Reply to Referee 1

We are grateful to the referee for the encouraging comments and careful revisions, which helped to improve the quality of our paper. In the following we quoted each review question in the square brackets and added our response after each paragraph.

[The paper can be improved with more in-depth discussion. In the introduction, the authors can write a more comprehensive literature review on the precipitation-aerosol relationship, such as, what are controversy issues, what are the research gaps and what are the possible underlying mechanisms for various processes. Then the review can lead to what the authors will address in this paper. The conclusions and abstract seem to have different emphasis. What do the authors really like to emphasize? Should the authors also discuss, in conclusion, the spatial correlation pattern between visibility and rainstorms and other issues emphasized in the abstract?]

Reply 1: Many thanks to the reviewer for the great suggestions. Following the suggestions, we have substantially improved the manuscript with more in-depth discussion with modifying the introduction about a more comprehensive literature review on the precipitation-aerosol relationship and highlighting our study results in both conclusions and abstract.

Please find the detailed revisions in the uploaded marked-up manuscript version with track changes.

[The presentation can be greatly improved. Please pay close attention on the presentation because poor presentation can hamper the readers from understanding the contents in the paper. There are numerous places requiring polishing on presentation and corrections for grammatical errors. Some examples are provided in Specific. The authors can take advantage of the editing service provided by the journal.]

Reply 2: We are grateful to the referee for encouraging comments. We have greatly improved the presentation with rewriting the sentences and correcting the grammatical errors in the revised manuscript. Please find the detailed revisions in the uploaded marked-up manuscript version with track changes.

[Figure 3 shows trends for different rain intensity. Have the authors looked into the total precipitation? What is the trend? What that trend tells us?]

Reply 3: Thanks for the suggestions. We have looked into the total precipitation averaged over Eastern China. The trend in the interannual variations of the total precipitation from 1961 to 2010 is insignificant, which indicates that the impact of aerosols on precipitation could be complicated by different rain intensity.

[Figure 10 can be improved in the presentation and discussion. How significant is the correlation at each level? The statement in line 204 “indicating they were negatively correlated at low boundary layer” is not supported by Figure 10a and 10b.]

Reply 4: Following the referee’s suggestion, we have modify Fig. 10 and the corresponding text in the revised manuscript as follows:

To reveal the relationship between aerosols and atmospheric vertical thermal structure, the correlation between surface $PM_{2.5}$ concentration and atmospheric thermal structure in both polluted and clean areas in July, 2013 was investigated (Fig. 10). The stations of Changsha and Hongjia located in Hunan and Zhejiang provinces in EC respectively were selected to represent the less light rain region while those of Linzhi and Dingriin of Tibet were selected to represent the high-frequency light rain region. The correlation coefficient profiles between the observed surface daily $PM_{2.5}$ concentration and atmospheric temperature profiles derived from high-resolution L-band sounding were calculated. The correlations at Changsha and Hongjia stations (Figs.10a-b) show that the correlation between $PM_{2.5}$ and temperature profiles presented an "inverse phase" pattern, reflecting the high aerosol concentrations in a thermal stable structure similar to temperature inversion layers with "cold at low-layer and warm at upper-layer" in the eastern China. On the contrary, the correlations in Linzhi and Dingri stations in the Tibetan Plateau (Fig. 10c-d) indicate that an unstable atmospheric structure with "warm at low-layer and cold at upper-layer" for a favorable condition for the occurrence and development of convection and light rain events in the Tibetan region.

.

[Line 33, delete “It is widely acknowledged that”.]

Reply 5: it has been deleted in the revised manuscript.

[Line 46, give the full expression of CCN IN.]

Reply 6: The full expressions of CCN and IN have been given with “cloud condensation nuclei” and “ice nuclei” in the revised muanscript.

[Line 51, use “An earlier study showed” to replace “The study shows”.]

Reply 7: It has been changed. .

[Line 75-82 Data, some descriptions on quality control would be helpful.]

Reply 8: The precipitation data are archived at the China Meteorological Administration（CMA） with the conventional quality control of global climate data.

[Line 76-77, some description on MODIS data would be helpful, for example, what is the resolution of the MODIS data? How are the data used in this study?]

Reply 9: because the MODIS aerosol products are not used in the result analysis of revised manuscript, we have deleted the sentence "annual average AOD data in 2001-2010 from Moderate Resolution Imaging Spectroradiometer (MODIS)" at the beginning of Section 2. Data. Therefore, we have not given any information on MODIS data in the revised manuscript..

[leave space between 200 and mm. Correct the same problem in the rest of the paper. For example, in Lines 78, 79, 94 and 95.]

Reply 10: Thank the referee for careful review. It has been corrected.

[Line 108, Xu et al. (2016) is missing in Reference]

Reply 11: we have added the following ACP-paper into References:

Xu, X., Zhao, T., Liu, F., Gong, S. L., Kristovich, D., Lu, C., Guo, Y., Cheng, X., Wang, Y., and Ding, G.: Climate modulation of the Tibetan Plateau on haze in China, Atmos. Chem. Phys., 16, 1365-1375, doi:10.5194/acp-16-1365-2016, 2016.

[Line 130, delete "trends" and "extreme".

Line 112, use "the differences in the trends between" to replace "the interannual variation trend differences for".

Line 117, use "rainstorm, especially large rainstorms, have presented a significant increase trend" to replace "rainstorm and especially large rainstorm extreme events presented significantly an increased trend".

Line 118, delete an extra comma.]

Reply 12: The careful reviews are greatly appreciated. All the errors have been corrected in the revised manuscript.

[Line 130, delete "trends" and "extreme".]

Reply 13: The have been deleted.

[Line 112, use "the differences in the trends between" to replace "the interannual variation trend differences for".]

Reply 14: It has been done in the revised manuscript.

[Line 117, use "rainstorm, especially large rainstorms, have presented a significant increase trend" to replace "rainstorm and especially large rainstorm extreme events presented significantly an increased trend".]

Reply 15: Following the referee's comments, it has been revised.

[Line 118, delete an extra comma.]

Reply 16: It has been deleted.

[Line 123-126, the sentence can be rephrased as "The areas with negative trends in light rain frequency almost matched with areas with positive trends in visibility and haze frequency in EC (Fig. 4a,b and c), which are well consistent with the area of high aerosol concentrations and frequent haze events (Fig.2a,b). The light rain frequency reduction in China was closely associated with the enhancement of aerosol levels in the atmosphere (Qian et al., 2009)."]

Reply 17 : Following the suggestion, the lines 123-126 have be rephrased as "The areas with negative trends in light rain frequency almost matched with areas with positive trends in visibility and haze frequency in EC (Fig. 4a,b and c), which are well consistent with the area of high aerosol concentrations and frequent haze events (Fig.2a,b). The light rain frequency reduction in China was closely associated with the enhancement of aerosol levels in the atmosphere (Qian et al., 2009)." in the revised manuscript.

[Line 123-126, what is light rain frequency? Is it the number of days with light rain in a year? What are visibility and haze frequencies? Please define them clearly in the paper.]

Reply 18: It has been clarified with " The light rain frequency is the number of days with light rain in a year; and the visibility is in unit of km, haze frequency is the number of days with haze" in the revised manuscript.

[Line 127, The sentence can be rephrased as "The areas with negative trends in light rain almost covered eastern

China and a large part of China".]

Reply 19: The sentence has been rephrased as "The areas with negative trends in light rain almost covered eastern China and a large part of China" following the referee's suggestion. .

[Line 142-143, change the phrase as "make the number of cloud droplets increase but the size of cloud droplets decrease".]

Reply 20: Thanks for the suggestion. Following the referee's suggestion, it has been changed.

[Line 159-160, change the phrase as "As shown in Fig. 6b (left), in the three periods".]

Reply 21: It has been changed.

[Line 171, use "significant increasing trends" instead.]

Reply 22: It has been done.

[Line 176, delete "could".]

Reply 23: Thank the referee for the kind suggestions. It has been done.

[Line 197, use "PM2.5" instead.]

Reply 24: It has been done.

[Lines 198, 219, 225, 226, add "s" after "concentration".]

Reply 25: It has been done.

[Lines 220, 225, 226, delete "s" after "droplet".]

Reply 26: It has been done.

[Line 224, use "These aircraft observations showed" instead.]

Reply 27: It has been changed in the revised manuscript.

[Line 229, use "and the effects depend" to replace "depending".]

Reply 28: It has been done in the revised manuscript.

[Line 235, delete “trend”.]

Reply 29: The “trend " has been deleted in the revised manuscript.

[Line 236, delete extra space between occurrence and more. Add a space between “with” and “an”]

Reply 30: It has been done in the revised manuscript.

[Line 237, add “the” before “1960”]

Reply 31: It has been changed in the revised manuscript.

[Line 234, delete “of precipitation events” before “and”.]

Reply 32: It has been deleted in the revised manuscript.

[There are various problems in the figures, their captions and annotations. The following are some examples for the authors to take into consideration.

1. Be consistent with the figure format;

2. Use the consistent fonts and font size;

3. Use correct term to label x-axis and y-axis.

4. Use capitalized words to label x-axis and y-axis;

5. Label sub-plots using letters (usually at the top, top-left, or top-right of a sub-plot);

6. Use superscripts and subscripts when necessary;

7. Provide the unit for the variable displayed if no unit, indicate with dimensionless or “(-)”;

8. Indicate the unit for the color bar.

9. Remove zeros for the most insignificant digit after a decimal.

10. Add significant level (p value) on trends.

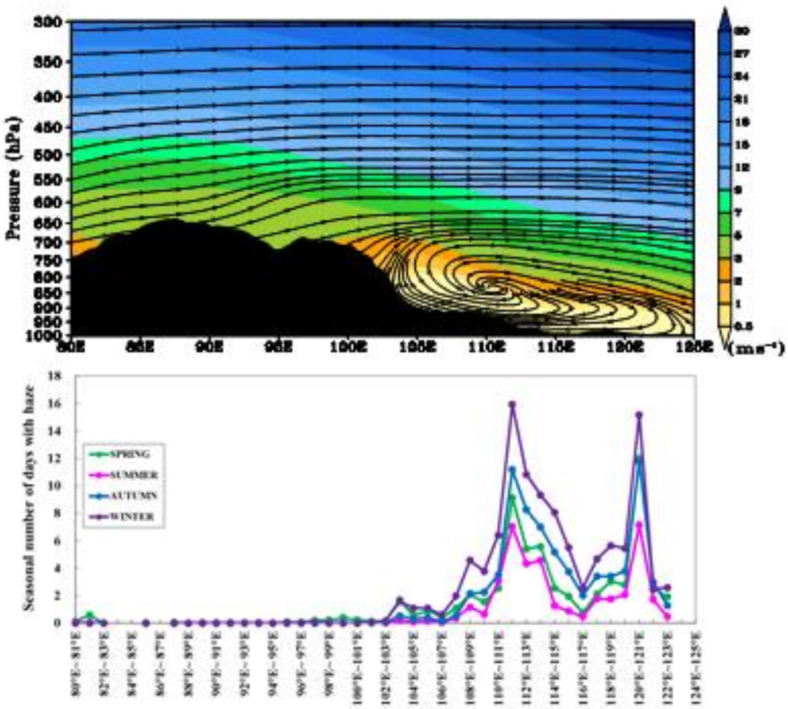
11. It is better to indicate latitude/longitude in the China maps in Figures 4 and 5.]

Reply 33: We are very grateful to the referee for the encouraging comments and careful revisions. All the mentioned problems in the figures, their captions and annotations have been corrected in the revised manuscript. All the figures have been redrawn following the referee’s suggetsions..

[Figure 2. Labelling sub-plots (a) and (b). Capitalize “pressure” for the label for the y-axis in Figure 2a. It should be “ Pressure (hPa)” so to leave a space between “pressure” and its unit. In the caption, wind speed

should have a unit of m s-1. Please use correct superscripts.]

Reply 34: Following the referee's suggestion, Figure 2 has been modified as follows:



[Figure 3. Use the same font and font size to label sub-plots. No need for zeros after a decimal point in y-axis. Label "Precipitation" or "Rain" for the y-axis in Figure 3a. Use "Year" to label x-axis (not "date"). Add significant level (p-value).]

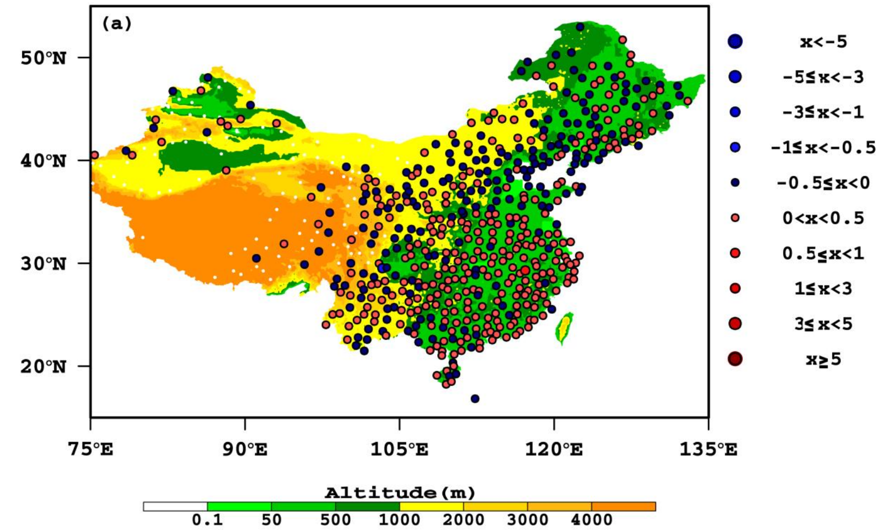
Reply 35: Following the suggestion, has Fig. 3 suggested been modified in the revised manuscript.

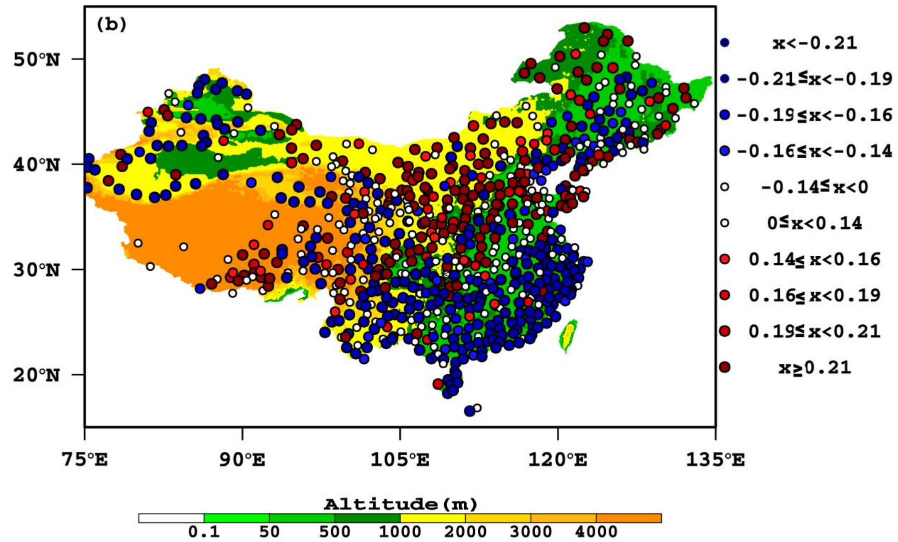
[Figure 4. Label (a), (b), (c) for the subplots. Provide the unit for haze frequency, visibility, and light rain frequency. Indicate what the dots and the background stand for. Indicate the unit for the color bar.]

Reply 36: We have changed Figure 4. Label (a), (b), (c) for the subplots. In the revised caption of Fig. 4, we have added "haze frequency (day), visibility (km), and light rain frequency (day). The dots stand for observation sites with shading by the variation trends, the background presents the terrain height in mainland China".

[Figure 5. Label (a) and (b) for the subplots. Provide the unit for the trend of the rainstorm frequency. Indicate what the dots and the background stand for. Indicate the unit for the color bar.]

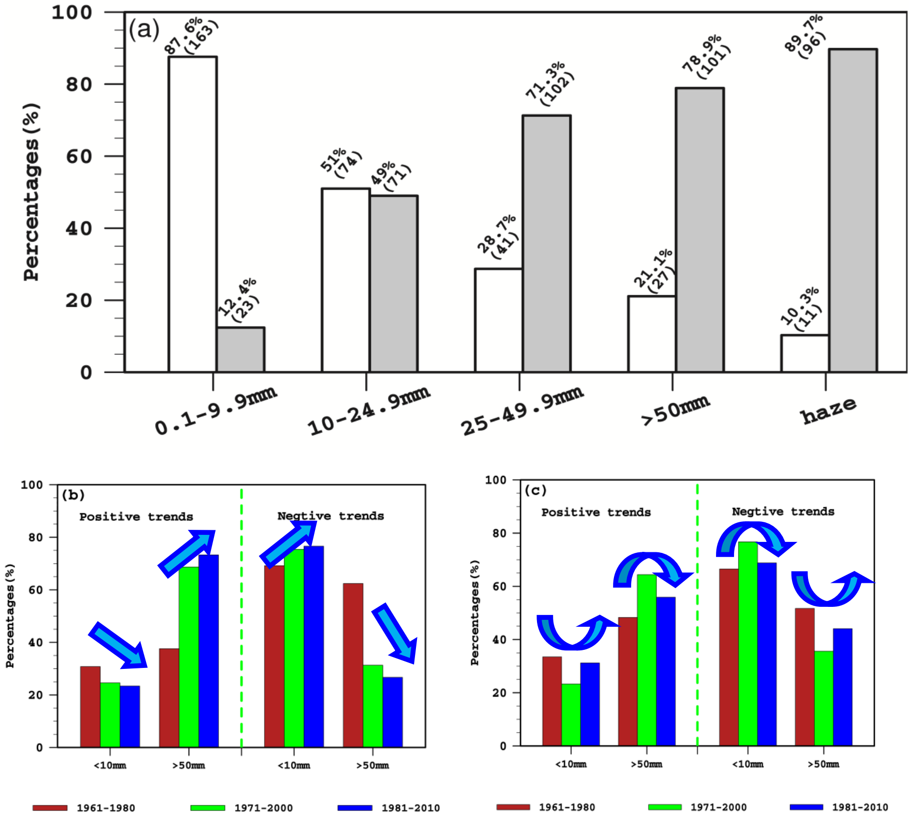
Reply 37: We have redrawn Fig. 4 as follows and revised the caption as "the trend (day per year) of the rainstorm frequency and the background (shaded colors) stands for the terrain height (m) in mainland China





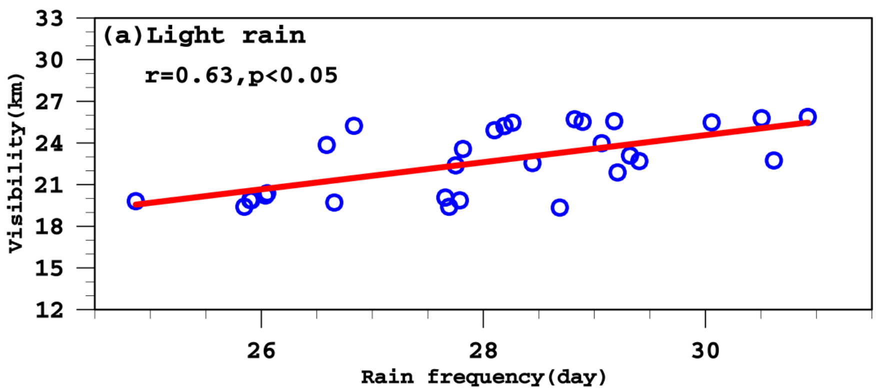
[Figure 6. Label (a), (b) and (c) for the subplots. In Figure 6a, no color is needed as this will cause confusion with Figure 6b and 6c. Good titles for each figure will help readers to understand the differences between Figure 6a and Figure 6b and 6c. Otherwise, the figure can be quite confusion. In the caption, it is better to use "the positive (negative) trend" than "the positive (negative) variability".]

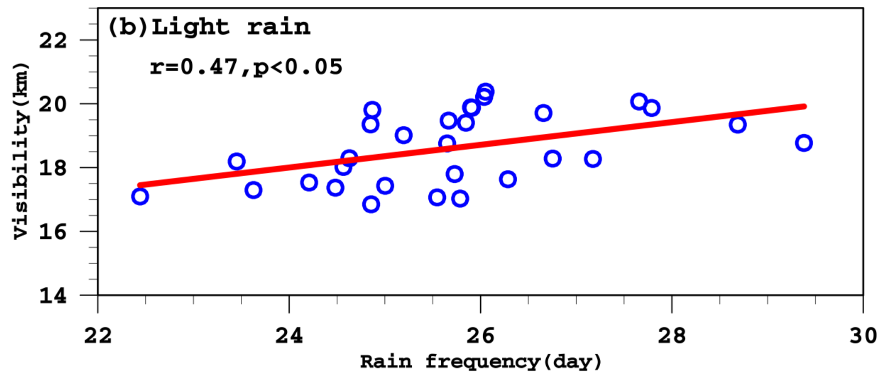
Reply 38: We have redrawn Fig. 5 as follows, and following the suggestiuon, the caption has been revised.

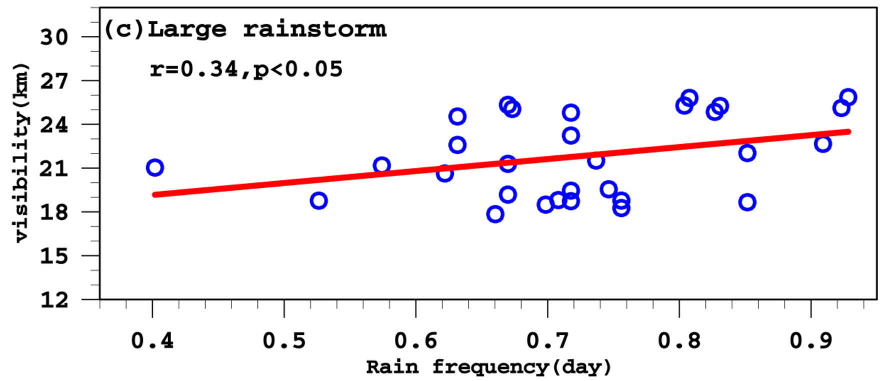


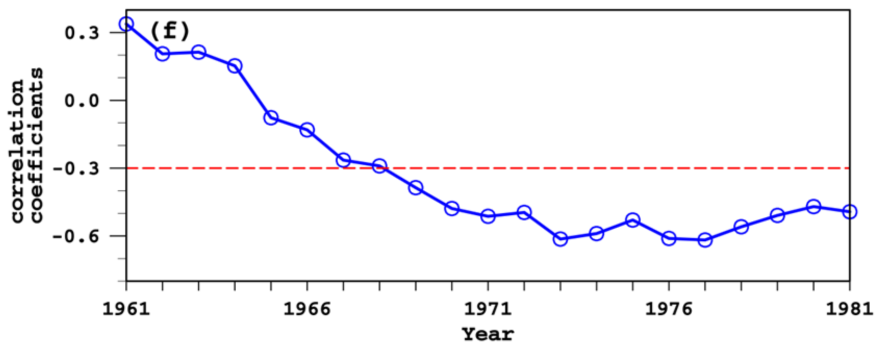
[Figure 7. Label sub-plots at the top, top-left, or top-right. Remove zeros for the most insignificant digit after a decimal. Keep sub-plots (a) –(d) the same size.]

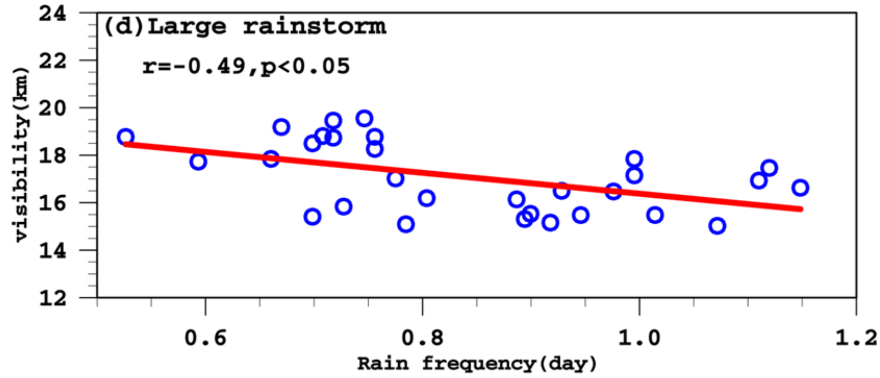
Reply 39: Following the referee's suggestion, in the revised manuscript, Figs. 7a -7f have been redrawn as follows:




(b)Light rain
r=0.47,p<0.05
Visibility(km)
Rain frequency(day)
22
20
18
16
14
22
24
26
28
30


(c)Large rainstorm
r=0.34,p<0.05
visibility(km)
Rain frequency(day)
30
27
24
21
18
15
12
0.4
0.5
0.6
0.7
0.8
0.9


(f)
correlation coefficients
Year
0.3
0.0
-0.3
-0.6
1961
1966
1971
1976
1981


(d)Large rainstorm
r=-0.49,p<0.05
visibility(km)
Rain frequency(day)
24
22
20
18
16
14
12
0.6
0.8
1.0
1.2

[Figure 9. Provide the unit for the dots.]

Reply 40: The revised caption of Figure 9 has provided the unit of day for the dots.

[Figure 10. For the label for the c-axis, remove "index".]

Reply 41: It has been removed in the revised manuscript.

[Figure 11. What are the different marks in Figure 11a?]

Reply 42: In the revised caption of Figure 11a, we have added "the different marks represent the different flights"**.**

Reply to Referee 2

We are grateful to the referee for the encouraging comments and careful revisions which helped to improve the quality of our paper. In the following we quoted each review question in the square brackets and added our response after each paragraph.

[The manuscript is thorough, clear, compelling, very well written, and presents the results with good figures and tables. I recommend publication after attending to the following detailed comments.]

Reply 1: the referee's encouraging comments are great appreciated. We have revised our manuscript following the detailed \ comments of referee.

[Line 71: Please give references for the previous investigations of this issue primarily focused on limited cases (references).]

Reply 2: Thanks for the suggestion. Accordingly, we have given the following references in the revised manuscript:

Li, Z., Niu, F., Fan, J., Liu, Y., Rosenfeld, D. and Ding, Y.: Long-term impacts of aerosols on the vertical development of clouds and precipitation, Nat. Geosci. 4, 888–894, 2011.

Rosenfeld, D., Dai, J., Yu, X., Yao, Z., Xu, X., Yang, X. and Du, C.: Inverse relations between amounts of air pollution and orographic precipitation, Science 315,1396-1398, 2007.

Zhao, T. Liu, D., Zheng, X., Yang, L., Gu, X., Hu, J., Shu, Z., Chang, J., Wu, X.: Revealed variations of air quality in industrial development over a remote plateau of Southwest China: an application of atmospheric visibility data, Meteorol Atmos Phys, doi:10.1007/s00703-016-0492-7, 2016.

[Please give a website or reference for MODIS data.]

Reply 3: because the MODIS aerosol products are not used in the result analysis of revised manuscript, we have deleted the sentence "annual average AOD data in 2001-2010 from Moderate Resolution Imaging Spectroradiometer (MODIS)" at the beginning of Section 2. Data. Therefore, we have not given any information on MODIS data in the revised manuscript..

[For all of Chinese map, if the author can use LambertEqualArea projection (http://ncl.ucar.edu/Applications/maponly.shtml), that would be nice.]

Reply 4: Thanks for the suggestion, In order to more clearly present the regional distributions of our results over mainland of China, we have used cylindrical map projection for all of Chinese map..

[Fig. 10: Please restrict the four panels in the same size.]

Reply 5: Following the referee's suggestion, we have restricted the four panels of Fig. 10 in the same size. Please see the modified Fig. 10 in the revised manuscript.

.

Are precipitation anomalies associated with aerosol variations over Eastern China?

Xiangde Xu[1], Xueliang Guo[1,2,*], Tianliang Zhao[3,*], Xingqin An[1] ,Yang Zhao[1], Jiannong Quan[4], Fei Mao[1], Yang Gao[4], Xinghong Cheng[1], Wenhui Zhu[1], and Yinjun Wang[1]

[1]State Key Laboratory of Severe Weather (LASW), Chinese Academy of Meteorological Sciences, Beijing 100081, China, [2]Key Laboratory for Cloud Physics, Chinese Academy of Meteorological Sciences, Beijing 100081, China , [3]Collaborative [3]Innovation Center on Forecast and Evaluation of Meteorological Disasters, Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science & Technology, Nanjing 210044,China, [4]Beijing Weather Modification Office, Beijing 100089, China

* *Correspondence to*: Tianliang Zhao (tlzhao@nuist.edu.cn); Xueliang Guo (guoxl@camscma.cn)

Abstracts. In Eastern China (EC), the strong anthropogenic emissions deteriorate the atmospheric environment harbored by the upstream Tibetan and Loess Plateaus, building a south-north zonal distribution of high anthropogenic aerosols harbored by the upstream Tibetan and Loess Plateaus in China. This research study climatologically analyzed the interannual variability of precipitations with different intensities in association with aerosol variations in over the EC region from 1961 to 2010.,– by using precipitation and visibility data in of more than 50 years and satellite, aircraft and surface aerosol data in recent years in China, the impacts of aerosol variations on interannual variability of various precipitation intensities of precipitation events and their physical causes are investigated. We found that the frequency of light rain significantly decreased and the occurrence of rainstorm, especially the extraordinary rainstorm significantly increased over the recent decades. The extreme precipitation events presented the same similar interannual variability pattern with the frequent haze events over the EC. Accompanied with the frequent haze events in EC, the light rain frequency trend significantly decreased , Especially, since the 1980s the extremely heavy precipitation event have occurred more frequently.Moreover, the extreme rainfall events of various intensities showed a regular interannual variability trend. During the 1980s, the regional precipitation trends in EC showed an obvious "transform" from more light rain to more extreme rainstorms. The running correlation analysis of interdecadal variation further verified that the correlation between the increasing aerosol aerosolsemissions and the frequency of abnormal precipitation events tended to be more significant in the EC. The correlation between atmospheric visibility and low cloud amounts, which are both closely related with aerosol concentrations, had a spatial distribution of "northern positive and southern negative" pattern, and the spatial distribution of the frequency variability of regional rainstorm frequency s was "southern positive and northern negative". After the 1990s, the visibility in summer season deteriorated more remarkably than other seasons, and the light rain frequency decreased obviously while the rainstorm and extraordinary heavy rainfall occurred more frequently. There were significant differences in the interdecadal variation trends in light rain and rainstorm events between the high aerosol concentration polluted areas in the EC and the relatively "clean area" in western plareau of China. The aircraft measurements over the EC confirmed that the diameters of

cloud droplets decreased under high aerosol concentration condition, thereby inhibiting weak precipitation process.

1. Introduction

It is widely acknowledged that the global mean temperature has been increasing since 1850 and will continue to increase in the following decades (IPCC, 2007). The long term forcing of a warming environment might change precipitation, the regional and global water cycle (Allan and Soden, 2008; Allan and Ingram, 2002). The heavy precipitation events showed a overall increasing trend as the result of global warming (Allan and Ingram, 2002; Trenberth et al., 2003). Since the 1950s, the precipitation has increased remarkably at high latitudes, also increased at tropical marine areas, but it underwent some decrease at tropical mainland (New et al., 2001; Kumar et al., 2006; Bosilvoich et al., 2005).

The variation of aerosols in atmosphere is also an important factor to influence the water cycle in regions where bearing long-term high aerosol loading (Ramanathan et al., 2005; Ramanathan et al., 2007; Koren et al., 2008; Levin and Cotton, 2009; Li et al., 2011). Under the background of global warming, the regional precipitation tends to have more complex temporal and spatial distribution patterns. The variations of precipitation could be reflected by the different-grade precipitation, and even by frequency changes of extreme precipitation events (Lau and Wu, 2007). , which could threaten the social economy and is seriously concerned by governments, public and scientific community.

Precipitation is not only influenced by atmospheric circulation structure related with land-sea discrepancy and land-sea water vapor exchange, but also by local cloud microphysical processes (e.g., CCN, IN). Studies have shown that atmospheric aerosols might add cloud droplets number concentrations (CDNC), and change cloud lifetime, and restrain or enhancemodify precipitation (Khain et al., 2005; Rosenfeld et al., 2007; Rosenfeld and Coauthors, 2008; Stevens and Feingold, 2009; Fan et al., 2013). Aerosols might also change Asian monsoon system (Bollasina et al., 2011). The interaction of aerosols and cloud-precipitaion is still a important issue with large uncertainties for climate change (IPCC, 2013).

Since the middle 1980s, China has been experienced experiencing a rapid development in industry and agriculture. As a result, a huge amount of industrial anthropogenic emissions and biomass burning significantly released particulate matters into the atmosphere. The study shows that there was no obvious change in annual precipitation in China, but the extremely heavy rainfall area, mainly in the EC, had expanded (Zhai et al., 1999). However, the regional annual precipitation, summer precipitation, and extreme precipitation events had an obvious rising tendencies in middle and lower Yangtz River Basin of EC (Wang and Zhou, 2005). The numerical simulations also presented that the increase of aerosols could decrease the summer convective precipitation in the intensity under 30 mm h^{-1}, and increase summer strong convective precipitation in the rates above 30 mm h^{-1} in China (Guo et al., 2014). With a rapid increase of aerosols, not only local light rain over wide areas could decrease, but also local extremely heavy rain could be triggered, inducing frequent flood (Guo et al., 2014; Fan et al., 2015). Light rain tended to decrease and at the same time the extremely heavy precipitation had increasing tendency in the EC (Choi et al., 2008; Qian et al., 2007; Qian et al., 2009). This phenomena might be the strong signal of climate variability connecting to global warming together with the increased emissions of anthropogenic aerosols.

Aerosols might also change Asian monsoon system (Bollasina et al., 2011). There are great uncertainties in the interactions between the internal influence factors including complex influences of land sea discrepancy, aerosols and cloud and precipitation processes of Asia monsoon system and external forcing factors.

The previous investigations of this issue primarily focused on limited cases with large discrpancies (Rosenfeld et al., 2007; Rosenfeld and Coauthors, 2008; Stevens and Feingold, 2009; Li et al., 2011; Zhao et al., 2016Fan et al., 2013). The climatic forcing of aerosols on precipitation extremes in a large-scale continent region and its physical causes remain uncertainhave been poorly understood. The long-term visibility data can be used to climatologically assess the air quality change (Wang et al. 2009; Che et al. 2009; Xia et al. 2006), as the atmospheric visibility is a good indicator of air pollutant levels in the environmental atmosphere (Zhao et al., 2016). By using precipitation and visibility data in a 50-year period and aircraft and surface aerosol observational data in recent years in China, the climatic impacts of aerosols on interannual variability of various precipitation intensities and their physical links were investigated in this study. .The large amounts of anthropogenic aerosols not only deteriorate the environment over large spatial scales, but they might induce the rapid change of regional climate and water cycle. In addition,, the high aerosol concentrations are accumulated zone in the north-south direction over China is located onover EC in connection with the eastern side of the Tibetan plateau and the Loess plateau, which might be connected with the leeward slopes of the large terrain structure effect of the Tibetan plateau and the Loess plateau in China (Xu, et al, 2016).the plateaus. The polluted EC regions from and the clean the plateaus to ECin China may be an the ideal places to identify the climate forcing of aerosols with following questions: with comparing the interannual variation trends in various precipitation intensities betweenthe polluted EC with the clean region over the Tibetan plateaufor exploring .the realtion of precipitation anomalies and aerosol variations. The previous investigations of this issue primarily focused on limited cases (Rosenfeld et al., 2007; Li et al., 2011; Zhao et al., 2016). The climatic forcing of aerosols on precipitation extremes in large-scale continent region and its physical causes remain uncertain. By using precipitation and visibility data in a 50-year period and satellite, aircraft and surface aerosol observational data in recent years in China, the climatic impacts of aerosols on interannual variability of various precipitation intensities and their physical links were investigated in this study.

2. Data

In this study, we classifed extraordinary storm, large rainstorm, rainstorm, large rain, moderate rain and light rain respectively with daily precipitation >200 and ranging between 100-200mm, 50-100mm, 25-50 mm, 10-25mm and 0.1-10mm in this study. In this work, we adopted annual average AOD data in 2001-2010 from Moderate Resolution

Imaging Spectroradiometer (MODIS);tThe monthly frequency data of different gradesintensity of precipitation events including of extraordinary storm (>200mm, the precipitation intensity classification standard for 24 hours),large rainstorm, rainstorm (100-200mm), large rainstorm heavy rain (25-50 mm), moderate rain (10-25mm), light rain (0.1-10mm) from 601 stations in China over 1961-2010 were adopted (Datasets from the National Meteorological Information Center of China Meteorological Administration); .In addition, the meteorological and environmental data including monthly haze days of 2513 stations, daily visibility of 598 stations and daily low cloud cover of 753 stations in 1961-2010in China as well as the daily $PM_{2.5}$ data of 946 stations in 2013-2014 in China were also used in this study.

In order to analyze the regional variations in aerosols over Eastern ChinaEC, we adopt the equivalent visibility by excluding the influence of natural factors (Rosenfeld et al., 2007) on the observed visibility based on the meteorological data observed from 598 stations in 1961-2010 were used in this study. The equivalent visibility was corrected VIS (dry) based on the the following formula (1) under the relative humidity from 40% to 9990%.

$$\frac{\mathrm{VIS}}{\mathrm{VIS(dry)}} = 0.26 + 0.4285\log(100 - \mathrm{RH}) \quad (1)$$

The characteristics of aerosol and cloud droplets size were comprehensively analyzed based on the aerosol-cloud data obtainedobserved from aircraft flights carried out inover Beijing and its surrounding regions during 2008-2010 by the Beijing Weather Modification Office. The scientific detection time was from May to August during 2008-2010.The observed clouds were mainly stratus cloud, stratocumulus and cumulus clouds, and the maximum detection altitude was 7000 m. There were 40 flights carried out during the experiment period. Aircraft measurements were usually carried out withinin 2-6 h before the clouds precipitated. The flight area and tracks were shown in Fig. 1. The Passive Cavity Aerosol Spectrometer Probe (PCASP-200，DMT Co.) was used for observing aerosol particle size in 0.1-0.3μm. The probe of Cloud, Aerosol and Precipitation Spectrometer (CAPS，DMT Co.) was used for observing cloud droplets in 0.6-50μm. The probes were returned to the DMT for standard calibration before starting measurements in each year. In addition, the probes were calibrated using the spheres of polystyrene latex (PSL) of Duke Scientific Corporation for each month. Considering the influence of cloud droplets on aerosol probing, the averaged aerosol concentration below 300m of cloud base was calculated to represent aerosol concentration in clouds. The cloud droplet –measurements were made within clouds at 100m height intervals. The data were processed into two or more samples when the clouds were multiply layered.

3 Haze distributions in Eastern China harbored by large plteaus

Due to the influence of the terrain on the typical westerly winds in Eastern China, the air flowing from the windward plateaus descends sinked in a north-south oriented zone between about 110°E and 125°E (upper panel of Fig. 2). Accompanying this strong downward current are were weak winds in the near-surface layers in the lee side of the plateaus. These air flow and wind condition lead to development of a "harbor" accumulating air pollutants in EC. The weak wind and downward current areas coincide well with the centers of frequent haze events in ChinaEC (lower panel of Fig. 2). The “susceptible region” of frequent haze events pollution over Eastern ChinaEC from the eastern edge of the plateaus to the lower flatlands is associated with the “harbor” effect of the unique topography under specific meteorological conditions that trap air pollutants (Xu etl al., 2016). The EC is clomatologically a region with frequent haze events over recent decades, where high aerosol pollution could excert an impact on the regional variation in precipitation.

4. Change trends in various precipitation intensities

The interannual variation trends interannual variation of extreme precipitation events with various intensities including light rain, moderate rain, heavy rain, rainstorm, the large rainstorm, extraordinary rainstorm (Fig. 3a) over EC were comparatively analyzed in Figure 3. and it is found that the interannual variation trend differences for the six various precipitation intensities were significant. Regionally averaged over EC,The the trends in light rain frequency had trend significantly decreased, while the events of rainstorm including large and extraordinary storm had increased significantly (Fig. 3a, A),), althrough the moderate rain frequency trend slightly declined (Fig. 3a, B), and the interannual change trend of heavy large rain frequency was not significant (Fig. 3a, C), the rainstorm and large rainstorm events increased significantly (Fig. 3a, D, E, F) in EC.. Especially since 1980s, the extremely heavy precipitation events have become more frequent, showing an obvious transforming characteristics of frequent heavy rain and torrential rainfrequent occrences of disatrous. Large rainstorm and especially large rainstorm extreme events presented significantly an increased trend, along with the frequent haze weather in EC. Overall rainstorm extreme events were on the rise trend, , but light rain tended to decline significantly. In contrast, stations in the Tibetan Plateau (atwith height altitude of >4000m), a relative clean area in China, were selected for a statistical analysis of interannual variation trend of light rain frequency. , indicating that tThe characteristic of the decreased trend of light rain frequency was not significant in the Tibetan Plateau over recent decades (Fig. 3b,A), implying an anomaly of aerosols restraining light rain frequency over EC..

5. Distribution of frequencyregioanl changes of extreme rainstormprecipitaion events, haze and visibility

We calculated the trends in interannual variations of precipitation and visibility at all the site in China (Fig. 4). The negative variability area with the negativeof trends in light rain frequency almostquite well matched with the areas of positive variability negative trends in of visibility and positive trends in haze frequency in EC (Figs. 4a,b and c)., which are well consistent with the area of high aerosol concentrations and frequent haze events (Fig. 2a,b). The light rain frequency reduction in China was closely associated with the enhancement –of aerosol levels in the atmosphere (Qian et al., 2009). It is noteworthy that the negative trend areas of light rain almost covered a large part of areas in China and all the sites in EC eastern China (Fig. 4c). This might be also closely related with temporal and spatial variations of n trends of summerEast

Asian summer monsoon~~s activity~~ which offered a suitable dynamic background for the effect of aerosols on clouds and precipitation. Figure 5a shows that the spatial distribution of the trends in rainstorm frequency ~~variability~~ was "southern positive and northern negative" in summer during 1961-2010, while the correlations between visibility and low-level cloud amount were distributed with the "northern positive and southern negative" pattern in EC during 1961-2010 in EC (Fig.5b), indicating that the effect of aerosols on summer convective precipitation was more obvious in southern part than that in northern part of EC.

There were obvious differences in the ~~interdecadal~~ precipitation ~~decreasing~~ change rate of~~ the~~ various precipitation intensities in the EC region (Fig.6a), where the ~~. In this region, the summer interdecadal precipitation variability revealed the influence features of aerosols on clouds and precipitation process, that~~ negative variability stations of light rain made up the majority (about 87.6%), the positive variability stations of moderate rain were approximately equal to the negative ones (about 51%), the positive variability stations of ~~heavy~~ large rain (about 71.3%) were much more than the negative ones indicating the reverse trend. The positive variability stations of rainstorm~~-~~with daily precipit~~-~~ation ~~—~~>50mm, including catastrophic rainstorm over 100mm occupied obvious majority (about 78.9%). ~~In China, in the recent decades, t~~The~~ rapid~~ increase of the anthropogenic aerosol particles in the atmosphere may not only ~~make the cloud droplet number concentration increased but the size of cloud droplet decreased, thus changing the life time of the cloud and~~ suppress~~ing the precipitation, especially for the~~ light rain (Qian et al., 2009), but also enhance~~.~~ the rainstorm precipitation with more frequent events in EC. ~~As mentioned above, the light rain frequency reduced significantly; the moderate rain frequency changed unobvious; heavy rain increased relatively obvious, rainstorm and catastrophic rainstorm increased significantly obvious in eastern China, indicating~~ the ~~obvious~~ anomalous change~~ characteristics~~s of regional precipitation from less light rain changed to more heavy rain and even the catastrophic rainstorm along with the frequent haze ~~trend~~ pollution in EC.

Although ~~severe~~ precipitation events ~~mainly~~ depended on dynamical and thermodynamic processes and water vapor source in the atmospheri~~c circulation and deep convective activity~~e, aerosol's "Albrecht effect" ~~considered that increased~~with increasing cloud droplet concentrations and ~~decreased~~ decreasing cloud droplet size i~~nfluenced by aerosol~~ ~~would~~ could suppress cloud precipitation process and extend cloud ~~maintenance~~ life time. The extension of the cloud life time might save the potential that triggering the abnormal severe precipitation extreme events ~~when the cloud droplets coagulation condition was mature~~. This mechanism could partly explain ~~the significant light rain reduction trend (Fig. 6a) and the spatial consistency indicating~~ the precipitation ~~rate transformation characteristics~~ degrading~~ of~~ from light rain to ~~heavy rain or~~ severe extreme ~~precipitation extreme~~ events (~~blue arrows in~~ Fig. 6a) in the polluted ~~eastern China~~EC region. ~~Moreover, in this research, in order to f~~Further~~-~~more~~we comparatively analyzed the effects of aerosol pollution in hazy EC on extreme precipitation events~~,~~ we selected~~ the region ~~of Tibetan Plateau~~ (west of 110°E, south of 40°N) of Tibetan Plateau (TP), a relative clean area in western China was selected~~,~~ as the reference area to comparatively analyze the effects of aerosol pollution in hazy EC on regional precipitation change, and . we calculated percentages of sites with negative frequency variability trends of light rain and positive trends of rainstorm events in total sites with the negative and positive and negative trends in visibilityhaze over the EC and TP regions duringin the three different interdecadal periods (1961-1980, 1971-2000, 1981-2010) in the (Fig. 6b) east and westEC and TP regions. As Deuing past more then 5 decades, could be seen from Fig. 6b (left), in the three stages, tThe positive variability of light rain and reainstorm were was steady a declining trended and augmented, receptively in the polluted EC, while the negative variability was an increasing trend in EC, while there were no obvious positive or and negative variability trend of light rain and rainstorm in the clean TP region Tibetan Plateau (double-headed arrows inright panel of Fig. 6b right).

6. interannual variability anomalies between atmospheric visibility and precipitation anomalies

Figure 7 further verified the relation of interannual variability of regional visibility and precipitation in EC over recent years. Regionally averged, less light rain events and more rainstorm occrences significantly from year to year in association with enhanced aerosol levels with declining vaisibility over EC (Figs. 7a, 7b, 7c and 7d). We calculated the correlation coefficients between regional averages of visibility with the frequency of light rain, heavy rain, extremely torrential rain over EC region (east to 110 °E, south to 40 °N), respectively in consideration of correlation pattern between visibility and various precipitation intensities. Therefore, Ttaking summer months (June, July and August) as examples, the 20-year running correlation coefficients of visibility and precipitation were obtained (presented in Figs. Figure 7e. It is very interesting that the interannual varaitions of visibility and precipitation over EC were evolved from positive correlations in the eraly 1960s to negative correlations in the 1970s and 1980s (Fig. 7e), reflecting the interaannul variation of the aerosol and precipitation interaction in changing climate. a, b and c). The running correlation coefficients curve of visibility and light rain reached the confidence level (90%), and the running correlation coefficients curve of visibility and heavy rain and extremely heavy rain reached the confidence level (90%). This statistical analysis results further verified that with the increase of aerosol emissions, visibility and various precipitation exhibited increasing significant correlation trends (Fig.6).

In order to investigate the seasonal and interannual variations of monthly correlation pattern between regional visibility and with light rain, as well as regional visibility and extremely precipitation events in EC, we illustrated the annual cross-section of monthly anomaly anomalies of visibility and number of days with light rain, visibility and heavy rainstrom, asin Figure 8. well as visibility and extremely heavy rainin. Through a comprehensive comparison of Figs. 8 a, b, c and d, we could find significant positive correlation between visibility and light rain, showing indicating that the poor visibility surpressed light rain frequency. Moreover, there was a significant difference between the changing trend of extremely precipitation events frequencyrainstorm and light precipitation frequency occurrences. The changes of heavy precipitationlarge and extraordinary rainstorm frequency from 1960s to 1980s ~~was~~ were not as prominent as ~~that~~ thoese at the latter period of 1990s, during which time visibility deteriorated remarkably, heavy and extremely heavy rain occurred frequently. Compared to other seasons, the influence effect of poor summer visibility was more significant in ~~China~~EC, showing summertime disastrous rainfalls happened more often with less light rain over recent years. ~~frequency decreasing significantly and sudden heavy rain and large heavy rain frequency increasing~~.

The increased atmospheric aerosol concentration may reduce the solar radiation to surface and decrease surface temperature. ~~At the same time, the polluted black carbon aerosols can strongly absorb solar short wave radiation and directly heat low-level atmosphere, and~~ forming a temperature inversion structure (Bollasina et al, 2011; Zhang et al., 2009; Bond et al., 2013; Bond et al., 2011; Grant et al., 2014; Seinfeld et al., 2008). ~~Therefore, the aerosol-radiation interaction could change the atmospheric stability and alter local or region atmospheric circulation and precipitation process.~~ This temperature inversion structure ~~increases~~ with the stability of atmospheric boundary layer ~~and~~ provides an important condition for the frequent occurrence of haze ~~and fog~~ events. The stable low-level structure also inhibits the weak convection development of atmospheric boundary layer, ~~so as to~~ reduc~~e~~ing the formation of low-level clouds and weak precipitation process. However, the strong dynamic convergence disturbance could destroy the stability of atmospheric boundary layer and cause the formation and development of severe rainstorms.

To further clarify the relation between aerosols ~~concentration~~ and light rain frequency, the light rain frequency distribution from 601 stations in July, 2013 is displayed (Fig.9). ~~It shows in Fig. 9 that t~~The light rain events have significantly declined in ~~the Yangtze River region of~~ EC with high aerosol concentrations have and but enhaced ~~while t~~ in the relative clean TP region ~~of Tibetan Plateau~~(Fig. 9).

To reveal the relationship between aerosols and atmospheric vertical thermal structure, the correlation between surface $PM_{2.5}$ concentrations and atmospheric thermal structure in both polluted and clean areas in July, 2013 was investigated (Fig. 10). The stations of Changsha and Hongjia located in Hunan and Zhejiang provinces in EC respectively were selected to represent the less light rain region while those of Linzhi and ~~Dingriin~~ Dingri of Tibet were selected to represent the high-frequency light rain region. The correlation coefficient profiles between the observed surface daily $PM_{2.5}$ concentration and atmospheric temperature profiles derived from high-resolution L-band sounding were calculated. The correlations at Changsha and Hongjia stations (Figs.10a-b) show that the correlation between $PM_{2.5}$ and temperature profiles presented an "inverse phase" ~~characteristic~~pattern, ~~indicating they were negatively correlated at low boundary layer and positively correlated at upper boundary layer or troposphere,~~ reflecting the high aerosol concentrations in a thermal stable structure similar to temperature inversion layers ~~like~~ with "cold at low-layer and warm at upper-layer" in the ~~eastern China~~EC. On the contrary, the correlations in Linzhi and Dingri stations in the ~~Tibetan Plateau~~TP (Fig. ~~9c~~10c,~~-~~d) indicate that an unstable atmospheric structure with "warm at low-layer and cold at upper-layer" ~~for~~ with a favorable condition for the occurrence and

带格式的：下标

development of weak convection and light rain events in the Tibetan regionTP.

7. Physical connection between aerosols and precipitation

According to the results of observation and modeling studies, the increased aerosol concentrations could reduced effective particle radius and increased number concentration of cloud droplets, and latent heat release (Khain et al., 2005; Van den Heever et al., 2006; Tao et al., 2007; Altaratz et al., 2014). The increase of cloud droplets concentrations would delay raindrop formation, thereby lessening light precipitation (Qian et al., 2009) leadingfor the negative correlation between aerosols and light precipitation in China (Choi et al., 2008).

In order to further investigate confirm the relationship between aerosols and cloud droplets, the cloud dropletobserved data observedcollected by aircraft in north China during 2008-2010 were used. The vertical profiles of cloud droplets data at each level under different aerosol state obtained by 40 aircraft is shown in Figure . 11.a. From Figures . 11a and Fig. 11b, aerosol Albrecht "cloud lifetime effect" was significant in the Northern northern EC. As shown in red profile of Fig. 11b, uUnder the background of high aerosol concentrations, the cloud droplets sizes were smaller and increased slowly with the increasing altitude (red profile of Fig. 11b). In addition, from the cloud base to 2000m, the cloud droplets size remained less than 20 microns (Fig.11b), resulting in precipitation delay, in favour of cloud system development to form heavy rain easily. In addition, cCloud droplets diameter enlarged quickly with the increase of height, and reached 30 microns easily to forming light rain at 1000m altitude under low aerosol concentrations (green profile in Fig.11b). The above aircraft observation analysis showed that under the condition of insufficient water vapor in the North China relative to that in the southern China, high aerosol concentrations could reduce cloud droplets size, increase cloud droplets concentrations, extend cloud lifetime, and thiswhich would could restrain the development of low clouds, especially restrict the light rain process.

8. Discussion and conclusions

Aerosols have complicated effects on clouds and precipitation, depending on many factors such as aerosol properties, topography and meteorological conditions. The most previous investigations of aerosol impacts on clouds and precipitation are primarily based on limited cases in relatively smaller spatial and temporal scales. the climate forcing of aerosols on precipitation in large-scale continent region and physical causes remain uncertain. By using precipitation and visibility data in of more than 50 years and satellite, aircraft and surface aerosol data in recent years in China, the impacts of aerosol variations on interannual variability of various precipitation intensities of precipitation events and their physical causes are investigated.

Accompanied with the frequent haze events in EC, the light rain frequency trend significantly decreased. Especially, since the 1980s the extremely heavy precipitation event have occurred –more frequently with an obvious transform from more light rain to more frequent heavy rain and rainstorm. ~~From 1960s to 1970s~~In the 1960s, the monthly visibility and light rain presented a significantly positive correlation, while the visibility was in good condition~~, and the light rain frequency was also in high value~~. In recent ~~20~~ 30 years, the dramatically increased aerosols resulted in poor visibility, and the light rain frequency decreased obviously, and, heavy and extremely heavy rain occurred more frequently.

The investigation of relation between aerosol concentrations and light rain frequency distributions~~ from 601 stations~~ in July, 2013 in China shows that that the light rain~~ in the Yangtze River region of EC with high aerosol concentration~~ appeared significantly low~~-~~frequency in the EC region with high aerosol concentrations , and but ~~while that in the relative clean region of Tibetan plateau presented significantly~~ high-frequency in the relative clean region of Tibetan plateau presented significantly. ~~. The physical cause of this relation was investigated, and found that the h~~High aerosol concentrations was strongly correlated to ~~the~~ warming low-level atmospheric ~~warming which tended~~ to forming a stable structure ~~that suppressed~~ suppressing the occurrence and development of ~~weak convection and~~ light rain events in ~~eastern China~~EC~~,~~. The aircraft measurements over the EC confirmed that the diameters of cloud droplets decreased under high aerosol concentration condition, thereby inhibiting weak precipitation process.~~while this was not be found in the relatively clean region over the Tibetan plateau~~.

The findings from this study have ~~some~~ important implications for aerosol and precipitation interaction. ~~:~~the frequent haze events in EC not only cause regional environment deterioration, but also ~~threaten the social economy and people life in large spatial and temporal scales, and possible~~ induce the long-term change of regional water cycle~~. This may exacerbate~~ with the effect ~~of~~ on regional climate change.

Acknowledgements

The study was supported by the National Key R & D Program Pilot Projects of China (JFYS2016ZY01002213; 2016YFC0203304), the National Natural ScienceFoundation of China (91544109; 91644223), the project of Environmental Protection (HY14093355; 201509001) in the Public Interest and Chinese Third Tibetan Plateau Atmospheric Experiment (GYHY201406001).

Reference

Allan, R. P. and Soden, B. J.: Atmospheric warming and the amplification of precipitation extremes, Science 321, 1481-1484, 2008.

Allen, M. R. and Ingram, W. J.: Constraints on future changes in climate and the hydrologic cycle, Nature 419, 224-232, 2002.

Altaratz, O., Koren, I., Remer, L. A. and Hirsch, E.: Review: Cloud invigoration by aerosols-coupling between microphysics and dynamics, Atmos. Res., 140-141, 38-60, 2014.

Bollasina, M. A., Ming, Y., and Ramaswamy, V.: Anthropogenic aerosols and the weakening of the South Asian summer monsoon, Science 334, 502-505, 2011.

Bond, T. C., and Coauthors: Bounding the role of black carbon in the climate system: A scientific assessment, J. Geophys. Res., 118, 5380-5552, 2013.

Bond, T. C., Zarzycki, C., Flanner, M. G., and Koch, D. M.: Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse, Atmos. Chem. Phys. 11, 1505-1525, 2011.

Bosilovich, M. G., Schubert, S. and Walker, G.: Global changes of the water cycle intensity, J. Climate 18, 1591–1607, 2005.

Choi, Y. S., Ho, C. H., Kim, J., Gong, D. Y. and Park, R. J.: The impact of aerosols on the summer rainfall frequency in China, J. Appl. Meteor Climatol.47, 1802-1813, 2008.

Fan, J., Leung, L. R., Rosenfeld, D., Chen, Q., Li, Z., Zhang J. and Yan H.: Microphysical effects determine macrophysical response for aerosol impacts on deep convective clouds. Proc. Natl. Acad. Sci.110, E4581-E4590, 2013.

Fan, J., Rosenfeld, D., Yang, Y., Zhao, C., Leung, L. R. and Li, Z.: Substantial contribution of anthropogenic air pollution to catastrophic floods in southwest China, Geophys. Res. Lett. 42, 6066-6075, 2015.

Fu, Q., Johanson, C. M., Wallace, J. M. and Reichler, T.: Enhanced midlatitude tropospheric warming in satellite measurements, Science 312, 1179, 2006.

Grant, L. D. and van den Heever, S. C.: Microphysical and dynamical characteristics of low-precipitation and classic supercells, J. Atmos. Sci. 71, 2604–2624, 2014.

Guo X. L., Fu, D. H., Guo, X. and Zhang, C. M.: A case study of aerosol impacts on summer convective clouds and precipitation over northern China, Atmos. Res.142,142-157, http://dx.doi.org/10.1016/j.atmosres.2013.10.006, 2014.

IPCC, In Summary for Policymakers, in Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 1-18, 2007.

Khain, A. P., Rosenfeld, D. and Pokrovsky, A.: Aerosol impact on the dynamics and microphysics of deep convective clouds, Quart. J. Roy. Meteor. Soc.131, 2639-2663, 2005.

Koren, I., Martins, J. V., Remer, L. A. and Afargan, H.: Smoke invigoration versus inhibition of clouds over the Amazon, Science 321, 946-949, 2008.

Kumar, A., Yang, F., Goddard, L. and Schubert, S.: Differing trends in the tropical surface temperatures and precipitation over land and oceans, Journal of Climate,17, 3, 653-664, 2004.

Lau, K. M. and Wu, H. T.: Detecting trends in tropical rainfall characteristics, 1979-2003, Int. J. Climatol., 27, 979-988, 2007.

Levin, Z. and Cotton, W. R.: Aerosol pollution impact on precipitation: A scientific review, Springer, 386, 2009.

Li, Z., Niu, F., Fan, J., Liu, Y., Rosenfeld, D. and Ding, Y.: Long-term impacts of aerosols on the vertical development of clouds and precipitation, Nat. Geosci. 4, 888–894, 2011.

Liu, S. C., Fu, C., Shiu, C. J., Chen, J. P. and Wu, F.: Temperature dependence of global precipitation extremes, Geophys. Res. Lett, 36, L17702, doi: 10. 1029/2009GL040218, 2009.

New, M., Todd, M., Hulme, M. and Jones, P.: Precipitation measurements and trends in the twentieth century, J. Climatol. 21, 1899–1922, 2001.

Qian, W., Fu, J., and Yan, Z.: Decrease of light rain events in summer associated with a warming environment in China during 1961-2005, Geophys. Res. Lett.34, L11705. DOI: 10.1029/2007GL029631, 2007.

Qian, Y., Gong, D. Y., Fan, J. W., Leung, L. R., Bennartz, R., Cheng, D. L. and Wang, W. G.: Heavy pollution suppresses light rain in China: Observations and modeling, J. Geophys. Res, 114, D00K02, doi: 10. 1029/2008JD011575, 2009.

Ramanathan, V., Chung, V. C. and Kim, D.: Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, Proc. Natl. Acad. Sci.102, 5326–5333, 2005.

Ramanathan, V., Ramana, M. V. and Roberts, G.: Warming trends in Asia amplified by brown cloud solar absorption, Nature 448, 575–578, 2007.

Rosenfeld, D. and Coauthors.: Flood or drought: How do aerosols affect precipitation? Science 321, 1309-1313, 2008.

Rosenfeld, D., Dai, J., Yu, X., Yao, Z., Xu, X., Yang, X. and Du, C.: Inverse relations between amounts of air pollution and orographic precipitation, Science 315,1396-1398, 2007.

Seinfeld, J.: Atmospheric science: Black carbon and brown clouds, Nat Geosci 1, 15–16, 2008.

Stevens, B. and Feingold, G.: Untangling aerosol effects on clouds and precipitation in a buffered system, Nature 461, 607-613, 2009.

Tao, W. K., Li, X., Khain, A., Matsui, T., Lang, S. and Simpson, J.: Role of atmospheric aerosol concentration on deep convective precipitation: Cloud-resolving model simulations, J. Geophys. Res., 112, D24S18, 2007.

Trenberth, K. E., Dai, A. Pasmussen, R. M. and Parsons, D. B.: The changing character of precipitation, Bull. Am. Meteorol. Soc. 84, 1205-1217, 2003.

Van den Heever, S. C., Carrió, G. G. Cotton, W. R. DeMott, P. J. and Prenni, A. J.: Impact of nucleating aerosol on Florida storms. Part I: Mesoscale simulations, J. Atmos. Sci.63, 1752-1775, 2006.

Wang, Y. and Zhou, L.: Observed trends in extreme precipitation events in China during 1961-2001 and the associated changes in large-scale circulation, Geophys. Res. Lett. 23, L09707, doi:10292005GL022574, 2005.

Zhai, P.M., Ren, F. M. and Zhang, Q.: Detection of trends in China's precipitation extremes, Acta Meteorologica Sinica, 57, 208-215, 1999.

Zhang, H., Wang, Z. L., Guo, P. W., and Wang, Z. Z.: A modeling study of theeffects of direct radiative forcing due to carbonaceous aerosol on the climate in East Asia, Adv. Atmos. Sci., 26, 57–66, 2009.

Zhao, T. Liu, D., Zheng, X., Yang, L., Gu, X., Hu, J., Shu, Z., Chang, J., Wu, X.: Revealed variations of air quality in industrial development over a remote plateau of Southwest China: an application of atmospheric visibility data, Meteorol Atmos Phys, doi:10.1007/s00703-016-0492-7, 2016.

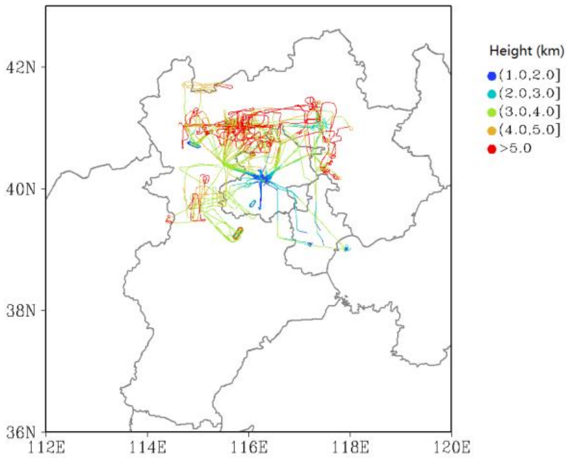
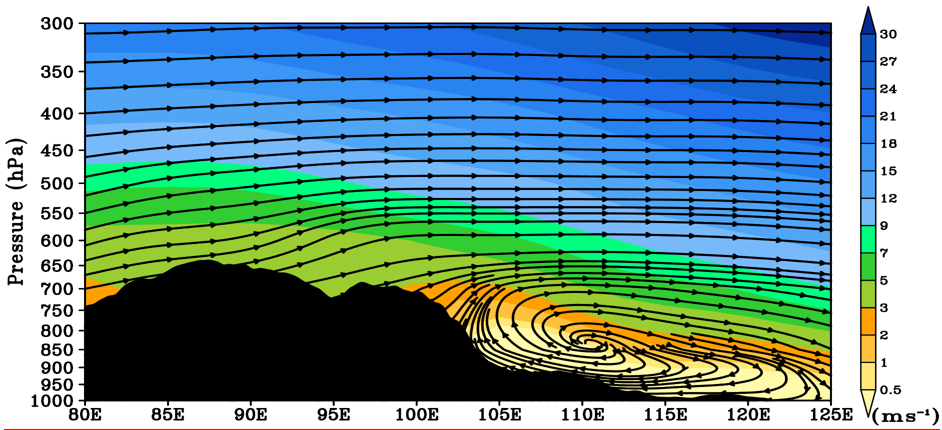
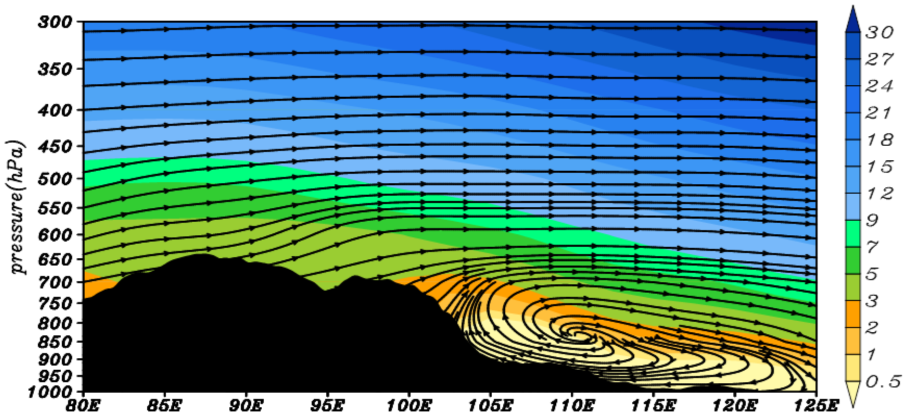
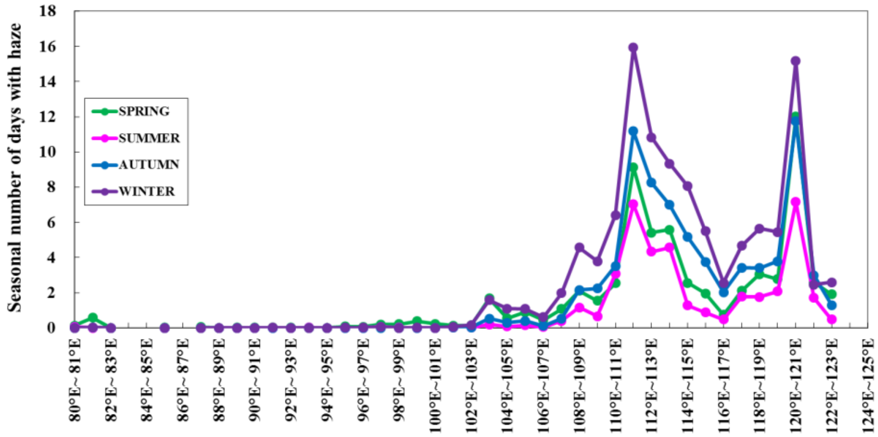


Figure 1 Area and tracks of 40 aircraft flights carried out in Beijing and its surrounding regions during aerosol-cloud experiment from 2008 to 2010 by the Beijing Weather Modification Office. China







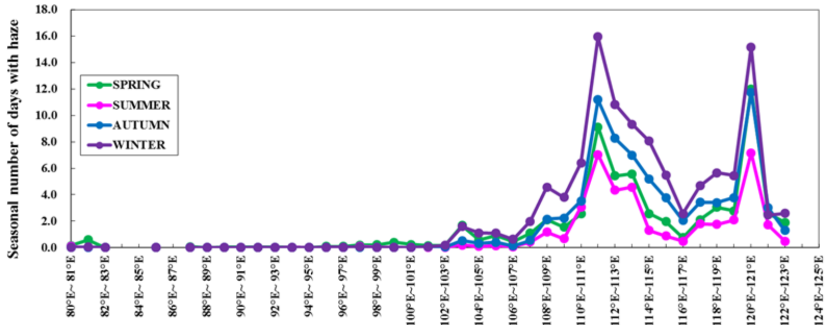
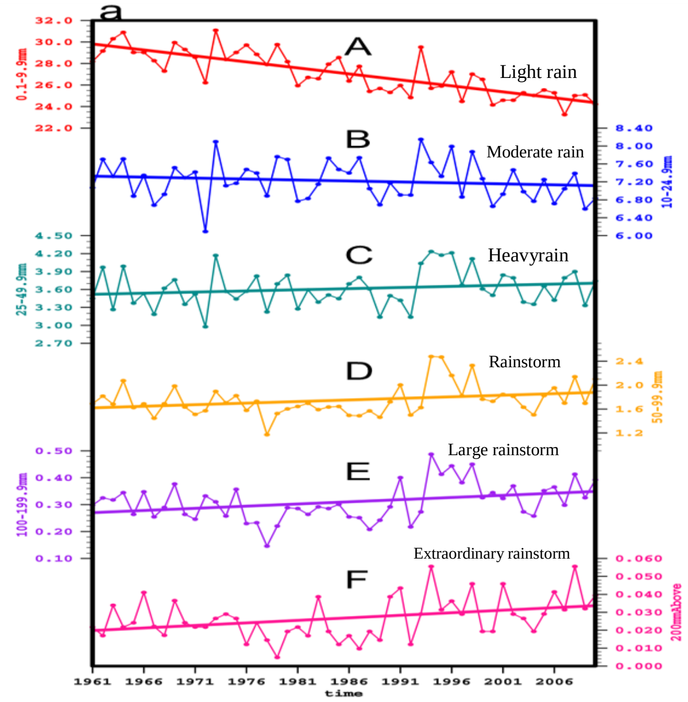
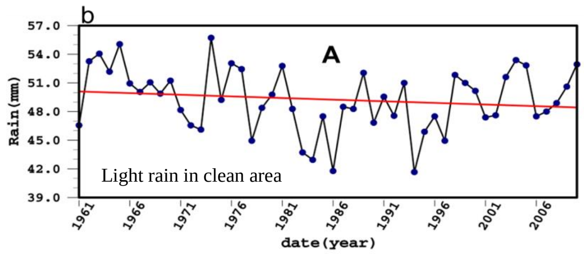


Figure 2. Cross sections of vertical circulations illustrated by stream lines (upper panel) with the horizontal wind speed (m s^{-1}; color contours) and zonal variations of annual haze event frequency (lower panel) at 27°N-41°N averaged in spring, summer, autumn and winter over 1961-2012. Note that near-surface vertical and horizontal winds are not illustrated well here due to north-south variations in the terrain and approximation of the location of the plateaus (black shaded area) in upper panel. All fields are for the annual-averages.

带格式的: 上标


a
A
Light rain
B
Moderate rain
C
Heavyrain
D
Rainstorm
E
Large rainstorm
F
Extraordinary rainstorm
0.1-9.9mm
10-24.9mm
25-49.9mm
50-99.9mm
100-199.9mm
200mmAbove
time


b
A
Rain(mm)
Light rain in clean area
date(year)

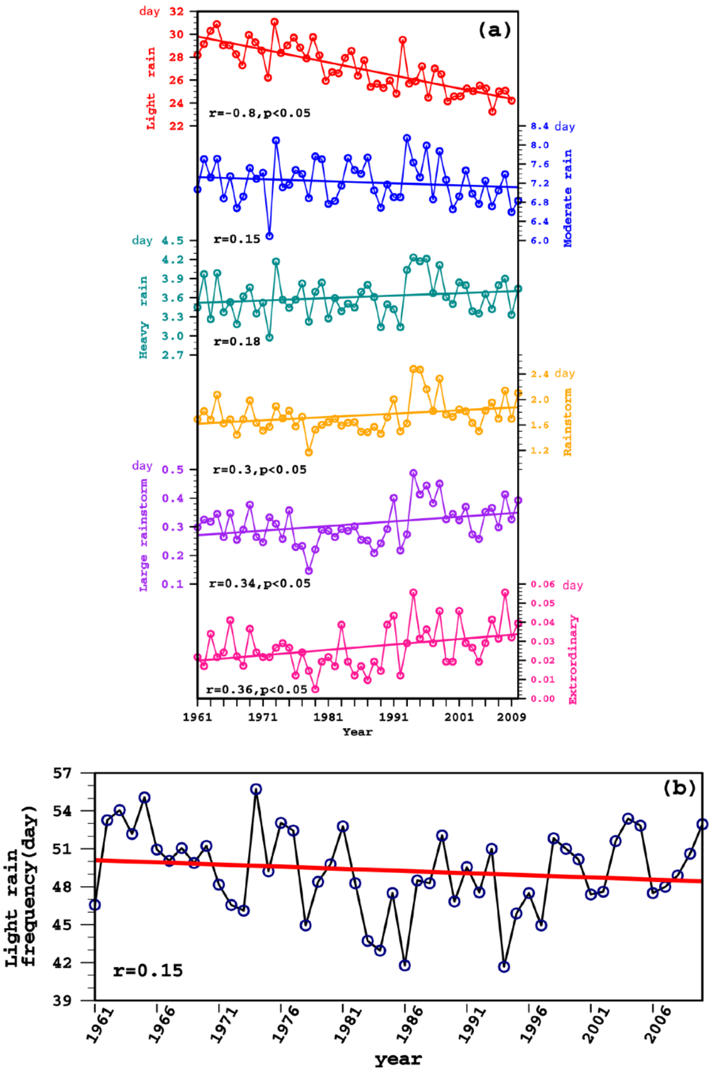
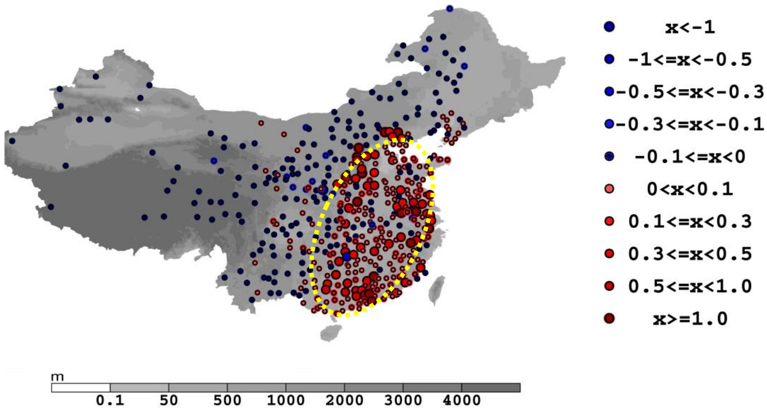
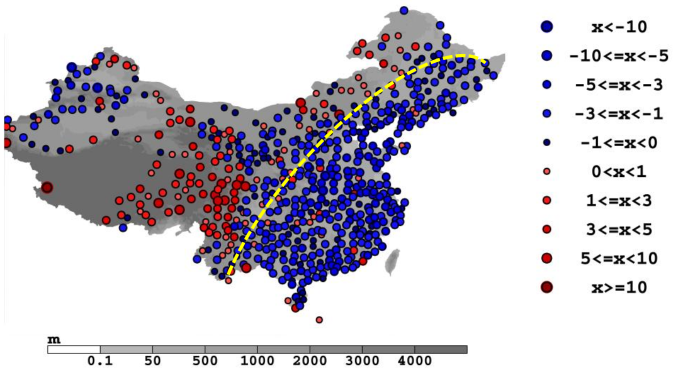
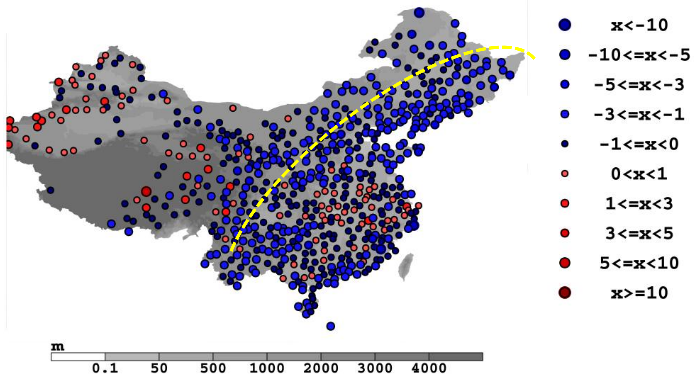


Figure 3 Interannual variations with their anomalies (broken lines) and trends (straight lines)~~trends~~ **in (a) various precipitation intensities in the high aerosol concentration area in** the ~~eastern China (east of 110° E)~~EC region **and (b) light rain in** the **relative clean area of** ~~Qinghai-~~**Tibet**an **Plateau**~~; Note: Various precipitation intensities included light rain (A), moderate rain (B), heavy rain (C), rainstorm (D), large rainstorm (E), and extraordinary storm (F)~~.







带格式的：缩进：左侧： 0 厘米，定义网格后不调整右缩进，不调整西文与中文之间的空格，不调整中文和数字之间的空格

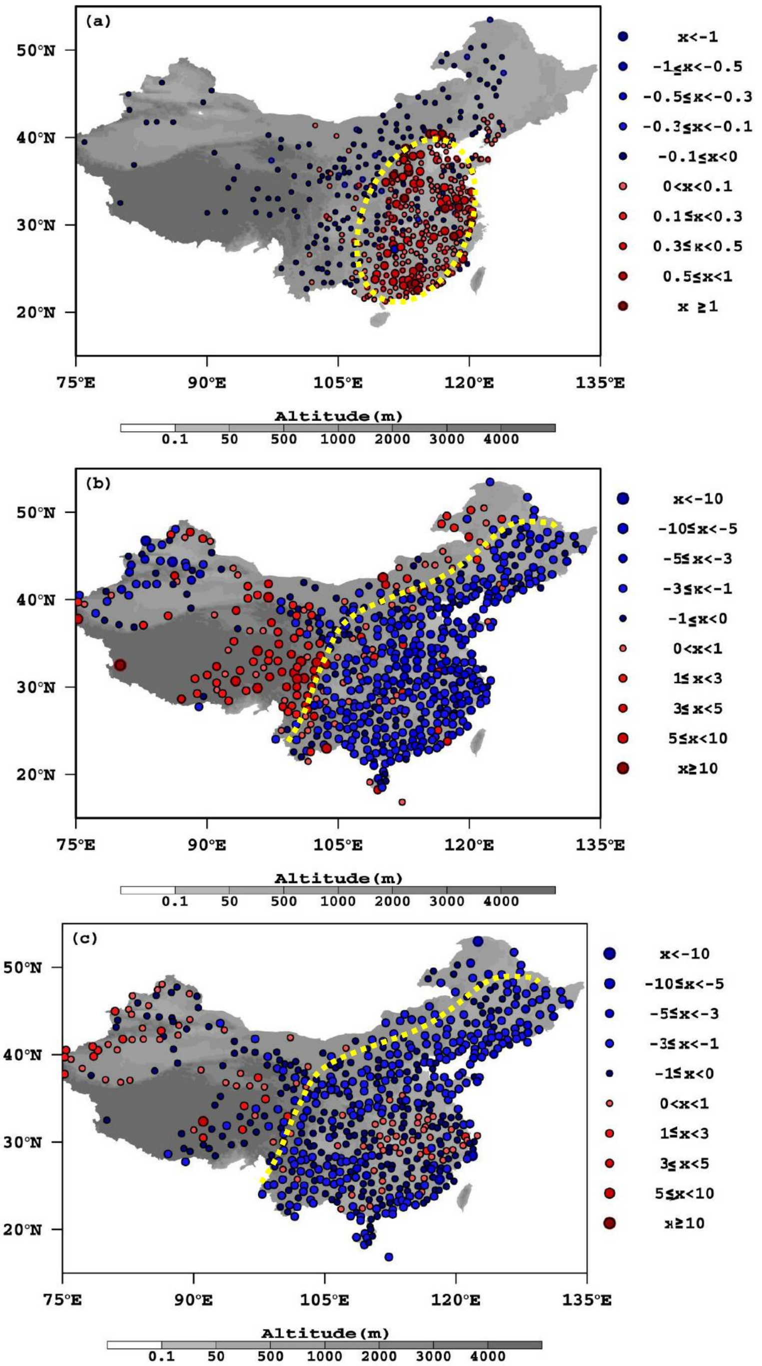
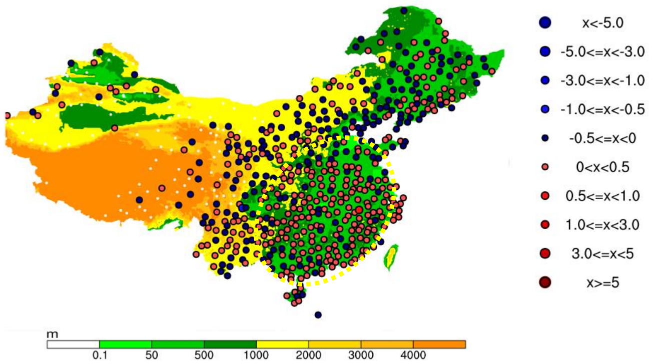
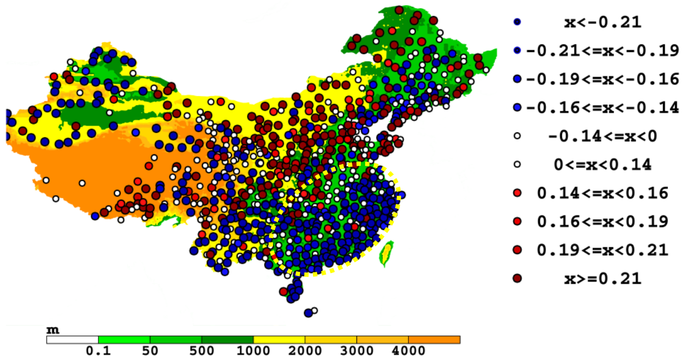


Figure 4 ~~Interannual variability d~~Distribution of interannual change trends (day per 10 years) in (a) haze frequency~~ (a)~~, (b)

visibility ~~(b)~~ and (c) light rain frequency ~~(c)~~ in summer in mainland China in 1961-2010. The yellow dash lines mark the borders of frequent haze area or the eastern borders of plateaus in China.



~~(a)~~



~~(b)~~

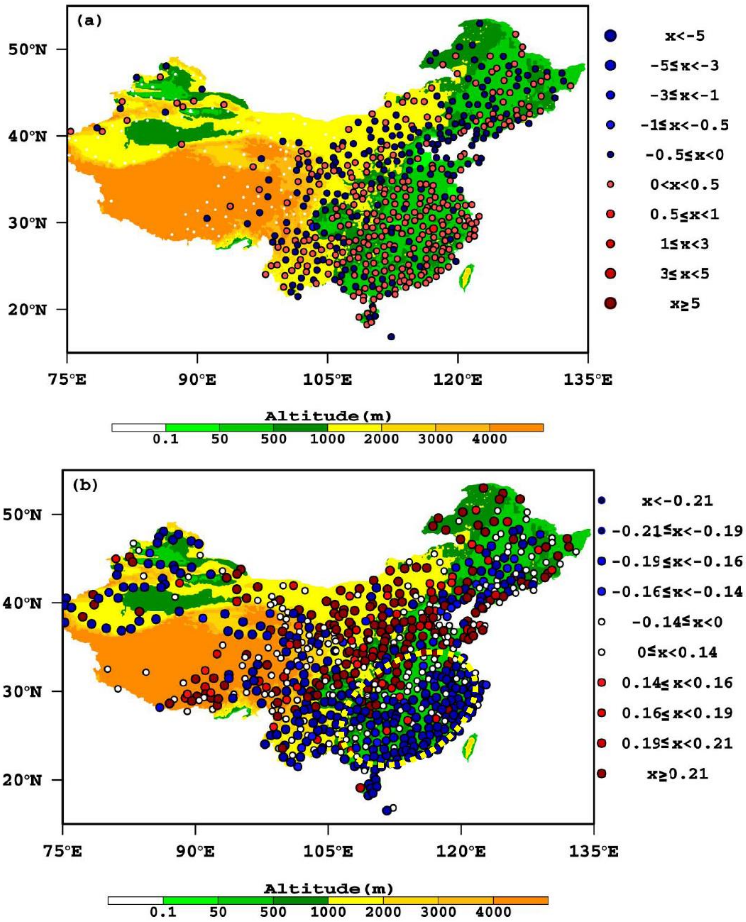
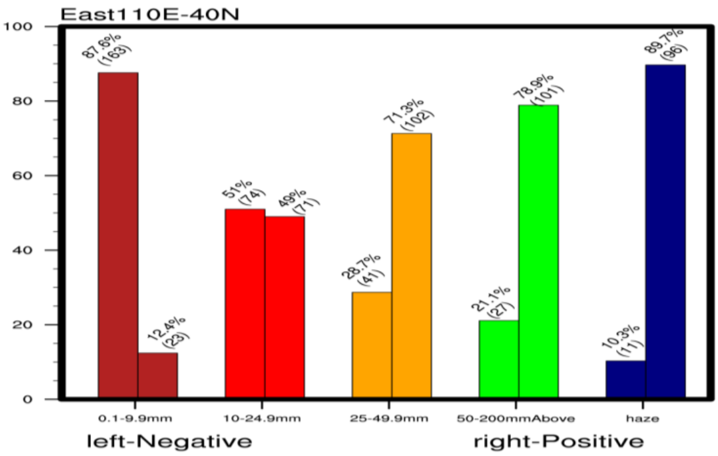
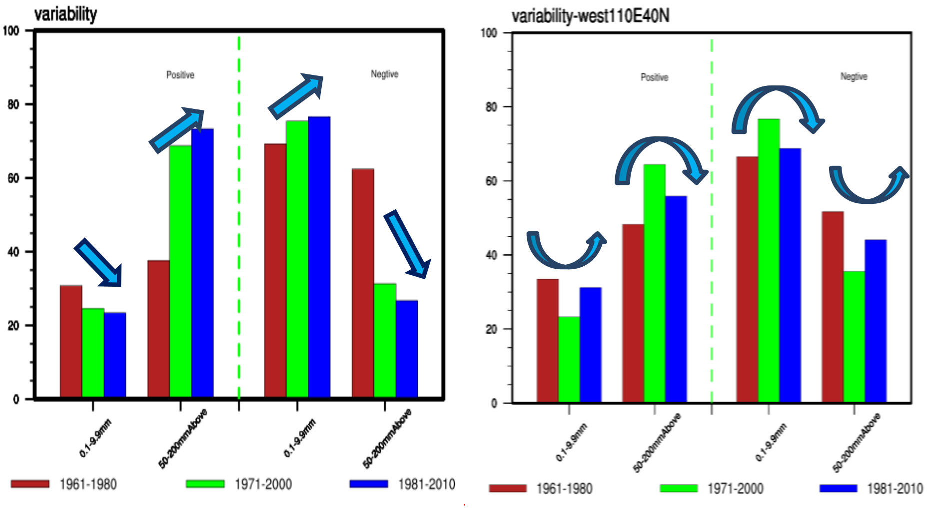


Figure 5 The spatial distributions of (a) trends (day per 10 years) in summertime rainstorm frequency over 1961-2010 in China and (b) correlation coefficients between visibility and low cloud amount in summer of 1961-2010. With the yellow dash line marking the borderof negative correlation area.





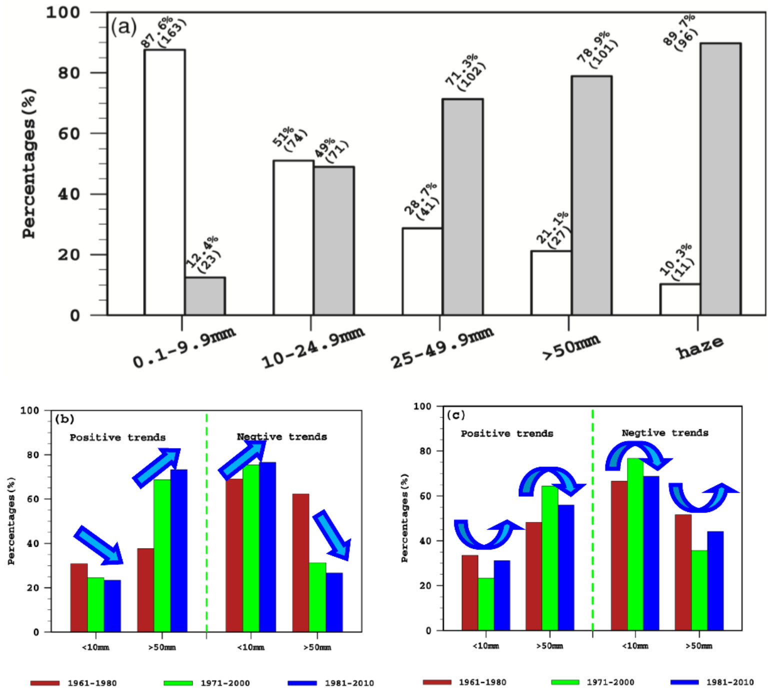
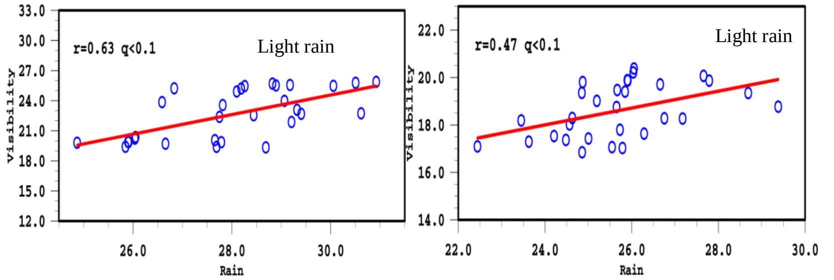
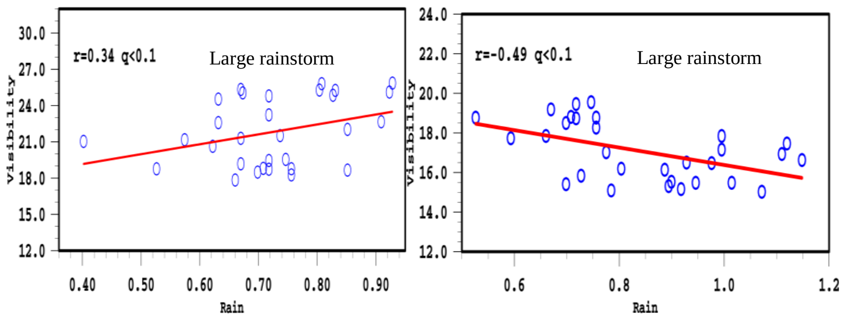


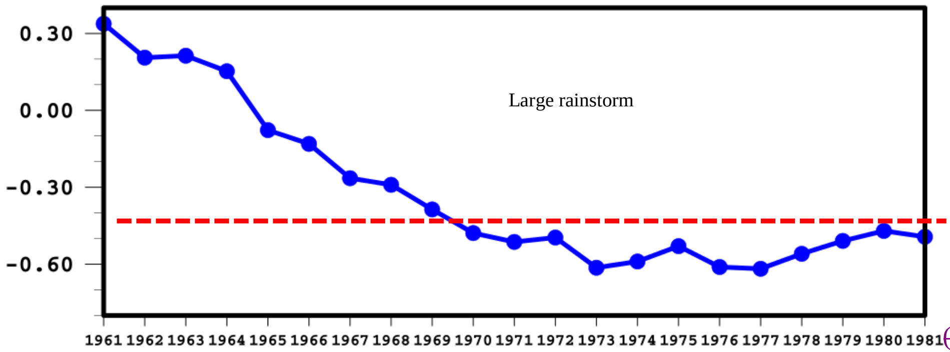
Figure 6 The(a) ratiopercentages of summer haze days and the stations covered with by positive and negative variability trends in number of day inat various precipitation grades from 1961 to 2010 over in the EC stayions east of 110 °E, south of 40 °N, (ab), .The percentages of sites with negative frequency trends of light rain and positive trends of rainstorm events in total sites with the and positive (left side) and negative (right side) trends in haze over (b) the EC and (c) TP regions during the three interdecadal periods (1961-1980, 1971-2000, 1981-2010)west of 110 °E, south of 40 °N (b). 601 precipitation stations and 598 visibility stations in eastern China. The right side is the positive variability and left side is the negative variability). The arrows indicate the interdecadal change patterns.



(a) (b)



(c) (d)



(e)

带格式的: 正文，缩进：首行缩进：0.75 厘米，定义网格后不调整右缩进，行距：多倍行距 1.15 字行，无项目符号或编号，不调整西文与中文之间的空格，不调整中文和数字之间的空格

带格式的: 缩进：左侧：0 厘米，首行缩进：0.75 厘米，定义网格后不调整右缩进，行距：多倍行距 1.15 字行，不调整西文与中文之间的空格，不调整中文和数字之间的空格

带格式的: 两端对齐，缩进：首行缩进：0.75 厘米

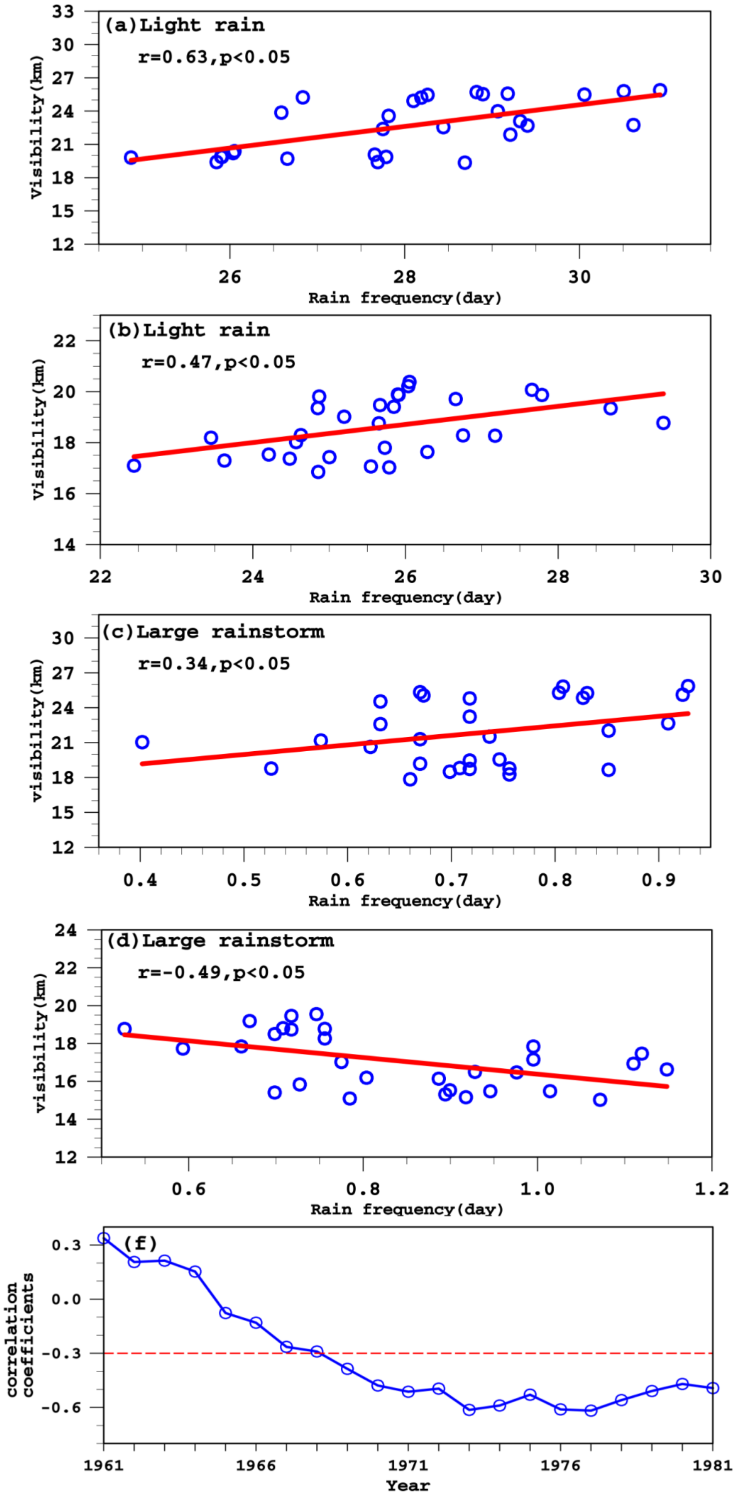
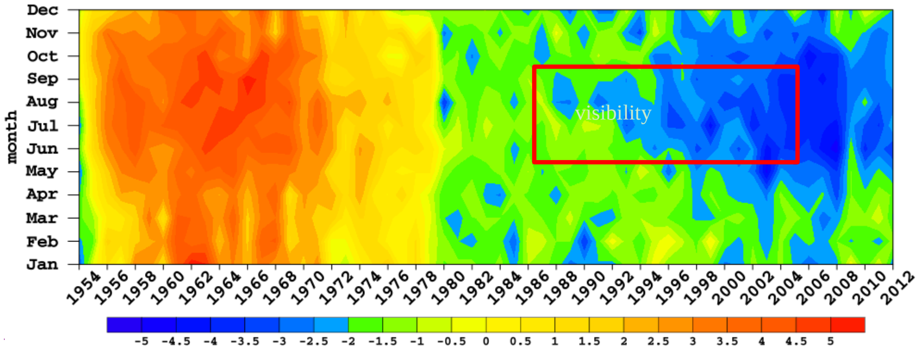
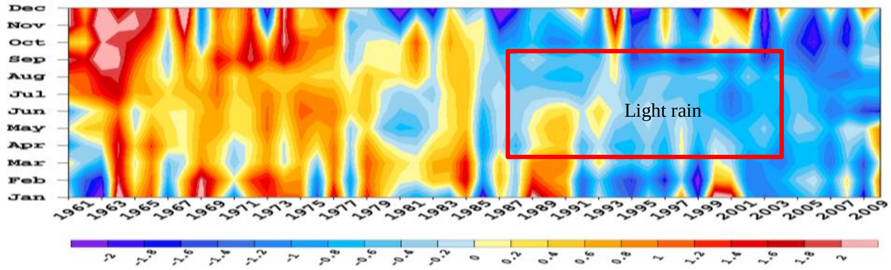


Figure 7 Correlation between summer average visibility (June, July and August) ~~and~~ with light rain frequency (a) in 1961-1990, ~~(a),~~ (b) light rain frequency in 1981-2010 ~~(b)~~, (c) extremely heavy rain event frequency in 1961-1990 ~~(c)~~, and (d) extreme heavy

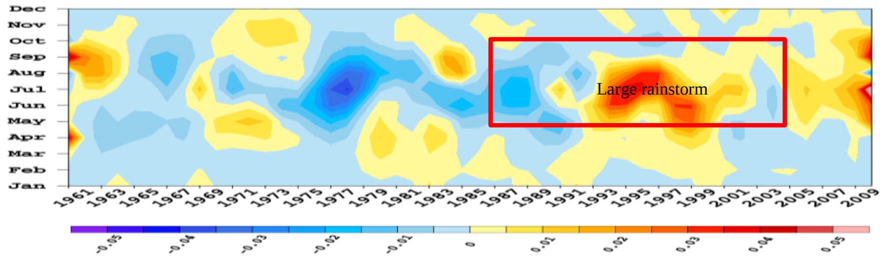
rain event frequency in 1981-2010; (d) and t(e) The 20-year running correlation coefficients of visibility and precipitation (e), over eastern China (east to 110 °E, south to 40 °N)EC with dash line standing for the correlation passing the confidence level of 90%.



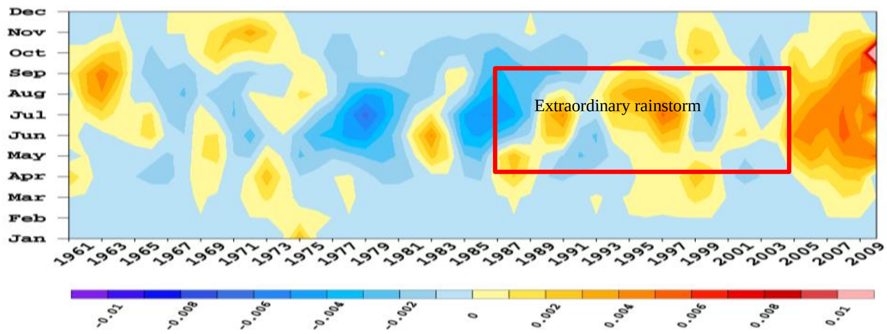
(a)



(b)



(c)



(d)

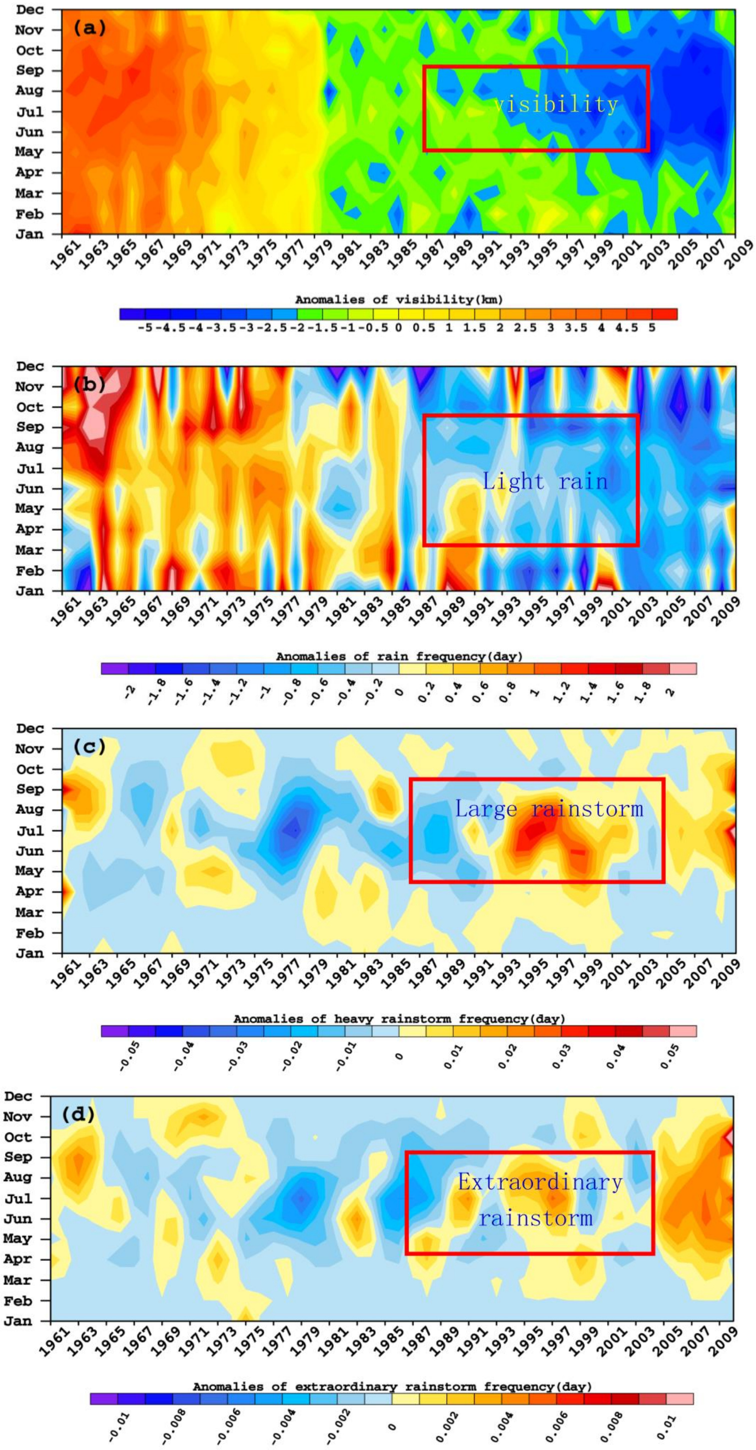
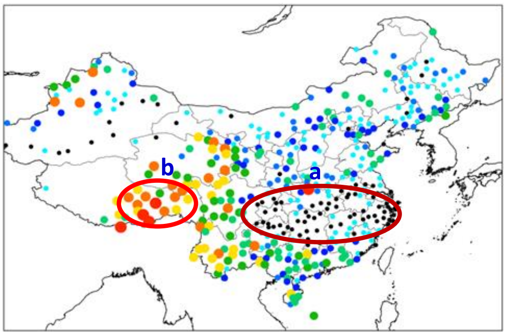


Figure 8 Annual cross section of mMonthly anomaly anomalies of number of days with (a) visibility, (ba), light rain, (cb), heavy rain (c), and (d) extremely heavy rain (d) from 1961-2010 averged over EC.



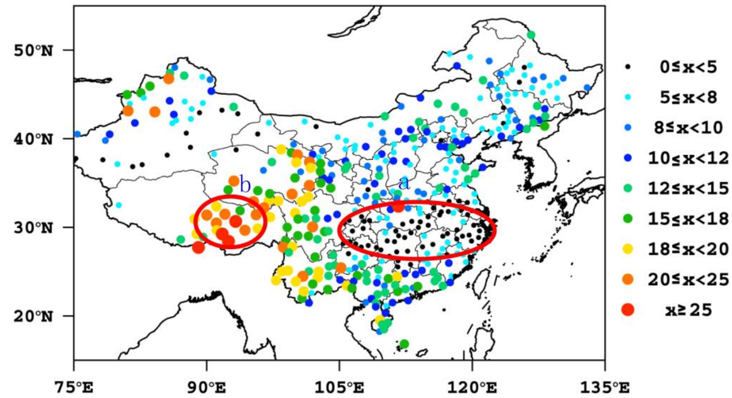
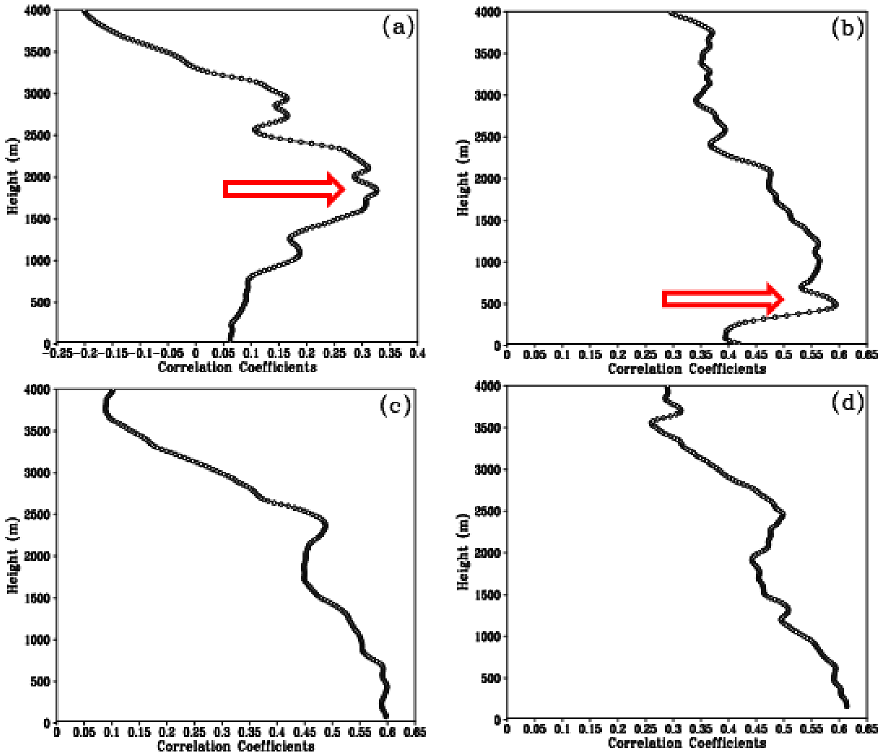
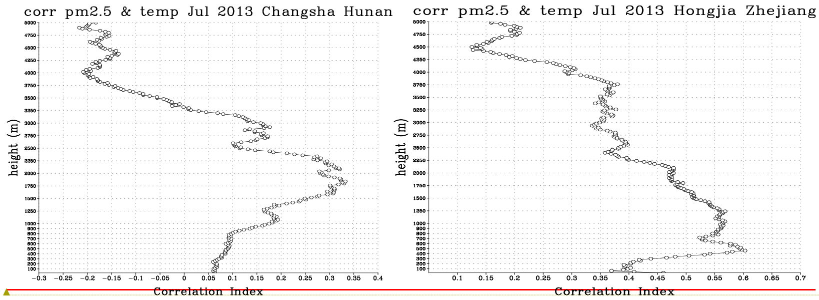
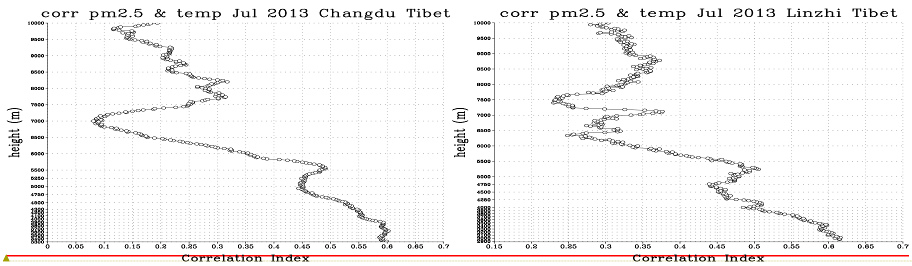


Figure 9 Light rain frequency distribution of 601 stations in China in July of 2013. The circled region on right is the low-frequency light rain region in middle and downstream region ~~of Yangtze River~~ in ~~eastern China~~EC, and that on left is the high-frequency light rain region in relative clean region over ~~Tibet plateau~~the TP.





~~(a)~~ ~~(b)~~

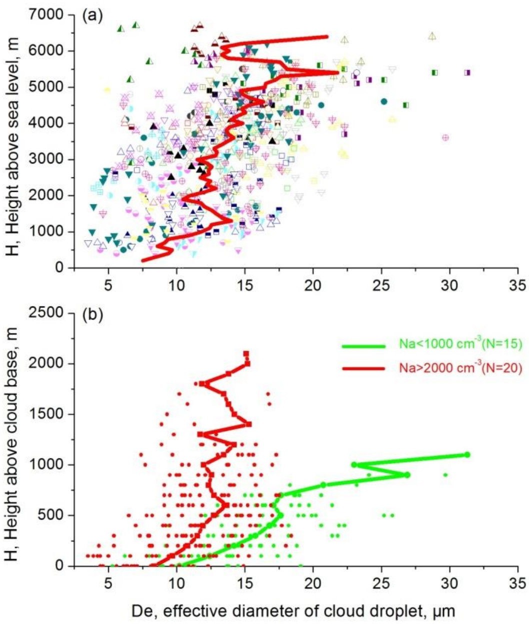


~~(c)~~ ~~(d)~~

Figure 10 Correlation coefficient profiles between the ~~daily~~ surface $PM_{2.5}$ concentration (12 hour intervals) and atmospheric temperature ~~at different vertical layer~~ from L-band sounding for representing low-frequency light rain regions at stations of (a) Changsha~~, Hunan (a)~~ and (b) Hongjia~~, Zhejiang~~ in EC ~~(b)~~, and for representing high-frequency light rain regions at relative "clean area" at stations of (c) Linzhi ~~(c)~~ and (d) Dingri ~~(d) of Qinghai Tibet Plateau~~over the TP with correlation coefficients of 0.24 passing the confidence level of 90%.

带格式的: 字体: (默认) Times New Roman

带格式的: 字体: (默认) Times New Roman


(a)
H, Height above sea level, m
7000
6000
5000
4000
3000
2000
1000
0
5
10
15
20
25
30
35
(b)
H, Height above cloud base, m
2500
2000
1500
1000
500
0
Na<1000 cm-3(N=15)
Na>2000 cm-3(N=20)
De, effective diameter of cloud droplet, µm

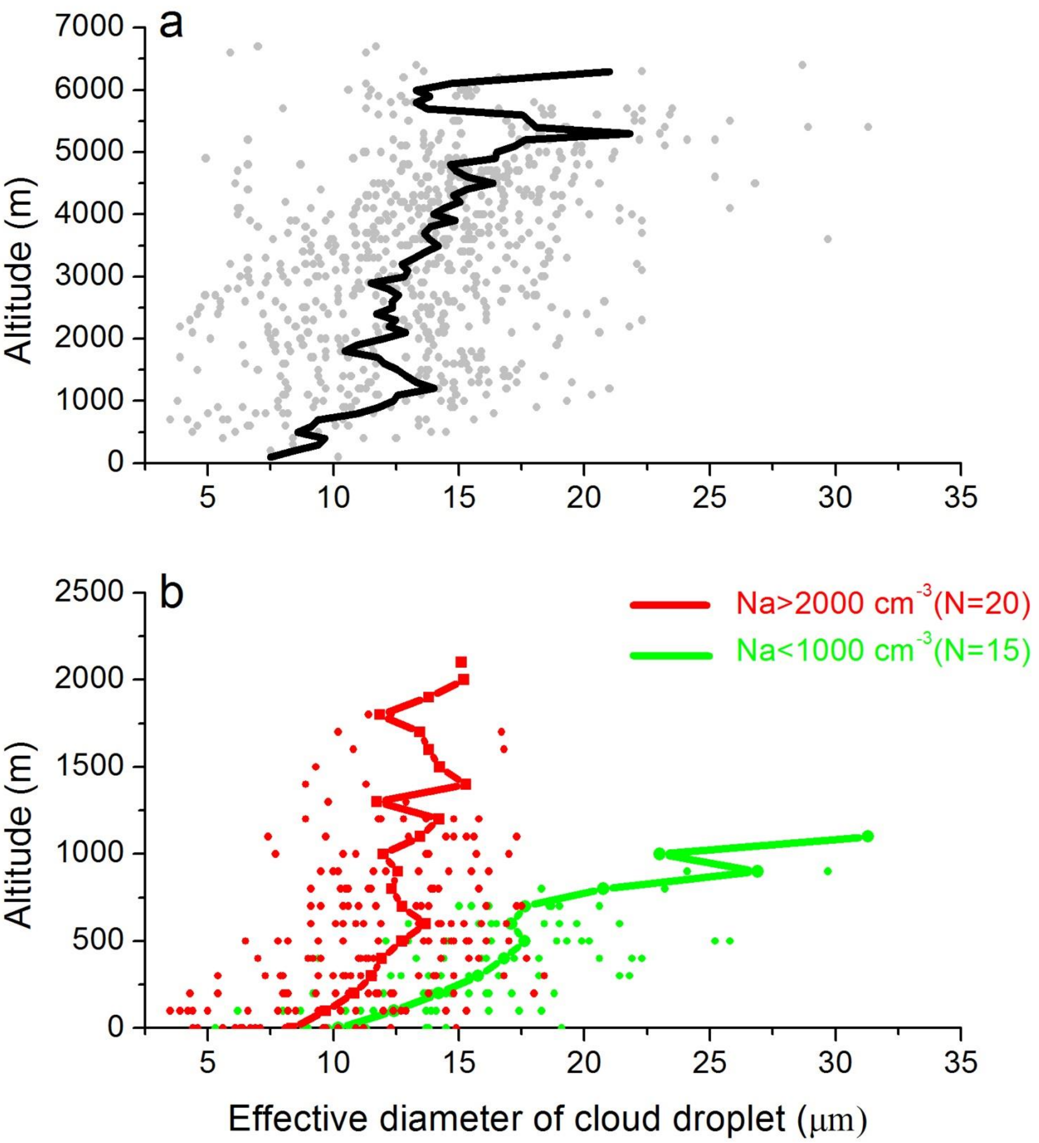


Figure 11 The vertical profiles of (a) sampling cloud droplets droplet size data at each level under different aerosol state(a) and concentration(b) detected by 40 aircraft, and (b) changes and number and diameters of (Green profile: cloud droplets diameter under low concentration; Red profile: cloud droplets diameter underand high aerosol number concentrations).