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Observational study of river-land breeze and its influence on distribution of PM_{10} concentrations over a main mining city in the Yangtze River Delta, China

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Wind data from air pollutant observation networks and meteorological stations are used to analyze the characteristics of river-land breeze near Tongling city (a main mining city in the Yangtze River Delta). The inhomogeneous distribution of pollutant matters near Tongling city due to river-land breeze is also investigated. Our results show the following conclusions. 1) The river breeze during the daytime is stronger than the land breeze at night. And the speed of river-land breeze is increased rapidly from 7:00 and arrived at the maximum at 12:00. After 15:00, the speed is slowed rapidly. 2) The river-land breeze in city area (east of Yangtze River, speed is .07 m/s) is weaker than the natural area (west of Yangtze River, speed is 0.18 m/s). Furthermore, the seasonal variations of breeze both in the west and east sides are different. In west side, the breeze is strongest in spring. And in the east side, the breeze is strongest in summer. 3) Under a weak breeze (≤0.45 m/s), the PM_{10} is moved by the breeze within the region and causes the heterogeneity. While with a strong breeze (>0.45 m/s), the PM_{10} is transported out of the region, and the PM_{10} concentration becomes homogenous. 4) The river breeze leads to a reduction of the pollutant concentration near the Yangtze River, but an increase in the city due to the transportation of pollutant particles from coast to city at daytime.

KEYWORDS

river-land breeze, the distribution of air pollutant, inhomogeneity, PM10, Yangtze River Delta

Highlights

Weak river-land breezes caused spatial heterogeneity of PM_{10}. And strong breezes produced spatial homogeneity.

1 Introduction

The Yangtze River Delta (YRD) is one of the most important economic zones in China, including 26 cities in Shanghai, Jiangsu, Zhejiang and Anhui provinces. It is a region has not only heavy industries such as machinery industry, chemical industry, automobile manufacturing and mining, but also has agricultural products like wheat, rice and corn. It is also a hub of transportation. With the significant economic growth of the YRD, environmental problems become more and more prominent in that region. Hu et al. (2014) pointed out some atmospheric environmental problems including increase of particle concentration, more haze weather and the deterioration of air quality. Fu et al. (2013) also showed that the average emission intensities in the YRD for some air pollutants (SO_2, NO_X, $PM_{2.5}$, PM_{10}, NMVOCs and NH_3) were 2–7 times higher than the national average value in 2010. The annual average concentrations of $PM_{2.5}$ in the cities of Shanghai, Nanjing and Hangzhou in 2013 were 5–7 times higher than the World Health Organization (WHO) Air Quality Guidelines (Wang et al., 2014). These problems of air pollution may cause loss of both human health and Economic wealth (Wang et al., 2015). Therefore, the atmospheric environmental problem in the YRD is one of the most important issues that researchers should pay a close attention to.

Tongling city, a major mining city, is located in the west of YRD and near the Yangtze River. There are various industries, such as ore mining, metal smelting and Energy-Chemical industry. And the source of air pollution is a complicated problem in Tongling. In addition, complex topography (the Yangtze River, hills, cities, *etc.*) also creates special regional meteorological conditions. Particularly the specific geographic distribution of water and urban land use will have a certain effect on regional climate. Previous studies indicate that physical property differences between water and land may cause local atmospheric motion, form weather phenomenon with significant diurnal variation such as Sea-Land Breeze, land-lake breeze, and river-land wind (Avissar and Pielke, 1989; Oliveira and Fitzjarrald, 1993; Porson et al., 2007; Crosman and Horel, 2010; Crosman and Horel, 2012; Choi et al., 2015). Local atmospheric motion can change wind direction and speed, and thus influence the distribution of air pollutants in the area (Clappier et al., 2000; Melas et al., 2006). For example, air pollutant could be transported from coast to land due to the effect of sea breeze (Alexandra et al., 2016).

Despite that the spatial scale of river-land breeze is smaller (about 20 km) than sea breeze, it can bring remarkable influences on local weather and air quality (Wang et al., 2010). Silva Dias et al. (2004) studied the Amazon basin and found that river-land breeze could induce local convergence and divergence and create a local climate with distinct geographical features. The contrast between the wide surface of the Yangtze River and the land is prone to the formation of river-land breezes under a certain condition, which creates local climate regime and corresponding distribution features of atmospheric pollutant concentration. Therefore, in this study, we analyze river-land breeze and its influence on regional air pollution in Tongling city.

We analyze the characteristics of river-land breeze and the influence on distribution of PM_{10} in the Yangtze River Delta, China. The remainder of this paper is organized as follows: The study area, observations, and data quality control methods used are described in Section 2. We analyze the results in Section 3. The Discussion are given in Section 4 and the conclusions are given in Section 5.

2 Materials and methods

2.1 Meteorological and air quality data

In this study, we focus on Tongling city and the area surrounding it. The study region (117.5E-118E, 30.8–31.1N) is shown in Figure 1. In this domain, the Yangtze River passes through from south to north and is almost perpendicular to the latitude in all lines. Therefore, the river breeze caused by the difference of land and surface contrast is mainly in east-west direction. Observation data from all meteorological stations (total 22 stations) and air quality monitoring stations (total four stations) in study region are collected for analyzing river breeze and its influences on pollutant particles distribution. These four air quality monitoring stations are located at the ninth middle school (NS), the wastewater factory (WF), the fourth middle school (FS) and the road bureau (RB).

The data from air pollutant observation stations (national stations of Ministry of Ecology and Environment, PRC) and meteorological observation stations (regional stations of China Meteorological Administration) in the whole year of 2011 (observation experiment period in Tongling) are used in this study, include concentration of PM_{10}, the wind speed and direction. The time frequency of these observation data is 1 h. Those concentration of PM_{10} were observed by the LGH-01B PM_{10} air particulate matter monitoring instrument (produced by Anhui Landun Photoelectron CO., LTD., Anhui, PRC). The wind speed was observed by the three-cup wind speed sensor (EL15-1A) and the wind direction was observed by the sensor of EL15-2A (produced by Zhonghuan TIG, Tianjin, PRC).

The data of PM_{10} are disposed according to the technical specifications of Ministry of Ecology and Environment, PRC (Technical Specifications for Installation and Acceptance of Continuous Automatic Monitoring System for Ambient Air Particulate Matter (PM_{10} and $PM_{2.5}$), HJ 655–2013). And the supplemental quality control of all these datasets had been carried out before analysis. The primary purpose of quality control is to eliminate the outliers. However, it is also assumed 10% of air pollutant data are unreliable. The quality control aims to eliminate not only the outliers, but also those unreliable data. So, first step is

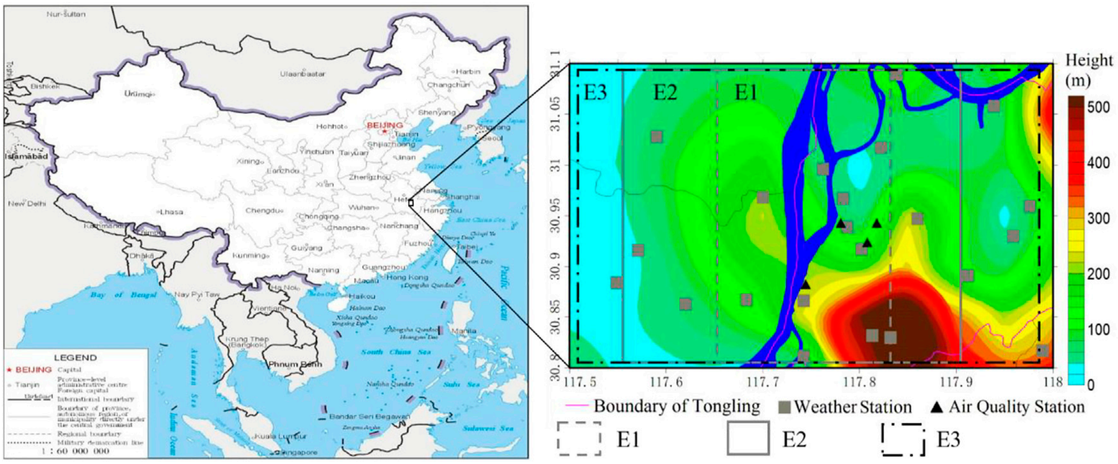

FIGURE 1
Map of the study region (squares are weather stations, and triangles are air quality stations, color shadow is altitude, blue is Yangtze River).

to calculate its probability distribution, then, a threshold is obtained to eliminate those 10% data.

2.2 River-land breeze calculation

According to formulas (1), it is clear that total wind ($\vec{V}$)can be decomposed into zonal ($u\vec{i}$), meridional ($v\vec{j}$) and vertical component ($w\vec{k}$). Because only horizontal wind data are collected in meteorological stations, and only zonal and meridional wind data are available. And for our case, the river-land breeze mainly affects the winds in east-west direction; therefore, only zonal winds (positive for westerly wind and negative for easterly wind) are analyzed. In addition, since river-land breeze is local deviated wind from environmental background wind, we further decompose zonal wind into environmental background wind ($\bar{u}$) and local deviated wind (Δu) as shown in formulas (2).

$$\vec{V} = u\vec{i} + v\vec{j} + w\vec{k} \tag{1}$$

$$u = \bar{u} + \Delta u \tag{2}$$

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{n} u_i \tag{3}$$

n is the number of weather stations in the study region, u_i is the zonal wind of the weather station i for the per hour observation data.

As the environment background wind ($\bar{u}$) is calculated with domain average method as formula (3) shown, the local deviated wind (Δu) is subtracted from the total zonal as formula (2). As the local deviated wind (Δu) is caused by the local geomorphic characteristics (river and land), and it is used to express river-land breeze in the following articles.

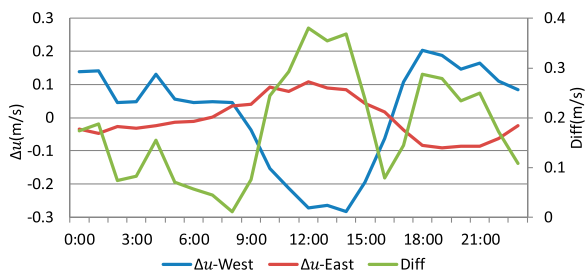

FIGURE 2
Diurnal variation of annual mean local deviated wind speed (Δu) in both sides of the Yangtze River and their difference in 2011 year.

Environment background wind ($\bar{u}$) is calculated with domain average method, and the formula is showed in formula (3). The difference (Diff) between the local deviated wind in the east (Δu_{east}) and west (Δu_{west}) bank of the Yangtze River is also calculated as formula (4).

$$\mathrm{Diff} = |\Delta u_{west} - \Delta u_{east}| \tag{4}$$

3 Results

3.1 Analysis of yangtze river breeze

Diurnal variation of annual mean local deviated wind (Δu) is shown in Figure 2. Generally, A “change inversely” relationship can be noticed between the west and east side of the river. During

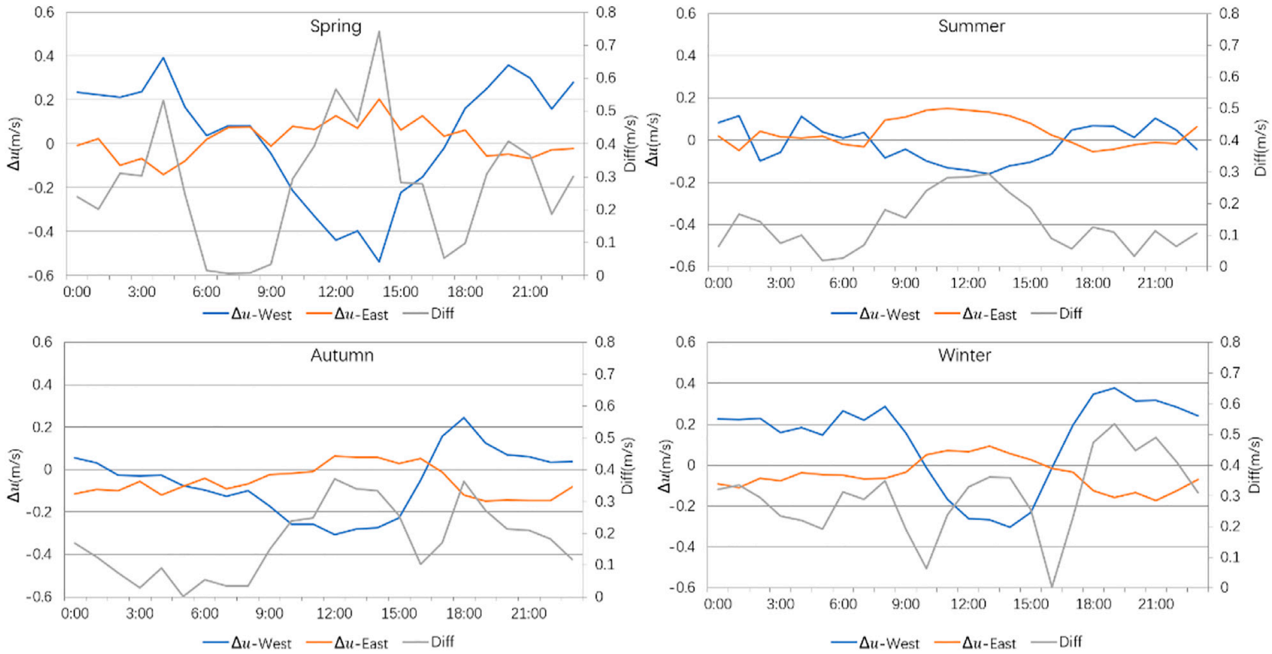

FIGURE 3
Diurnal variation of local deviated wind (Δu) in both sides of Yangtze River and their differences for different seasons.

8:00–16:00 (local time, and same hereafter), It is easterly wind in the west of the Yangtze River and westerly wind in the east, exhibiting a divergence pattern. In contrast, during 16:00–1:00, the local winds reverse the direction, which forms a convergence pattern. It can also be noticed that the local deviated zonal wind speed Δu in both east and west sides of the Yangtze River increases from 8:00a.m., reaching the maximum between 12:00–14:00, and gradually decreases afterwards. According to the difference between Δu in the east and west (Diff), there are two maximums in a diurnal cycle. The first one occurs between 12:00–14:00 when both u' and Diff reach their maximums (the largest Δu is 0.28 m/s and occurs in the west side of the Yangtze River, while the largest Diff is 0.37 m/s). The second maximum occurs between 16:00–22:00, and both Δu and Diff (0.2 m/s and 0.29 m/s respectively) are smaller in magnitude compared with the first maximum.

The diurnal variation of local deviated wind (Δu) in the east and west side of Yangtze River and their difference for different seasons are shown in Figure 3. It shows the following information. 1) For the pairs of Δu maximum at any season, in the daytime, it is always negative in the west side and positive in the east side of the Yangtze River. The only difference about this aspect for different seasons is the strength of Δu and the duration time of strong wind reversal. 2) In the daytime, the difference between the winds in either side of the Yangtze River is most significant in spring, followed by autumn, winter and summer. 3) In the nighttime, the difference between the

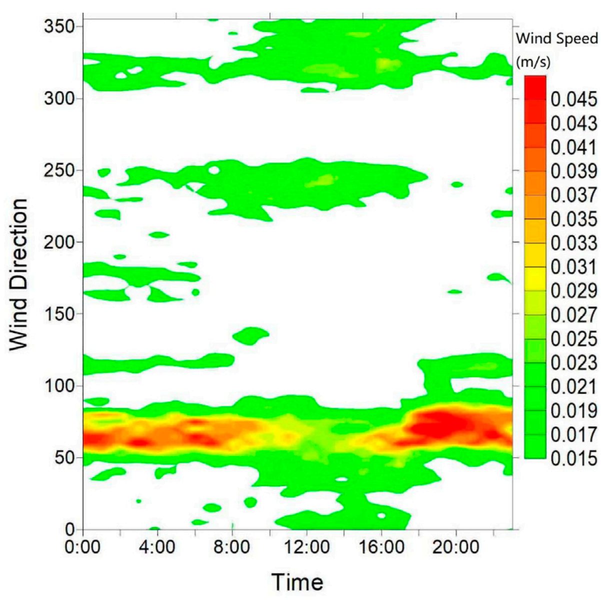

FIGURE 4
Diurnal variation of wind direction in east side of the Yangtze River.

winds in either side of the Yangtze River is the most obvious in winter, followed by spring and autumn, and the smallest difference occurs in summer too. 4) “Diff” is larger in the

TABLE 1 The mean of local deviated wind Δu in the west and east side of the Yangtze River (negative value indicates easterly wind; positive value indicates westerly wind).

		West (m/s)	East (m/s)
annual	day	−0.18(±0.09)	0.07(±0.03)
	night	0.13(±0.05)	−0.06(±0.03)
spring	day	−0.29(±0.16)	0.09(±0.06)
	night	0.27(±0.07)	−0.05(±0.05)
summer	day	−0.11(±0.04)	0.11(±0.04)
	night	0.03(±0.08)	0.00(±0.04)
autumn	day	−0.23(±0.08)	0.04(±0.05)
	night	0.03(±0.05)	−0.06(±0.05)
winter	day	−0.14(±0.16)	0.04(±0.04)
	night	0.26(±0.07)	−0.10(±0.04)

nighttime than daytime in winter, while *vice versa* for other seasons. For the Diff represents the difference of wind between the east and west sides of the Yangtze River, as formula (4), it can be used to represent the speed of river-land breeze. As Figure 3 shown, the speed of river-land breeze at night is greater than that in daytime in winter, and it is just the opposite in other seasons.

The mean local deviated wind speed and standard deviations are calculated during daytime (9:00–16:00) and nighttime (19:00–04:00). As shown in Table 1, the land breeze in the west side of Yangtze River is stronger than that in the east. The mean Δu in the west and east are −0.18 m/s (negative sign indicates easterly wind) and .07 m/s (positive sign indicates westerly wind) respectively. In the west side, the river-land breeze is strongest in spring. And the average easterly/westerly wind speed is 0.29/0.27 m/s. However, in the east side, the river breeze in summer is the most prominent (0.11 m/s), so is the land breeze in winter. For the wind different between the west and east side, the maximum occurs during daytime in spring, and the minimum occurs during nighttime in summer.

As shown in Figure 4, the results from this analysis support that easterly winds (land breezes) are dominant during nighttime, but westerly winds (river breezes) appear during 10:00–16:00, which has crucial impacts on dominant winds over Tongling. During the diurnal cycle, when the maximum occurs with westerly winds in the east and easterly winds in the west during 10:00–16:00, the river breezes are dominant winds; when the maximum occurs with westerly winds in the west and easterly winds in the east during 16:00–22:00, the land breezes are dominant winds. The difference is more significant in the daytime than nighttime.

3.2 The origin and effects of river breeze

The main cause of river-land breeze is the different heat capacity between river and land. Suppose Q (J/m^2) is solar radiation flux, C is specific heat capacity of surface (land and water), dT represents the change of temperature due to radiation, and m indicates unit mass of atmosphere. Then the formula of solar radiation flux is as following:

$$Q = C \cdot dT \cdot m \tag{5}$$

Because specific heat capacity of land (denoted as CL) is smaller than that of water (denoted as CW), for same solar radiation, temperature change of water (denoted as dTW) is less than that of land (denoted as dTL). In the daytime, temperatures of both land and the Yangtze River rise because of solar radiation, but the land is heated much quicker than the river, resulting in warm land and cold water. In contrast, during the night, temperatures of both land and the Yangtze River decrease due to radiation cooling, but the land cools much quicker than the river, resulting in cold land and warm water. A pressure gradient is generated due to the temperature difference between the Yangtze River, which leads to airflow movement.

According to atmospheric state equation $p = \rho RT$, if there is a difference between the temperatures in two regions, their corresponding atmospheric pressure (p) will respond to the change of temperature gradient by increasing their gradient accordingly. Based on equation of atmospheric motion [formula (6)], wind speed as well as the change rate of the wind speed with time will follow the changes of the pressure gradient, resulting in an increase of the local deviated wind speed. In another word, the river-land breeze increases the amplitude of the perturbed wind component, which further aggravate the inhomogeneity of the wind fields. Therefore, river-land breeze increases the change rate of the wind with time, amplifies the perturbations of the total wind and finally effects the diffusion of the atmospheric polluted matters.

$$\begin{cases} \dfrac{du}{dt} - fv = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x} + F_x \\ \dfrac{dv}{dt} + fu = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial y} + F_y \\ \dfrac{dw}{dt} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial z} - g + F_z \end{cases} \tag{6}$$

Diurnal variation of the speed of Δu and the regional average concentration of PM_{10} are shown in Figure 5. We can find that the Δu is generally low speed (<0.35 m/s) from 0:00 to 7:00. A quick increase can be noticed after 7:00, and it reaches maximum around 16:00 and then decreases abruptly afterwards. Also, it is obvious that the speed of Δu is small during the night, and less than 0.4 m/s after 20:00.

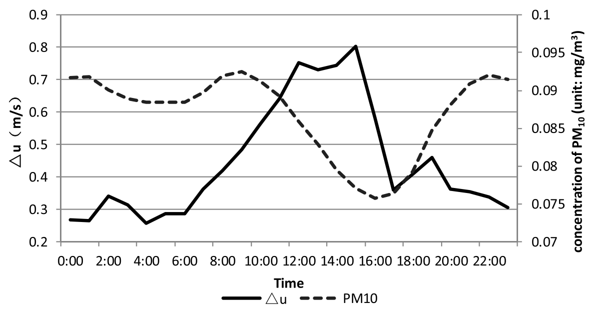

FIGURE 5
Diurnal variation of Δu (unit: m/s) and regional average concentration of PM_{10} (unit: mg/m^3).

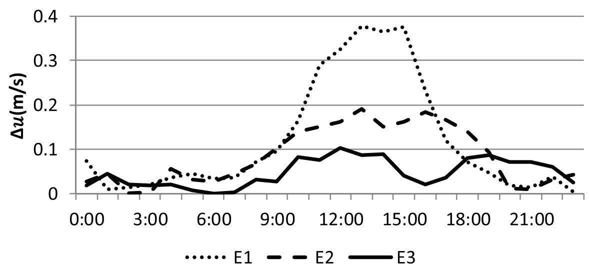

FIGURE 7
Diurnal variation of the local deviated wind speed (Δu) in three regions east side of the Yangtze River (E1: close to the Yangtze River; E2: moderate distance from the Yangtze River; E3: far from the Yangtze River).

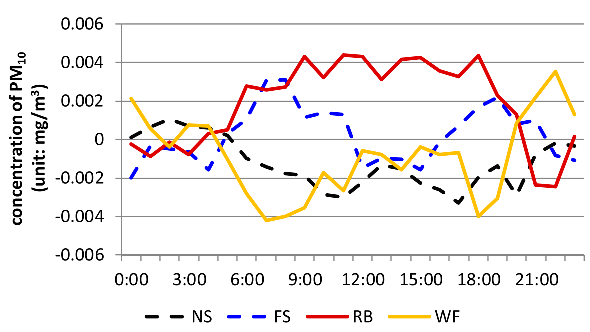

FIGURE 6
Diurnal variation of PM_{10} anomalies at individual stations.

4 Discussion

Unlike the variation of PM_{10} concentration which is primarily determined by the meteorological conditions, the variation of the NO_2 and SO_2 concentrations is much more complicated and subjected to combined effects from multiple factors. Therefore, we use PM_{10} as a representative of air pollutant to study the impact of river-land breeze on its spatial distribution.

We first calculate the domain-averaged concentration of the PM_{10}, then the PM_{10} anomalies at each observation station can be obtained by subtracting the averaged PM_{10} value from the observed PM_{10}. Those anomalies reflect the inhomogeneity of the PM_{10} spatial distribution.

According to the diurnal variation of averaged PM_{10} concentration from four stations, the main period of reduced concentration is 9:00–16:00. During that period, the speed of Δu is larger than 0.45 m/s. This implies the local perturbed winds can effectively enhance the diffusion of atmospheric pollutants for the concentration of PM_{10} is decreased significant. We can also notice from Figure 6 that the PM_{10} concentrations at stations FS and RB are larger than those at station NS and WF, and the former two stations are the farthest from the Yangtze River while the latter are the closest. This indicates the PM_{10} concentration is lower near the Yangtze River. Diurnal variation of local deviated wind in three different regions from the east side of the Yangtze River is depicted in Figure 7. E1, E2 and E3 respectively represent the region whose distance from the Yangtze River is less than 10km, between 10 and 20 km and more than 20 km. It is clear that u' varies inversely with the distance from the Yangtze River. As a result, the local deviated wind speed is stronger and pollutant concentration is less near the Yangtze River.

The diurnal variation of pollutant concentration is also obvious in Figure 6. The anomalous PM_{10} concentration at those four stations gradually increase starting from 6:00 and decrease after 20:00. This period corresponds to the exact time frame when the local deviated winds are enhanced (Figure 7), indicating a strong correlation between the pollutant concentration and the local deviated winds. In addition, there are also remarkable diurnal variation for the differences of averaged Δu in E1, E2 and E3. The difference of averaged Δu between E1 and E2 reaches maximum (0.21 m/s) around 14:00 and the ratio is 2.4. The difference of averaged Δu between E2 and E3 reaches maximum (0.16 m/s) around 16:00 and the ratio is 9.2. In general, u' increases rapidly after 6:00, which causes stronger winds in the areas along the Yangtze River.

There are strong correlations about the diurnal variation of pollutant concentration between the stations. The correlation coefficient is -0.75 between stations NS and RB and -0.71 between stations WF and FS. The strong negative correlations between these two pairs of stations imply a plausible scenario that the pollutants are transported between stations: the concentration of pollutant in one observation point is increased, while the concentration of pollutant in the other point is decreased.

Figure 8 is the scatter diagram of local deviations of PM_{10} concentration (SD-PM_{10}) and the speed of Δu. As the speed less

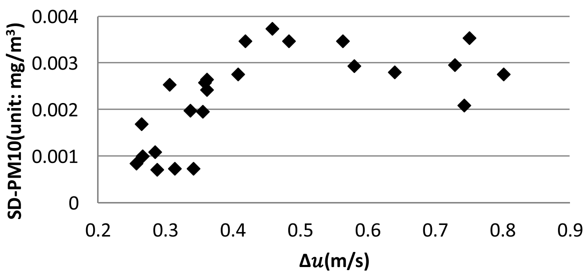

FIGURE 8
Scatter diagram of the local deviations of PM_{10} concentration (SD-PM_{10}) and the local deviated wind (Δu).

than 0.45 m/s, the SD-PM10 increases quickly with the speed of u'. However, after the speed of Δu more than 0.45 m/s, the SD-PM_{10} decreases gradually with the 0.45 m/s. That is to say, the PM_{10} distribution generally becomes homogenous after Δu more than 0.45 m/s.

The above analysis shows: 1) river-land breeze causes strong local wind in the area near the Yangtze River and helps to spread the air pollutants, which results in a low concentration of pollutant in this area; 2) in the daytime, river breeze transports the pollutants away from the Yangtze River, leading to a negative correlation of the pollutant concentration between the areas close to and far away from the river. 3) Under a weak river breeze ($\Delta u \leq 0.45$ m/s) scenario, the PM_{10} is transported by the breeze within the study region and causes the heterogeneity of PM_{10} concentration. While under a strong river breeze ($\Delta u > 0.45$ m/s) scenario, the PM_{10} is transported out of the study region, and the PM_{10} concentration becomes homogenous.

5 Conclusion

A river-land breeze is a regional meteorological phenomenon caused by the difference of heat capacity between water and land. As one of the major mining cities near the Yangtze River, Tongling is subjected to significant influences from the river-land breezes. The river-land breezes in Tongling have the following characteristics:

1) During the spring, the local deviated wind (river-land breeze) is more prominent, and the speed of breeze in daytime is stronger than the speed at night.
2) Although the dominant winds in Tongling are easterlies, they frequently turn to westerlies due to the influences of breezes.
3) The river-land wind component is large for area near the Yangtze River and small for those far from, and it exhibits a significant non-linear decreasing relation with the increase of the distance from Yangtze River.

Under the influence of the river-land breezes, the spatial distribution of PM_{10} concentration in Tongling has the following characteristics:

1) PM_{10} concentration is lower at the stations near the Yangtze River and higher at the stations far away. The discrepancies of concentration between different stations gradually increase after 6:00.
2) In the daytime, river breeze transports the pollutants away from the Yangtze River, leading to a negative correlation of the pollutant concentration between the areas close to and far away from the river.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, HZ; methodology, YH; software, XW; validation, XH; formal analysis, SW; investigation YH; resources, HZ; data curation, YH; writing—original draft preparation, HZ; writing—review and editing, YH; visualization, YH; supervision, YH; project administration, HZ; funding acquisition, HZ. All authors have read and agreed to the published version of the manuscript. Authorship must be limited to those who have contributed substantially to the work reported.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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