce the precipitation efficiency) significantly reduces fall and winter precipitation from 3 % to 20 % across East Asia, although it was **dependent on the auto-conversion scheme assumed.**

References cited in the response letter:

Bréon, F.-M., and Doutriaux-Boucher, M.: A comparison of cloud droplet radii measured from space, IEEE Transactions on Geoscience and Remote Sensing, 43, 1796-1805, 2005.

Clarke, A., Howell, S., Quinn, P., Bates, T., Ogren, J., Andrews, E., Jefferson, A., Massling, A., Mayol-Bracero, O., and Maring, H.: INDOEX aerosol: A comparison and summary of chemical, microphysical, and optical properties observed from land, ship, and aircraft, Journal of Geophysical Research: Atmospheres, 107, INX2 32-31-INX32 32-32, 2002.

Grosvenor, D. P., Sourdeval, O., Zuidema, P., Ackerman, A., Alexandrov, M. D., Bennartz, R., Boers, R., Cairns, B., Chiu, J. C., and Christensen, M.: Remote sensing of droplet number concentration in warm clouds: A review of the current state of knowledge and perspectives, Reviews of Geophysics, 56, 409-453, 2018.

King, M. D., Platnick, S., Yang, P., Arnold, G. T., Gray, M. A., Riedi, J. C., Ackerman, S. A., and Liou, K.-N.: Remote sensing of liquid water and ice cloud optical thickness and effective radius in the Arctic: Application of airborne multispectral MAS data, Journal of Atmospheric and Oceanic Technology, 21, 857-875, 2004.

Levy, R., Mattoo, S., Munchak, L., Remer, L., Sayer, A., Patadia, F., and Hsu, N.: The Collection 6 MODIS aerosol products over land and ocean, Atmospheric Measurement Techniques, 6, 2989, 2013.

Li, S., Joseph, E., Min, Q., and Yin, B.: Multi-year ground-based observations of aerosol-cloud interactions in the Mid-Atlantic of the United States, Journal of Quantitative Spectroscopy and Radiative Transfer, 188, 192-199, 2017.

Liu, C., Wang, T., Rosenfeld, D., Zhu, Y., Yue, Z., Yu, X., Xie, X., Li, S., Zhuang, B., and Cheng, T.: Anthropogenic effects on Cloud condensation nuclei distribution and rain initiation in East Asia, Geophysical Research Letters, 47, e2019GL086184, 2020.

Liu, J., and Li, Z.: Estimation of cloud condensation nuclei concentration from aerosol optical quantities: influential factors and uncertainties, Atmospheric Chemistry & Physics, 14, 2014.

Liu, J., and Li, Z.: Significant underestimation in the optically based estimation of the aerosol first indirect effect induced by the aerosol swelling effect, Geophysical Research Letters, 45, 5690-5699, 2018.

Nakajima, T., and King, M. D.: Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: Theory, Journal of the atmospheric sciences, 47, 1878-1893, 1990.

Platnick, S., Meyer, K. G., King, M. D., Wind, G., Amarasinghe, N., Marchant, B., Arnold, G. T., Zhang, Z., Hubanks, P. A., and Holz, R. E.: The MODIS cloud optical and microphysical products: Collection 6 updates and examples from Terra and Aqua, IEEE Transactions on Geoscience and Remote Sensing, 55, 502-525, 2016.

Rosenfeld, D.: Suppression of rain and snow by urban and industrial air pollution, Science, 287, 1793-1796, 2000.

Rosenfeld, D., Cattani, E., Melani, S., and Levizzani, V.: Considerations on daylight operation of 1.6-versus 3.7-μm channel on NOAA and Metop satellites, Bulletin of the American Meteorological Society, 85, 873-882, 2004.

References are added in the revised manuscript:

Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., Boucher, O., Carslaw, K., Christensen, M., and Daniau, A. L.: Bounding global aerosol radiative forcing of climate change, Reviews of Geophysics, 58, e2019RG000660, 2020.

Christensen, M. W., Neubauer, D., Poulsen, C. A., Thomas, G. E., McGarragh, G. R., Povey, A. C., Proud, S. R., and Grainger, R. G.: Unveiling aerosol–cloud interactions–Part 1: Cloud contamination in satellite products enhances the aerosol indirect forcing estimate, Atmospheric Chemistry and Physics, 17, 2017.

Ghan, S. J., Guzman, G., and Abdul-Razzak, H.: Competition between sea salt and sulfate particles as cloud condensation nuclei, Journal of the atmospheric sciences, 55, 3340-3347, 1998.

Maletto, A., McKendry, I., and Strawbridge, K.: Profiles of particulate matter size distributions using a balloon-borne lightweight aerosol spectrometer in the planetary boundary layer, Atmospheric Environment, 37, 661-670, 2003.

Shen, Z., Cao, J., Arimoto, R., Han, Z., Zhang, R., Han, Y., Liu, S., Okuda, T., Nakao, S., and Tanaka, S.: Ionic composition of TSP and PM2.5 during dust storms and air pollution episodes at Xi'an, China, Atmospheric Environment, 43, 2911-2918, 2009.

Small, J. D., Chuang, P. Y., Feingold, G., and Jiang, H.: Can aerosol decrease cloud lifetime?, Geophysical Research Letters, 36, 2009.

Stocker, T.: Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2014.

Twohy, C. H., Coakley Jr, J. A., and Tahnk, W. R.: Effect of changes in relative humidity on aerosol scattering near clouds, Journal of Geophysical Research: Atmospheres, 114, 2009.

Xu, L., Chen, X., Chen, J., Zhang, F., He, C., Zhao, J., and Yin, L.: Seasonal variations and chemical compositions of PM2.5 aerosol in the urban area of Fuzhou, China, Atmospheric Research, 104, 264-272, 2012.