Aerosol and Air Quality Research, 14: 829–839, 2014
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ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2012.12.0365

Effects of Particulate Matter of Various Sizes Derived from Suburban Farmland, Woodland and Grassland on Air Quality of the Central District in Tianjin, China

Li Chen[1,2], Jincheng Gao[3], Yaqin Ji[4*], Zhipeng Bai[1], Mengshuang Shi[2], Hui Liu[2]

[1] *Chinese Research Academy of Environmental Science, Beijing 100012, China*
[2] *College of Urban and Environmental Sciences, Tianjin Normal University, Tianjin 300387, China*
[3] *Department of Agronomy, Kansas State University, USA*
[4] *China State Environmental Protection Key Laboratory of Urban Ambient Air Particulate Matter Pollution and Control, College of Environmental Science and Engineering, Nankai University, Tianjin 300071, China*

ABSTRACT

Poor air quality directly affects human health and has become an increasingly important environmental issue in Tianjin, China. The suspension of particulate matter (PM) in the atmosphere is not only from industrial pollutants, but also soil wind erosion; however, the contributions from farmland, woodland, and grassland have rarely been considered in this region. We conducted an assessment of PM sources through wind erosion, dust emission, and dust transportation from urban and rural areas to the central district in Tianjin, and our results demonstrated that the spatial variability of wind erosion and dust emission strongly depends on land use, particle size distribution and meteorological conditions. The equations in this study were empirical, and soil properties such as aggregation and crusting, as well as surface characteristics such as canopy height and residue cover, were not considered. The dust emission capacity of woodland and grassland was the lowest because of vegetation coverage. The values obtained in this study may overestimate emissions, because soil aggregation was not considered. The yearly dust amounts of $PM_{15–20}$ (particles with aerodynamic diameter from 15 µm to 20 µm), $PM_{10–15}$ (particles with aerodynamic diameter from 10 µm to 15 µm), and PM_{10} (particles with aerodynamic diameter less than 10 µm) from wind erosion in 2009 from the urban area in Tianjin were estimated as 5,400 t, 5700 t and 17,300 t, respectively, while those from the rural area were 14,000 t, 15,300 t and 40,700 t, respectively. The dust emission contributed from farmland accounted for 99.5%, and that from woodland and grassland only accounted for 0.5%. The PM_{10} transported to the central district and PM_{10} concentrations in the days with the 20% highest PM_{10} concentrations in the central district in 2009 were compared. The R^2 was 0.74, which meant the two variables were highly correlated.

Keywords: Wind erosion; Dust emission; Modeling; Particulate matter; GIS; Tianjin.

INTRODUCTION

Poor air quality has become a serious environmental problem in Tianjin, China. Particulate matter with an aerodynamic diameter of less than 10µm (PM_{10}) is a major air pollutant in Tianjin. PM_{10} was the principal pollutant in 71.5% of the days (261 out of 365 days) in 2009 (TBEP, 2010). Dust Storms frequently occurred in Tianjin, especially during the sand period, and therefore the coarser particulate matters such as $PM_{10–15}$ and $PM_{15–20}$ were also of our concern. Particulate matter in the atmosphere has been noted for its effects on visibility (Hyslop *et al.*, 2009) and global climate change, primarily a cooling effect due to increased scattering light to space as the atmospheric aerosol burden increased (Chen *et al.*, 2003), as well as on human health. Particulate matter adversely affects the respiratory system and contributes to lung cancer, pulmonary disease, and asthma (Dockery *et al.*, 1993).

Particulate matter is tiny solid matter suspended in air; it originates not only from a variety of mobile and stationary sources (automobiles, power plants, industrial processes, etc.), but also from wind erosion of agricultural land. Wind erosion on agricultural land is a serious environmental problem in northern China, especially in the arid and semi-arid regions. Wind erosion can change surface soil properties, degrade soil fertility, and, more importantly, degrade air quality. Fine particulates eroded from farmland and subsequently suspended in the atmosphere recently were raised concern about air quality in the western United States (Sharratt *et al.*, 2007). Saxton (1995) reported that windblown dust from farmland was the major non-compliance source of the U.S. EPA National Ambient Air

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[*] Corresponding author.
Tel.: +862223503397; Fax: +862223503397
E-mail address: jiyaqin@nankai.edu.cn

Quality Standard for PM_{10} within the Columbia Plateau region in the Pacific Northwest. Dust from soil erosion is also the major source of particulate matter in the atmosphere in Tianjin, China, most notably during the dry season (from October to May). Recent observation of air quality in Tianjin showed that PM_{10} concentration was higher in October, November, and December than in other months in 2009 (TBEP, 2010). The sources of PM_{10} in Tianjin were analyzed using a chemical mass balance (CMB) receptor model, and the PM_{10} contribution of soil dust source was 104 µg/m^3 (39%) in 2002 (Bi *et al.*, 2007).

Accurately estimating soil loss from wind erosion is essential for conservation planning, natural resource inventories, and air quality monitoring. Simulation of soil loss from wind erosion is a difficult process as emission capacity is affected by many factors including wind speed, soil texture, and land use (Goossens *et al.*, 2011; Juneng *et al.*, 2011; Sharratt *et al.*, 2011).

Wind erosion is a complex, dynamic process consisting of detachment, transport, and deposition of soil particles (Skidmore *et al.*, 1986; Zobeck *et al.*, 2006). Soil particulates normally move in three ways in the wind erosion process: creep, saltation and suspension. Soil erosion by wind is initiated when the wind speed exceeds the saltation threshold velocity for a given soil at a surface condition. Most of the eroding material moves only a short distance above the soil surface by creep and saltation of larger particles (Grivas *et al.*, 2008; Zhang *et al.*, 2011). The bouncing and abrasive action of larger particles on the soil surface gives rise to suspension of small particulates that can be carried over thousands of kilometers in the atmosphere (Karaca *et al.*, 2009; Martet *et al.*, 2009). Models have been developed in recent years to simulate soil erosion and dust emission to the atmosphere (Holmén *et al.*, 2001; Zender *et al.*, 2003; Funk *et al.*, 2004; Vautard *et al.*, 2005; Visser *et al.*, 2005; Shaw *et al.*, 2008; Kavouras *et al.*, 2009), but the quantity of the dust moving from the urban area to the central district in the air has not been thoroughly estimated.

The main purpose of this study was to estimate dust emissions from farmland, woodland and grassland, and to evaluate their impact on air quality. The objectives of the research included: (1) to estimate the wind erosion modulus and the dust emission modulus and the dust emission amount from each district/county in the urban and rural areas of Tianjin; (2) to compare the effects of wind erosion and dust emission on pollution from farmland, woodland, and grassland in the central district; and (3) to assess the transport of PM_{10}, PM_{10-15} and PM_{15-20} from urban and rural areas to the central district.

MATERIALS AND METHODS

Study Location

Our research focused on Tianjin (38°34′N~ 40°15′N, 116°43′E~118°194′E) (see Fig. 1), which is located about 120 km southeast of Beijing and is the fourth largest city in China, with a population of more than 10 million people and an area of 11,919.7 km^2, including 15 districts and three counties. The 18 administrative districts range from urban to relatively rural. The urban area includes Beichen (BC), Xiqing (XQ), Dongli (DL), and Jinnan (JN), and the rural area includes Jixian (JX), Jinghai (JH), Tanggu (TG), Hangu (HG), Dagang (DG), Baodi (BD), Ninghe (NH) and Wuqing (WQ). The other districts –Heping, Hexi, Hedong, Hebei, Nankai and Hongqiao belong to the central district (CD).

Tianjin is located in the northeastern part of the Huabei Plain adjacent to the Bohai gulf. It receives the typical continental monsoon climate: cold and dry in winter and hot and wet in summer. The average annual temperature is around 12.3°C, and the annual precipitation ranges from 550 to 680 mm. About 82% of the total annual precipitation is distributed in the summer and fall. Winds are predominantly from the northwest in the winter and southeast in the summer. Strong winds always occur in the spring and are accompanied by dust storms. Tianjin is an industrial city, with major industries ranging from electronics, automobiles, petrochemicals, metallurgy, biomedical industry to alternative energy.

The lands of the urban and rural areas in Tianjin are divided into potentially erodible lands including farmland, woodland, grassland, bare land, and non-erodible construction

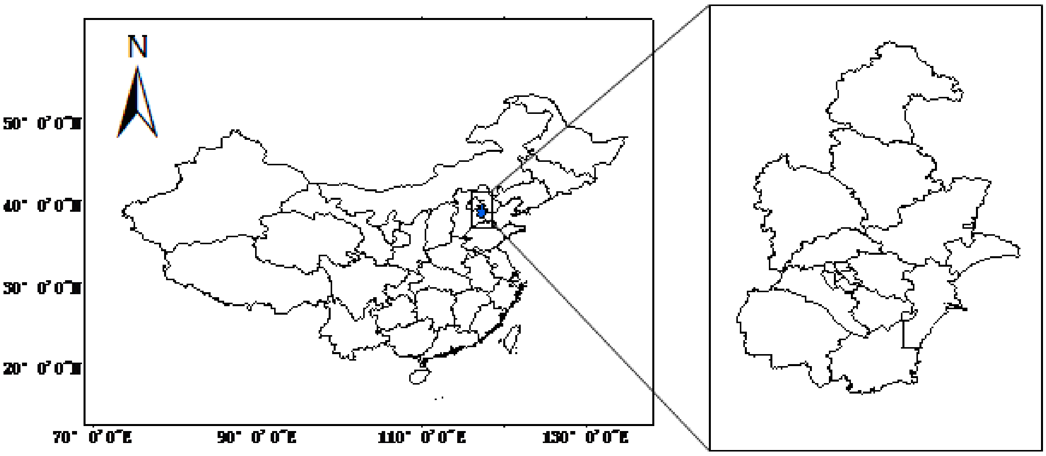

Fig. 1. Location of Tianjin, China.

land or land covered by water. The land use type dataset was obtained from Tianjin Bureau of Environmental Protection (TBEP). The land use map of Tianjin was shown in Fig. 2. The construction land, including buildings, streets and commercial land, was considered to contribute limited amounts of blown dust (TBEP, 2010). So both water-covered and construction lands were regarded as non-erodible and consequently not included in our analysis.

Sample Collection and Analysis

Based on soil profile characteristics, soil types, and land use, we collected in the summer of 2009 a total of 398 soil samples from erodible lands, of which 343 are from farmland, 39 from woodland, and 16 from grassland (see Fig. 3). Among these samples, 94 are taken from the urban area and 304 from the rural area. The soil samples were collected from a depth of 0–15 cm. Obvious extraneous matter was not collected in sampling. The coordinates of sampling locations were recorded with a GPS.

Soil samples were dried in the laboratory and screened by a 60-mesh nylon sieve. Particle size distribution of all samples was analyzed with a BT-9300S Laser Particle Size Analyzer. The instrument has a capability of measuring particle sizes from 0.1 to 340 µm. Thus, three particle sizes (PM_{10}, $PM_{10\text{–}15}$, and $PM_{15\text{–}20}$) of surface soil were measured. The repeatability error of this instrument is less than 1%.

The wind data including wind speed and direction were collected at the weather station of each district/county in Tianjin. The wind speed threshold, at which particle motion just begins, is a critical parameter of any accurate formulation that expresses the transport rate of particles such as sand and soil as a function of horizontal wind-speed in the Earth's atmosphere. The wind threshold velocity was set as 5 m/s in the urban and rural areas according to the research on soils in northern China (Chen *et al.*, 1994) and wind tunnel experiments (Zhang *et al.*, 2005). The height of the wind speed threshold of 5 m/s in this study was assumed to be 10 meters.

Wind Erosion and Dust Emission

To estimate wind erosion and dust emission, we used the following empirical formulas based on wind speed and surface soil types. The formulas were developed and validated through wind tunnel experiments with soils in Northwestern China (Gao *et al.*, 2008). The formulas were limited for soils from farmland, woodland, and grassland, especially in an arid and semi-arid region. And so soil water content was not regarded as a main factor to affect wind erosion and dust emission and was not considered in their formulas (Zhang *et al.*, 2005).

Wind Erosion Modulus

Wind erosion modulus refers to the average amount of wind erosion dust in per unit of time and per unit of area. The equations in this study were empirical, and soil properties such as aggregation, crusting and surface characteristics

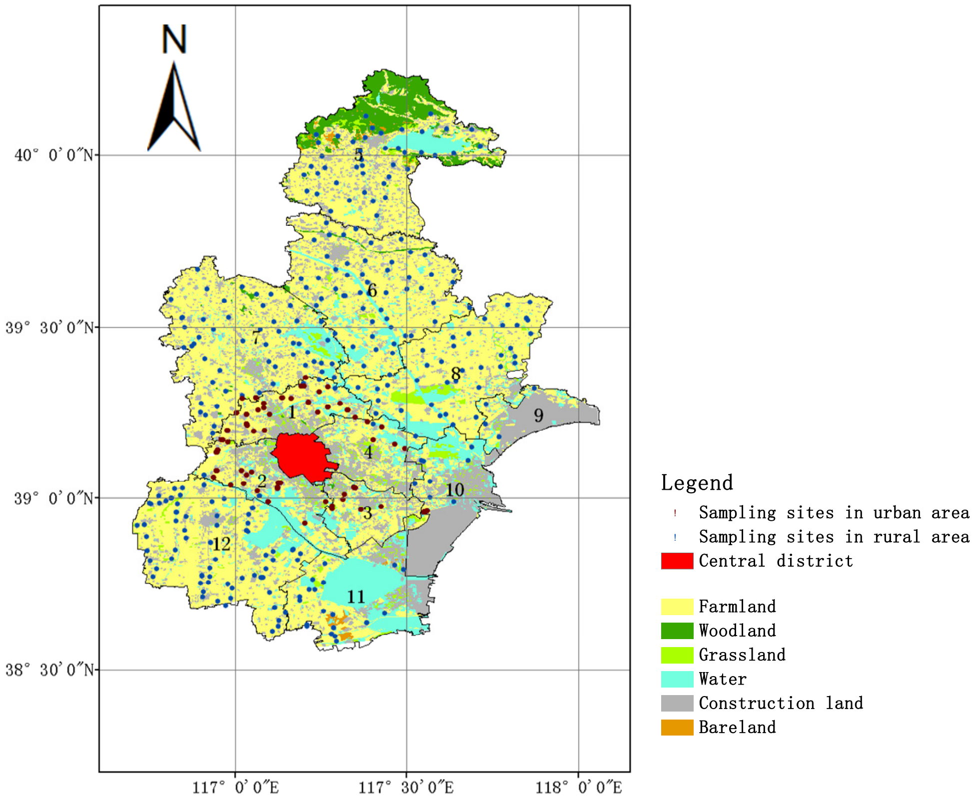

Fig. 2. Land use and samplings in the 12 districts of Tianjin, China (94 sample sites in the urban area including CD, BC, DL, XQ and JN, and 304 sample sites in the rural area including JX, JH, TG, HG, DG, BD, NH and WQ); 1:BC, 2:XQ, 3:JN, 4:DL, 5:JX, 6:BD, 7:WQ, 8:NH, 9:HG, 10:TG, 11:DG, 12:JH.

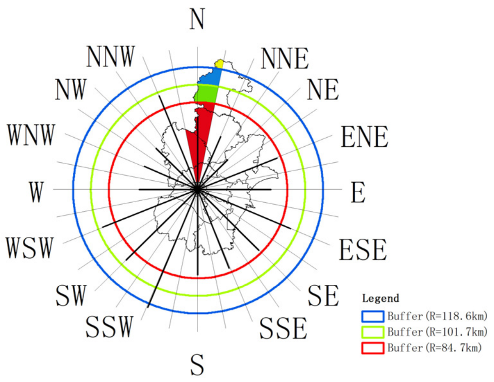

Fig. 3. Dust emission areas under the condition of 16 wind directions at different wind speeds (5 m/s–18 m/s).

such as canopy height, residue cover were not considered. The wind erosion modulus on farmland was calculated with Eq. (1).

$$Q_{\mathrm{fa}} = 10\cdot\hat{C}\cdot\sum_{j=1}\left\langle T_j\cdot\exp\left\{-9.208+\frac{0.018}{Z_0}+1.955\cdot\left[\left(A\cdot U_j\right)^{0.5}\right]\right\}\right\rangle \tag{1}$$

where Q_{fa} is a wind erosion modulus on farmland t/(ha). $\hat{C}$ is a scale-revised coefficient of about 0.0018; A is the wind speed revised coefficient of about 0.89; U_j is the j$^{\mathrm{th}}$ hourly wind speed. Z_0 is surface aerodynamic roughness (cm), about 0.55 cm in northern China; T_j is the accumulation time in which the wind speed is U_j and the wind erosion occurred (min). The threshold of wind speed is defined as 5 m/s on dry farmland in northern China and is slightly higher on sandy surfaces. j is the wind speed category. The first category of wind speed is 5–6 m/s, and the average wind speed is 5.5 m/s, so $U_{j=1}$ = 5.5 m/s, $U_{j=2}$ = 6.5 m/s, and so on. The highest U_j is the maximum wind speed recorded in the category at the weather station. The height of the wind speed observation is 10 meters.

The estimation of wind erosion modulus on woodland and grassland was calculated with the following equation:

$$Q_{\mathrm{fgf}} = 10\cdot\hat{C}\sum_{j=1}\left\{T_j\cdot\exp\left[2.4869-0.0014VC^2-54.9472/(AU_j)\right]\right\} \tag{2}$$

where Q_{fgf} is the wind erosion modulus of woodland or grassland whose coverage of vegetation is VC[t/(ha·yr)]. U_j is the jth hourly wind speed, which is higher than threshold value. T_j is the accumulation time in which the wind speed is U_j (min). $\hat{C}$ is the scale-revised coefficient of about 0.0018; A is the wind speed revised coefficient, about 0.89.

Dust Emission Modulus

Dust emission modulus refers to the average amount of the wind erosion dust that actually enters the atmosphere in per unit of time and per unit of area.

The dust emission from farmland was estimated with the wind erosion modulus, using the following equation:

$$Q_{\mathrm{fd}} = a\cdot Q_{\mathrm{fa}} \tag{3}$$

where Q_{fd} is farmland dust emission modulus and a is the mass percentage of particulates (PM_{10}, PM_{10-15} and PM_{15-20}) from farmland.

Eq. (4) was used to estimate dust emission on woodland and grassland:

$$Q_{\mathrm{fgd}} = 0.45\cdot b\cdot Q_{\mathrm{fgf}} \tag{4}$$

where Q_{fgd} is woodland and grassland dust emission modulus and b is the mass percentage of particulates(PM_{10}, PM_{10-15} and PM_{15-20}) from woodland and grassland.

Estimating Dust Emission Transported to the Central District

The wind speed and direction in the central district were recorded from the routine measurement at a height of 10 m. The starting wind speed for dust emission was set at 5 m/s with a 1-h interval. Wind direction frequencies were calculated for each of the 16 directions.

The 16 wind direction lines to the center of the central district were drawn. An irregular sector was formed based on the two lines on either side of the wind direction line ± 11.25° and the boundary of the city. The sector area of each wind direction was calculated. For example, the sector of the N direction contained the red, green, blue and yellow areas as shown in Fig. 3. As the farthest distance from the central district to the boundary of Tianjin is 128 km, and the transportation distance of dust with D = 20 µm is 84.7 km at the wind speed of 5 m/s, 101.7 km at 6 m/s, and 118.6 km at 7 m/s (Gao *et al.*, 2008; see Table 1), the red area indicated the dust emission area when the wind speed was 5 m/s; when the wind speed increased to 6 m/s, the dust emission area extended to the green area until it extended to the yellow area at the greater wind speed. The same applied to the other wind directions.

The dust transportation capacity of wind speeds from the urban and the rural to the central district was calculated with the following formula:

$$Q_{fdc} = \sum_{j=1}^{j=17}\left\{\sum_{i=1}^{i=3}\left[\lambda_i\cdot\sum_{\substack{h=1\\k=1}}^{\substack{k=16\\h=12}}\left(S_{hjk}\cdot Q_{jk}\right)\right]\right\} \tag{5}$$

$$Q_{fgdc} = \sum_{j=1}^{j=17}\left\{0.45\cdot\sum_{i=1}^{i=3}\left[\lambda_i\cdot\sum_{\substack{h=1\\k=1}}^{\substack{k=16\\h=12}}\left(S_{hjk}\cdot Q_{jk}\right)\right]\right\} \tag{6}$$

where λ_i, I = 1,2,3, is the mass percentage of dust particles in the surface soil with $D \le 10$ µm, $10 < D \le 15$ µm, and $15 < D \le 20$ µm, respectively. S_{hjk} is the sector area with the k wind direction and the U_j , j = 5,6,7,…,17; wind speed. Q_{jk}

Table 1. The transportation distance (km) of the dust with different particle sizes (D = 20 µm, 15 µm and 10 µm) under the various wind speeds.

Wind speed (m/s)	Particle size (µm)		
	20	15	10
5	90	270	1360
6	100	320	1630
7	120	380	1900
8	140	430	2170
9	150	480	2440
10	170	540	2710
11	190	590	2980
12	200	640	3250
13	220	700	3530
14	240	750	3800
15	250	800	4070
16	270	860	4340
17	290	910	4610
18	310	960	4880

is the wind erosion modulus of the h district (BC, XQ, JN, DL, JX, JH, TG, HG, DG, BD, NH, WQ) with the U_j wind speed. The dust with D ≤ 15 µm would be transported for a long distance with surpassing the administrative boundary if the dust were released into the air; so the dust emission area is the sector area with different wind directions. Q_{fdc} is the farmland dust estimation from the urban and the rural to central district, and Q_{fgdc} is the woodland and grassland dust estimation from the urban and the rural to central district. All work of this study was based on the data collected in 2009.

RESULTS AND DISCUSSION

Particle Size Composition of Surface Soil

We generated the spatial distribution map of topsoil particle size composition by kriging and classified the surface soil in the urban and rural areas into nine categories based on particle size composition with ArcGIS 9.2 (Fig. 4); the soil particle size distribution was listed in Table 2. The finest soil particle size distribution was found in DL, with D ≤ 10 µm up to 57% and D ≤ 20 µm up to 78%, and BC and JN with D ≤ 10 µm comprising 49% and 43% of the surface soil, respectively. These three districts all belong to the urban area. The maximum particle size distribution was found in JX, the farthest rural district north of the central district, with D ≤ 10 µm comprising 18% and D ≤ 20 µm comprising 35% of the surface soil. In general, the soil particle size distribution is coarser in the northern and the western regions than in the southern and the eastern regions of Tianjin. The distribution of soil particle size distribution is consistent with the topography in Tianjin, which is high in the northwest and low in the southeast.

Wind Regime

The wind regime in 2009 was collected at one station in each district of Tianjin including hourly wind speeds and directions. The accumulation time of wind speed in each category was calculated and listed in Table 3. The highest wind frequency with wind speed over 5 m/s was found in JN with over 900 h, followed by WQ, TG, HG, and XQ, with 743, 728, 713, and 695 h, respectively. The lowest frequency was located in JX with 112 h, followed by BC and JH with 211 and 273 h, respectively. The highest wind speeds recorded in 2009 were found in WQ with speeds at 15–16 m/s for 2 h and at 16–17 m/s for 1 h. Thus, the strongest wind over the threshold occurred in the northwest and the southeast regions.

Wind Erosion Modulus

Wind erosion was not supposed to occur during the rainy season or when the ground was covered with snow. We ran the simulation of wind erosion with soil in a dry condition.

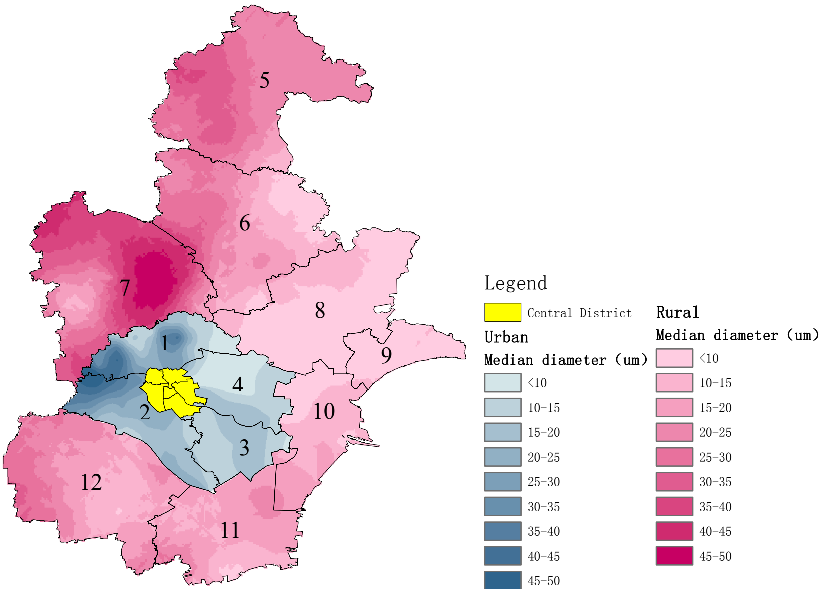

Fig. 4. Particle size composition of surface soil in the urban and rural areas in Tianjin, China, based on Kriging interpolation.

Table 2. Particle size composition of surface soil in 12 districts in Tianjin, China (%).

District	Particle diameter range									
	≤ 10 μm	10–15 μm	15–20 μm	20–25 μm	25–30 μm	30–35 μm	35–40 μm	40–45 μm	45–50 μm	> 50 μm
1	49	11	9	6	5	3	2	2	2	10
2	28	11	11	8	8	4	4	4	4	17
3	43	12	10	7	7	3	3	3	3	10
4	57	12	10	6	5	2	2	2	2	3
5	18	8	9	7	8	4	4	4	4	34
6	25	10	9	7	8	4	4	4	4	25
7	38	15	14	10	9	4	3	3	2	2
8	35	15	14	10	9	4	3	3	2	4
9	39	9	7	4	4	2	2	3	3	27
10	39	14	12	8	8	4	3	3	3	8
11	24	8	8	7	9	5	5	5	5	22
12	31	10	8	6	7	4	4	4	4	21

Table 3 The accumulation time of wind speed at different levels from weather stations in 2009 (h).

Wind speed (m/s)	Urbans				Rurals							
	1	2	3	4	5	6	7	8	9	10	11	12
0–1	2709	1502	873	2424	3195	2866	1739	1653	1649	1020	1272	1237
1–2	2848	2905	2749	2841	3209	2686	2594	2719	2516	2265	3091	3457
2–3	1790	1924	2187	1732	1427	1531	1996	1966	1854	2300	2493	2151
3–4	899	1066	1280	931	549	796	1124	1221	1268	1620	1166	1162
4–5	303	658	764	442	257	413	564	658	746	827	457	480
5–6	130	345	401	190	83	238	301	269	370	391	177	178
6–7	53	165	224	94	24	114	184	154	175	182	63	58
7–8	21	84	125	56	4	69	105	73	86	83	31	26
8–9	6	47	70	18	1	26	71	32	44	41	8	10
9–10	1	26	44	11	0	17	31	6	27	19	2	1
10–11	0	15	17	3	0	2	24	7	8	7	0	0
11–12	0	9	12	1	0	2	10	0	2	4	0	0
12–13	0	2	8	0	0	0	9	1	1	0	0	0
13–14	0	2	3	0	0	0	4	0	0	1	0	0
14–15	0	0	3	0	0	0	1	0	0	0	0	0
15–16	0	0	0	0	0	0	2	0	0	0	0	0
16–17	0	0	0	0	0	0	1	0	0	0	0	0

The rainy and snowy days were removed from the simulation. The wind erosion modulus of each district was calculated and listed in Table 4. The total soil wind erosion from the urban and rural areas in 2009 was estimated as 173,200 t, including 171,600 t from farmland, which was over 99% of the total. The total erosion from woodland and grassland was only estimated as 1,700 t, less than 1% of the total. The yearly wind erosion modulus was about 13 t/ha from farmland and 5 t/ha from woodland and grassland in 2009.

The highest erosion modulus was found in JN with 27 t/ha, followed by WQ with 24 t/ha from farmland. Both JN and WQ were found with the highest frequency of wind speeds over 5 m/s. The average modulus from farmland in the four urban districts was 14 t/ha compared with the average modulus in the rural area of 12 t/ha from farmland. This means that the wind erodibility was higher in the urban area than in the rural area.

Dust Emission

Dust emission modulus was calculated with the dust emission equation in each district and the results were listed in Table 5. Total dust emission in 2009 was estimated in the urban and rural areas up to 98,500 t for particle diameter size (D) less than 20 μm, including 58,000 t (D ≤ 10 μm), 21,000 t (10 < D ≤ 15 μm), and 19,400 t (15 < D ≤ 20 μm). PM_{10} was the dominant component of dust emission, which took up to 60% of the total particle size composition and was the major source of dust in the central district. $PM_{10\text{–}15}$ and $PM_{15\text{–}20}$ were 21% and 19% of the total dust emission, respectively.

The dust emission modulus in the urban area was obviously higher than in the rural area. The dust emission modulus on farmland in the urban area was 6 t/ha with D ≤ 10 μm, 1.7 t/ha with 10 < D ≤ 15 μm, and 1.5 t/ha with 15 < D ≤ 20 μm; in contrast, dust emission modulus on farmland in the rural area was 4.1 t/ha with D ≤ 10 μm, 1.4 t/ha with 10 < D ≤ 15 μm, and 1.3 t/ha with 15 < D ≤ 20 μm. The average dust emission modulus on woodland and grassland in the urban area was 1.1 t/ha with D ≤ 10 μm, 0.3 t/ha with 10 < D ≤ 15 μm, and 0.3 t/ha with 15 < D ≤ 20 μm, but the average dust emission modulus in the rural area was 0.6 t/ha with $D \leq 10$ μm, 0.2 t/ha with $10 < D \leq 15$ μm, and 0.2 t/ha

Table 4. Estimated wind erosion modulus and wind erosion amount from each district.

District	Land use type*	Area (ha)	Wind erosion modulus (t/ha)	Wind erosion amount (t)
1	FL	1574	4.0	6370
	WGL	17.3	0.3	6
2	FL	1772	18.4	32670
	WGL	24.2	8.5	210
3	FL	298.8	26.7	8000
	WGL	17.7	14.8	260
4	FL	289.5	8.6	2470
	WGL	33.87	2.1	70
5	FL	1324.6	1.9	2500
	WGL	476.4	0.1	20
6	FL	2853.1	10.9	31070
	WGL	32.7	2.9	100
7	FL	1654.3	24.5	40500
	WGL	42.4	14.0	600
8	FL	1691.3	12.3	20750
	WGL	58.7	2.9	170
9	FL	717.4	16.9	12110
	WGL	4.2	5.4	20
10	FL	338.6	16.8	5680
	WGL	38.3	5.0	190
11	FL	338.6	5.4	1830
	WGL	38.3	0.5	20
12	FL	1465.0	5.2	7600
	WGL	25.3	0.5	10

FL: Farmland, WGL: Woodland and grassland.

Table 5. Estimated dust emission modulus and dust emission amount of each district.

District	Land use type	Dust emission modulus (t/ha)			Dust emission amount (t)		
		≤ 10 μm	10–15 μm	15–20 μm	≤ 10 μm	10–15 μm	15–20 μm
1	FL	1.98	0.46	0.38	3120	720	600
	WGL	0.07	0.02	0.01	1	0.4	0.2
2	FL	5.23	2.08	2.07	9270	3690	3670
	WGL	1.08	0.43	0.43	30	10	10
3	FL	11.53	3.26	2.72	3450	970	810
	WGL	2.86	0.81	0.67	50	10	10
4	FL	4.83	0.98	0.86	1400	280	250
	WGL	0.53	0.11	0.09	20	4	3
5	FL	0.33	0.16	0.16	440	210	210
	WGL	0.003	0.001	0.002	1	0.5	1
6	FL	2.73	1.08	1.02	7790	3080	2910
	WGL	0.33	0.13	0.12	10	4	4
7	FL	9.23	3.70	3.38	15270	6120	5590
	WGL	2.38	0.95	0.87	100	40	40
8	FL	4.35	1.82	1.77	7360	3080	2990
	WGL	0.46	0.19	0.18	27	11	10
9	FL	6.58	1.53	1.10	4720	1100	790
	WGL	0.94	0.22	0.16	4	1	1
10	FL	6.48	2.31	1.99	2190	780	670
	WGL	0.87	0.31	0.27	30	10	10
11	FL	1.32	0.45	0.46	450	150	160
	WGL	0.05	0.02	0.02	2	1	1
12	FL	1.59	0.50	0.44	2330	730	650
	WGL	0.07	0.02	0.02	2	1	0.5

with $15 < D \leq 20$ μm. The regional difference was mainly determined by the particle size composition. The fine soil particle size distribution in the urban area provided more dust sources for emission. Because of the increase in the surface coverage of woods and grasses, the dust emission from woodland and grassland was much lower than that from farmland. The dust emissions in both the urban and rural areas were mainly contributed from farmland, with over 99.45% of the total emission from all the three types of land.

Dust Estimation from the URBAN and RURAL Areas to the Central District

Based on the weather station data, we generated the wind frequencies of each district in the urban and rural areas with the wind direction pointing to the central district in 2009 as shown in Fig. 3 and listed in Table 6. For example, with winds coming from the north direction (N) or the north-northeast (NNE), the districts that may bring about potential dust emission to the central district include JX, BD, WQ, NH, BC, and DL.

We estimated the dust of various particle sizes blown from the urban and rural areas to the central district (Table 6). In 2009, PM_{20} from the urban and rural areas to the central district were 45,800 t, including PM_{10} of 26,900 t, $PM_{10–15}$ of 9,800 t, and $PM_{15–20}$ of 9,000 t. In the urban area, PM_{20} was 11,300 t, including PM_{10} of 6,800 t, $PM_{10–15}$ of 2,300 t, and $PM_{15–20}$ of 2,300 t. In the rural area, PM_{20} was 29,900 t, including PM_{10} of 16,900 t, $PM_{10–15}$ of 6,700 t, and $PM_{15–20}$ of 6,300 t.

Most of the PM_{10} transported to the CD was contributed from the N or NNE direction. The PM_{10} contribution was up to 30.57% from WQ, and up to 15% was from BD and NH. Minimal contribution was from DG, HG, and JX with less than 1%. In general, PM_{10} transported to the central district was mostly contributed from the rural area with 71.31%; only 28.69% came from the urban area.

PM_{20} from the urban and rural areas to CD was 45,800 t, including PM_{10} of 26,900 t. Windblown dust originated from the urban and rural areas, especially from farmland, is the primary source of PM_{10} in the central district, although there are other sources such as unpaved roads and construction lands. The estimation of PM_{10} from farmland may be overestimated due to the use of particle size distribution. We did not consider the effect of soil aggregation structure.

Comparison of PM_{10} Transported with Concentration in CD

The days with the 20% highest PM_{10} concentrations in 2009, which were from 0.135 mg/m^3 to 0.415 mg/m^3, were selected, and the PM_{10} transported to CD during these days were estimated based on the above-mentioned method. The correlation between the PM_{10} transported to CD and PM_{10} concentration in the days with the 20% highest PM_{10} concentrations in CD in 2009 was shown in Fig. 5. The R^2 was 0.74, which meant the two variables were highly correlated.

CONCLUSIONS

Windblown dust emission was treated as a non-continuous spatio-temporal process (Korcz *et al.*, 2009). The spatial distribution of wind erosion and dust emission was strongly determined by wind speed over threshold velocity. Winds with northwest and southeast directions are the dominant wind regime in Tianjin. The northwest winds prevailing in the winter and the spring are the main forces that cause dust emission. In the rural area, the northern districts excluding JX had higher wind speeds over the threshold and provided more dust emission to the central district compared with the southern districts (Fig. 6). In the urban area, XQ was the main contributor of dust emission to CD compared with the other three districts.

DG and HG contributed minor amounts of dust emission to CD. The prevailing wind directions with wind speed > 5 m/s were NNW, N, and E in DG and NNW and NW in HG; thus, dust emission from these two districts were rarely blown into CD.

There are some limitations in this study. It only accounted for particle size distribution, not aggregate size distribution though it may also affect wind erosion. Therefore, the values obtained in this study may overestimate emissions. Besides, the equations in this study were empirical, and soil properties such as aggregation, crusting and surface characteristics such as canopy height, residue cover were

Table 6. The dust of various sizes transported from the urban and rural areas to the central district in 2009 (t).

District	Particle diameter range			
	≤ 10 μm	10–15 μm	15–20 μm	≤ 20 μm
1	1470	340	280	2090
2	4370	1740	1730	7830
3	640	70	90	800
4	300	160	150	620
5	210	200	200	610
6	3670	1450	1370	6490
7	7220	2900	2650	12770
8	3470	1450	1410	6330
9	120	20	70	200
10	1050	370	320	1740
11	20	10	4	40
12	1100	350	300	1740

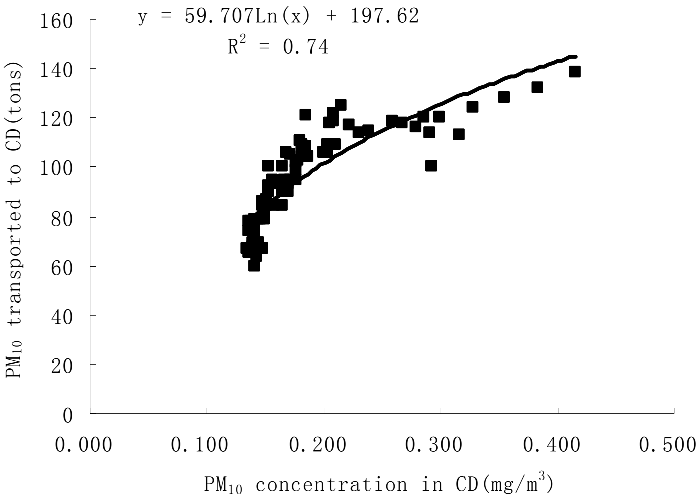

Fig. 5. Comparison of PM_{10} transported to the central district and PM_{10} concentrations in the days with the 20% highest PM_{10} concentrations in 2009.

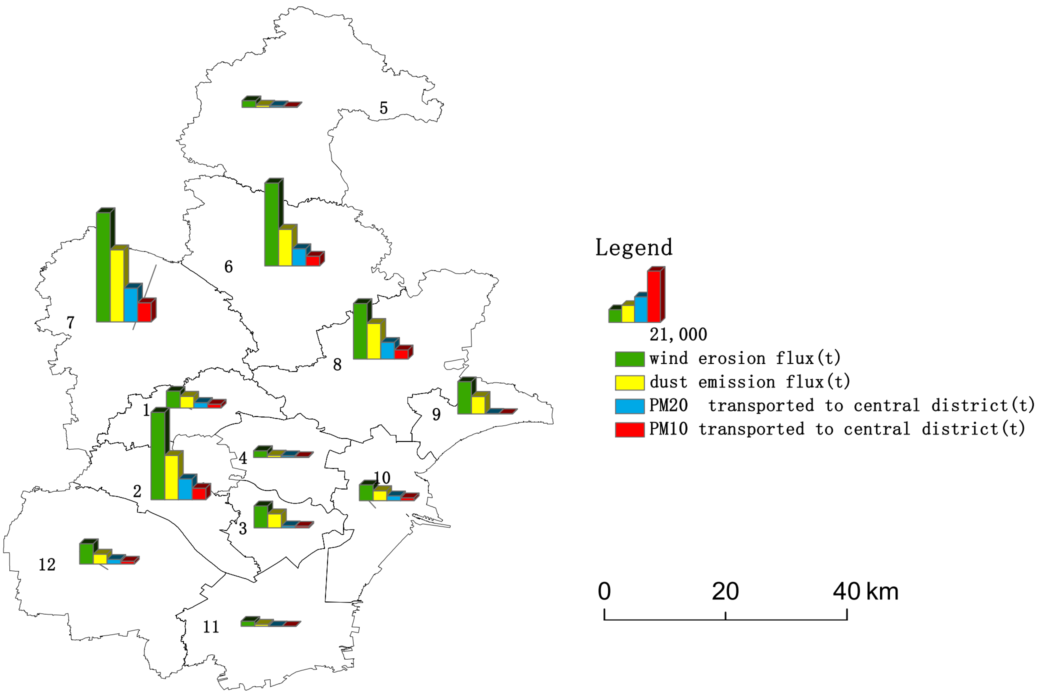

Fig. 6. Wind erosion flux, dust emission flux, PM_{20} transported to the central district, and PM_{10} transported to the central district of each district in the urban and rural areas

not considered. In this study, soil samples were screened by a 60-mesh nylon sieve, and the soil aggregation with the diameter more than 0.3 mm was excluded from estimating the dust emission. Particle size distributions of the 398 samples were analyzed using a Laser Analyzer, but the water used may destroy the soil aggregation structure with the diameter less than 0.3 mm. We did not consider soil water content in the simulation, although the factor is important for wind erosion. We supposed the soils were in a drought condition with low water content and the water content had minor influence on surface soil emission. Actually, soil water content was very low in summer and spring in Northern China. Dust transportation is also regarded as a complex procession. The particulate matter may have creep, saltation, and suspension depending on the carriage of wind energy. The simulation of our research was only to estimate the potential contribution of particulate matter from farmland in Tianjin. Over 99% of all dust emission was contributed by farmland, only a small amount from woodland and grassland. Most dust emission came from the four districts of WQ, XQ, BD and NH, which were located to the north or northwest of CD, with north as their prevailing wind direction.

The four urban districts have fine particle size distribution with dominant percentage of fine particulate matter, especially the composition of PM_{10}. The fine particle size distribution soils in the urban area provide the potential sources of suspension to CD. Although PM_{10} may come from other sources such as constructed lands, unpaved roads, and automobiles, the farmland in the urban area of Tianjin were still regarded as the main source of dust emission, comprising up to 60% of the total emission.

Through this research, we found that up to 4.7 t/ha of PM_{10} was lost from farmland in 2009. The emission of PM_{10} was much higher than that in the U.S. Pacific Northwest, which was only 0.4 t/ha annual loss according to a wind erosion processing system (WEPS) simulation in the summer fallow land (Feng and Sharratt, 2007). Because no field observation and field experiments of dust emission were conducted, it is difficult to validate the dust emission. The model simulation results may be overestimated as we considered the whole soil composition to suffer wind erosion, without considering the surface condition. In future study, soil surface emission can be measured with wind tunnel experiments and WEPS simulations with the support of the local climatic data and land use to further compare with the results from this research.

ACKNOWLEDGEMENTS

This work was supported by National Natural Science Funds of China (Grant No. 41205101/D0512), the Special Environmental Research Funds for Public Welfare (200909005) and the Doctor Funds of Tianjin Normal University (No. 52XB1110). Special thanks go to Tianjin Environmental Protection Bureau for help with air quality monitoring data. Contribution number 12-360-J from the Kansas Agricultural Experiment Station.

REFERENCES

Bi, X.H., Feng, Y.C., Wu, J.H., Wang, Y.Q. and T. Zhu. (2007). Source Apportionment of PM_{10} in Six Cities of Northern China. *Atmos. Environ.* 41: 903–912.

Chen, W., Dong, Z., Li, Z. and Yang, Z. (1996). Wind Tunnel Test of the Influence of Moisture on the Erodibility of Loessial Sandy Loam Soils by Wind. *J. Arid. Environ.* 34: 391–402.

Dockery, D.W., Pope, C.A., Xu, X.P., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G. and Speizer, F.E. (1993). An Association between Air-pollution and Mortality in 6 United States Cities. *New Engl. J. Med.* 329: 1753–1759.

Feng, G. and Sharratt, B. (200). Scaling from Field to Region for Wind Erosion Prediction Using the Wind Erosion Prediction System and Graphical Information Systems. *Appl. Res.* 62: 321–328.

Funk, R., Skidmore, E.L. and Hagen, L.J. (2004). Comparison of Wind Erosion Measurements in Germany with Simulated Soil Losses by WEPS. *Environ. Modell. Softw.* 19: 177–183.

Gao, S.Y., Zhang, C.L., Zou, X.Y., Wu, Y.Q., Shi, S. and Li, H.D. (2008). Benefits of Beijing-Tianjin Sand Source Control Engineering.

Goossens, D. and Buck, B. (2011). Effects of Wind Erosion, Off-road Vehicular Activity, Atmospheric Conditions and the Proximity of a Metropolitan Area on PM_{10} Characteristics in a Recreational Site. *Atmos. Environ.* 45: 94–107.

Grivas, G., Chaloulakou, A. and Kassomenos, P. (2008). An Overview of the PM_{10} Pollution Problem, in the Metropolitan Area of Athens, Greece. Assessment of Controlling Factors and Potential Impact of Long Range Transport. *Sci. Total Environ. 3*89: 165–177.

Holmén, B.A., James, T.A., Ashbaugh, L.L. and Flocchini, R.G. (2001). Lidar-assisted Measurement of PM_{10} Emissions from Agricultural Tilling in California's San Joaquin Valley-Part I: Lidar. *Atmos. Environ.* 35: 3251–3264.

Hyslop, N.P. (2009). Impaired Visibility: The Air Pollution People See. *Atmos. Environ.* 43: 182–195.

Juneng, L., Latif, M.T. and Tangang, F. (2011). Factors Influencing the Variations of PM_{10} Aerosol Dust in Klang Valley, Malaysia during the Summer. *Atmos. Environ.* 45: 4370–4378.

Karaca, F., Anil, I. and Alagha, O. (2009). Long-range Potential Source Contributions of Episodic Aerosol Events to PM_{10} Profile of a Megacity. *Atmos. Environ.* 43: 5713–5722.

Kavouras, I.G., Etyemezian, V. and DuBois, D.W. (2009). Development of a Geospatial Screening Tool to Identify Source Areas of Windblown Dust. *Environ. Modell. Softw.* 24: 1003–1011.

Korcz, M., Fuda1a, J. and Klis, C. (2009). Estimation of Wind Blown Dust Emissions in Europe and Its Vicinity. *Atmos. Environ.* 43: 1410–1420.

Martet, M., Peuch, V.H., Laurent, B., Marticorena, B. and Bergametti, G. (2009). Evaluation of Long-range Transport and Deposition of Desert Dust with the CTM MOCAGE. *Tellus Ser. B* 61: 449–463.

Saxton, K. (1995). Wind Erosion and Its Impact on Off-site Air Quality in the Columbia Plateau – An Integrated Research Plan. *Trans. ASAE* 38: 1031–1038.

Sharratt, B., Feng, G. and Wendling, L. (2007). Loss of Soil and PM_{10} from Agricultural Fields Associated with High Winds on the Columbia Plateau. *Earth Surf. Processes Landforms* 32: 621–630.

Sharratt, B.S. and Edgar, R. (2011). Implications of Changing PM_{10} Air Quality Standards on Pacific Northwest Communities Affected by Windblown Dust. *Atmos. Environ.* 45: 4533–4814.

Shaw, W.J., Allwine, K.J., Fritz. B.G., Rutz, F.C., Rishel, J.P. and Chapman, E.G. (2008). An Evaluation of the Wind Erosion Module in DUSTRAN. *Atmos. Environ.* 42: 1907–1921.

Skidmore, E.L. (1986). Soil Erosion by Wind: An Overview, In *Physics of Desertification*, El-baz, F. and Hassan, M.H.A. (Eds.), Dordrecht, p. 263–271.

Tianjin Bureau of Environmental Protection (TBEP). Tianjin Environmental Quality Reports 2009, Tianjin Bureau of Environmental Protection, 2010.

Vautard, R., Bassagnet, B., Chin, M. and Menut, L. (2005). On the Contribution of Natural Aeolian Sources to Particulate Matter Concentrations in Europe: Testing

Hypotheses with a Modeling Approach. *Atmos. Environ.* 39: 291–3303.

Visser, S.M., Sterk, G. and Karssenberg, D. (2005). Wind Erosion Modeling in a Sahelian Environment. *Environ. Modell. Softw.* 20: 69–84.

Zender, C.S., Bian, H. and Newman, D. (2003). Mineral Dust Entrainment and Deposition (DEAD) Model: Description and 1990s Dust Climatology. *J. Geophys. Res.* 108: 4416–4439.

Zhang, C.L., Dong, G.R., Zou, X.Y., Cheng, H. and Yang, S. (2005). Contributing Ratios of Several Factors to the Steppe Desertification in Guinan, Qinhai Province. *J. Desert Res.* 25: 511–518 (in Chinese).

Zhang, Z., Wieland, R., Reiche, M., Funk, R., Hoffmann, C., Li, Y. and Sommer, M. (2011). Wind Modeling for Wind Erosion Research by Open Source Computational Fluid Dynamics. *Ecol. Inf.* 6: 316–324.

Zobeck, T.M. and Pelt, R.S.V. (2006). Wind-induced Dust Generation and Transport Mechanics on a Bare Agricultural Field. *J. Hazard. Mater.* 132: 26–38.

Received for review, December 24, 2012
Accepted, September 9, 2013