Response to short comments

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

Specific comments:

The climatology of MLH at four sites over NCP was investigated using long-term measurements. However, lots of statements in the manuscript and part of conclusions were not well supported. Thus, a major revision is suggested.

Comment 1:

LINE 214-215, the definitions of rainy, sandstorm and windy conditions should be given.

Response 1:

Thank you for your suggestion. The criterion to exclude the data points for special conditions with (a) precipitation, i.e. cloud base lower than 4000 m and the attenuated backscattering coefficient of at least 2×10^{-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. We also modified the relevant contents in section 2.2 in the revised manuscript.

Comment 2:

LINE 317-318, "the TJ station was supposed to be an inland site", the TJ site is quite close to the Bohai sea, which should be considered as a coastal station.

Response 2:

Actually, the Tianjin (TJ) site was set in the courtyard of the Tianjin Meteorological Bureau, which was located south of the urban area (117.20° E, 39.13° N) with about 50 km away from the coast. While, the Qinhuangdao (QHD) station was set up in the Environmental Management College of China (119.57° E, 39.95° N) with only about 2 km away from the coastline. Therefore, the TJ site, by contrast, was supposed to be an inland site. Besides, the mixing layer height (MLH) at the coastal region was affected by the thermal internal boundary layer (TIBL), not the sea breeze. When the cold air mass came with sea breeze and the top of the mixing layer was higher than the top of the air mass, the TIBL will form within the origin mixing layer, interrupt the origin mixing layer development and decrease the MLH. With distance inland, the top of the sea air mass will enhance and exceed the local MLH, if so, the TIBL will not form. Since the TIBL impact will only matters within a distance of about 10 km out to the sea (Stull, 1988), although The TJ station is close to the sea, the MLH in TJ was not influenced by the TIBL. From another point of view, the definition of a coastal station should be the one that was affected by the TIBL.

Comment 3:

LINE 319-324, the definition of sea-breeze used in this study should be given. The sea-breeze cannot be identified merely by the near-surface wind speed and direction.

How to identify the sea-breeze from background wind? How to calculate the occurrence frequency of sea-breeze at TJ and QHD?

Response 3:

Thank you for your suggestion. The sea-land breeze was a local circulation, it happens when there is no large scale synoptic system pass by. In our study, we first exclude days with large-scale synoptic systems. Then according to the coastline orientation, if the southeast wind at the TJ station and south and southwest winds at the QHD station occurred at around 11:00 LT, and the northwest wind started to blow at around 20:00 LT, then this kind of circulation was supposed to be a sea-land circulation. The prevailed southeast wind at the TJ station and the south and southwest wind at the QHD station were regarded as sea breezes.

Comment 4:

LINE 326-335, more evidences should be given to support the statement that the movement of sea-breeze suppress the MLH at QHD site in summer. The TJ site also locates in the coastal regions, why the diurnal patterns and seasonal variations of MLH are quite different?

Response 4:

Thank you for your suggestion. 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 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. Since the MLH at the coastal region was affected by the TIBL, not the sea breeze, and the TIBL impact will only matters within a distance of about 10 km out to the sea (Stull, 1988), the TIBL will not form in the TJ station. The MLH for TJ was as high as those inland sites (Beijing (BJ) and Shijiazhuang (SJZ)). The relevant contents were modified in section 3.2.2 in our revised manuscript

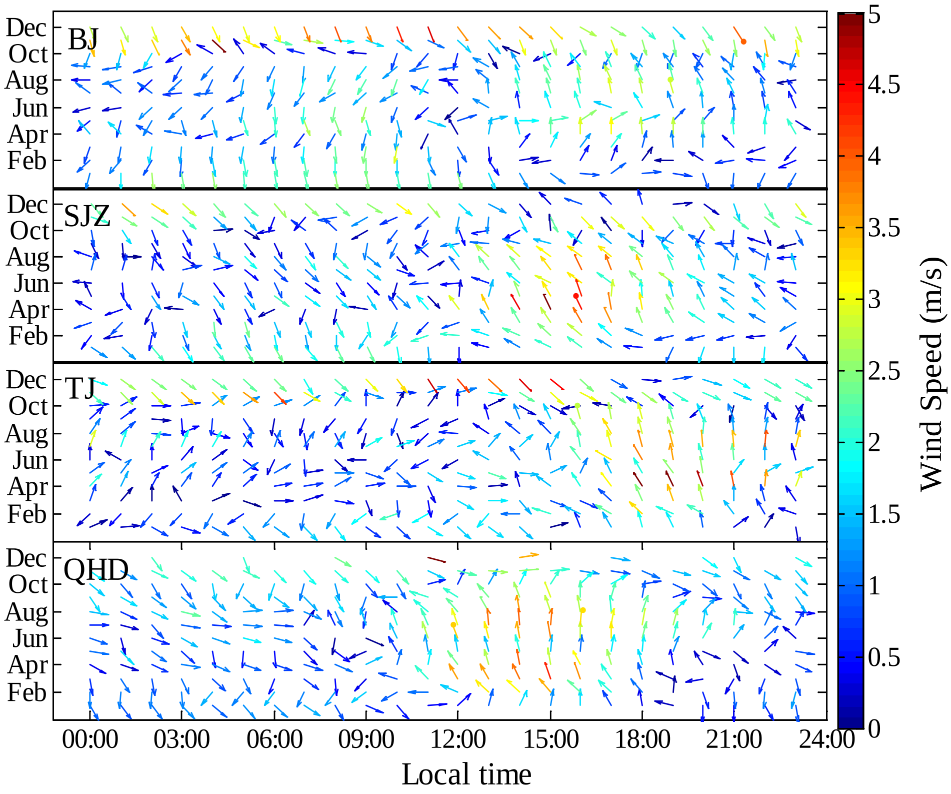

Fig. 1 Monthly variations of prevailed wind at the BJ, SJZ, TJ and QHD stations from December 2013 to November 2014.

Comment 5:

LINE 362-364, the buoyancy fluxes are determined by the surface sensible heat fluxes, not the net radiations. The statements here are inaccurate.

Response 5:

Thank you for your suggestion. The sensible heat fluxes data were not available, so we used net radiation for the analysis. Considering your suggestion, the net radiation analysis was replaced by gradient Richardson number (*Ri*) studies, and *Ri* is an index which can evaluate the turbulent stability from both of the perspective of thermal and mechanism forces. Then the low MLH in southern Hebei was mainly resulted from the stable turbulent stratification (Fig.2). Relevant contents were modified in section 4.1 in the revised manuscript.

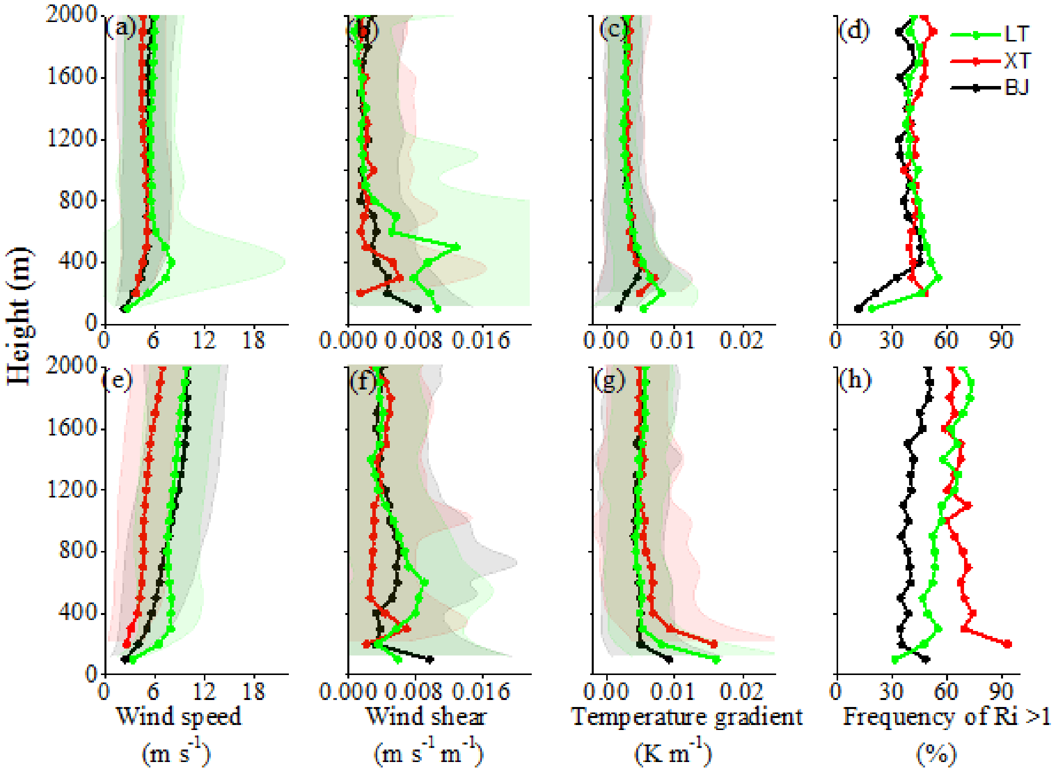

Fig.2 Vertical profiles of (a, e) horizontal WS, (b, f) wind shear, (c, g) virtual potential temperature gradient and (d, h) percentage of *Ri*>1 at the BJ, XT and LT stations in summer (upper panel) and winter (lower panel).

Comment 6:

LINE 371-375, before using the sounding data of XT as a replacement of SJZ, the data consistency must be examined and presented, since there are90 km between these two sites. At least, the general characteristics of MLH at SJZ at 08:00 and 20:00 LT should be well reflected by the sounding data at XT. The data consistency also should be check between the LT site and QHD site.

Response 6:

Thank you for your suggestion. Since we didn't have sounding data at the SJZ and QHD stations, we used the reanalysis data to do the examination instead. The reanalysis data were downloaded from the ECMWF website (http://apps.ecmwf.int/datasets/data/interim-full-mnth/levtype=pl/). Take the wind speed as an example, comparisons of the wind speed between the Xingtai (XT) and SJZ stations and the Laoting (LT) and QHD stations were shown in Fig.3. Wind speed between the XT and SJZ stations, LT and QHD stations were highly correlated, respectively, which indicated that the sounding data in the SJZ and QHD stations could be replaced by data in the XT and LT stations, respectively.

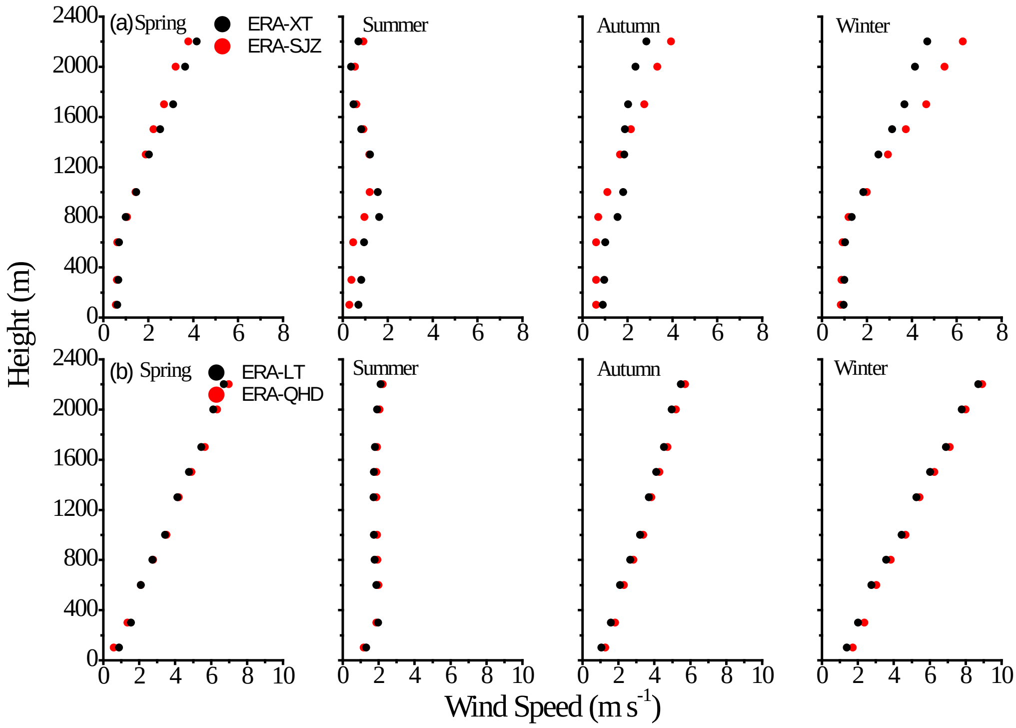

Fig. 3 Comparisons of seasonal wind speed profiles between the (a) XT and SJZ stations and the (b) LT and QHD stations with reanalysis data.

Comment 7:

As shown in Fig. 7, the profiles at XT are almost the same in different season and different moment, which is different from the profiles of other sites. The prevailing wind speed and direction are different in different season, why the profiles are almost the same? The error-bar of the profiles should also be given. In spring and summer, at 20:00 LT there are lots of fluctuations in the profiles at LT, why? Do the terrains play a role in the profiles in different regions?

Response 7:

Although the prevailing wind speed and direction at the XT station were different in different moment and season, vertical variation of each wind speed profiles changed slightly. Since the wind shear was defined as the degree of wind speed and direction variation between the upper layer and the lower layer ($\text{wind shear} = \sqrt{\left(\frac{\Delta \bar{u}}{\Delta z}\right)^2 + \left(\frac{\Delta \bar{v}}{\Delta z}\right)^2}$), the almost consistent wind shear profiles in different season and different moment indicated a relatively stable atmosphere stratification. Similarly, the stronger variation and higher value of wind shear in the vertical direction at the BJ station suggested unstable atmosphere stratification, which was probably due to the frequent occurrence of cold air mass passage. From Fig. 1 we can see that the sea breeze changed to land breeze at around 20:00 LT, thus the fluctuations in the profiles at LT could be attributed to the transitory stages of sea-land breeze alternation. Therefore, the terrains certainly play a role in the wind shear profiles in different regions. To further interpret the reasons for low MLH at the southern Hebei, we added analysis of gradient Richardson number (*Ri*) profiles at the BJ, XT and LT stations in the revised manuscript. Since the comparison results at 08:00 LT and 20:00 LT made no difference, we combined the sounding profiles at 08:00 LT and 20:00 LT to make our paper concise and easier to be understood (Fig. 2). Then the low MLH in southern Hebei was mainly resulted from the stable turbulent stratification

Comment 8:

LINE 390-392, the authors merely presented the profiles at 20:00 LT, which cannot support the statement "during the whole night". More evidences should be given.

Response 8:

Thank you for your suggestion. In our revised manuscript, the meteorological profiles were averaged over 08:00 LT and 20:00 LT, and the wind shear and virtual potential temperature gradient profiles were compared between southern Hebei and northern NCP (Fig. 2). The wind shear in southern Hebei was lower than that in the southern NCP above 300 m, while the virtual potential temperature gradient was on the opposite, leading to a conclusion that the low MLH in southern Hebei was resulted from the stable turbulent stratification. In summer, this discrepancy was largely decreased and the MLHs were consistent between these two areas. The relevant contents were modified in section 4.1 in the revised manuscript.

Comment 9:

LINE 404-405, please give evidences to support the statement "the front usually does not reach southern Hebei".

Comment 10:

LINE 406-408, please give evidences to support the statement "the lessened effects of the front system and strong turbulent exchange will lead to less wind shear contrast in the vertical direction between southern Hebei and the northern NCP."

Response 9 and 10:

Thank you for your suggestion and we are sorry for our misrepresentation. Although haze evolution in the NCP area usually behave regional consistency, the pollution intensity various in different regions, which will be partially attributed to the impact of different position of weather system. The NCP region usually influenced by the continental high in the spring, autumn and winter in lower troposphere. When the high pressure is relatively weak, the northern and southern areas usually located in the front and south of the system, respectively. Thus, the weak cold and clean air may be partially responsible for the lighter pollution degree in the northern NCP areas (Su et al., 2004), meanwhile, the cold front resulted from the cold air flow over the northern NCP will enhanced the wind shear. In summer, due to the northward lift and westward intrusion of the subtropical high on the NCP, the lessened effect of the weak cold air on northern NCP accompanied with strong solar radiation and turbulent activities will lead to less wind shear contrast in the vertical direction between southern Hebei and the northern NCP. Based on this, we have made modifications in section 4.1 in our revised manuscript.

Comment 11:

LINE 410-419, the authors attribute the high PM concentration in SJZ to the low MLH. It is inaccurate, the different anthropogenic emissions of pollutants in SJZ and BJ should be considered.

Response 11:

Thank you for your suggestion. Since the particle has direct emission sources and secondary sources, and the distribution of direct emissions cannot represent the total contribution of emissions to the particle concentration. The near-ground $PM_{2.5}$ concentration could represent the particle concentrations at the ground, but considering that the lifetime of particle is much longer than that of trace gases, the concentrations of particles are nearly uniform in the mixing layer because of the strong vertical mixing. Therefore, near-ground $PM_{2.5}$ concentrations cannot be used to evaluate the emissions influences between different regions if the mixing layer heights are different. AOD, which represent the aerosol column concentration, is a much better indicator for the emissions difference. In the revised manuscript, we checked the AOD distribution in NCP to evaluate the emission effect. The AOD data were retrieved with the dark target algorithm from the Moderate Resolution Imaging Spectra-radiometer (MODIS) aerosol products on board the NASA EOS (Earth observing system) Terra satellite. As shown in Fig. 4, the averaged AOD value at the southern NCP (SJZ, Handan (HD) and Xingtai (XT)) stations was 1.2 times higher than the AOD at the northern NCP (the BJ, and TJ stations) regions, while the near-ground $PM_{2.5}$ concentration in southern Hebei was 1.5 times higher than that in the northern NCP. If the difference of AOD represents the emission discrepancy, the remaining differences of $PM_{2.5}$ concentration may be induced by the meteorology. In other words, except for the emission effect, the meteorological conditions also play an important role in pollutant contrast between these two areas. Relevant contents were also modified in section 4.2 in our revised manuscript.

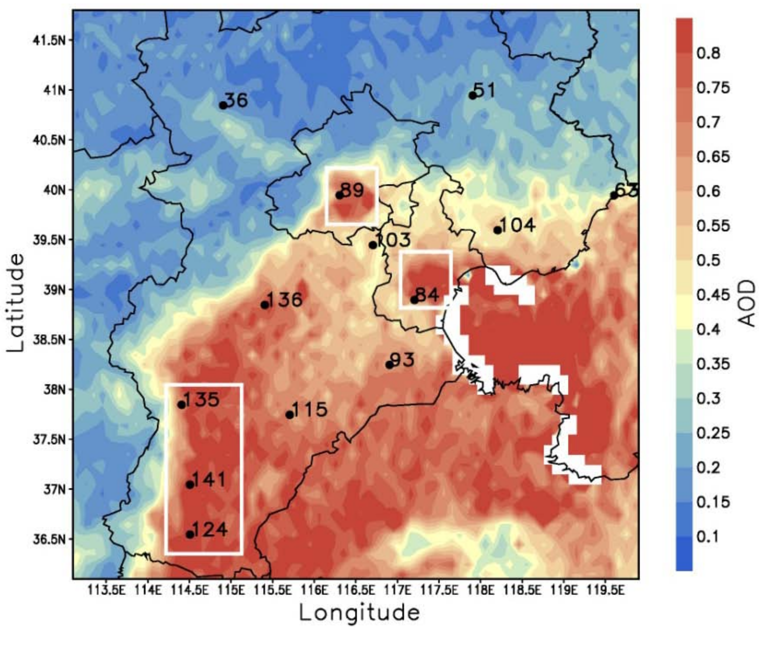

Fig. 4 Distribution of AOD from December 2013 to November 2014 in the NCP. The $PM_{2.5}$ concentrations of the 13 observation sites were also marked beside each station. Major sites in the Northern NCP (BJ and TJ) and the Southern Hebei (SJZ, XT and HD) were circled by white rectangles.

Comment 12:
LINE 420-422, although the RH can affect the visibility, it cannot significantly affect the aerosol concentration. Is there any direct physical connections between the high RH conditions and high aerosol concentration?
Response 12:
The RH can not only affect the visibility, but also the aerosol concentrations. The direct physical mechanism is the fine particle's hygroscopic growth and the RH has positive correlation with fine particle's number and mass concentrations (Hu et al., 2006; Liu et al., 2011; Seinfeld et al., 1998).

Comment 13:
LINE 426-427, "temperature is the main factor in new particle formation," any evidences to support this statement in NCP.
Response 13:
Thank you for your suggestion and we are sorry for this inappropriate illustration. Actually, the temperature has impact on the particles physicochemical reaction rate, the particles' nucleation and other secondary transformation processes are most efficient in a relatively high temperature and RH. If the temperature was lower than the ideal value, the aerosol's secondary transformation processes will be less effective (Seinfeldet al., 1998).

Comment 14:
LINE 437-440, the RH in SJZ is higher than that in TJ (closer to sea), why?
Response 14:
Thank you for your suggestion. As shown in Fig. 5, 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 north 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. 5a). 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. 5c and 5d). Besides, the higher RH in the southern Hebei could also be affected by the subtropical high (wet southeast flow from the yellow sea).

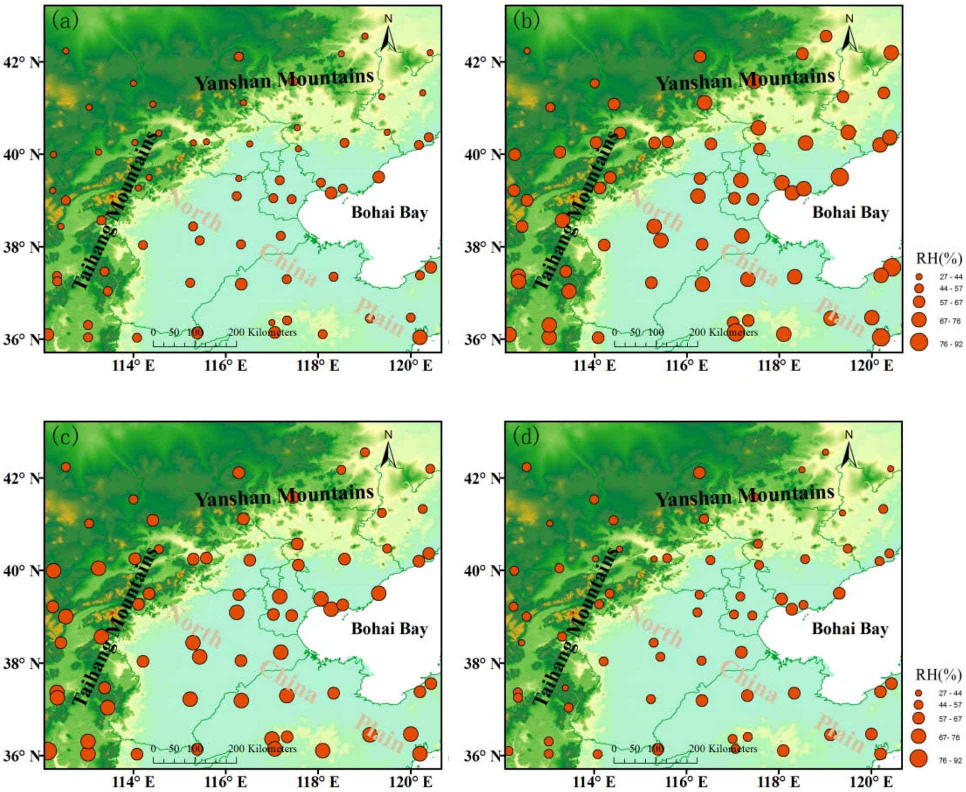

Fig. 5 Distributions of seasonal averaged RH in the NCP from December 2013 to November 2014: (a) spring, (b) summer, (c) autumn and (d) winter.

Comment 15:

Section 4.2.1, the authors attribute the higher PM in SJZ to new particle formation, which is quite complex and cannot be understood merely by the surface temperature and RH. And the direct emissions of pollutants should be considered.

Response 15:

Thank you for your suggestion. Since the particle has direct emission sources and secondary sources, and the distribution of direct emissions cannot represent the total contribution of emissions to the particle concentration. The near-ground $PM_{2.5}$ concentration could represent the particle concentrations at the ground, but considering that the lifetime of particle is much longer than that of trace gases, the concentrations of particles are nearly uniform in the mixing layer because of the strong vertical mixing. Therefore, near-ground $PM_{2.5}$ concentrations cannot be used to evaluate the emissions influences between different regions if the mixing layer heights are different. AOD, which represent the aerosol column concentration, is a much better indicator for the emissions difference. As shown in Fig. 4, the averaged AOD value at the southern NCP (SJZ, HD and XT) stations was 1.2 times higher than the AOD at the northern NCP (BJ and TJ) regions, while the near-ground $PM_{2.5}$ concentration in southern Hebei was 1.5 times higher than that in the northern NCP. If the difference of AOD represents the emission discrepancy, the remaining differences of $PM_{2.5}$ concentration may be induced by the meteorology. In other words, except for the emission effect, the meteorological conditions also play an important role in pollutant contrast between these two areas. The lower MLH combined with higher RH and weaker diffusion ability contributed a lot to heavier haze in the southern Hebei and the meteorological contrast between these two areas will accounted for 60% in the near-ground $PM_{2.5}$ concentration difference. Relevant contents were also modified in section 4.2 in our revised manuscript.

Comment 16:

LINE 470-473, “it was considered reasonable to regard the sounding data of WS as a climatological constant”, during a day, the WS within ML would change due to the momentum exchanges between the ML and free troposphere. The WS cannot be considered as a constant. As illustrated in Fig. S2, there are differences in profiles at 08:00 and 20:00 LT. The error-bar of wind speed should be given.

Response 16:

Thank you for your suggestion, we are sorry for this inaccurate expression. The wind speed in our study was supposed to be a climatological feature, not a climate constant. And the wind speeds at 08:00 LT and 20:00 LT were used to calculate the ventilation coefficient approximately. Although it will be better to include the sounding data at noon, this is the best choice at present due to the acquired data confined. Relevant contents were supplemented in the conclusion section to explain the uncertainties of our study.

References:

Hu M., S. Liu, Z. J. Wu, J. Zhang, Y. L. Zhao, W. Birgit, and W. Alfred: Effects of high temperature, high relative humidity and rain process on particle size distributions in the summer of Beijing, Environ. Sci., 27(11), 2006.

Liu Z. R., Y. Sun, L. Li and Y. S. Wang: Particle mass concentrations and size distribution during and after the Beijing Olympic Games, Environ. Sci., 32(4), doi:10.13227/j.hjkx.2011.04.015, 2011.

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.