Aerosol Impacts on Meteorological Elements and Surface Energy Budget over an Urban Cluster Region in the Yangtze River Delta

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ABSTRACT

The Yangtze River Delta (YRD) is a typical example of regions that are dramatically influenced by both human activity and a monsoonal climate. Data on the near-surface micro-meteorology, radiation, and energy fluxes were collected and analyzed at the Lishui field observation site in the suburb of Nanjing to investigate aerosol impacts on the radiation budget and land surface-atmosphere heat, water, and mass exchanges. Cluster analysis, composite analysis, and case study were applied to selected typical polluted/non-polluted days. The results indicate that the mean daily surface pressure is 6.6 hPa lower on polluted than non-polluted days in Nanjing. Northeasterly winds often prevail on the polluted days, with wind speeds being 60% lower than on non-polluted days. Aerosols directly reduce the net radiation flux at the surface, with a maximum reduction of 180 W m^{-2} . During the early stage of air pollution events, the surface pressure is lower, and wind speeds rapidly decrease, whereas during the peak of pollution, low surface pressure and wind speeds linger, effectively preventing the dispersion of air pollutants. Meanwhile, the temperature often decreases, and the relative humidity subsequently increases. As the wind speed and surface pressure increase, the AQI gradually decreases, and the air pollution event ends.

Keywords: Urban cluster region; Meteorological elements; Surface energy budget.

INTRODUCTION

Atmospheric aerosols refer to a mixture of multi-phase solid and liquid particles with a diameter of $0.001\text{--}100 \text{ }\mu\text{m}$ suspended in the atmosphere. In addition to natural background aerosols (dust, sea salt, biogenic emissions, volcanic eruptions, etc.), anthropogenic aerosols and pollutant emissions have been increasing with rapid economic development and intensified human activities such as urbanization, transportation, fossil fuel combustion, and industrial and agricultural processes (Guo *et al.*, 2011; Li *et al.*, 2017). Toxic fine airborne particles can damage human health. Previous studies have shown that a high $\text{PM}_{2.5}$ concentration has significant impacts on the development of childhood lung function. In detail, for every $10 \text{ }\mu\text{g m}^{-3}$ increase in $\text{PM}_{2.5}$ the risk of lung cancer and heart disease increases by 6–8%, reducing the life expectancy of people in North China by an average of 5.5 years (Chen *et al.*, 2013b).

Due to the well-known radiative and microphysical effects of aerosols particles, the study of aerosol impacts on weather and climate has become a cutting-edge topic in atmospheric science, oceanography and environmental studies.

Aerosols can affect global and regional climate via the following processes: (1) Aerosol radiative effects reduce incoming solar radiation, change the radiative heating distribution in the atmosphere, and directly affect radiative forcing via dissipation and absorption of solar radiation (Miller and Tegen, 1998; Han *et al.*, 2013; Huang *et al.*, 2015); (2) as cloud condensation and ice nuclei, aerosols affect cloud physics and cloud duration, and aerosol in turn delays the precipitation (indirect effect; Twomey, 1974; Fan *et al.*, 2008; Guo *et al.*, 2016a; Lee *et al.*, 2016; Xu *et al.*, 2018); and (3) aerosol radiative effects can heat air masses, leading to cloud drop evaporation and thus affecting cloud numbers and albedo (semi-direct effect; Koren *et al.*, 2004; Huang *et al.*, 2006; Helmert *et al.*, 2007; Koch and Del Genio, 2010). Interaction between aerosols and the atmosphere is quite complicated because of the different physical-chemical properties of various types of aerosols, thus large uncertainties still exist in the study of aerosol impacts on global climate and climate change (Parajuli *et*

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al., 2013; Wang *et al.*, 2014). The IPCC (2013) noted that direct radiative forcing by aerosols is -0.4 W m^{-2} (approximately from -0.2 to -0.6 W m^{-2}) globally, among which the global average radiative forcing is 0.2 W m^{-2} (-0.05 to 0.35 W m^{-2}) by black carbon and -0.05 W m^{-2} by organic carbon aerosols. Uncertainties in the climatic effects of aerosols are largely related to uncertainties in the spatial and temporal distributions of aerosols and an incomplete understanding of the aerosol-climate feedback.

The Yangtze River Delta (YRD) is a major region in China that has undergone rapid economic development and dramatic human activities accompanied by significant energy and resources consumption, resulting in various air pollutants emitted into the atmosphere. Fine particles from dust events and biomass burning (via long-distance transport) that have strong extinction effects on radiation also affect this region. As a result, air pollution in this region presents special regional characteristics of high complexity. Globally, eastern China, the northern Indian Peninsula and southern Himalayas, and south-central Sahara in Africa are the major regions with severe and continuous aerosol pollution, where the average aerosol optical thickness (AOD) can reach approximately 0.8 (Chen *et al.*, 2013b; Liu *et al.*, 2018). Areas with AOD greater than 1.0 have been increasing most rapidly during recent years, and the increasing rate is much higher in urban clusters on flat plains than those in mountainous regions (Tegen *et al.*, 2000; Luo *et al.*, 2001; Li *et al.*, 2003; Tegen *et al.*, 2009; Rasheed *et al.*, 2015). Human activities are the major source of aerosols in eastern China, and sulfate emissions in economically developed eastern China account for 97.7% of China's total emission (Ren *et al.*, 2012). Under certain meteorological conditions, anthropogenic aerosols can rapidly accumulate on the YRD and influence the formation of local secondary pollution via heterogeneous reactions with dust and aerosols produced by biomass burning (Nie *et al.*, 2015). Therefore, it is necessary to investigate in detail the radiative effects of aerosols on the YRD.

The increase in aerosol concentration is related to air pollution and is the primary reason for the reduction of net shortwave radiation in eastern China. Observations at weather stations indicate that the total surface radiation at most of the stations has decreased by more than 6% per decade, and the largest decrease has occurred on the YRD, where human activities are the most intense (Zhang *et al.*, 2004; Che *et al.*, 2005; Richter *et al.*, 2005; Qian *et al.*, 2006, 2007, 2011). Xia *et al.* (2007) analyzed the aerosol optical properties and radiative effects on the YRD based on data from 2005–2006 collected at the Taihu Station in the EAST-AIRE field experiment. They found that a high concentration of aerosols reduced the direct radiation by 112.6 W m^{-2} and increased the diffusive shortwave radiation by 67.1 W m^{-2} respectively, which finally reduced the total shortwave radiation by 45.5 W m^{-2} . Wang and Shi (2002) investigated the impact of changes in cloud and surface albedo on direct radiative effects of aerosols, and found that a higher surface albedo reduces the sulfate radiative effects of direct radiation, and vice versa. Furthermore, the impact of sulfates on the surface radiation balance is

equivalent to that of the atmosphere. Aerosol effects have led to a decrease in the surface temperature in mainland China, with large decreases of -0.4°C and -0.5°C from the Sichuan Basin to the middle and lower reaches of the Yangtze River and from the northern Tibetan Plateau to the Ordos Loop region, respectively. The spatial and temporal distribution of aerosols is undoubtedly affected by the East Asian monsoon, that is, aerosol effects can reduce the surface temperature and precipitation during the summer, leading to a weakened summer monsoon in East (or South) Asia (Liu *et al.*, 2009; Zhang *et al.*, 2012; Jin *et al.*, 2014; Huang *et al.*, 2016). While the main causes induced by aerosol for the weakening summer monsoon at least include the reduced land-sea thermal contrast (Li *et al.*, 2016; Yang *et al.*, 2017). In addition, Xu (2001) proposed that the “south flood-north drought” phenomenon that continuously occurred during the late 1990s in China can be attributed to the southward shift of the rain belt, which was induced by the radiative effect of anthropogenic sulfate aerosols. Fine particles can weaken the urban heat island (UHI) intensities by reducing urban warming during the day (Wu *et al.*, 2017; Li *et al.*, 2018). Studies also found that stronger UHI intensity can drive a strong PBL circulation cell, which redistribute and transport more pollutants far from the emission center (Li *et al.*, 2015). Interaction and feedback between the surface and atmosphere on the YRD is significant with large impacts on water, energy, and momentum exchanges, which makes it important to further study the aerosol impacts on meteorological elements and the surface energy budget (Ding *et al.*, 2013; Cai *et al.*, 2018).

Most previous studies on long-term climatic impacts and short-term meteorological changes by aerosols have been conducted (e.g., Ling *et al.*, 2014; Zhang *et al.*, 2014; Yang *et al.*, 2016), especially over eastern China (Zhuang *et al.*, 2014, 2016, 2017; Shen *et al.*, 2018) and southern China (Zhou *et al.*, 2016). The urban cluster in the Nanjing area was taken as an example in the present study to investigate aerosol impacts on weather and climate in this study. Various regional air pollutant concentration, micro-meteorology and surface radiation budget, and sensible and latent heat flux data were collected and classified based on daily weather conditions. Variations in near-surface meteorological elements, surface energy balance and radiation budget were analyzed. The aim of the present study was to quantitatively evaluate radiative forcing and climatic impacts of air pollution in the region and provide a scientific basis and theoretical support for the development of aerosol radiative modules in climatic models.

DATA AND METHODOLOGY

Data

The air quality data were assessed from the daily air quality index (AQI) and $\text{PM}_{2.5}$ concentration issued by the Nanjing Environmental Monitoring Station and Nanjing Meteorological Bureau. AQI is a dimensionless index for quantitative description of air quality condition, which comprehensively consider the contribution of sulfur

dioxide (SO), nitrogen dioxide (NO), PM₁₀, PM_{2.5}, carbon monoxide (CO), ozone (O₃) and other pollutants. The comparison between AQI and PM_{2.5} can be used to analyze the contribution of particles, and other pollutants.

In order to consider the contribution of absorbing aerosols, the OMAERUV remote sensing data products were analyzed. The daily ultraviolet aerosol index (UVAI) is derived from the Ozone Monitoring Instrument (OMI) of the Earth Observing System (EOS) AURA satellite launched in July 2004 (Ahmad *et al.*, 2003; Peter *et al.*, 2017). The space resolution is $1^{\circ} \times 1^{\circ}$, and we consider the value from the product grid that is the nearest to the Lishui Station as the aerosol index for absorbing aerosols.

Meteorological elements and radiation were extracted from daily observations collected at Lishui Station in suburban Nanjing (Guo *et al.*, 2014b). Observations at this station have been applied for comparative studies of long-term surface-atmosphere interaction in this region. Lishui

Station ($31^{\circ}43'N$, $118^{\circ}58'E$) is a satellite station of SORPES-NJU in southern Nanjing with two sites: farmland (LS-crop) and grassland (LS-grass), respectively. Fig. 1 shows the locations in Nanjing, surface conditions for LS-crop and LS-grass, and instruments for the different observed variables. The grassland site was used for observations from January 2012 to February 2014, and the surface was largely covered by grass with a height of approximately 60 cm. There is no large-scale surface emission source in the surrounding area. The cropland site was used from January 2013 to February 2014. Winter wheat grows during the winter half-year (from the middle of November to early June) and rice grows from the middle of June to early November in this region. Note that the distance between the cropland and grassland sites was 1.62 km and their altitudes were nearly the same, thus the two sites were similarly representative of the region for air quality studies.

Fig. 1. Location of (a) Lishui Station; surface condition at the (b) crop station (LS-crop) and (c) grass station (LS-grass); and instruments for (d) precipitation, (e–f) surface flux monitoring, (g) surface radiation monitoring, and (h–i) soil parameter monitoring.

The near surface micro-meteorological elements included temperature (Ta), pressure (P), relative humidity (RH), wind speed (Ws), and wind direction (Wd) at intervals of 30 min. Near surface radiation elements included upward and downward solar radiation and longwave radiation. Momentum and heat fluxes were derived from observations of an eddy covariance (EC) system with a sampling frequency of 10 Hz. A strict data quality control procedure was applied to the observations and the final data products used for the present study were flux data at 30-min intervals (see Table 1). Weather conditions were obtained from the weather website (<http://lishi.tianqi.com/>).

Methodology

Cluster analysis, composite analysis and typical case analysis were used in the present study. For the cluster analysis, representative pollution events were selected based on PM_{2.5} concentration, AQI and weather condition. Typical polluted days and non-polluted days were selected. Meteorological elements and energy budgets under different aerosol conditions were arithmetically averaged to remove the influences of background weather conditions. Diurnal variations in micro-meteorological elements and radiation fluxes were analyzed and compared under different aerosol distributions. To further analyze the evolution of the aforementioned elements and momentum fluxes during the pollution process, a typical pollution event that occurred from November 28 to December 12 during 2013 was selected to study the characteristic variations in the micro-meteorological elements and radiation budget.

Classification of Weather Conditions

Fig. 2 shows the daily PM_{2.5} concentration, AQI, and UVAI during the period October 1–December 31, 2013. AQI and PM_{2.5} concentration show consistent variational features, for AQI is highly dependent on PM_{2.5} concentration.

The ratio of PM_{2.5} concentration and AQI is high when AQI/PM_{2.5} concentration is high, indicating that fine particles are the main polluted materials during polluted events. In addition, the UVAI is high when AQI/PM_{2.5} concentration is high, with the correlation coefficient of 0.63 and 0.60 respectively. Therefore, the two variables can both be used to describe aerosols in the atmosphere.

During the period October 1–December 31, 2013, three pollution episodes were identified based on the criteria that the AQI was greater than 100 during a continuous 48-h period and the PM_{2.5} concentration was greater than 174 $\mu\text{g m}^{-3}$. The three episodes occurred during the periods December 3–8, December 19–20 and December 24–26. Eleven typical pollution days were identified and rainy days were excluded to avoid the impact of rainfall on aerosol distribution. Four non-polluted days were identified within five days before and after the pollution episodes with the AQI not exceeding 100. Rainy days within five days before and after the identified non-polluted/pollution days and the day before and after the rainy days were excluded, and the arithmetical averages of the meteorological elements and aerosol data for the remaining days were treated as the background values for comparative analysis.

A large-scale pollution event occurred from late November to early December during 2013. The selected episodes only covered a short period of time, which can to a certain extent remove the influence of solar zenith angle and seasonality. Rainy days and the day before and after the rainy day were excluded to minimize the impacts of clouds and precipitation. In addition, the selection of consecutive days for weather analysis can eliminate the influence of different weather conditions on meteorological elements and surface radiation budget and increase the reliability of the results.

Based on the aforementioned criteria, the background API is 197 and the PM_{2.5} concentration is 155 $\mu\text{g m}^{-3}$;

Fig. 2. Time series of daily PM_{2.5} concentration, AQI and UVAI during the period October 1–December 31, 2013.

during pollution days, the API is 324 and the $\text{PM}_{2.5}$ concentration is $274 \mu\text{g m}^{-3}$; during non-polluted days, the API is 91 and the $\text{PM}_{2.5}$ concentration is $55 \mu\text{g m}^{-3}$. Details can be found in Table 2.

COMPARATIVE ANALYSIS OF METEOROLOGICAL ELEMENTS AND RADIATION BUDGET UNDER DIFFERENT WEATHER CONDITIONS

Differences in Surface Meteorological Elements

Aerosol particles are suspended in the atmosphere, affecting surface meteorological elements by influencing direct radiation at the surface. Fig. 3 presents daily surface temperature and RH, pressure, wind speed and wind roses from October to December of 2013 under typical polluted and non-polluted days. Fig. 3(a) shows that the diurnal variations in temperature and RH are in opposite phases on both non-polluted and polluted days, while they have similar variational patterns on non-polluted and polluted days. The daily average temperature is 4.54°C higher on polluted days than on non-polluted days, which might be because aerosols suspended in the air are firstly impacted by temperature, and then reacting to it. Temperature changes on the non-polluted days are always earlier than those on polluted days, indicating that the temperature response to solar radiation is slower on polluted days than on non-polluted days. To interpret this phenomenon, the warm effect of aerosols during night and the cool effect during the daytime would weaken the direct exchange of energy between the land surface and the atmosphere. The RH is higher on polluted days than that on non-polluted days with an average difference of 26%. The average RH values are 50.2% and 76.3% on polluted days and non-polluted days, respectively. Changes in RH are possibly caused by hygroscopic growth of aerosols and temperature changes. According to Zhuang *et al.* (2014), scattering coefficient (SC) for aerosols and high level of visibility are likely found in high RH ranges. This is consistent with

Ding *et al.* (2013) that the stagnant meteorology is typically characterized by weak wind speed and high RH in the formation of polluted events over eastern China. Furthermore, the increased RH tends to favor the hygroscopic growth of aerosols, and could enhance the formation of secondary aerosols (Li *et al.*, 2017). As shown in Fig. 3(b), the diurnal variational pattern in surface pressure on non-polluted and polluted days is similar to the background variation. The average difference between non-polluted and polluted days is 6.6 hPa, which is possibly associated with convergence and pollutant accumulation under a low-pressure condition. Fig. 3(c) shows that the wind speed has no distinct diurnal variation on polluted days, and it remains approximately $0.5\text{--}1 \text{ m s}^{-1}$ on non-polluted days and increases with time later, reaching $2.5\text{--}3 \text{ m s}^{-1}$ during the period 10:00–17:00 local time (LT) and then decreases rapidly to approximately 1 m s^{-1} . The wind speed on non-polluted days is higher than that on polluted days with an average difference of 0.88 m s^{-1} . This wind speed difference is particularly distinct during the period 10:00–14:00 LT, suggesting that low wind speeds on the YRD are favorable for pollutant accumulation and thus formation of pollution episodes. Figs. 3(d)–3(e) shows wind roses under three weather conditions. In general, westerly and southerly winds prevail with a homogeneous wind speed distribution. On non-polluted days, westerly winds prevail with a higher wind speed; on polluted days, northwesterly winds prevail with most wind speeds less than 1 m s^{-1} .

Differences in Surface Energy Budget

Aerosols can modify the partitioning of solar energy between atmosphere and land by absorbing and scattering solar radiation, which may influence regional climate. Fig. 4 shows the diurnal variations in surface shortwave, longwave, net radiation flux, and sensible and latent heat fluxes on typical polluted days and non-polluted days and under background conditions.

The diurnal variations in upward and downward shortwave radiation flux on polluted days, non-polluted

Table 1. Instruments used at Lishui Station.

Instrument name	Instrument type	Observed variables	Company
Eddy covariance system	CSAT3, Li-CS7500	CO_2 , LE, HS	Campbell, LI-COR
Humidity/temperature probe	HMP45C-L	Temperature, RH	Vaisala
Soil temperature profile	STP01-L50, 107-L	Soil Temperature	Hukseflux
Water content reflectometer	CS616_L	Soil Moisture	Campbell
Tipping bucket rain gage	TE525MM_L	Precipitation	Texas Electronics
Pyranometer (SW flux)	CM21	Total/Solar Radiation	Kipp & Zonen
Total sky imager	ASI	Cloud	ASI

Table 2. Typical polluted days and non-polluted days and their corresponding aerosol concentrations.

Polluted days			Non-polluted days		
Date	AQI	$\text{PM}_{2.5} (\mu\text{g m}^{-3})$	Date	AQI	$\text{PM}_{2.5} (\mu\text{g m}^{-3})$
03 DEC	245	195	28 NOV	86	45
04 DEC	377	327	29 NOV	93	54
07 DEC	363	313	10 DEC	98	73
25 DEC	309	259	27 DEC	88	49

Fig. 3. Diurnal variations in surface micro-meteorological elements from October to December of 2013: (a) temperature and RH, (b) surface pressure, (c) wind speed, (d) wind roses of wind direction frequency (%), and (e) wind roses of wind speed frequency (%).

days, and under background weather conditions are shown in Fig. 4(a), which shows that upward and downward solar radiation both present a unimodal diurnal variation pattern under the three conditions. During the day, the upward and downward shortwave radiation fluxes are both smaller on polluted days than those on non-polluted days with the largest differences of 280 W m^{-2} and 50 W m^{-2} , respectively. It can be deduced that the aerosol particles suspended in

the air to some extent reduce the solar radiation that reaches the surface and weakens the solar heating. Reflective solar radiation correspondingly decreases under the same underlying surface condition. Fig. 4(b) shows that longwave radiation flux reaches the surface and upward longwave radiation are both greater on polluted days than on non-polluted days with differences of 23 W m^{-2} and 63 W m^{-2} , respectively. Combined with Fig. 3(a), polluted days are

Fig. 4. Diurnal variations of surface energy budget from October to December of 2013 under three typical conditions: (a) shortwave radiation flux (R_s), (b) longwave radiation flux (R_l), (c) net radiation flux (R_n) and sensible and latent heat fluxes (H_s and LE).

always accompanied by higher temperature, namely, the larger longwave radiation. Furthermore, the longwave radiation emitted from the surface and the lower level of the atmosphere are absorbed and then re-emitted to the surface via aerosol particles suspended in the air. The strong downward longwave radiation can be explained with the heating of absorbing aerosols.

During the day, however, although the aerosol particles still behave similar to an insulation layer because of their impact on longwave radiation, their impact on shortwave radiation is much stronger. Downward shortwave radiation is scattered and reflected by aerosol particles in the air, leading to large decreases in solar radiation that can reach the surface. As a result, net radiation in the surface is much less on polluted days than that on non-polluted days during the day, but slightly greater during the night. As shown in Fig. 4(c), the diurnal variation in surface net radiation presents a unimodal pattern under different weather conditions, while the net radiation flux during the day (08:00–16:00 LT) is much higher on non-polluted days than that on polluted days with a greatest difference of nearly 180 W m^{-2} . In contrast, net radiation flux during the night shows little difference under different weather conditions and is only slightly higher on polluted days than on non-polluted days. From the perspective of the entire day, the net radiation flux on polluted days is 19 W m^{-2} less than that on non-polluted days. Therefore, the impact of aerosols on the surface-atmosphere system is not limited to the aerosol heating effect on the lower atmosphere. Decreases in surface net radiation caused by aerosol radiative effects should also be considered.

Fig. 4(c) shows that the magnitudes of the sensible and latent heat fluxes are equivalent, and their diurnal variations are similar to those of net radiation flux with a unimodal feature. The peak values occur at approximately 12:00 LT. During the day (09:00–15:00 LT), the sensible heat flux is greater than the latent heat flux. Both the sensible and latent heat fluxes during the day are smaller on polluted days than on non-polluted days, suggesting

that under a high concentration of aerosols, although solar radiation energy can still be transferred from the surface to the atmosphere during the day, sensible heat flux decreases because of the aerosol absorption of shortwave radiation and the reduced temperature difference between the surface and the atmosphere. On polluted days, the relatively high RH leads to a decreased difference in RH between the surface and the atmosphere, and subsequently reduces the latent heat flux. On polluted days, the sensible and latent heat fluxes account for 88% and 34% of the total net radiation flux, respectively; on non-polluted days, the values are 64% and 53%, respectively.

ANALYSIS OF A TYPICAL POLLUTION EPISODE

To further analyze aerosol impacts on meteorological elements, surface energy budget, and sensible/latent heat fluxes in the urban cluster region of the YRD, a typical heavy pollution episode was selected for analysis in the present study.

Weather Condition

A severe pollution event occurred during the period of December 2 to 12 in 2013 in eastern China. This pollution episode covered a large area and affected nearly all of central and eastern China. The AQI index reached Level 6, the severe pollution level, in multiple locations such as Tianjin, Hebei, Shandong, Jiangsu, Anhui, Henan, Zhejiang, and Shanghai. Fig. 5 showed the scenario of air pollution days (December 8, 2013) and usual days in Nanjing. The average $\text{PM}_{2.5}$ concentration was greater than $150 \mu\text{g m}^{-3}$ and the value reached $300\text{--}500 \mu\text{g m}^{-3}$ in some areas. The most severe pollution occurred in central and southern Jiangsu, and the air quality in Nanjing reached the extremely severe pollution level for five consecutive days and the severe level for nine consecutive days. The $\text{PM}_{2.5}$ concentration reached $943 \mu\text{g m}^{-3}$ at 11:00 LT on December 3, 2013.

(a) Scenario of air pollution days

(b) Scenario of usual days

Fig. 5. (a) A polluted day (December 8, 2013) and (b) a normal day at the Xianlin campus of Nanjing University.

Fig. 6 shows the geopotential height fields at (a, c) 500 hPa and (b, d) 850 hPa at 12:00 UTC on (a, b) December 5 and (c, d) December 10, 2013, representing the synoptic situation for the polluted and non-polluted day respectively. The 4-times daily geopotential height data (Kalnay *et al.*, 1996) with the resolution of $1^\circ \times 1^\circ$ is obtained from the National Center for Atmospheric Research (NCAR). The region of $70^\circ\text{--}140^\circ\text{E}$, $20^\circ\text{--}60^\circ\text{N}$ is used to analyze the background circulation, and the location of $31^\circ43'\text{N}$, $118^\circ58'\text{E}$ is treated as the Lishui station. On December 5, there was a gentle westerly air stream prevailing at the 500 hPa over eastern China without significant trough and ridge. At the 850 hPa level, the isopiestic line is sparse over the eastern China. This configuration of high-level and low-level synoptic situation is stable, which suppress the diffusion of aerosols. On December 10, the density of isopiestic line is higher over eastern China, which favor to the pollutant dispersion.

Changes in Surface Meteorological Elements

Fig. 7 shows daily changes in surface pressure, temperature, RH, and wind speed from November 28 to December 13 of 2013. Fig. 7(a) shows that the surface pressure oscillated at approximately 1025 hPa on November 28, and then rapidly decreased, accompanied by a rapid increase in the pollutant concentration. During several days of heavy pollution, the surface pressure oscillated at approximately 1015 hPa; following December 9, the surface

pressure gradually increased, and the pollution episode ended. It is clear that changes in surface pressure and pollutant concentration are negatively correlated. Low surface pressure and weak convergence of airflow suppressed the diffusion of aerosols during the developing stage of this severe pollution episode. As shown in Fig. 7(b), daily changes in temperature were in opposite phase to those of RH during the entire process, and the magnitude of the diurnal variation for temperature on the polluted days was higher at the outbreak of the pollution episode than on the other days. During the late stage of the pollution episode, the temperature began to decrease, suggesting that the aerosol particles suspended in the air effectively dissipated the solar radiation and reduced the surface net radiation. Furthermore, the case study method cannot eliminate the influence of synoptic situation. RH was higher on the polluted days than on the other days, and nearly reached a saturation level on December 7 and 8. During the pollution event (Fig. 7(c)) from November 28 to December 4, the surface wind speed was low all of the time and the concentration of pollutants remained high. The wind speed was approximately 1 m s^{-1} during the period of December 4–8 without distinct diurnal variation. During the late stage of the pollution episode, the wind speed showed a rapid increase. It can be deduced that during this pollution episode, the weak wind speed undermined dispersion and caused pollutant accumulation, resulting in the outbreak. The rapid increase in wind speed during the later stage of the

Fig. 6. Geopotential height (in dagpm) fields at (a, c) 500 hPa and (b, d) 850 hPa at 12:00 UTC on (a, b) December 5 and (c, d) December 10, 2013.

Fig. 7. Daily changes in the surface micro-meteorological elements from November 28 to December 14, 2013: (a) surface pressure, (b) temperature and RH, and (c) wind speed. The green lines are utilized to mark the daytime and nighttime.

pollution episode provided a favorable condition for dispersion of pollutants and the event ended.

Changes in Surface Radiation Budget and Energy Balance

Daily changes in each variable of the surface radiation budget are shown in Fig. 8, which shows significant responses of these variables to changes in aerosol concentration. Combined with Figs. 8(a)–8(b), it can be seen that aerosols reduced the net surface radiation mainly via a reduction in downward solar radiation during the day. With the same surface albedo, upward solar radiation consequently decreased. Under a condition of severe pollution, downward longwave radiation at the surface was much higher than on non-polluted days, indicating that the upward longwave radiation emitted by the surface was reflected back to the surface via aerosol particles suspended in the air. The aerosol particles behaved similar to an insulation layer. Fig. 8(c) shows that from December 3 to 8, the net surface radiation was distinctly lower than that on the non-polluted days, and the peak value of net radiation on December 7 was 240 W m^{-2} less than that on December 8. Following the decrease in surface net radiation, the partitions to sensible and latent heat fluxes correspondingly decreased. During the entire process, the sensible heat flux always remained larger than the latent heat flux, which can be attributed to the decreased temperature difference between the surface and the atmosphere and the weakened sensible heat flux exchange.

Response of Dynamic Variables in the Surface

Temporal variations in dynamic variables during the pollution event are shown in Fig. 9, which were used to analyze fluctuations of horizontal and vertical wind components. Fig. 9(a) show the variance of vertical wind speed, reflecting the turbulence of atmosphere. During the polluted days, the fluctuation of vertical air velocity is small, indicating stable atmospheric, which suppress the diffusion of aerosols. During the late stage of the pollution episode, vertical wind velocity fluctuations gradually increased and air turbulence intensified. As a result, the pollutant concentration decreased. The change pattern for horizontal wind speed variance (Fig. 9(b)) is similar to the vertical wind speed, with the lowest value during the polluted days. Both U and V components reached their maximum at 19:00 LT. The largest value for momentum and variance of horizontal wind speed can be found on December 9 when aerosol concentration began to decrease, meaning that strong wind speed fluctuation can favor the diffusion of aerosols. Fig. 9(c) shows the covariance between the vertical and horizontal winds, which reflects the correlative relationship between horizontal and vertical winds during this pollution episode. During the pollution event, the v and w show positive relationship, implying that the aerosols might come from the north of Nanjing. During this pollution event, high aerosols concentration is associated with low wind speed. It can be seen that accompanied by strong wind speed fluctuations during the period of November 28 to 30, pollutants rapidly accumulated

and mixed in the region, leading to the outbreak. Since that time, vertical wind speed fluctuations significantly weakened, suggesting that turbulence was weak and the condition was unfavorable for pollutant dispersal. During the late stage of the episode, vertical wind speed fluctuations gradually intensified with stronger turbulence, and the pollutant concentration decreased.

DISCUSSION AND CONCLUSION

In this study, the meteorological elements and surface energy balance during different pollution conditions were compared. A typical pollution episode was also analyzed. The major conclusions are as follows:

- (1) Over the urban cluster area of the YRD, represented by Nanjing, the mean daily temperature is approximately 4.5°C higher, the RH is 26% higher, the surface pressure is 6.6 hPa lower, and the wind speed is 60% lower on polluted days than on non-polluted days. Northeasterly winds prevail on the polluted days.
- (2) Radiative aerosol effects lead to decreased net surface radiation, resulting in a maximum difference of 180 W m^{-2} between polluted and non-polluted days. The maximum sensible and latent heat fluxes account for 88% and 34%, and 64% and 53% of the net radiation on polluted and non-polluted days, respectively.
- (3) Prior to the onset of the pollution event from November 28 to December 14, 2013, the surface pressure dropped, and the wind speed rapidly decreased. During the period of high aerosol concentrations, both the surface pressure and wind speed remained low, thus inhibiting pollutant dispersion. Additionally, the surface temperature was distinctly higher during the onset of the pollution episode than prior to it, and the RH increased. Accompanied by an increase in wind speed and surface pressure as well as temperature, the meteorological conditions became favorable to pollutant dispersion. On polluted days, the net surface radiation flux, upward and downward shortwave radiation fluxes, and latent and sensible heat fluxes decreased.
- (4) During the pollution process, changes in the vertical velocity fluctuation were consistent with changes in the variance of horizontal wind speed. During the polluted days, the wind speed fluctuations remained low, turbulence was weak, and pollutants could not easily disperse. During the latter stage of the pollution episode, the vertical wind velocity fluctuations gradually increased, and turbulence intensified. As a result, the pollutant concentration decreased.

Because the samples used in the present study are limited, these results must be further verified against long-term observations. Furthermore, the sources of pollutants in urban cluster regions are often complex, and the radiative effects of various pollutants on different physical and chemical properties may vary. Therefore, further analysis of aerosol impacts over an urban cluster region based on the different sources and properties of the pollutants is required, as is the application of explicit models for better understanding the mechanisms regulating aerosol-radiation interaction.

Fig. 8. Daily changes in each individual term of the surface radiation budget from November 28 to December 14: (a) surface shortwave radiation flux, (b) longwave radiation flux, and (c) net radiation flux and sensible and latent heat fluxes. The green lines are utilized to mark the daytime and nighttime.

Fig. 9. Daily changes in the dynamic variables from November 28 to December 13, 2013: (a) vertical wind speed variance, (b) horizontal wind speed variance, and (c) covariance of vertical and horizontal wind speeds. The green lines are utilized to mark the daytime and nighttime.

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