Effects of Rain and Snow on the Air Quality Index, PM_{2.5} Levels, and Dry Deposition Flux of PCDD/Fs

Xueying Tian¹, Kangping Cui^{1*}, Hwey-Lin Sheu^{2*}, Yen-Kung Hsieh³,
Fanxuan Yu¹

¹School of Resources and Environmental Engineering, Hefei University of Technology, Hefei 246011, China

²Department of Environmental Engineering, Kun Shan University, Tainan 71070, Taiwan

³Marine Ecology and Conservation Research Center, National Academy of Marine Research, Kaohsiung 80661, Taiwan

ABSTRACT

The effects of eighteen precipitation (rain and snow) events in both Jinan and Qingdao cities in Shandong Province, China, on the air quality and dry deposition flux in PCDD/Fs were investigated. A total of fifteen precipitation events were positive for AQI reductions. In these events, the AQI ranged between 29 and 195 and averaged 79, and the PM_{2.5} concentration ranged between 10 and 146 $\mu\text{g m}^{-3}$ and averaged 39 $\mu\text{g m}^{-3}$. A comparison of the average of the fifteen events during and after the precipitation, respectively, with that before the precipitation, showed AQI reduction fractions of 23% and 32%, respectively, while those for the PM_{2.5} concentration were 27% and 42%, respectively; the PCDD/F dry deposition ranged between 145.7 and 1152 pg WHO₂₀₀₅-TEQ $\text{m}^{-2} \text{day}^{-1}$ and averaged 476.7 pg WHO₂₀₀₅-TEQ $\text{m}^{-2} \text{day}^{-1}$. A comparison of the above events after the precipitation showed that the reduction in the fraction of the PCDD/F dry deposition flux averaged 35%. However, the other three precipitation events demonstrated an elevation in the AQI, where the AQI ranged between 24 and 147 and averaged 91, and the PM_{2.5} concentration ranged between 4 and 112 $\mu\text{g m}^{-3}$ and averaged 42 $\mu\text{g m}^{-3}$. A comparison of the values during and after the precipitation, respectively with those before the precipitation, revealed increased AQI fractions of -18% and 28%, respectively, while those for the PM_{2.5} concentration were 16% and 51%, respectively. In the three AQI elevation events, the PCDD/F dry deposition flux ranged between 191.3 and 946.2 pg WHO₂₀₀₅-TEQ $\text{m}^{-2} \text{day}^{-1}$ and averaged 473.0 pg WHO₂₀₀₅-TEQ $\text{m}^{-2} \text{day}^{-1}$. A comparison of the period after the precipitation with that before the precipitation showed that the increase in the fraction of the PCDD dry deposition flux averaged 20%. The above results revealed that, in general, rain and snow did improve the air quality in the areas of interest. This was due to the fact that the particulates or dissolved gaseous pollutants were scavenged out of the air and carried the aerosols down to the ground. However, in some events, after rainy or snowy days, increases in the source emissions and reductions in the atmospheric vertical convection did result in an elevation in the AQI, PM_{2.5} concentrations, and PCDD/F dry deposition in the ambient air. The results of this study provided useful information contributing to air quality management.

Keywords: Rain, Snow, AQI, PM_{2.5}, PCDD/Fs, Dry deposition

1 INTRODUCTION

In the past few decades, with the rapid development of the social economy, industrial production, vehicle exhaust emissions, coal and other energy combustion has produced a large number of pollutants, which have seriously harmed the atmospheric environment (Liu *et al.*, 2012). Many studies have shown that air pollution is closely related to the incidence of lung cancer, cardiovascular diseases, and other diseases that seriously threaten human health (McDonnell *et al.*, 2000; Pope *et al.*, 2009).

OPEN ACCESS

Received: June 30, 2021

Revised: July 21, 2021

Accepted: July 22, 2021

* Corresponding Authors:

Kangping Cui
cuikangping@163.com
Hwey-Lin Sheu
sheu@mail.ksu.edu.tw

Publisher:

Taiwan Association for Aerosol
Research

ISSN: 1680-8584 print

ISSN: 2071-1409 online

Copyright: The Author(s). This is an open access article distributed under the terms of the [Creative Commons Attribution License \(CC BY 4.0\)](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are cited.

The Air Quality Index (AQI) is an index that can quantitatively describe air quality and can represent the short-term air quality status and trends in variation in a city. $PM_{2.5}$ is an important factor causing haze, which has a great impact on environmental air quality (Li *et al.*, 2015). The number of deaths caused by respiratory diseases is positively correlated with atmospheric particulate matter (PM). $PM_{2.5}$ is small in diameter, highly active, and prone to carrying toxic and harmful substances (Dai *et al.*, 2015). Therefore, issues related to air quality are attracting increasing attention from the public (Brauer *et al.*, 2016).

Dioxins are polyhalogenated or polychlorinated aromatic compounds with a high degree of similarity in terms of structure and properties. They comprise POPs (persistent organic compounds). There are many homologous isomers, including coplanar polychlorinated biphenyl (co-PCBs), polychlorinated dibenzo-*p*-dioxins (PCDDs), and polychlorinated dibenzo furans (PCDFs) (Schecter *et al.*, 2006; Redfern *et al.*, 2017). PCDDs are derivatives of dibenzo-*p*-dioxins. There are 75 compounds in total, 7 of which have strong biological toxicity. Among them, 2,3,7,8-TCDD is the most toxic compound discovered so far. Its toxicity is about 900 times that of arsenic, and it is called “the poison of the century” (Van den Berg *et al.*, 1998; Li *et al.*, 2016). PCDFs, derivatives of dibenzofuran, comprise 135 compounds, 10 of which are biotoxic. PCDD/Fs are mainly produced by natural factors and human activities. Natural factors include volcanic eruptions, forest fires, lightning, and photochemical reactions (Prange *et al.*, 2002; Kim *et al.*, 2003). Human activities include the use of large quantities of chlorinated chemicals in industrial production (Ma *et al.*, 2019), waste incineration (Lin *et al.*, 2014), the pharmaceutical industry, coal-based power generation, and heating (Cheruiyot *et al.*, 2016; Zhan *et al.*, 2019; Qiu *et al.*, 2020). In addition, vehicles that use diesel or gasoline fuel, such as cars and motorcycles, also emit PCDD/Fs in their exhaust (Zhao *et al.*, 2019; Chen *et al.*, 2020). Human exposure to a high PCDD/F environment can cause facial irritation accompanied by skin and liver damage (Marinković *et al.*, 2010). They may also cause endocrine disorders, damage the reproductive system, and may cause immune dysfunction and mental irritability, among other symptoms (Srogi *et al.*, 2008). After PCDD/Fs are discharged into the atmosphere, they are transported, mixed, and diluted as a result of horizontal movement of the atmosphere, vertical turbulence, and diffusion movement in the atmosphere at different scales. Atmospheric transport transfers PCDD/Fs to water and soil, and eventually into the food chain and human bodies (Lohmann and Jones, 1998; Hu *et al.*, 2009).

The removal of persistent organic pollutants occurs mainly through atmospheric subsidence. This refers to the process of atmospheric pollutants being settled on the ground or water in specific ways, which can be divided into dry and wet deposition (Brzuzy and Hites 1996; Jurado *et al.*, 2005). It has been found that environmental pollutants such as PCDD/Fs can be removed using these processes (Huang *et al.*, 2011). Wet deposition refers to the process of removing particulate matter from the atmosphere through rainfall, snowfall, etc. It is an effective method by which to remove atmospheric particles and trace gaseous pollutants (Moon *et al.*, 2005; Melymuk *et al.*, 2011). Studies have shown that rainfall can improve air quality. The larger the initial concentration of particulate matter, the better the rainfall cleaning effect is, and the clearer effect of PM_{10} is better than that of $PM_{2.5}$ (Zhou *et al.*, 2020). Due to the effective removal of particulate pollutants, air quality is generally improved after the precipitation process. Ambient temperature, rainfall intensity, particle size, and concentration of particulate pollutants do affect the wet deposition process (Chang *et al.*, 2004; Wu *et al.*, 2009; Wang *et al.*, 2010). Dry deposition is a process of sedimentation of various particles suspended in the atmosphere at their own final velocity, which is one of the important ways for air pollutants to enter the ecosystem (Mi *et al.*, 2012). Wind speed, ambient temperature, humidity, particle size, and the state of pollutants all affect the dry deposition flux (Chandra *et al.*, 2015).

In this study, a total of eighteen precipitation (rain or snow) events were chosen in Jinan and Qingdao cities, respectively. They were divided into AQI reduction or AQI elevation events. The AQI $PM_{2.5}$ concentrations before precipitation, in the precipitation, and after precipitation are presented and discussed. In addition, the effects of precipitation on the dry deposition flux of total PCDD/Fs-WHO₂₀₀₅-TEQ were investigated and are discussed.

2 METHODS

Two cities, Jinan (36°40'N, 117°00'E) and Qingdao (36°0'N, 120°3'E) in Shandong Province,

China, were selected and evaluated in this study. Data for three years (from 2018 to 2020) were obtained for both Jinan and Qingdao. The PM concentration (including daily PM_{2.5} and PM₁₀), gaseous pollutants (including daily SO₂, NO₂, CO, and O₃), and daily precipitation records were obtained from local air quality monitoring stations, local weather bureaus, and the Statistics Yearbook of China.

2.1 PCDD/F Concentration

The total PCDD/F concentration was simulated using a regression analysis of the PM₁₀ concentrations. Tang *et al.* (2017) reported that there is a high correlation between PM₁₀ values and total PCDD/F mass concentrations. Their research included the following two regression equations:

$$Y_1 = 0.0138x + 0.0472; \quad (1)$$

$$Y_2 = 0.0117x - 0.021, \quad (2)$$

where Y_1 , Y_2 represent the total PCDD/F concentration (pg m⁻³); x represents the PM₁₀ concentration in ambient air (μg m⁻³), and where the final total PCDD/F concentration is the average of Y_1 and Y_2 .

2.2 Dry Deposition

The dry deposition flux is composed of the addition of the diffusion of gaseous matter and the deposition of particulate matter.

$$F_T = F_g + F_p \quad (3)$$

$$C_T \times V_{d,T} = C_g \times V_{d,g} + C_p \times V_{d,p} \quad (4)$$

where F_T is the total dry deposition flux (pg WHO₂₀₀₅-TEQ m⁻² month⁻¹); F_g is the diffusion of gaseous matter producing dry deposition flux (pg WHO₂₀₀₅-TEQ m⁻² month⁻¹); F_p is the gravitational settling of particulate matter contributing to dry deposition flux (pg WHO₂₀₀₅-TEQ m⁻² month⁻¹); C_T is total PCDD/F concentration in the atmosphere (pg m⁻³); $V_{d,T}$ is the dry deposition velocity of PCDD/Fs (gas+particle phases), 0.42 cm s⁻¹ (Shih *et al.*, 2006).

C_g is the calculated PCDD/F concentration in the gas phase (pg m⁻³); $V_{d,g}$ is the dry deposition velocity of PCDD/Fs in gas phase, 0.01 cm s⁻¹ (Sheu *et al.*, 1996); C_p is the calculated PCDD/F concentration in the particle phase (pg m⁻³), and $V_{d,p}$ is the dry deposition velocity of PCDD/Fs in the particle phase (cm s⁻¹).

2.3 Air Quality Index (AQI)

The air quality index (AQI) is a quantitative description of air quality data, which can represent the short-term air quality status and trends in a city. The sub-AQI of the six criteria pollutants were first calculated with the observation concentrations, as shown in Eq. (5) (Shen *et al.*, 2017; She *et al.*, 2017). The overall AQI represents the maximum of the sub-AQI of all pollutants, where when the AQI is higher than 50, the highest sub-AQI contributor is defined as the primary pollutant on that day, as shown in Eq. (6) (Shen *et al.*, 2017; She *et al.*, 2017):

$$IAQI_p = \frac{I_{high} - I_{low}}{C_{high} - C_{low}} (C_p - C_{low}) + I_{low} \quad (5)$$

$$AQI = \max(I_1, I_2, \dots, I_n) \quad (6)$$

where $IAQI_p$ represents the air quality sub index for air pollutant p ; C_p represents the concentration of pollutant p ; C_{low} represents the concentration breakpoint that is $\leq C_p$; C_{high} represents the concentration breakpoint that is $\geq C_p$; I_{low} represents the index breakpoint corresponding to C_{low} , and I_{high} represents the index breakpoint corresponding to C_{high} .

The six air pollutants under consideration in this work have acute effects on human health. The daily AQIs were calculated using the 24-hour average concentrations of SO₂, NO₂, PM_{2.5}, PM₁₀, and CO, and the daily average 8-hour maximum concentration of O₃. The United States Environmental Protection Agency (US EPA) AQI has classified the ranges of AQI values related to air quality into six classes: Grade I: 0–50 (Good, Green); Grade II: 51–100 (Moderate, Yellow); Grade III: 101–150 (Unhealthy for Sensitive Groups; Orange); Grade IV: 151–200 (Unhealthy; Red); Grade V: 201–300 (Very unhealthy; Purple), and Grade VI: 300–500 (Hazardous; Maroon) (Hu *et al.*, 2015; Lanzafame *et al.*, 2015; She *et al.*, 2017; Zhao *et al.*, 2018a).

3 RESULTS AND DISCUSSION

3.1 Effects of Precipitation on Reductions in the AQI

In Jinan, from 2018–2020, there were a total of nine precipitation events (seven rain and two snow events) selected for the purposes of this study. In terms of the air quality index, in these nine events, for seven of them, six of which were rain, and one of which was snow, the air quality index was reduced; in other words, in these seven events, the air quality improved. In Qingdao, during the same period, there were a total nine precipitation events selected as well; six of them were rain events, and three of them were snow events. In eight of them, the air quality index was reduced. The dates, duration of precipitation, and amount of precipitation are shown in Table 1.

Table 1. The AQI values and precipitation intensity in Jinan and Qingdao from 2018 to 2020.

City	Date	Scenarios	AQI	Precipitation intensity (mm)
Jinan	1	Jan. 25, 2018	before the snow	71
		Jan. 26, 2018	before the snow	66
		Jan. 27, 2018	during the snow	122 3.2
		Jan. 28, 2018	during the snow	104 1.0
		Jan. 29, 2018	after the snow	147
		Jan. 30, 2018	after the snow	110
	2	Apr. 20, 2018	before the rain	131
		Apr. 21, 2018	before the rain	116
		Apr. 23, 2018	during the rain	43 59.3
		Apr. 24, 2018	during the rain	57 4.0
		Apr. 25, 2018	after the rain	83
		Apr. 26, 2018	after the rain	100
	3	Aug. 28, 2018	before the rain	115
		Aug. 29, 2018	before the rain	121
		Aug. 30, 2018	during the rain	62 9.2
		Aug. 31, 2018	during the rain	72 7.3
		Sept. 1, 2018	after the rain	99
		Sept. 2, 2018	after the rain	61
	4	Jun. 3, 2019	before the rain	150
		Jun. 4, 2019	before the rain	168
		Jun. 5, 2019	during the rain	138 1.9
		Jun. 6, 2019	during the rain	88 1.1
		Jun. 7, 2019	after the rain	119
		Jun. 8, 2019	after the rain	142
	5	Sept. 9, 2019	before the rain	138
		Sept. 10, 2019	before the rain	82
		Sept. 11, 2019	during the rain	53 1.4
		Sept. 12, 2019	during the rain	59 13.3
		Sept. 13, 2019	during the rain	44 16.6
		Sept. 14, 2019	after the rain	64
		Sept. 15, 2019	after the rain	58
	6	Dec. 23, 2019	before the rain	195

Table 1. (continued).

City	Date	Scenarios	AQI	Precipitation intensity (mm)
Qingdao	Dec. 24, 2019	before the rain	128	
	Dec. 25, 2019	during the rain	152	2.5
	Dec. 26, 2019	during the rain	94	1.2
	Dec. 27, 2019	after the rain	71	
	Dec. 28, 2019	after the rain	80	
	7 Feb. 12, 2020	before the rain	74	
	Feb. 13, 2020	before the rain	65	
	Feb. 14, 2020	during the rain	52	6.1
	Feb. 15, 2020	during the rain	38	9.7
	Feb. 16, 2020	during the rain	41	
	Feb. 17, 2020	after the rain	41	
	8 Jun. 14, 2020	after the rain	130	
	Jun. 15, 2020	before the rain	125	
	Jun. 16, 2020	before the rain	93	
	Jun. 17, 2020	during the rain	55	1.1
	Jun. 18, 2020	during the rain	69	8.1
	Jun. 19, 2020	during the rain	121	1.4
	Jun. 20, 2020	after the rain	139	
	9 Nov. 29, 2020	before the snow	123	
	Nov. 30, 2020	before the snow	117	
	Dec. 1, 2020	during the snow	113	2.0
	Dec. 2, 2020	during the snow	138	2.4
	Dec. 3, 2020	after the snow	69	
	Dec. 4, 2020	after the snow	99	
	10 Jun. 11, 2018	before the rain	76	
	Jun. 12, 2018	before the rain	60	
	Jun. 13, 2018	during the rain	88	54.1
	Jun. 14, 2018	during the rain	80	14.8
	Jun. 15, 2018	after the rain	43	
	Jun. 16, 2018	after the rain	44	
	11 Oct. 23, 2018	before the rain	68	
	Oct. 24, 2018	before the rain	77	
	Oct. 25, 2018	during the rain	79	0.1
	Oct. 26, 2018	during the rain	66	4.7
	Oct. 27, 2018	after the rain	56	
	Oct. 28, 2018	after the rain	66	
	12 Dec. 3, 2018	before the snow	71	
	Dec. 4, 2018	before the snow	61	
	Dec. 5, 2018	during the snow	56	0.9
	Dec. 6, 2018	during the snow	53	2.3
	Dec. 7, 2018	during the snow	40	0.3
	Dec. 8, 2018	after the snow	54	
	Dec. 9, 2018	after the snow	64	
	13 Feb. 11, 2019	before the snow	29	
	Feb. 12, 2019	before the snow	105	
	Feb. 13, 2019	during the snow	112	0.2
	Feb. 14, 2019	during the snow	78	3.7
	Feb. 15, 2019	after the snow	47	
	Feb. 16, 2019	after the snow	64	
	14 May 9, 2019	before the rain	117	
	May 10, 2019	before the rain	83	
	May 11, 2019	during the rain	72	0.1
	May 12, 2019	during the rain	87	1.4

Table 1. (continued).

City	Date	Scenarios	AQI	Precipitation intensity (mm)
15	May 13, 2019	during the rain	87	0.3
	May 14, 2019	after the rain	60	
	May 15, 2019	after the rain	48	
	Jul. 16, 2019	before the snow	100	
	Jul. 17, 2019	before the snow	41	
	Jul. 18, 2019	during the snow	46	1.3
	Jul. 19, 2019	during the snow	24	0.1
	Jul. 20, 2019	after the snow	70	
	Jul. 21, 2019	after the snow	94	
	Feb. 12, 2020	before the snow	39	
	Feb. 13, 2020	before the snow	49	
	Feb. 14, 2020	during the snow	42	0.3
	Feb. 15, 2020	during the snow	33	16.6
	Feb. 16, 2020	after the snow	38	
	Feb. 17, 2020	after the snow	37	
	Sept. 8, 2020	before the rain	85	
	Sept. 9, 2020	before the rain	92	
	Sept. 10, 2020	during the rain	70	0.4
	Sept. 11, 2020	during the rain	70	16.3
	Sept. 12, 2020	during the rain	51	1.4
	Sept. 13, 2020	after the rain	46	
18	Sept. 14, 2020	after the rain	47	
	Nov. 29, 2020	before the snow	64	
	Nov. 30, 2020	before the snow	88	
	Dec. 1, 2020	during the snow	74	1.6
	Dec. 2, 2020	during the snow	87	1.2
	Dec. 3, 2020	after the snow	55	
	Dec. 4, 2020	after the snow	68	

3.1.1 AQI analysis

In Jinan, the seven events for which the air quality index was reduced are shown in Table 1. The AQI before the rain ranged between 65 and 195 and averaged 124 (Figs. 1(a2–a7)), while during the rain, the AQI ranged between 38 and 152 and averaged 73 (Figs. 1(b2–b7)); however, after the rain, the values ranged from 41 to 142 and averaged 80 (Figs. 1(c2–c7)). The primary air pollutant was O_3 . Comparing the AQI during the rain with that before rain, respectively, the AQI reduction during the rain ranged between 24% and 60% and averaged 41% lower than that before the rain, respectively. Regarding the AQI after rain with that before the rain, respectively, the AQI reduction after the rain was between 18% and 73% and averaged 35% lower than that before the rain, respectively. This was mainly due to the occurrence of wet deposition, the process of removing particles from the atmosphere through precipitation processes. It is an effective method by which to remove atmospheric particles and trace gaseous pollutants. Because rain depends on particles floating in the air, it falls with them to the ground, reducing the concentration of particulate pollutants in the atmosphere (Kaupp and McLachlan, 1998). Wind also dilutes the horizontal transport of pollutants. Rainfall when the wind speed is large or small, up and down, around the irregular swing, and this irregular, random swing can make other components mixed, is conducive to the dilution and diffusion of pollutants. The above results did reveal that, in Jinan, the rain improved the ambient air quality.

As for the one snow event in Jinan, the AQI before the snow ranged between 117 and 123 and averaged 120 (Fig. 1(a9)). During the snow, it ranged between 113 and 138 and averaged 126 (Fig. 1(b9)); however, the AQI after the snow ranged from 69 to 99 and averaged 84. The primary air pollutant was PM_{10} . Comparing the AQI during the snow with that before the snow, the AQI during the snow was 5.0% higher than that before the snow, and the value after the snow was 32%

Fig. 1. The fractions of the six AQI categories for Jinan (a2 –7, 9) before the precipitation, (b2 –7,9) during the precipitation and (c2 –7, 9), and after the precipitation from 2018–2020 for AQI reduction events.

Fig. 1. (continued).

As a whole, combined both in Jinan and in Qingdao, there were totally fifteen precipitation events were positively for the AQI reduction, the AQI ranged between 29 and 195 and averaged 79, compared the AQI in and after the precipitation, respectively, with that of before precipitation, the reduction fraction of AQI were 23% and 32%, respectively.

Fig. 3. shows the PM_{2.5} concentration variations in the events in Jinan (b–g) before the rain, during the rain, and

Fig. 2. The fractions of the six AQI categories for Qingdao for reductions in the AQI (a10-14, 16-18) before the precipitation, (b10-14, 16-18) during the precipitation, and (c10-14, 16-18) after the precipitation for the period 2018-2020.

Fig. 2. (continued).

Fig. 2. (continued).

after the rain for the period 2018–2020 when the AQI was reduced.

In Jinan, of the seven events where the air quality index was found to be reduced, six of them were rain events. As Fig. 3. shows, the $PM_{2.5}$ concentrations in the six rain events before the rain ranged between 28 and 146 $\mu g m^{-3}$ and averaged 58 $\mu g m^{-3}$; during the rain, they ranged between 17 and 116 $\mu g m^{-3}$ and averaged 39 $\mu g m^{-3}$, and the $PM_{2.5}$ concentrations after the rain ranged from 14 to 59 $\mu g m^{-3}$ and averaged 32 $\mu g m^{-3}$. Comparing the $PM_{2.5}$ concentration during the rain with that before the rain, respectively, the $PM_{2.5}$ concentration reduction in the rain ranged between 14% and 55% and averaged 32% lower than that before the rain, respectively. Regarding the $PM_{2.5}$ concentration after the rain with that before the rain, respectively, the $PM_{2.5}$ concentration reductions after the rain ranged between 21% and 73% and averaged 45% lower than that before the rain, respectively. During the rainfall period, the $PM_{2.5}$ concentration continued to decrease, indicating that rainfall can improve air quality to a certain extent. This due to the fact that the rain scavenged the $PM_{2.5}$ out of the air and gravity caused it to settle on the ground.

As to the one snow event where the AQI was reduced in Jinan (Fig. 3(i)), the $PM_{2.5}$ concentration before the snow ranged between 88 and 93 $\mu g m^{-3}$ and averaged 91 $\mu g m^{-3}$; during the snow, the concentration ranged between 85 and 105 $\mu g m^{-3}$ and averaged 95 $\mu g m^{-3}$ (Fig. 3(i)), and after the snow the concentration ranged from 50 to 74 $\mu g m^{-3}$ and averaged 62 $\mu g m^{-3}$ (Fig. 3(i)). The $PM_{2.5}$ concentrations during the snow were 4.0% higher than those before the snow, and were 32% lower after the snow than before the snow, respectively. Snowfall can wash away pollutants in the air to a certain extent. During the crystallization of water molecules in the air to form snowflakes, the surface area increases rapidly, so particles can be effectively absorbed in the air and brought down to the ground. This mechanism revealed that the particulates in the air were removed by the rain and resulted in a positive effect on air quality.

As shown in Figs. 4(a–e, g–i), in Qingdao, of the eight events where the air quality index was reduced, five of them were rain events. The $PM_{2.5}$ concentrations before the rain were between 18 and 38 $\mu g m^{-3}$ and averaged 29 $\mu g m^{-3}$ (Figs. 4(a–b, e, g–h)); those during the rain ranged between 11 and 38 $\mu g m^{-3}$ and averaged 24 $\mu g m^{-3}$, and those after the rain ranged from 10 to 3 $\mu g m^{-3}$ and averaged 18 $\mu g m^{-3}$. Comparing the $PM_{2.5}$ concentration during the rain with that before the rain, respectively, the $PM_{2.5}$ concentration reductions during the rain ranged between 0% and 50% and averaged 21% lower than those before the rain, respectively. Comparing the $PM_{2.5}$ concentrations after the rain with those before rain showed that the $PM_{2.5}$ concentration reduction after the rain ranged between 25% and 61% and averaged 37% lower than that before the rain. Rainfall in atmospheric particulate matter removal effect lag period, a period of time after the rain can still affect the particle concentration, this may be due to rainfall process that leads to increased atmospheric humidity, particles are more likely to collide with raindrops fusion and deposition, and rainfall is usually accompanied by strong winds, is more advantageous to aerosol particles dissipate (Guo *et al.*, 2016).

For the three snow events where the air quality index was reduced in Qingdao, the $PM_{2.5}$ concentrations before the snow ranged between 17 and 84 $\mu g m^{-3}$ and averaged 56 $\mu g m^{-3}$ (Figs. 4(c–d)); during the snow, they ranged between 13 and 64 $\mu g m^{-3}$ and averaged 37 $\mu g m^{-3}$, and after the snow, they ranged from 15 to 46 $\mu g m^{-3}$ and averaged 33 $\mu g m^{-3}$. Comparing the $PM_{2.5}$ concentration during the snow with that before the snow, the $PM_{2.5}$ concentration reductions during the snow ranged between –2% and 46% and averaged 27% lower than those before the snow, respectively. Comparing the $PM_{2.5}$ concentrations after the snow with those before the snow, respectively, the reductions after the snow between 24% and 56% and averaged 37 % lower than that before the snow, respectively. The average $PM_{2.5}$ concentration in Weihai and Qingdao are lower than that in Jinan, this is related to the abundant rainfall, strong wind and fast air circulation in coastal cities, which are conducive to the wet deposition and thus accelerate the diffusion of pollutants (Zhao *et al.*, 2018b).

3.1.3 Dry deposition flux of Total-PCDD/Fs-WHO₂₀₀₅-TEQ

Fig. 5. shows the dry deposition flux for the variations in the total PCDD/Fs-WHO₂₀₀₅-TEQ in Jinan, where Figs. 5(b–g) is before the rain, during the rain, and after the rain from 2018–2020 for the reduced AQI events.

Fig. 3. Variations in the $PM_{2.5}$ concentration for Jinan (b–g, i) before the precipitation, during the precipitation, and after the precipitation from 2018–2020 for the reduced AQI events.

Fig. 4. Variations in the PM_{2.5} concentration in Qingdao (a–e, g–i) before the precipitation, during the precipitation, and after the precipitation from 2018 –2020 for the reduced AQI events.

Fig. 5. Variations in the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ in Jinan (b–g, i) before the precipitation, during the precipitation, and after the precipitation from 2018–2020 for reduced AQI events.

In Jinan, of the seven events where the air quality index values were reduced, six of them were rain events, and one of them was a snow event. As shown in Fig. 5., the dry deposition flux of total-PCDD/Fs-WHO₂₀₀₅-TEQ for the six rain events before the rain ranged between 388.1 and 1152 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 676.7 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹; the dry deposition flux for the total PCDD/Fs-WHO₂₀₀₅-TEQ after the rain ranged from 157.8 to 600.1 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 408.6 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹. Comparing the dry deposition flux for the total PCDD/Fs-WHO₂₀₀₅-TEQ after the rain with that before the rain, the dry deposition flux for the reduction in the total PCDD/Fs-WHO₂₀₀₅-TEQ after the rain ranged between 11% and 60% and averaged 40% lower than that before the rain, respectively.

For the one snow event where the dry deposition flux for the total PCDD/Fs-WHO₂₀₀₅-TEQ reduced in Jinan (Fig. 5(i)), the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ before the snow ranged between 904.8 and 984.1 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 944.5 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹; the dry deposition of flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ after the snow ranged from 436.8 to 697.4 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 558.1 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ (Fig. 3(i)). A comparison of the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ after the snow indicated that the total PCDD/Fs-WHO₂₀₀₅-TEQ was 41% lower than that before the snow.

As shown in Figs. 6(a–e, g–i), in Qingdao, of the eight events where there was a reduction in the AQI, five of them were rain events, where the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ before the rain ranged between 145.7 and 667.1 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 402.3 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ (Figs. 6(a–b, e, g–h)); the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ after the rain ranged from 145.7 to 548.3 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 288.4 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹. Comparing the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ after the rain with that before the rain, the reductions after the rain ranged between 2.0% and 51% and averaged 28% lower than those before the rain.

For the three snow events where the air quality index was reduced in Qingdao, the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ before the snow ranged between 368.8 and 726.5 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 552.5 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ (Figs. 6(c–d, i)); after the snow, these values ranged from 333.7 to 479.3 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 392.3 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹. Comparing the dry deposition of flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ after the snow with that before the snow, the reduction in the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ after the snow ranged between 17% and 37% and averaged 29% lower than that before the snow.

As a whole, a total of fifteen precipitation events reduced the AQI, where the PCDD/F dry deposition flux ranged between 145.7 and 1152 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 476.7 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹. Comparing the above events after the precipitation with those before the precipitation, the reduction in the PCDD/Fs dry deposition fraction averaged 35%. In fact, the removal efficiency of persistent organic pollutants by snow or rain depends on the nature of human pollutants and snow, and the ambient temperature. Below 0°C, rain generally clears more organic vapors than snow, because the surface of snow has less ability to absorb these chemicals than liquid droplets. For organic macromolecule vapors with low water solubility, the change of specific surface area and particle scavenging rate of snow will make the snow removal rate stronger. Below –10°C, the more chemicals that change from gas to liquid form are present in atmospheric particles and on the surface of snow, which is more conducive to pollutant (Lei *et al.*, 2004).

3.2 Effects of Precipitation on AQI Elevation

In Jinan, from 2018–2020, there was a total of nine events of precipitation (seven rain and two snow events) selected for the purposes of this study, where two events (1 and 8) exhibited elevated AQI values. In Qingdao, during the same period, there were a total of nine events of precipitation, and six rain events and three snow events were selected in this study. Among these, one (event 15) had an elevated AQI (Table 1).

3.2.1 AQI analysis

In Jinan, for the two events with an elevated AQI (Table 1), the AQI before the rain ranged between 125 and 130 and averaged 128 (Fig. 7(a8)). During the rain, the AQI values ranged between 55 and 93 and averaged 72 (Fig. 7(a8)), and values after the rain ranged from 121 to 139

Fig. 6. Variations in the dry deposition flux in the total PCDD/Fs -WHO2005-TEQ for Qingdao (a –e, g –i) before the precipitation, during the precipitation, and after the precipitation from 2018–2020 for reduced AQI events.

Fig. 7. The fractions for the six AQI categories for linan in (a1, 8) before the precipitation, (b1, 8) during the precipitation, and (c1 , 8) after the precipitation from 2018 – 2020 for the elevated AQI events.

and averaged 130 (Fig. 7(a8)). The AQI during the rain averaged 43% lower than that before the rain; and the AQI after the rain was 2.0% higher than that before the rain. This may have been due to a weak summer high wind and too little precipitation, which is not conducive to the dilution and diffusion of pollutants. On rainy days, air pollutants will be covered with water vapor, which is more likely to cause the accumulation of pollutants, increase the particulate concentration, and thus elevate the AQI.

In the one snow event with an elevated AQI in Jinan (Table 1), the AQI before the snow ranged between 66 and 71 and averaged 69 (Fig. 7(a1)). During the snow, the values ranged between 104 and 122 and averaged 113 (Fig. 9(a1)), and the values after the snow ranged from 110 to 147 and averaged 129. Comparing the AQI during and after the snow, the AQI values were 65% and 88% higher than those before the snow, respectively. This is because in cold winter, the wind speed is low, the atmosphere become more stable, resulting in both poor both atmospheric vertical convection and horizontal dispersion, so the AQI were elevated. At the same time, at a certain event of snowstorm, both automobile exhaust and stationary source emission increased and then result in an increase of AQI (Nidzgorska-Lencewicz *et al.*, 2020).

In Qingdao, for the one event where the AQI was elevated (Table 1), the AQI before the rain ranged between 41 and 100 and averaged 71 (Fig. 8). During the rain, the values ranged between 24 and 46 and averaged 35. The AQI values after the rain ranged from 70 to 94 and averaged 82. The AQI values during the rain were 51% lower than those before the rain. However, the values before the rain averaged 16% higher than those before the rain.

As a whole, a total of three precipitation events displayed the AQI elevation in Jinan and Qingdao, where the AQI ranged between 24 and 147 and averaged 91. When comparing the values during and after the precipitation with those before the precipitation, the increased AQI fractions were -18% and 28%, respectively.

3.2.2 PM_{2.5} concentration

Fig. 9 shows the variations in the PM_{2.5} concentration in Jinan in (a, h) before the precipitation, during the precipitation, and after the precipitation from 2018–2020 for the elevated AQI events.

Fig. 8. The fractions of the six AQI categories for Qingdao (a15) before the precipitation, (b15) during the precipitation, and (c15) after the precipitation from 2018–2020 for the elevated AQI event.

Fig. 9. The variations in the PM_{2.5} concentration in Jinan (a, h) before the precipitation, during the precipitation, and after the precipitation from 2018–2020 for the elevated AQI events.

Fig. 10. The variations in the PM_{2.5} concentration in Qingdao (f) before the precipitation, during the precipitation, and after the precipitation from 2018–2020 for the elevated AQI event.

In Jinan, for the one rain event with an elevated AQI (Fig. 9), the PM_{2.5} concentration before the rain ranged between 25 and 27 μg m⁻³ and averaged 26 μg m⁻³. During the rain, the concentration ranged between 19 and 48 μg m⁻³ and averaged 34 μg m⁻³. After the rain, it ranged from 34 to 36 μg m⁻³ and averaged 35 μg m⁻³. Comparing the average PM_{2.5} concentration during the rain and after the rain with that before the rain, the increased fractions were 32% and 35%, respectively.

For the one snow event with an elevated AQI in Jinan (Fig. 9(a)), the PM_{2.5} concentration before the snow ranged between 46 and 50 μg m⁻³ and averaged 48 μg m⁻³. During the snowstorm, the concentration ranged between 78 and 92 μg m⁻³ and averaged 85 μg m⁻³. After the snowstorm, the concentration ranged from 83 to 112 μg m⁻³ and averaged 98 μg m⁻³. The PM_{2.5} concentration during the snow was 77% higher than that before the snow, and after the snow, the concentration was 103% higher than that before the snow. Since snowfall occurs in winter, northern cities burn coal and other resources for heating, resulting in increased PCDD/Fs emissions and air quality becomes worse (Cheruiyot *et al.*, 2015).

In Qingdao, for one event with an elevated AQI (Fig. 10), the PM_{2.5} concentration before the rain ranged between 17 and 42 μg m⁻³ and averaged 30 μg m⁻³. During the rain, the concentration was 4.0 μg m⁻³ and also averaged 4.0 μg m⁻³. The PM_{2.5} concentration after the rain ranged from 20 to 28 μg m⁻³ and averaged 24 μg m⁻³. The PM_{2.5} concentration during the rain was 86% lower than that before the rain, and the concentration after the rain was 19% lower than that before the rain.

3.2.3 Dry deposition flux for the total-PCDD/Fs-WHO₂₀₀₅-TEQ

In Jinan, for the two events with elevated AQI values, in the one rain event shown in Fig. 11, the

Fig. 11. Variations in the dry deposition flux in the total-PCDD/Fs- WHO_{2005} -TEQ for Jinan (a, h) before the precipitation and after the precipitation from 2018–2020 for the elevated AQI events.

Fig. 12. Variations in the dry deposition flux in the total-PCDD/Fs- WHO_{2005} -TEQ for Qingdao (f) before the precipitation, and after the precipitation during 2018–2020 for AQI elevation events.

dry deposition flux in the total-PCDD/Fs- WHO_{2005} -TEQ before the rain ranged between 444.3 and 517.4 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$ and averaged 480.9 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$. The flux after the rain ranged from 365.6 to 388.1 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$ and averaged 376.8 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$. The dry deposition flux in the total-PCDD/Fs- WHO_{2005} -TEQ after the rain was 22% lower than that before the rain.

For the one snow event in Jinan, the dry deposition flux in the total-PCDD/Fs- WHO_{2005} -TEQ before the snow ranged between 55 and 56 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$ and averaged 527.8 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$. The values after the snow ranged from 794.6 to 946.2 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$ and averaged 870.4 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$. The dry deposition flux in the total-PCDD/Fs- WHO_{2005} -TEQ after the snow was 65% higher than that before the snow.

In Qingdao, for the one rain event with an elevated AQI shown in Fig. 12, the dry deposition flux in the total-PCDD/Fs- WHO_{2005} -TEQ before the rain ranged between 191.3 and 371.2 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$ and averaged 281.3 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$. The values after the rain ranged from 270.0 to 331.9 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$ and averaged 300.9 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$. The dry deposition flux in the total-PCDD/Fs- WHO_{2005} -TEQ after the rain was 7.0% higher than that before the rain.

As a whole, a total of three precipitation events exhibited an elevation in the AQI, where the PCDD/F dry deposition flux values ranged between 191.3 and 946.2 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$ and averaged 473.0 $\text{pg WHO}_{2005}\text{-TEQ m}^{-2} \text{ day}^{-1}$. Comparing these values after the precipitation with those before the precipitation, the increase in the dry deposition fraction of PCDD/Fs was 20%.

4 CONCLUSION

This study provided an investigation of the effects of eighteen precipitation events (rain or snow) in both Jinan and Qingdao in Shandong Province, China, on the air quality index, PM_{2.5} concentrations, and dry deposition of PCDD/Fs. The results are summarized as follows:

1. In Jinan, in the seven precipitation events demonstrating reductions in the AQI, the AQI ranged between 38 and 195 and averaged 94. As a whole, compared to during and after the precipitation, before the precipitation, the AQI reduction fractions were 34% and 40%, respectively. In Qingdao, for the eight precipitation events demonstrating reductions in the AQI, the AQI reductions ranged between 29 and 112 and averaged 65. As a whole, compared that in and after the precipitation, respectively, with that of before the precipitation, the reductions in the AQI fractions were 2.0% and 26%, respectively.
2. For Jinan, in the two precipitation events demonstrating an elevation in the AQI, the AQI ranged between 55 and 147 and averaged 104. As a whole, compared that in and after the precipitation, respectively, with that of before the precipitation, the increase fraction of AQI were 11% and 45%, respectively. For Qingdao, the one precipitation event with a reduction in the AQI, the AQI ranged between 24 and 100 and averaged 63. As a whole, compared that in and after the precipitation, respectively, with that of before the precipitation, the increased fraction of AQI were 51% and 16%, respectively.
3. In Jinan, for the seven precipitation events demonstrating a reduction in the AQI, the PM_{2.5} concentration ranged between 14 and 146 $\mu\text{g m}^{-3}$ and averaged 49 $\mu\text{g m}^{-3}$. As a whole, compared that in and after the precipitation, respectively, with that of before the precipitation, the reduction fraction of PM_{2.5} concentration were 25% and 43%, respectively. In Qingdao, for the eight precipitation events demonstrating a reduction in the AQI, the PM_{2.5} concentration ranged between 10 and 84 $\mu\text{g m}^{-3}$ and averaged 47 $\mu\text{g m}^{-3}$. As a whole, comparing the concentration after the precipitation with that before the precipitation, the reductions in the PM_{2.5} concentration were 26% and -90%, respectively.
4. For the two precipitation events demonstrating an elevation in the AQI in Jinan, the PM_{2.5} concentration ranged between 19 and 112 $\mu\text{g m}^{-3}$ and averaged 54 $\mu\text{g m}^{-3}$. Comparing the concentration after the precipitation with that before the precipitation, the increases in the PM_{2.5} concentration were 57% and 81%, respectively. For Qingdao, for the one precipitation event showing an elevation in the AQI, the PM_{2.5} concentration ranged between 4.0 and 42 $\mu\text{g m}^{-3}$ and averaged 20 $\mu\text{g m}^{-3}$. Comparing the concentration after the precipitation with that before the precipitation, the reductions in the PM_{2.5} concentration were 87% and 20%, respectively.
5. In Jinan, for the seven precipitation events demonstrating a reduction in the AQI, the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ ranged between 157.8 and 1152 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 572.5 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹. Comparing the fraction after the precipitation with that before the precipitation, the reduction in the PCDD/Fs dry deposition fraction averaged 39%. In Qingdao, for the eight precipitation events demonstrating a reduction in the AQI, the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ ranged between 145.7 and 726.5 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 393.0 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹. Comparing the values after the precipitation with those before the precipitation, the reduction in the dry deposition flux was 28%.
6. For the two precipitation events demonstration an elevation in the AQI in Jinan, the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ ranged between 365.6 and 946.2 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 560.4 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹. Comparing the flux after the precipitation with that before the precipitation, the increase in the PCDD/Fs dry deposition flux averaged 22%. In Qingdao, in the one precipitation event demonstrating an elevation in the AQI elevation, the dry deposition flux in the total PCDD/Fs-WHO₂₀₀₅-TEQ ranged between 191.3 and 371.2 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹ and averaged 291.1 pg WHO₂₀₀₅-TEQ m⁻² day⁻¹. Comparing the values after the precipitation with those before the precipitation, the increase in the PCDD/Fs dry deposition flux was 7.0%.
7. The results of this study revealed that, in general, rain and snow did improve air quality. This is due to the fact that the particulates or dissolved the gaseous pollutants were scavenged

out of the air and carried the aerosols down to the ground. However, in some events, after the rainy or snowy days, an increase in the source emissions and a reduction in the atmospheric vertical convection did result in an elevation of the AQI, PM_{2.5} concentrations, and PCDD/F dry deposition in the ambient air.

8. The results of this study provided useful information for air quality management.

REFERENCES

- Brauer, M., Freedman, G., Frostad, J., Van Donkelaar, A., Martin, R.V., Dentener, F., Balakrishnan, K. (2016). Ambient Air pollution exposure estimation for the global burden of disease 2013. *Environ. Sci. Technol.* 50, 79–88. <https://doi.org/10.1021/acs.est.5b03709>
- Brzuzny, L.P., Hites, R.A. (1996). Global mass balance for polychlorinated dibenzo-*p*-dioxins and dibenzofurans. *Environ. Sci. Technol.* 30, 1797–1804. <https://doi.org/10.1021/es950714n>
- Chandra Suryani, R., Lee, W.J., Endah Mutiara, M., Mwangi, J.K., Wang, L.C., Lin, N.H., Chang-Chien, G.P. (2015). Atmospheric deposition of polychlorinated dibenzo-*p*-dioxins and dibenzofurans at coastal and high mountain areas in Taiwan. *Aerosol Air Qual. Res.* 15, 1390–1411. <https://doi.org/10.4209/aaqr.2015.04.0246>
- Chang, M.O., Chow, J.C., Watson, J.G., Hopke, P.K., Yi, S.M., England, G.C. (2004). Measurement of ultrafine particle size distributions from coal, oil, and gas-fired stationary combustion sources. *J. Air Waste Manage. Assoc.* 54, 1494–1505. <https://doi.org/10.1080/10473289.2004.10471010>
- Chen, H.H., Shen, Y.H., Yang, H.H., Lu, J.H., Wang, L.C., Hsieh, Y.K., Lee, C.F., Lin, S.L. (2020). Newer generation of scooters: Polychlorinated dibenzo-*p*-dioxin and dibenzofuran and polychlorinated biphenyl reductions. *Aerosol Air Qual. Res.* 20, 1495–1509. <https://doi.org/10.4209/aaqr.2020.04.0138>
- Cheruiyot, N.K., Lee, W.J., Mwangi, J.K., Wang, L.C., Lin, N.H., Lin, Y.C., Cao, J., Zhang, R., Chang-Chien, G.P. (2015). An overview: Polycyclic aromatic hydrocarbon emissions from the stationary and mobile sources and in the ambient air. *Aerosol Air Qual. Res.* 15, 2730–2762. <https://doi.org/10.4209/aaqr.2015.11.0627>
- Cheruiyot, N.K., Lee, W.J., Yan, P., Mwangi, J.K., Wang, L.C., Gao, X., Lin, N.H., Chang-Chien, G.P. (2016). An overview of PCDD/F inventories and emission factors from stationary and mobile sources: What we know and what is missing. *Aerosol Air Qual. Res.* 16, 2965–2988. <https://doi.org/10.4209/aaqr.2016.10.0447>
- Dai, S., Bi, X., Chan, L.Y., He, J., Wang, B., Wang, X., Peng, P., Sheng, G., Fu, J. (2015). Chemical and stable carbon isotopic composition of PM_{2.5} from on-road vehicle emissions in the PRD region and implications for vehicle emission control policy. *Atmos. Chem. Phys.* 15, 3097–3108. <https://doi.org/10.5194/acp-15-3097-2015>
- Guo, L.C., Zhang, Y., Lin, H., Zeng, W., Liu, T., Xiao, J., Rutherford, S., You, J., Ma, W. (2016). The washout effects of rainfall on atmospheric particulate pollution in two Chinese cities. *Environ. Pollut.* 215, 195–202. <https://doi.org/10.1016/j.envpol.2016.05.003>
- Hu, J.L., Ying, Q., Wang, Y.G., Zhang, H.L. (2015). Characterizing multi-pollutant air pollution in China: Comparison of three air quality indices. *J. Environ. Int.* 15, 17–25. <https://doi.org/10.1016/j.envint.2015.06.014>
- Hu, M.T., Chen, S.J., Lai, Y.C., Huang, K.L., Chang-Chien, G.P., Tsai, J.H. (2009). Characteristics of polychlorinated dibenzo-*p*-dioxins/dibenzofuran from joss paper burned in Taiwanese temples. *Aerosol Air Qual. Res.* 9, 369–377. <https://doi.org/10.4209/aaqr.2009.01.0006>
- Huang, C.J., Chen, K.S., Lai, Y.C., Wang, L.C., Chang-Chien, G.P. (2011). Wet deposition of polychlorinated dibenzo-*p*-dioxins/dibenzofuran in a rural area of Taiwan. *Aerosol Air Qual. Res.* 11, 732–748. <http://doi.org/10.4209/aaqr.2011.08.0123>
- Jurado, E., Jaward, F., Lohmann, R., Jones, K., Simó, R., Dachs, J. (2005). Wet deposition of persistent organic pollutants to the global oceans. *Environ. Sci. Technol.* 39, 2426–2435. <https://doi.org/10.1021/es050660+>
- Kaupp, H., McLachlan, M.S. (1998). Atmospheric particle size distributions of polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) and polycyclic aromatic hydrocarbons (PAHs) and their implications for wet and dry deposition. *Atmos. Environ.* 33, 85–95. [https://doi.org/10.1016/S1352-2310\(98\)00129-0](https://doi.org/10.1016/S1352-2310(98)00129-0)

- Kim, E.J., Oh, J.E., Chang, Y.S. (2003). Effects of forest fire on the level and distribution of PCDD/Fs and PAHs in soil. *Sci. Total Environ.* 311, 177–189. [https://doi.org/10.1016/S0048-9697\(03\)00095-0](https://doi.org/10.1016/S0048-9697(03)00095-0)
- Krupnova, T.G., Rakova, O.V., Struchkova, G.P., Tikhonova, S.A., Kapitonova, T.A., Gavrilkina, S.V., Bulanova, A.V., Yakimova, O.N. (2021). Insights into particle-bound metal(loid)s in winter snow cover: Geochemical monitoring of the Korkinsky coal mine area, South Ural Region, Russia. *Sustainability* 13, 4596. <https://doi.org/10.3390/su13094596>
- Lanzafame, R., Monforte, P., Patane, G., Strano, S. (2015). Trend analysis of air quality index in Catania from 2010 to 2014. *Energy Procedia* 82, 708–715. <https://doi.org/10.1016/j.egypro.2015.11.796>
- Lei, Y.D., Wania, F. (2004). Is rain or snow a more efficient scavenger of organic chemicals? *Atmos. Environ.* 38, 3557–3571. <https://doi.org/10.1016/j.atmosenv.2004.03.039>
- Li, P., Yan, R., Yu, S., Wang, S., Liu, W., Bao, H. (2015). Reinstatement regional transport of PM_{2.5} as a major cause of severe haze in Beijing. *Proc. Natl. Acad. Sci. U.S.A.* 112, E2739–E2740. <https://doi.org/10.1073/pnas.1502596112>
- Li, W.W., Lin, X.Q., Yu, M.F., Mubeen, I., Buekens, A., Li, X.D. (2016). Experimental study on PCDD/Fs adsorption onto nano-graphite. *Aerosol Air Qual. Res.* 16, 3281–3289. <https://doi.org/10.4209/aaqr.2016.08.0353>
- Lin, X., Huang, Q., Chen, T., Li, X., Lu, S., Wu, H., Yan, J., Zhou, M., Wang, H. (2014). PCDD/F and PCBz emissions during start-up and normal operation of a hazardous waste incinerator in China. *Aerosol Air Qual. Res.* 14, 1142–1151. <https://doi.org/10.4209/aaqr.2013.03.0068>
- Liu, Y., Zhang, J., Pan, J., Tang, A. (2012). Investigation on the removal of NO from SO₂-containing simulated flue gas by an ultraviolet/Fenton-like reaction. *Energy Fuel* 26, 5430–5436. <https://doi.org/10.1021/ef3008568>
- Lohmann, R., Jones, K.C. (1998). Dioxins and furans in air and deposition: A review of levels, behaviour and processes. *Sci. Total Environ.* 219, 53–81. [https://doi.org/10.1016/S0048-9697\(98\)00237-X](https://doi.org/10.1016/S0048-9697(98)00237-X)
- Ma, Y.F., Lin, X.Q., Chen, Z.L., Chen, T., Zhan, M.X., Xu, S.X., Wu, H.L., Li, X.D., Yan, J.H. (2019). Emission characteristics and formation pathways of polychlorinated dibenzo-*p*-dioxins and dibenzofurans from a typical pesticide plant. *Aerosol Air Qual. Res.* 19, 1390–1399. <https://doi.org/10.4209/aaqr.2019.04.0224>
- Marinković, N., Pašalić, D., Ferenčak, G., Gršković, B., Stavljenić Rukavina A. (2010). Dioxins and human toxicity. *Arch. Ind. Hyg. Toxicol.* 61, 445–453. <https://doi.org/10.2478/10004-1254-61-2010-2024>
- McDonnell, W.F., Nishino-Ishikawa, N., Petersen, F.F., Chen, L.H., Abbey, D.E. (2000). Relationships of mortality with the fine and coarse fractions of long-term ambient PM₁₀ concentrations in nonsmokers. *J. Exposure Sci. Environ. Epidemiol.* 10, 427–436. <https://doi.org/10.2478/10004-1254-61-2010-2024>
- Melymuk, L., Robson, M., Diamond, M.L., Bradley, L.E., Backus, S. (2011). Wet deposition loadings of organic contaminants to Lake Ontario: Assessing the influence of precipitation from urban and rural sites. *Atmos. Environ.* 45, 5042–5049. <https://doi.org/10.1016/j.atmosenv.2011.02.007>
- Mi, H.H., Wu, Z.S., Lin, L.F., Lai, Y.C., Lee, Y.Y., Wang, L.C., Chang-Chien, G.P. (2012). Atmospheric dry deposition of polychlorinated dibenzo-*p*-dioxins/dibenzofurans (PCDD/Fs) and polychlorinated biphenyls (PCBs) in southern Taiwan. *Aerosol Air Qual. Res.* 12, 1016–1029. <https://doi.org/10.4209/aaqr.2012.07.0172>
- Moon, H.B., Lee, S.J., Choi, H.G., Ok, G. (2005). Atmospheric deposition of polychlorinated dibenzo-*p*-dioxins (PCDDs) and dibenzofurans (PCDFs) in urban and suburban areas of Korea. *Chemosphere* 58, 1525–1534. <http://doi.org/10.1016/j.chemosphere.2004.11.014>
- Nidzgorska-Lencewicz, J., Czarnecka, M. (2020). Thermal inversion and particulate matter concentration in Wrocław in winter season. *Atmosphere* 11, 1351. <https://doi.org/10.3390/atmos11121351>
- Pope, III, C.A., Ezzati, M., Dockery, D.W. (2009). Fine-particulate air pollution and life expectancy in the United States. *N. Engl. J. Med.* 360, 376–386. <https://doi.org/10.1056/NEJMsa0805646>
- Prange, J.A., Gaus, C., Pöpke, O., Müller, J.F. (2002). Investigations into the PCDD contamination of topsoil, river sediments and kaolinite clay in Queensland, Australia. *Chemosphere* 46, 1335–1342. [https://doi.org/10.1016/S0045-6535\(01\)00266-1](https://doi.org/10.1016/S0045-6535(01)00266-1)

- Qiu, J., Tang, M.H., Peng, Y.Q., Lu, S.Y., Li, X.D., Yan, J.H. (2020). Characteristics of PCDD/Fs in flue gas from MSWIs and HWIs: Emission levels, profiles and environmental influence. *Aerosol Air Qual. Res.* 20, 2085–2097. <http://doi.org/10.4209/aaqr.2019.11.0610>
- Redfern, F.M., Lee, W.J., Yan, P., Mwangi, J.K., Wang, L.C., Shih, C.H. (2017). Overview and perspectives on emissions of polybrominated diphenyl ethers on a global basis: Evaporative and fugitive releases from commercial PBDE mixtures and emissions from combustion sources. *Aerosol Air Qual. Res.* 17, 1117–1131. <https://doi.org/10.4209/aaqr.2016.12.0579>
- Schecter, A., Birnbaum, L., Ryan, J.J., Constable, J.D. (2006). Dioxins: An overview. *Environ. Res.* 101, 419–428. <https://doi.org/10.1016/j.envres.2005.12.003>
- She, Q.N., Peng, X., Xu, Q., Long, L.B., Wei, N. Liu, M., Jia, W.X. (2017). Air quality and its response to satellite-derived urban form in the Yangtze River Delta, China. *Environ. Res. Sci.* 75, 297–306. <https://doi.org/10.1016/j.ecolind.2016.12.045>
- Shen, F.Z., Ge, X.L., Hu, J.L., Nie, D.Y., Tian, L., Chen, M.D. (2017). Air pollution characteristics and health risks in Henan Province, China. *Environ. Res. Sci.* 156, 625–634. <https://doi.org/10.1016/j.envres.2017.04.026>
- Sheu, H.L., Lee, W.J. (1996). Dry deposition of polycyclic aromatic hydrocarbons in ambient air. *J. Environ. Eng.* 122, 1101–1112. [https://doi.org/10.1061/\(ASCE\)0733-9372\(1996\)122:12\(1101\)](https://doi.org/10.1061/(ASCE)0733-9372(1996)122:12(1101))
- Shih, M., Lee, W.S., Chang-Chien, G.P., Wang, L.C., Hung, C.Y., Lin, K.C. (2006). Dry deposition of polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in ambient air. *Chemosphere* 62, 411–416. <https://doi.org/10.1016/j.chemosphere.2005.04.064>
- Srogi, K. (2008). Levels and congener distributions of PCDDs, PCDFs and dioxin-like PCBs in environmental and human samples: A review. *Environ. Chem. Lett.* 6, 1–28. <https://doi.org/10.1007/s10311-007-0105-2>
- Tang, H.Y., Cui, K.P., Xing, J., Zhu, J.N., Lee, W.J., Mwangi, J.K., Lee, Y.C. (2017). Part I: PM_{2.5} and polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in the ambient air of southern China. *Aerosol Air Qual. Res.* 17, 1550–1569. <https://doi.org/10.4209/aaqr.2017.03.0117>
- Van den Berg, M., Birnbaum, L., Bosveld, A., Brunström, B., Cook, P., Feeley, M., Giesy, J.P., Hanberg, A., Hasegawa, R., Kennedy, S.W. (1998). Toxic equivalency factors (TEFs) for PCBs, PCDDs, PCDFs for humans and wildlife. *Environ. Health Perspect.* 106, 775–792. <https://doi.org/10.1289/ehp.98106775>
- Wang, Y.F., Hou, H.C., Li, H.W., Lin, L.F., Wang, L.C., Chang-Chien, G.P., You, Y.S. (2010). Dry and wet depositions of polychlorinated dibenzo-*p*-dioxins and dibenzofurans in the atmosphere in Taiwan. *Aerosol Air Qual. Res.* 10, 378–390. <https://doi.org/10.4209/aaqr.2010.04.0024>
- Wu, Y.L., Lin, L.F., Hsieh, L.T., Wang, L.C., Chang-Chien, G.P. (2009). Atmospheric dry deposition of polychlorinated dibenzo-*p*-dioxins and dibenzofurans in the vicinity of municipal solid waste incinerators. *J. Hazard. Mater.* 162, 521–529. <https://doi.org/10.1016/j.jhazmat.2008.05.075>
- Zhan, M.X., Ma, Y.F., Lin, X.Q., Chen, Z.L., Chen, T., Li, X.D., Yan, J.H. (2019). PCDD/F emission from pharmaceutical industries. *Aerosol Air Qual. Res.* 19, 2070–2082. <https://doi.org/10.4209/aaqr.2019.06.0284>
- Zhao, R., Cui, K., Wang, W., Wang, L.C., Yan, P. (2018a). Atmospheric PM_{2.5} and total PCDD/Fs-WHO₂₀₀₅-TEQ Level: A case of Handan and Kaifeng cities, China. *Aerosol and Air Qual. Res.* 18, 994–1007. <https://doi.org/10.4209/aaqr.2018.02.0040>
- Zhao, Y.X., Cui, K., Chen, S., Yin, Z., Chao, H.R., Chang-Chien, G.P. (2018b). Atmospheric PM_{2.5}, total PCDD/Fs-WHO₂₀₀₅-TEQ level and wet deposition: Cases of Jinan and Weihai cities, China. *Aerosol and Air Qual. Res.* 18, 3081–3095. <https://doi.org/10.4209/aaqr.2018.11.0395>
- Zhao, Y.X., Cui, K.P., Zhu, J.N., Chen, S.D., Wang, L.C., Cheruiyot, N.K., Mutuku, J.K. (2019). Effects of retarding fuel injection timing on toxic organic pollutant emissions from diesel engines. *Aerosol Air Qual. Res.* 19, 1346–1354. <https://doi.org/10.4209/aaqr.2019.03.0112>
- Zhou, Y., Yue, Y., Bai, Y., Zhang, L. (2020). Effects of rainfall on PM_{2.5} and PM₁₀ in the middle reaches of the Yangtze River. *Adv. Meteorol.* 2020, 2398146. <https://doi.org/10.1155/2020/2398146>