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EFFECTS OF AEROSOLS ON AUTUMN PRECIPITATION OVER MID-EASTERN CHINA

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Abstract: Long-term observational data indicated a decreasing trend for the amount of autumn precipitation (i.e. 54.3 mm per decade) over Mid-Eastern China, especially after the 1980s (~ 5.6% per decade). To examine the cause of the decreasing trend, the mechanisms associated with the change of autumn precipitation were investigated from the perspective of water vapor transportation, atmospheric stability and cloud microphysics. Results show that the decrease of convective available potential energy (i.e. 12.81 J kg^{-1}/ decade) and change of cloud microphysics, which were closely related to the increase of aerosol loading during the past twenty years, were the two primary factors responsible for the decrease of autumn precipitation. Our results showed that increased aerosol could enhance the atmospheric stability thus weaken the convection. Meanwhile, more aerosols also led to a significant decline of raindrop concentration and to a delay of raindrop formation because of smaller size of cloud droplets. Thus, increased aerosols produced by air pollution could be one of the major reasons for the decrease of autumn precipitation. Furthermore, we found that the aerosol effects on precipitation in autumn was more significant than in other seasons, partly due to relatively more stable synoptic systems in autumn. The impact of large-scale circulation dominant in autumn and the dynamic influence on precipitation was more important than the thermodynamic activity.

Key words: aerosol; autumn precipitation; atmospheric stability; cloud microphysical properties

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1 INTRODUCTION

Precipitation is a key physical process that links many aspects of climate, weather and the hydrological cycle, which have significant impacts on agricultural production, aviation, marine, transportation, water conservancy construction, floods and droughts, etc.[1]. Previous studies mainly focused on the precipitation change during summer at both global and regional scales such as China[2-5]. However, the change of autumn precipitation will directly affect agricultural production in the coming year. In addition, autumn precipitation anomaly could also have potential effects on winter precipitation in the current year and summer precipitation in the following year, resulting in floods, droughts and other disasters[6]. In order to comprehensively understand the climate change and its effects, more emphasis is needed on autumn precipitation. So far, very few studies have investigated the spatial-temporal variations of autumn precipitation. Xu and Lin[7] analyzed autumn precipitation change characteristics and related physical mechanisms over Western China. Li et al.[8] investigated the spatial and temporal variations of spring temperature anomalies over Western China and the correlation between the sea surface temperature anomalies (SSTA) of the North Pacific and the spring rainfall anomalies in Western China for the period of 1960–1994. In addition, Li et al.[9, 10] analyzed the autumn rainfall anomaly over Northwest China and investigated the circulation variations during the El Niño/La Niña periods. Their results showed good relationship between the SSTA over East Equatorial Pacific and the autumn rainfall anomaly over the Northwest China. In El Niño years, relatively smaller amount of autumn precipitation was generated over the Northwest China whereas more autumn precipitation was generated in La Niña years. Song and Zhang[11] pointed out that the variability and trend

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of autumn precipitation are more significant than that in other seasons during the 20th century over the Northwest China. Zhang et al.[12] found that the change of general atmospheric circulation and the influence of ENSO events under global warming could be the direct factors in effecting the autumn precipitation generation over Northwest China. Shi[13] found a good relationship between precipitation anomaly in autumn and rainfall in the flood season of the following year. However, the above studies were limited only to the Northwest China region, with a focus on the interactions between autumn precipitation and natural climate variability (e.g., ENSO) at large scale. In this study, we investigated the causes of the autumn precipitation anomalies from the perspective of physical mechanisms influencing the precipitation change over Mid-Eastern China.

Generally speaking, there are three dominant conditions for the formation of precipitation: (1) Horizontal transportation: water vapor is transported to the precipitation zones from source regions; (2) Convergence and upward movement: the strong upward motion is associated with the surface convergence over the precipitation regions. Water vapor condenses into cloud droplets or ice crystals in the adiabatic expansion during the lifting process. (3) Microphysical conditions with growth of the cloud droplets: The saturated air tends to condense on condensation nuclei and then water droplets grow, become heavier, and fall to the ground as precipitation[1]. Aerosol particles, which have close relationship with the last two points of conditions, are the dominant factors for the formation of precipitation[14-16]. Based on the observational data and modeling approach, Qian et al.[17] found a decreasing trend of light rain events over North America, Europe and Asia from 1973–2009, especially over East Asia, where a remarkable shift from light to heavy rain events has been observed. Besides, Qian et al.[18] pointed out that aerosols are at least partly responsible for the decreasing frequency and amount of light rain in summer over Eastern China. Huang et al.[19, 20] found that dust could heat cloud droplets, increase the evaporation of cloud droplets and further reduce the cloud water path, which may play an important role in cloud development and contribute to the reduction of precipitation over arid and semi-arid areas. Zhao et al.[21] also found a positive feedback mechanism between increased aerosol loadings and reduced precipitation over Mid-Eastern China. Based on 194 observation stations, Gong et al.[22] investigated the frequency change of daily precipitation in summer during 1979–2002 and found an obvious weekly cycle effects.

Was the change of autumn precipitation over Mid-Eastern China related to the high aerosol loadings in autumn when the weather system is relatively stable? How do aerosols affect autumn precipitation in heavily polluted China? What kinds of precipitation will be affected mostly by aerosol? In this study, we try to address these questions from the perspective of precipitation formation mechanism over Mid-Eastern China which is featured by the heavy pollution, dense meteorological station and records, and frequent precipitation events records[23]. The paper is organized as follows: Data and methodology are described in sections 2. The part of effects of aerosols on autumn precipitation over Mid-Eastern China is presented in section 3. Conclusions and discussions are presented in section 4.

2 DATA AND METHODOLOGY

The following types of data are used in this study:

(1) Daily observational data were obtained from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do). We screened all daily precipitation records from 1959 to 2008 over 503 observation stations and included them in our following analysis. It also should be noted that the drizzle being not recorded by precipitation instruments was used and assigned the value of 0 mm and only the liquid precipitation was considered in our study.

(2) Visibility data were widely used to study the relationship between aerosol and precipitation, due to its relatively long historic records[24-26]. The variability of atmospheric visibility, which is a good measure of environmental pollution, is consistent with that of aerosol optical depth (AOD)[27]. The unit of visibility dataset changed from level (bins) to kilometer after 1980 in China, resulting in systematic discrepancies in data processing. Thus, only the visibility data after 1980 were used in this study and data was further revised by applying the Rosenfeld method[28] to reduce the effects induced by relative humidity and precipitation.

(3) We collected the sounding data from Chinese international exchange stations, including the mean monthly air pressure, altitude, temperature, dew temperature and wind speed from January 1951. The dew temperature and air temperature from 28 observational stations were used to calculate the specific humidity, of which only the results under 300 hPa were considered for deducing the perceptible water vapor.

(4) Aerosol optical depth, cloud fraction and cloud particle effective radius from Moderate Resolution Imaging Spectroradiometer (MODIS)[29, 30] were used in this study. The AOD at 550 nm as a proxy of aerosol loading was sorted into 10 bins at a regular interval of 0.1. Cloud microphysical and optical parameters for cloud optical depth are sorted

into individual AOD bins, of which mean values and standard errors (i.e., σ / (n − 1)1 / 2, where σ and n are standard deviation and the number of data points, respectively) are then calculated.

3 RESULTS

3.1 *Change trends of precipitation*

Figure 1 shows the spatial distributions of trends for seasonal precipitation amounts during the past 50 years over Mid-Eastern China, estimated using the least squares technique. Decreasing trends of spring precipitation were mainly centered in the regions around the Yangtze River and Southeast China, with the largest decreasing trends (i.e. from –2%/decade to –8%/decade) over the Loess Plateau region. Increasing trends of spring mean precipitation were mainly found over the Northeastern China, Beijing, Tianjin, North China Plain, Yunnan-Guizhou Plateau and Tibet Plateau. The decreasing trends for summer precipitation are larger (i.e. from –1%/decade to –5%/decade) than for spring over Northeast China, Beijing, Tianjin, Shandong Peninsula and Loess Plateau. Positive change trends of summer mean precipitation were found over Southern China, with the largest increasing trends (from 1%/decade to 10%/decade) over the Yangtze River Plain. The trends for winter mean precipitation were generally positive over China, except for Beijing, Tianjin and Inner Mongolia. The decreasing trends of precipitation in autumn were distributed more broadly and homogeneously than that in other seasons. Significant decreasing trends of autumn mean precipitation were found over the Yangtze River Plain, Sichuan Plateau, North China Plain and Yunnan-Guizhou Plateau. As a whole, lower amount of precipitation was generated over the Mid-Eastern China, especially over Northeast China, Central China and South China.

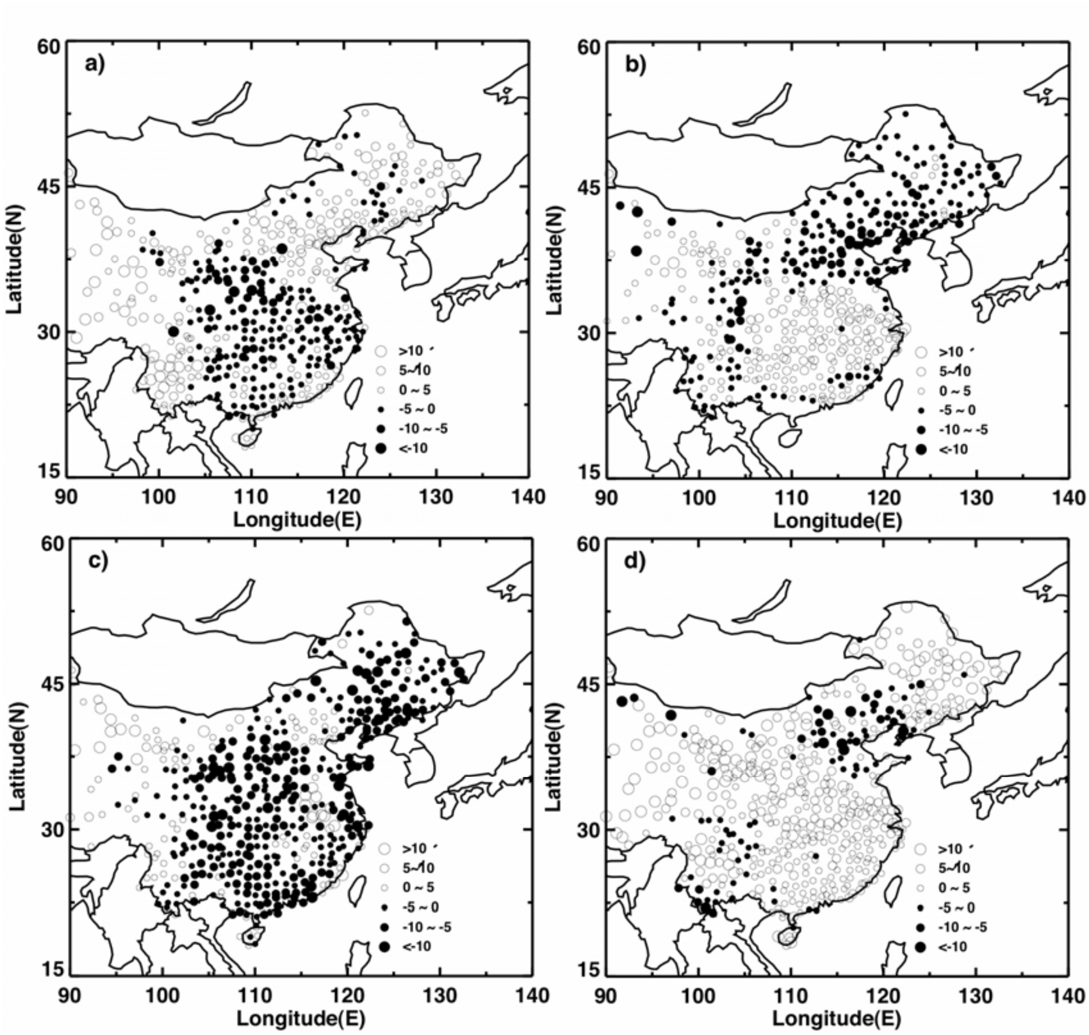

Figure 1. Spatial distribution of the trend (% per decade) of precipitation in (a) spring (b) summer (c) autumn (d) winter precipitation amount from 1959 to 2008.

Figure 2 shows the temporal variation of seasonal mean precipitation averaged for all observational stations in the Mid-Eastern China. Increasing trends of precipitation were found for summer and winter whereas decreasing trends were found for spring and autumn. The trend of autumn mean precipitation was more significant over Yangtze-Delta region (i.e. –5.6%/decade) since 1980 and later on, contributed to the characteristic of autumn mean precipitation variations over Mid-Eastern China.

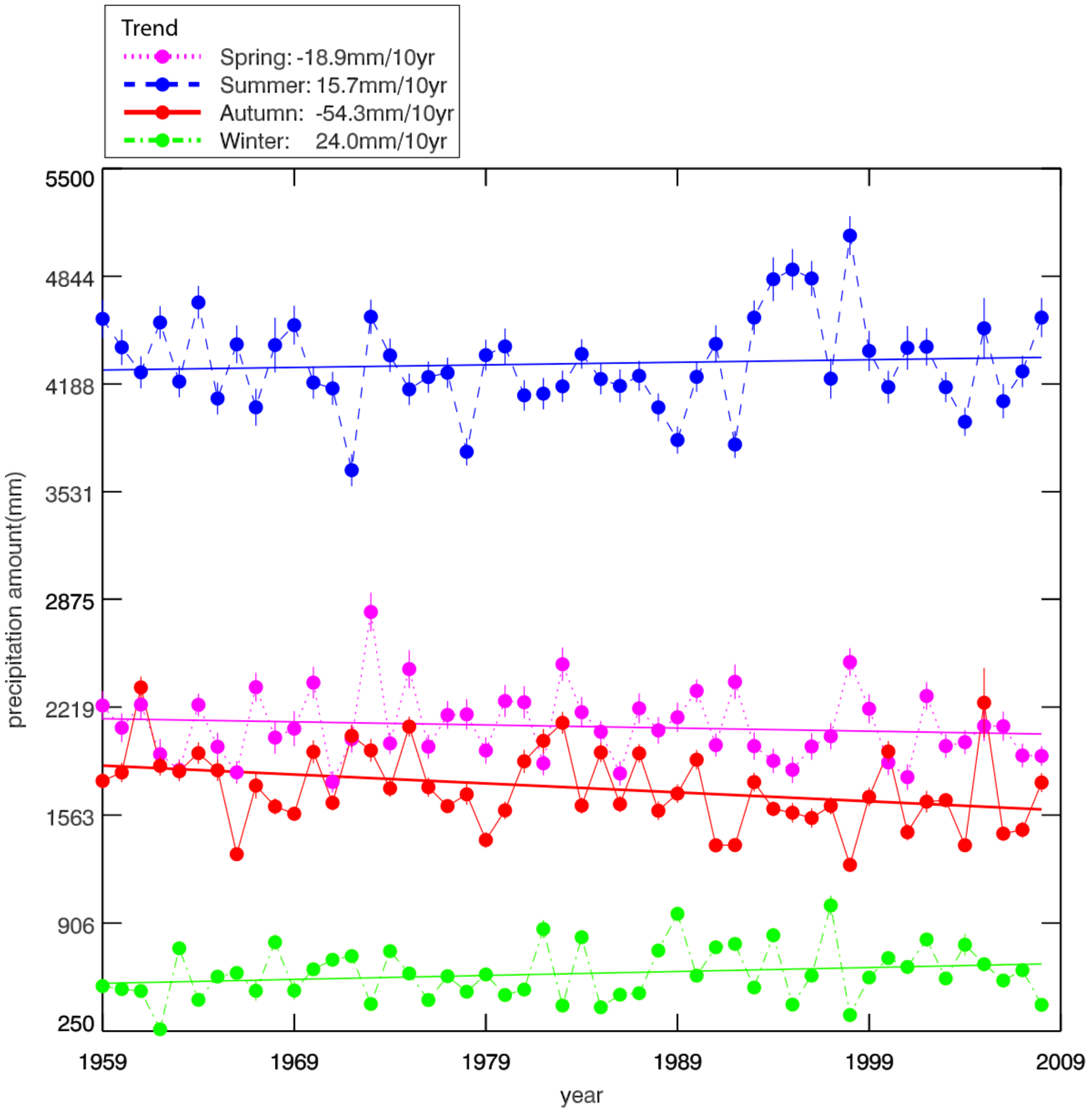

Figure 2. Time series of precipitation anomaly (%) in spring, summer, autumn and winter from 1959 to 2008 averaged over Mid-Eastern China.

3.2 *Change trends of atmospheric water content*

Figure 3 shows the temporal variations of autumn atmospheric water content averaged over Mid-Eastern China during 1959–2002. The year of 1975 tends to be the turning point of atmospheric water content, indicating a transition from negative to positive trend. The lowest atmospheric water content during the past 50 years was found at the end of 1960s, while two peaks at the end of 1990s (i.e. 15%) and at the begging of the 21 century (25%) respectively. Most of the regions over Mid-Eastern China experienced a positive change trend of atmospheric water content, especially over Yangtze River, Southeast, Southwest and Northeast of China with an increase of 0.3–0.6 mm/decade generally. The least square method was applied to calculate the change trends of autumn mean precipitation during the past 50 years over Mid-Eastern China. Based on the above analysis, no evidences were found to support that the decreasing autumn precipitation trend over Mid-Eastern China was related to changes of the large-scale atmospheric water content. We believe other factors could play more important roles in influencing the autumn precipitation characteristics over Mid-Eastern China.

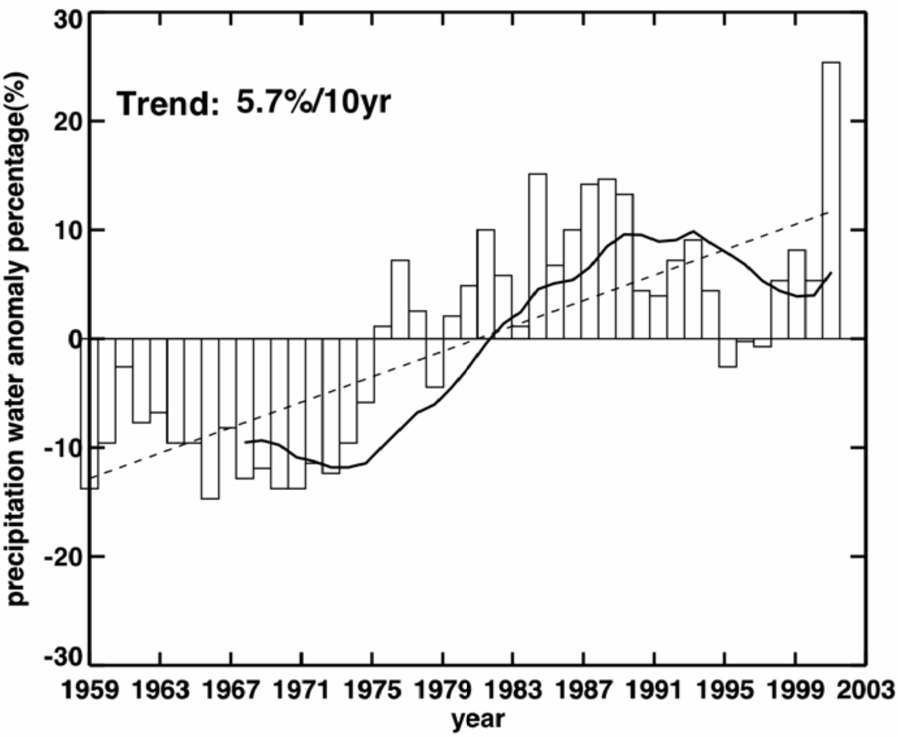

Figure 3. Time series of autumn precipitable water anomaly (%) in autumn from 1959 to 2008 averaged over Mid-Eastern China. The dashed line represents the linear trend of precipitable water anomaly. The solid line represents the moving average of precipitable water.

3.3 *Effects of aerosols on precipitation*

3.3.1 SPATIAL VARIATION OF AOD AND VISIBILITY

Aerosols could directly and indirectly affect the radiation budgets of the earth system, with substantial effects on regional even global climate[31-36]. Thus, further analysis was done to demonstrate the role of aerosols on precipitation over Mid-Eastern China. Fig. 4 shows the spatial distribution of annual mean AOD derived from MODIS retrievals and visibilities from observational data in autumn. AOD values larger than 0.6 were found over the Sichuan Basin, Yellow River, the middle and lower reaches of Yangtze River. The spatial variations of annual mean AOD were also consistent with the findings of previous studies (Luo et al.[37], Wang et al.[38]). Visibility data also showed a consistent spatial pattern with that for AOD. It should be noted that the spatial distribution of visibility was of the opposite sign with that of AOD (i.e. larger AOD with smaller visibility), which gave more confidence to represent the characteristics of aerosol particles using visibility datasets.

3.3.2 SVD ANALYSIS OF VISIBILITY AND PRECIPITATION

The Singular Value Decomposition (SVD) analysis, a useful tool in demonstrating the spatial correlation of two atmospheric variables, has been widely used in various studies[39]. Autumn mean visibility was treated as the left field whereas the autumn mean precipitation was treated as the right field. The coupling relationship between the anomalous distribution of autumn mean precipitation and the variation of visibility has been investigated using SVD analysis. It should be pointed out that only the simultaneous correlation was considered in this study due to the large spatial variation and short life period of aerosol particles.

The variance contribution, cumulative variance and correlation coefficient for the first five SVD modes of singular vector were shown in Table 1. It was found that the first five pairs of singular vector contributed up to 75% of the total variance. Thus, they can be used to depict the coupling relationship of precipitation and visibility variations over Mid-Eastern China. The first mode of visibility and precipitation indicated a significant decrease of temporal coefficient (R=0.87, P<0.01). The heterogeneous correlation coefficient of the right field of the mode for visibility and precipitation was dominated by positive values, with negative correlation found over a few small regions. High positive correlation was found over Southeastern China and Northeastern China (17.5°–36°N, 105°–120°E), which was characterized by the significant coupling of the first mode. Thus, it can be inferred from the consistence of spatial variations between aerosol and precipitation that aerosol could have large impacts on precipitation, with more aerosol loadings and lower precipitation.

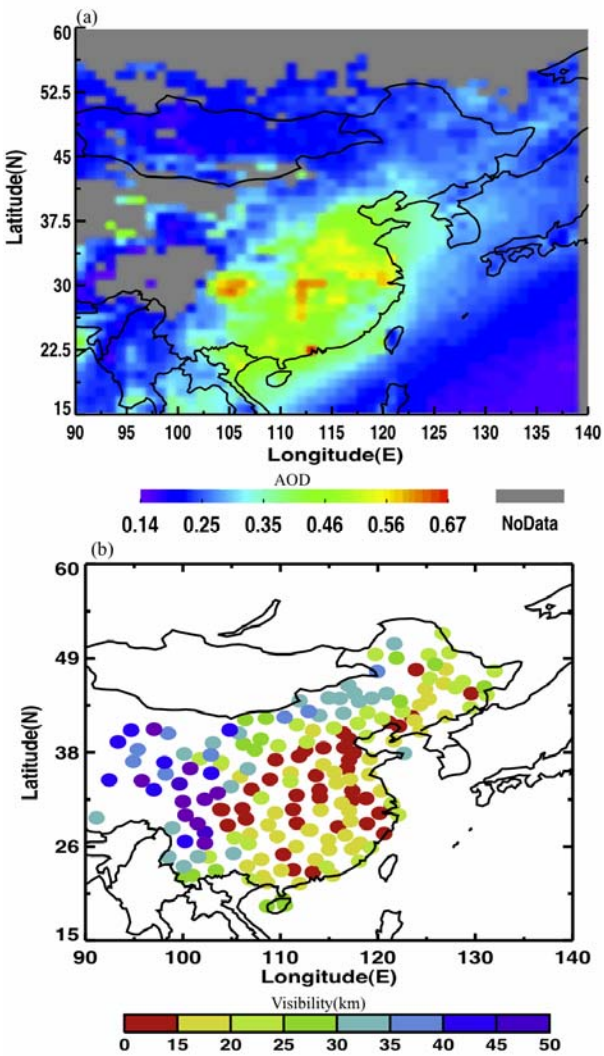

Figure 4. Spatial distribution of AOD retrievals from MODIS averaged for the autumns of 2002-2008 (a) and the corrected visibility for the autumns of 1959-2008 (b) over Mid-Eastern China.

Table 1. The variance contribution, cumulative variance and correlation coefficient explained by the first five pairs (*q*=1, 2, 3, 4, 5) of singular vector in this study.

Singular vector	Variance contribution	Cumulativ e variance	Correlation coefficient
q=1	36.56%	36.56%	0.83
q=2	21.34%	58.19%	0.90
q=3	7.94%	66.13%	0.92
q=4	6.50%	72.63%	0.87
q=5	4.86%	77.47%	0.90

By absorbing and scattering radiation, aerosols could alter regional atmospheric stability and vertical motions, and affect the large-scale circulation and hydrologic cycle with significant regional climate effects[40-43]. In addition, aerosol particles serve as condensation nuclei for the formation of both cloud droplets and atmospheric ice particles, exerting large influence on the formation of precipitation[44-48]. With the rapid development of urbanization, pollutant emission has increased dramatically over Mid-Eastern China for the last few decades. Due to the production of more black carbon aerosols and sulfate aerosols, Mid-Eastern China became the unique experimental region for studying the impacts of aerosol on regional climate and hydrological cycle. Next, we try to focus on the effects of aerosol mechanisms on autumn precipitation from the perspective of atmospheric stability conditions and the cloud microphysical conditions.

3.3.3 CHANGE TRENDS OF CONVECTIVE AVAILABLE POTENTIAL ENERGY (CAPE), CONVECTIVE INHIBITION ENERGY AND REVISED VISIBILITY

Figure 5 shows the temporal variations of CAPE, Convective Inhibition Energy (CIN) and revised visibility in autumn averaged over Mid-Eastern China during the past 50 years. High CAPE was accompanied by low CIN, suggesting an inverse correlation between CAPE and CIN. CIN increased by 28.67 J/kg per decade, while CAPE decreased by 12.81 J/Kg per decade. More specifically, air stability increased significantly after the 1980s, accompanied by the decrease of CIN by –2.1%/year and the increase of CAPE by 4.7%/year.

A decreasing trend (i.e. –2.7%/year) was found for visibility variation, which was consistent with the trend of CAPE. Thus, it can be concluded that aerosols could suppress vertical motion of air and increase regional atmospheric stability, resulting in the decrease of autumn mean precipitation.

3.3.4 RELATIONSHIP BETWEEN AEROSOLS AND CLOUD EFFECTIVE PARTICLE RADIUS

Figure 6 shows the comparison of autumn mean aerosol optical depth and cloud droplet effective radius under different cloud top temperature and liquid water path for 2002–2008. The solid line represents the relationship between aerosols and cloud effective particle radius when liquid water path exceeds 70 g m^{-2}. A positive correlation between cloud droplet effective radius and liquid water path could be found when the magnitude of aerosol optical depth was lower than 0.2. Cloud droplet effective radius decreases quickly with the increase of aerosol optical depth, which is more significant with higher cloud top temperature. A decrease of cloud droplet effective radius (i.e. 5 μm) was found with the increase of aerosol optical depth when cloud droplet effective radius exceeds 289 K. Thus, it can be inferred that more aerosols in autumn over Mid-Eastern China lead to smaller cloud droplet effective radius, which in turn decreases the conversion efficiency of cloud droplet into raindrop and suppresses the formation of precipitation in autumn.

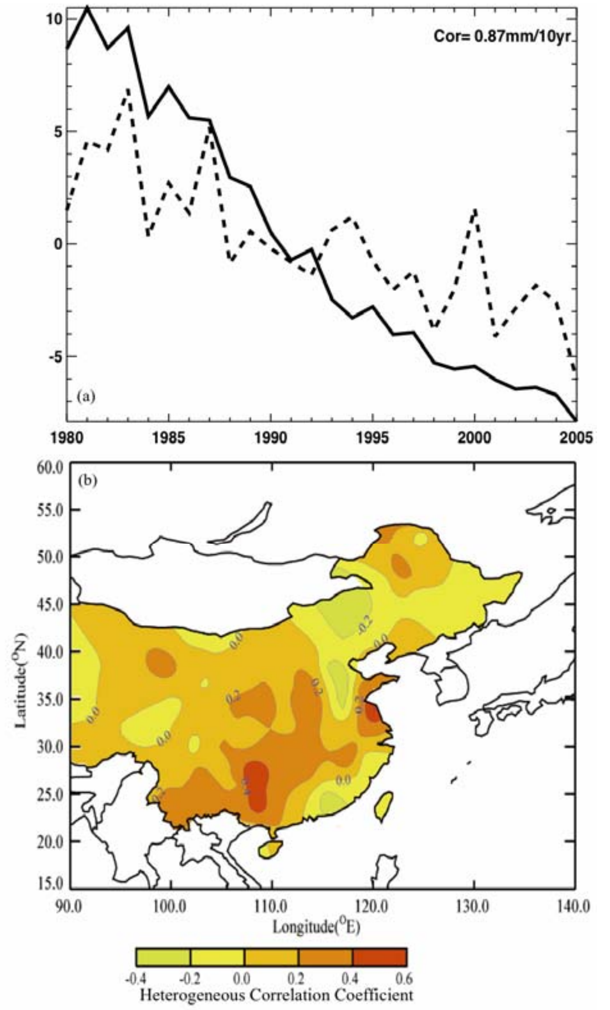

Figure 5. The first SVD mode of the autumn visibility and autumn precipitation for the period 1980-2005. (a) The temporal coefficients of autumn visibility (solid line) and autumn precipitation (dash line); (b) The spatial pattern of heterogeneous correlation coefficient.

From the perspective of precipitation formation mechanism, increased atmospheric stability and modified cloud microphysics could result in the decrease of autumn precipitation over Mid-Eastern China. Increased atmospheric stability induced by more aerosols may decrease the surface net radiation, inhibit the ascending motion of air and decrease the formation of precipitation. On the other hand, aerosols also change the characteristics of cloud microphysics by influencing the process of cloud condensation nucleus and lead to decreased precipitation.

4 CONCLUSIONS AND DISCUSSION

In this study, the effects of aerosol on the autumn precipitation over Mid-Eastern China were investigated using ground observations, satellite retrievals and NCEP reanalysis dataset. Main conclusions are as follows.

Precipitation decreased more significantly in autumn (i.e. 54.3 mm/decade) than in other seasons during the past 50 years over Mid-Eastern China. The decreasing trend of autumn precipitation was more significant after the 1980s, with an average decrease of 5.6% per year.

From the perspective of precipitation formation mechanisms, water vapor, atmospheric stability and cloud microphysics could lead to the decrease of autumn precipitation. We found that the increased aerosols produced by enhanced industrialization and environmental pollution could result in the change of atmospheric stability and cloud microphysics, which were at least partly responsible for the decreased autumn precipitation observed over Mid-Eastern China for the past 20 years.

The effects of aerosol on autumn precipitation were more outstanding than that on other seasons because the weather system in autumn was relatively stable compared to that in other seasons and the dynamical influence was greater than that of thermal dynamical activity. The wet removal of precipitation on aerosol was relatively small in autumn compared to that in summer, leading to the greater effects of aerosol on precipitation in autumn than in summer. Generally speaking, the high frequency of dust aerosol occurred in spring, which may be caused by relatively high frequency of convective weather outbreak and the dry loose soil. However, the impact of dynamical activity in spring also plays an important role in the spring precipitation change. Therefore it is hard to distinguish which factor is the most significant for precipitation change in spring. In winter, various types of precipitation could occur, including rain, snow and hail, leading to larger difficulty in detecting precipitation in winter than in other seasons. Furthermore, relatively more stable weather systems near the surface and the stable visibility could both lead to difficulty in studying the aerosol variations in winter. Thus, the precipitation change in winter was not considered in this study.

In summary, the effects of aerosols on autumn precipitation change over Mid-Eastern China were demonstrated using observed datasets from the perspective of precipitation formation mechanisms. More efforts will be spent to study the physical interactions between precipitation change and aerosol variations.

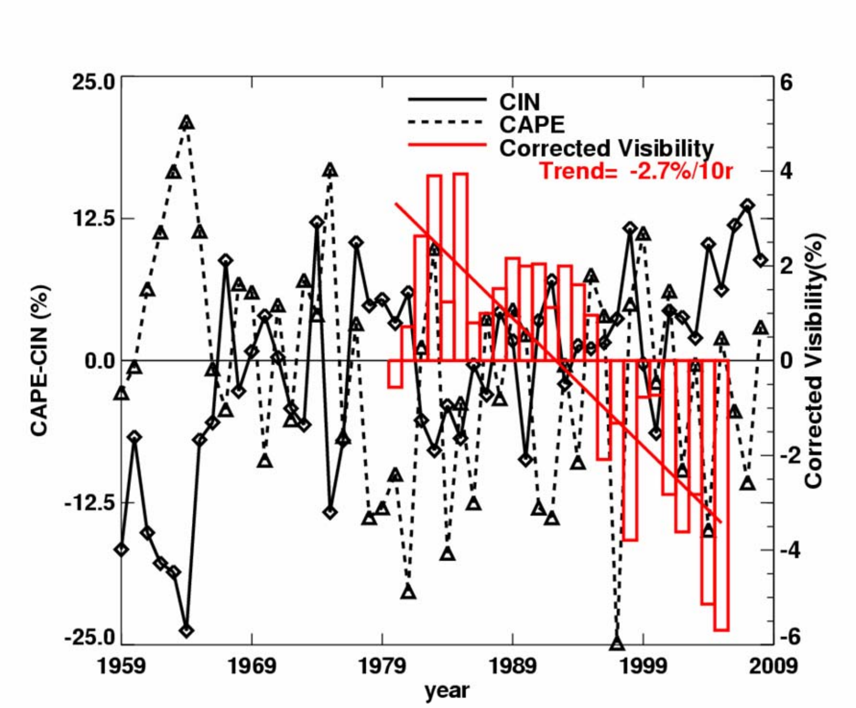

Figure 6. Time series of convective available potential energy (dash line), convective inhibition energy (solid line) and revised visibility (red histogram) anomalies in autumn over Mid-Eastern China. The red line represents linear trend of revised visibility anomaly.

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