Sensitivity Analysis for Dry Deposition and PM$_{2.5}$-bound Content of PCDD/Fs in the Ambient Air

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ABSTRACT

This study mainly involved conducting an atmospheric sensitivity analysis of the dry deposition and PM$_{2.5}$-bound content of total PCDD/Fs-WHO$_{2005}$-TEQ, respectively. The results for Fuzhou and Xiamen cities showed that the total PCDD/F mass concentration was the factor most positively correlated to the dry deposition flux: When $\Delta P/P$ ranged from -50% to 0%, $\Delta S/S$ ranged from -66.0% to 0%, but when $\Delta P/P$ increased from 0% to $+50\%$, $\Delta S/S$ increased from 0% to $+66.0\%$, respectively. The second factor positively correlated with the deposition flux was the PM$_{2.5}$ concentration: When $\Delta P/P$ ranged from -50% to 0%, $\Delta S/S$ ranged from -63.3% to 0%; when $\Delta P/P$ increased from 0% to $+50\%$ and $+100\%$, $\Delta S/S$ ranged from 0% to $+20.8$ and -0.9%, respectively. Ambient air temperature was found to be less sensitive to dry deposition fluxes in total PCDD/Fs-WHO$_{2005}$-TEQ: When $\Delta P/P$ ranged from -50% to -17% and 0%, $\Delta S/S$ ranged from -17.0% to $+5.6\%$ and 0%; when $\Delta P/P$ increased from 0% to $+50\%$, $\Delta S/S$ increased from 0% to -84.5%, respectively. The sensitivity analysis for PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content had similar results to those for dry deposition flux. In addition, in 2018, 2019, and 2020, the annual average PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content at Fuzhou and Xiamen was 0.430, 0.127, 0.303, and 0.426 ng-WHO$_{2005}$-TEQ g^{-1} in the spring, summer, autumn and winter, respectively, which showed that summer had the lowest content, while spring and winter had the highest. The results of this study provided useful information for gaining a deeper understanding of both dry deposition and particle-bound of PCDD/Fs in the ambient air.

Keywords: Sensitivity analysis, Dry deposition, PCDD/Fs, TEQ, PM$_{2.5}$, COVID-19

1 INTRODUCTION

Dry deposition is one of the main ways for air pollutants to enter the ecosystem (Mi *et al.*, 2012). The dry deposition of PCDD/Fs is the sum of deposition in the gas phase and particle phase (Zhu *et al.*, 2017). Ambient air temperature, wind direction, particle size and other factors also affect the atmospheric deposition process (Wu *et al.*, 2009; Chi *et al.*, 2011).

PCDDs, PCDFs, and PCBs are classified as persistent organic pollutants (POPs) due to their toxicity, carcinogenicity and persistence in the human body (Anezaki *et al.*, 2021). Among them, polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are collectively known as PCDD/Fs (Wang *et al.*, 2020). They have been identified as pollutants and are present in almost every component of the global ecosystem, including air, aquatic and marine sediments, fish, wildlife, and human adipose tissue and blood (Goldman *et al.*, 1989; Safe *et al.*, 1993). PCDD/Fs are generally produced through waste combustion (Qiu *et al.*, 2020) or are impurities in the production of agricultural chemicals placed side by side in the environment, in turn causing pollution (Safe *et al.*, 1990); for example, the highly toxic 2,3,7, 8-tetrachlorodibenzo-p-dioxin (TCDD) is
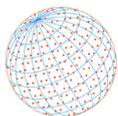
the main pollutant in herbicides (Kimbrough *et al*., 1984). A complex mixture of halogenated aromatic hydrocarbons in food and in the environment is the main source of human exposure to PCDD/Fs. The current risk assessment for these compounds is based on toxicity equivalent factors (TEFs), in which each of the 17 compounds is referred to as the highest toxicity 2,3,7,8-TCDD, which has a reference value equal to one. Toxicity is affected by the position of the chlorine atom in the molecule, where 2,3,7 and 8 are the positions where the highest toxicity is presumed. Each additional chlorine atom at these locations usually reduces the potential toxicity by a factor of several times (Ahlborg *et al*., 1992; Viluksela *et al*., 1998; Tuomisto *et al*., 2012; Schröder *et al*., 2021).

Particulate matter (PM) comprises suspended particles in the atmosphere in the form of aerosols (Ghosh *et al*., 2014). According to the aerodynamic diameter, PM can be divided into TSP (0–100 μm), PM_{10} (0–10 μm), and $PM_{2.5}$ (0–2.5 μm). The harmful effects of air pollutants on the human body are different. In addition to affecting air visibility and affecting global climate change, $PM_{2.5}$ is also linked to cardiovascular disease and lung cancer (Du *et al*., 2018; Yin *et al*., 2019). $PM_{2.5}$ is ubiquitous in the environment and increases the risk of heart, lung, and respiratory diseases. Also, exposure to these particles can cause short-term health effects such as inflammation of the eyes, nose, throat, and lungs (Polezer *et al*., 2018; Maciejczyk *et al*., 2018). $PM_{2.5}$ is produced through combustion processes and other human activities, such as those taking place in power plants, waste incineration facilities, and the steel manufacturing industry (Li *et al*., 2018; Mari *et al*., 2016). In addition, $PM_{2.5}$ has a large surface area and easily adsorbs toxic compounds such as polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), polychlorinated dioxins/furans (PCDD/Fs) (Chung *et al*., 2019). In the environment, $PM_{2.5}$ can be used as the propagation medium of PCDD/Fs for long-distance transmission, which seriously harms human health. Therefore, it is of great significance to study the $PM_{2.5}$-bound content of total PCDD/Fs-WHO_{2005}-TEQ in the atmosphere.

The results of sensitivity analyses indicate the degree of response of some parameters to the state quantity of a system. In the study of the distribution of pollutants in air, sensitivity analyses can quantitatively reflect the influence of atmospheric environmental factors on the concentration of toxic pollutants, so as to determine the dominant factors controlling air pollution (Chen *et al*., 2018).

In this study, from 2018 to 2020, a sensitivity analysis of dry deposition and $PM_{2.5}$-bound content of total PCDD/Fs-WHO_{2005}-TEQ in two cities (Fuzhou and Xiamen) in the south of China was carried out, compared, and discussed.

2. METHODS

From 2018 to 2020, the air quality levels in Fuzhou and Xiamen were analyzed, including total PCDD/Fs-WHO_{2005}-TEQ concentrations, $PM_{2.5}$ concentrations, $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content, and dry deposition of total PCDD/Fs-WHO_{2005}-TEQ and sensitivity analyses were conducted.

Fuzhou is located in the eastern part of China, in the eastern part of Fujian, the lower reaches of the Minjiang River and the coastal areas, at an east longitude of 118°08′–120°31′ and a north latitude of 25°15′–26°39′. It has a subtropical monsoon climate. The average annual temperature in Fuzhou ranges from 20°C–25°C; the average annual sunshine is 1700–1980 hours, and the average annual precipitation is 900–2100 mm. The annual relative humidity is about 77%. The dominant wind direction in Fuzhou is northeast, with southerly winds dominating in summer. The weather is hot from July to September, which is the period with the most typhoon activity, and two typhoons directly land in the city, on average, every year.

Xiamen is located in the southeast of Fujian Province in East China, at an east longitude of 117°53′–118°26′ and a north latitude of 24°23′–24°54′. It has a subtropical maritime monsoon climate. The average annual temperature in Xiamen is about 21°C, which is neither severely cold in winter nor extremely hot in summer. The annual average rainfall is about 1200 mm, and the period from May to August has the most rainfall every year. The wind is generally at a level of 3–4 m s^{-1}, often to the dominant wind for the northeast wind. It is affected by 4–5 typhoons, on average, every year, and most of them occur from July to September.
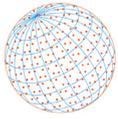
2.1 PCDD/F Concentration

In the absence of measured data, the PCDD/F concentration can be simulated using a regression analysis. Two regression analysis equations were selected, and the results were averaged. The two analysis equations are as follows (Huang *et al.*, 2011; Lee *et al.*, 2016):

$$Y_1 = 0.0138X \pm 0.0472 \tag{1}$$

$$Y_2 = 0.0117X - 0.021 \tag{2}$$

where Y_1 and Y_2 represent the total PCDD/F concentration, and X represents the PM_{10} concentration in the urban atmosphere.

The goodness-of-fit for the regression equation is $R^2 = 0.9855$ (Wang *et al.*, 2010; Suryani *et al.*, 2015). The results indicate good forecasting reliability and goodness of fit. In this study, a regression was used to solve the total PCDD/F concentration. The total PCDD/F mass concentration was obtained from the mean values of Y_1 and Y_2, and the PCDD/Fs were analyzed and discussed respectively by combining the meteorological data for the cities of interest.

2.2 Dry Deposition Flux

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

$$F_T = F_g + F_p \tag{3}$$

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

where F_T represents the total dry deposition flux (pg WHO_{2005}-TEQ m^{-2} $month^{-1}$); F_g represents the diffusion of gaseous matter producing dry deposition flux (pg WHO_{2005}-TEQ m^{-2} $month^{-1}$); F_p represents the gravitational settling of particulate matter contributing to dry deposition flux (pg WHO_{2005}-TEQ m^{-2} $month^{-1}$); C_T represents the total PCDD/F concentration in the atmosphere (pg m^{-3}); $V_{d,T}$ represents the dry deposition velocity of PCDD/Fs (gas+particle phases), 0.42 cm s^{-1} (Shih *et al.*, 2006); C_g represents the calculated PCDD/F concentration in the gas phase (pg m^{-3}); $V_{d,g}$ represents the dry deposition velocity of PCDD/Fs in the gas phase, 0.01 cm s^{-1} (Sheu *et al.*, 1996); C_p represents the calculated PCDD/F concentration in the particle phase (pg m^{-3}), and $V_{d,p}$ represents the dry deposition velocity of PCDD/Fs in the particle phase (cm s^{-1}).
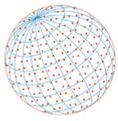
2.3 Sensitivity Analysis

In a sensitivity analysis, the influence value σ_i is used to evaluate the degree of influence of changes in the parameters on the output value, where a higher level of sensitivity indicates a greater influence on the system state variables, and vice versa.

$$\sigma_i = \frac{X_i}{Y_i} \tag{5}$$

$$X_i = \frac{\Delta P}{P_0} = \frac{(P_i - P_0)}{P_0} \tag{6}$$

$$Y_i = \frac{\Delta S}{S_0} = \frac{(S_i - S_0)}{S_0} \tag{7}$$

where P_0 and P_i represent the initial and modified value of a parameter; ΔP represents the amount of the parameter to add or subtract; S_0 and S_i represent the initial and predicted values of the parameters, and ΔS represents the response value for each parameter (Zhao *et al.*, 2018a).

3. RESULTS AND DISCUSSION

3.1 Sensitivity Analysis of Dry Deposition Flux

In this study, the sensitivity analysis of the dry deposition flux for total PCDD/Fs-WHO$_{2005}$-TEQ was mainly focused on the total PCDD/F mass concentration, the PM$_{2.5}$ concentration, and the ambient air temperature.

In Fuzhou, the sensitivity analysis work was found to be dependent on the initial total PCDD/F mass concentration = 0.5231 pg m^{-3}, PM$_{2.5}$ = 23 µg m^{-3} and an ambient air temperature = 21.5°C. The sensitivity analysis for Xiamen was dependent on the initial total PCDD/F mass concentration values = 0.5231 pg m^{-3}, PM$_{2.5}$ = 22 µg m^{-3}, and ambient air temperature = 22.5°C. The parametric sensitivity for the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ in Fuzhou and Xiamen are shown in Figs. 1 and 2, respectively.

According to the sensitivity analysis (Figs. 1 and 2), in terms of the total PCDD/F mass concentration, when $\Delta P/P$ ranged from −50% to 0%, $\Delta S/S$ ranged from −71.1% to 0%; when $\Delta P/P$ increased from 0% to +50% and +80%, $\Delta S/S$ ranged from 0% to +71.1% and +85.3%, respectively in Fuzhou. In the case of Xiamen, when $\Delta P/P$ ranged from −50% to 0%, $\Delta S/S$ ranged from −60.8% to 0%; when $\Delta P/P$ increased from 0% to +50% and +60%, $\Delta S/S$ increased from 0% to +60.8% and +73.0%, respectively. In Fuzhou and Xiamen, the effect of the total PCDD/F mass concentration on the dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ increased with increases in the concentration. The sensitivity analysis of the PCDD/Fs showed that the total PCDD/F mass concentration in the ambient air had a significant influence on the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ, where the sensitivity of this factor was obviously higher than that for other factors.

In Fuzhou (Fig. 1), the impact of the PM$_{2.5}$ concentration on the dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ can be divided into two parts: When $\Delta P/P$ ranged from −45% to 0%, $\Delta S/S$ ranged from −52.9% to 0%, but when $\Delta P/P$ increased from 0% to +45% and +100%, $\Delta S/S$ fluctuated from 0% to +17.3% and −10.0%, respectively. In the case of Xiamen (Fig. 2), for the PM$_{2.5}$
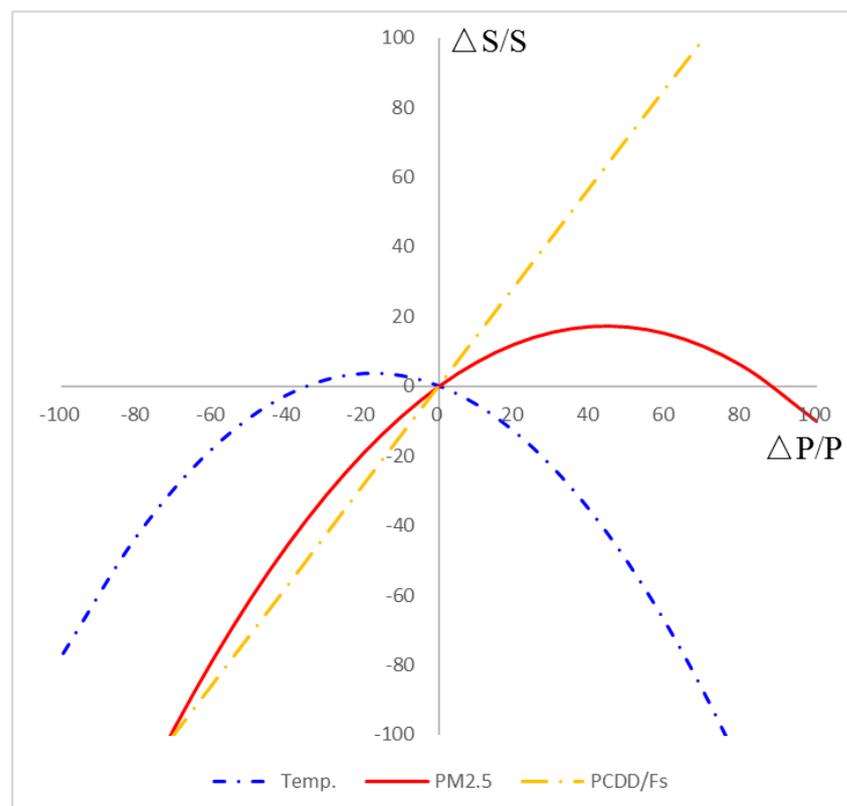

Fig. 1. The results of the sensitivity analysis for the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ in Fuzhou.
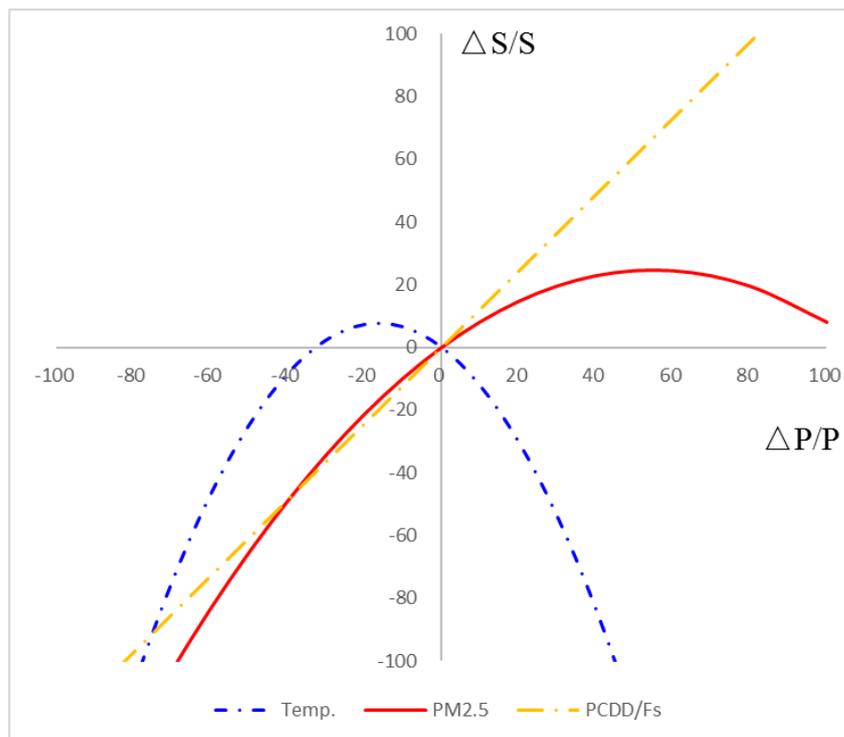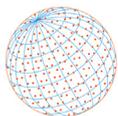
Fig. 2. The results of the sensitivity analysis for the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ for Xiamen.

concentration, when ΔP/P ranged from −55% to 0%, ΔS/S ranged from −74.4% to 0%, but when ΔP/P increased from 0% to +55% and +100%, ΔS/S increased from 0% to +24.8% and +8.2%, respectively. PM can thus reflect the PCDD/F mass concentration in the particle phase. In Fuzhou and Xiamen, the effect of the PM$_{2.5}$ concentration on the dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ increased first and then decreased with increases in the PM$_{2.5}$ concentration. The above results indicated that the sensitivity of the PM$_{2.5}$ concentration on the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ was weaker when the PM$_{2.5}$ concentration was higher than 23 μg m^{-3}, or the total PCDD/F mass concentration was greater than 0.523 pg m^{-3}.

When the PM$_{2.5}$ concentration increases (Figs. 1 and 2), the effect of the ambient air temperature on the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ increases first and then decreases. For Fuzhou, when ΔP/P ranged from −50% to −17% and 0%, ΔS/S ranged from −8.9% to +3.7% and 0%, but when ΔP/P increased from 0% to +50%, ΔS/S decreased from 0% to −50.6%, respectively. In the case of Xiamen, when ΔP/P ranged from −50% to −17% and 0%, ΔS/S ranged from −25.2% to +7.5% and 0%, and when ΔP/P increased from 0% to +40%, ΔS/S decreased from 0% to −83.2%, respectively. Temperature affects the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ by changing the gas-particle distribution of PCDD/Fs. As the temperature increases, the PCDD/Fs will cause a larger amount of particle- phase PCDD/F mass to evaporate into the gas phase. When the temperature is lower than −17.0°C, this parameter has a positive effect on the dry deposition flux of the total PCDD/Fs-WHO$_{2005}$-TEQ; when the temperature is higher than −17.0°C, the air temperature is negatively correlated with the dry deposition flux of the total PCDD/Fs-WHO$_{2005}$-TEQ.

The average sensitivity analysis values for the dry deposition flux of the total PCDD/Fs-WHO$_{2005}$-TEQ in Fuzhou and Xiamen are provided in Fig. 3. In terms of the PCDD/F mass concentration, when ΔP/P ranged from −50% to 0%, ΔS/S ranged from −66.0% to 0%, but when ΔP/P increased from 0% to +50%, ΔS/S increased from 0% to +66.0%, respectively. In terms of the PM$_{2.5}$ concentration, when ΔP/P ranged from −50% to 0%, ΔS/S ranged from −63.3% to 0%; when ΔP/P increased from 0% to +50% and +100%, ΔS/S fluctuated from 0% to +20.8 and −0.9%, respectively. As for the ambient air temperature, when ΔP/P ranged from −50% to −17% and 0%, ΔS/S ranged from −17.0% to +5.6% and 0%; when ΔP/P increased from 0% to +50%, ΔS/S decreased from 0% to −84.5%, respectively.
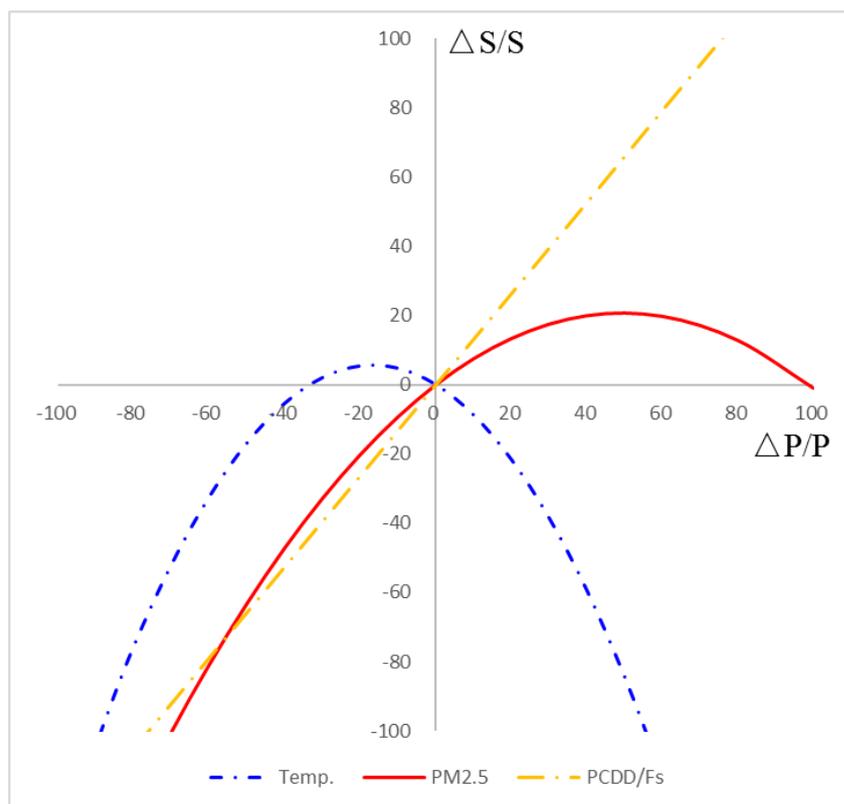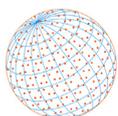
Fig. 3. The results of the average sensitivity analysis for the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ for Fuzhou and Xiamen.

The above results show that the total PCDD/F mass concentration had the most significant positive influence on the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ, followed by the PM$_{2.5}$ concentration and the ambient air temperature.

3.2 Level of Dry Deposition of Total PCDD/Fs-WHO$_{2005}$-TEQ

The monthly dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in Fuzhou and Xiamen in 2018, 2019, and 2020 are presented in Fig. 4.

As shown in Fig. 4(a), in Fuzhou, the average dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ in 2018 was 290.8 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}; the highest monthly average value occurred in April (542.3 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}), and the lowest was in August (185.7 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}); the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in the four seasons (spring, summer, autumn, winter) of 2018 were 419.4, 200.7, 257.7, and 285.2 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively, and were 52.2% higher in spring (419.4 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) than in summer (200.7 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}). In Fuzhou, the average dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ of 2019 was 282.0 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}; the highest monthly average value occurred in April (397.8 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}), and the lowest concentration was in August (185.7 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}). In Fuzhou, in the four seasons (spring, summer, autumn, winter) of 2019, the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ were 366.4, 200.7, 299.5, and 265.0 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively; which were 45.2% higher in spring (366.4 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) than in summer (200.7 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}). In Fuzhou during 2020, the average dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ was 250.5 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}; the highest monthly average value occurred in April (354.3 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}), and the lowest concentration was in August (196.9 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}); the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in the four seasons (spring, summer, autumn, winter) of 2020 were 306.2, 219.4, 257.7, and 218.5 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively, which were 28.3% higher in spring (306.2 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) than in summer (219.4 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}).
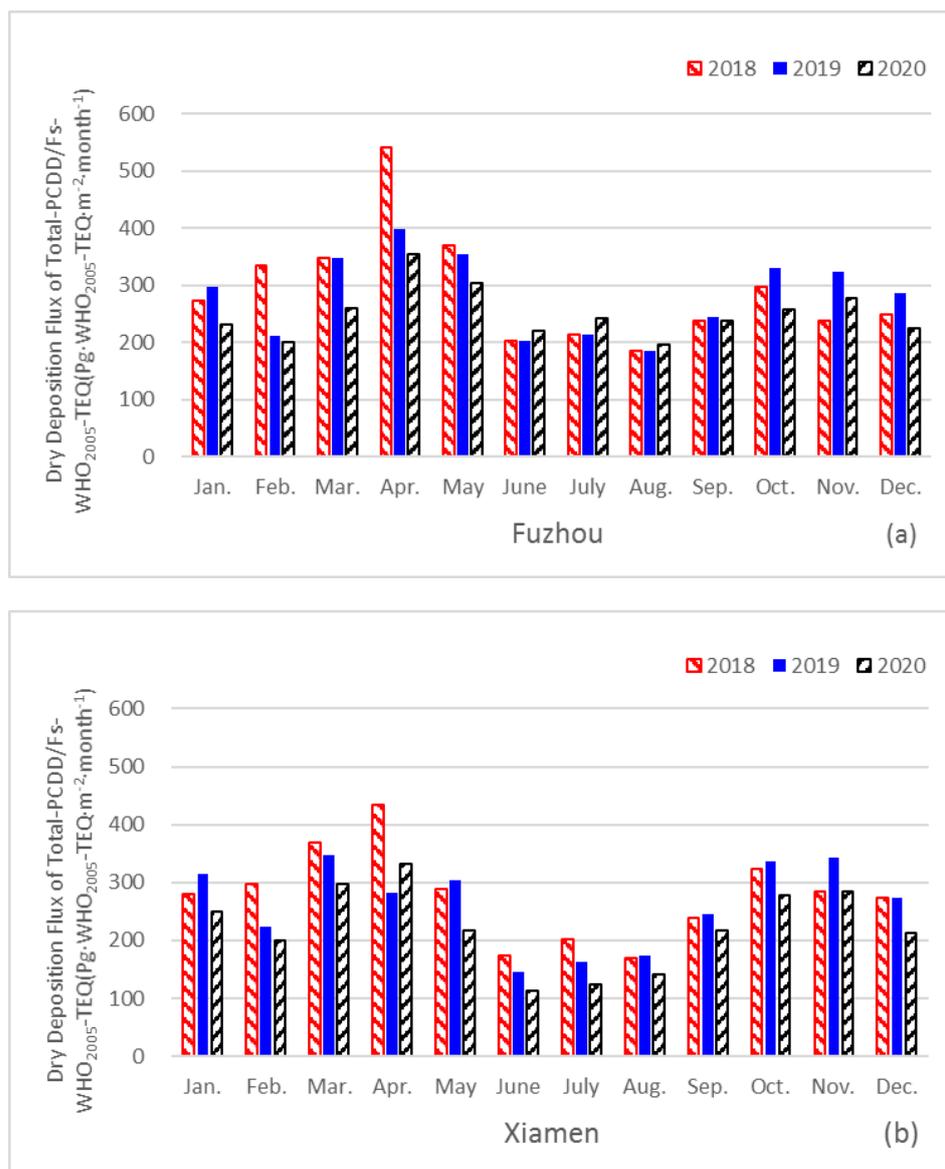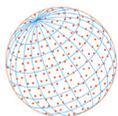
Fig. 4. Monthly dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in Fuzhou and Xiamen in 2018, 2019, and 2020, respectively.

Compared with the average annual dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ of Fuzhou in 2018–2019 (286.8 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}), the dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in 2020 (250.5 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) decreased by 12.4%. In February 2020, Fuzhou began to implement strict epidemic prevention and control measures due to COVID-19, and the dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in February 2020 (200.3 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) were 26.7% lower than those in 2018–2019 (273.1 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}). In 2018–2020, the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ of Fuzhou in the four seasons (spring, summer, autumn, winter) were 364.0, 206.9, 271.7, and 256.2 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively, which were 43.2% higher in spring than in summer.

As shown in Fig. 4(b), the average dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ in Xiamen in 2018 was 277.8 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}; the highest monthly average value occurred in April (433.9 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}), and the lowest concentration was in August (168.8 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}); the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in the four seasons (spring, summer, autumn, winter) of 2018 were 364.0, 181.9, 281.9, and 283.2 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively, and were 50.0% higher in spring (364.0 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) than in summer (181.9 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}). In Xiamen, the average dry
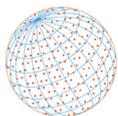
deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ in 2019 was 262.9 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}; the highest monthly average value occurred in April (347.2 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}), and the lowest concentration was in August (146.3 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}). In Xiamen, in the four seasons (spring, summer, autumn, winter) of 2019, the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ were 311.0, 161.3 308.3, and 271.1 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively, and were 48.1% higher in spring (311.0 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) than in summer (161.3 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}). In Xiamen in 2020, the average dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ was 222.1 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}; the highest monthly average value occurred in April (332.7 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}), and the lowest concentration was in August (112.6 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}); the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in the four seasons (spring, summer, autumn, winter) of 2020 were 282.1, 125.7, 259.9, and 220.5 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively, which were 55.4% higher in spring (282.1 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) than in summer (125.7 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}). Compared with the average annual dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ of Xiamen in 2018–2019 (270.4 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}), the dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in 2020 (222.1 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) decreased by 17.9%. Specifically, the monthly average dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ in Xiamen in February 2020 (200.3 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}) was 23.2% lower than those in 2018–2019 (260.9 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}), respectively. From 2018–2020, the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ of Xiamen in the four seasons (spring, summer, autumn, winter) were 319.0, 156.3, 283.4, and 258.2 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively, which were 51.0% higher in spring than in summer.

The dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in Fuzhou and Xiamen were the lowest in summer and the highest in spring. The results showed that the particulate phase PCDD/Fs were easily removed by dry deposition, and the temperature was negatively correlated with the particle phase concentration. At low temperatures, PCDD/Fs mainly exists in the particle phase, and more PCDD/Fs in the particle phase are removed by dry deposition under the force of gravity, so the dry deposition flux increases with a decrease in the temperature.

3.3 Sensitivity Analysis of PM$_{2.5}$-bound Total PCDD/Fs-WHO$_{2005}$-TEQ Content

A sensitivity analysis can provide a basis for determining some important parameters of PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content. In this study, the total PCDD/F mass concentration, PM$_{2.5}$ concentration, and the ambient air temperature may have affected the total PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content. In the sensitivity analysis for Fuzhou, the initial values of the total PCDD/F mass concentration = 0.4976 pg m^{-3}; the PM$_{2.5}$ = 22 μg m^{-3}, and the ambient air temperature = 21.5°C. The parametric sensitivity for the PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content in Fuzhou is shown in Fig. 5. In the sensitivity analysis of Xiamen, the initial values of the total PCDD/F mass concentration = 0.5231 pg m^{-3}, the PM$_{2.5}$ = 22 μg m^{-3}, and the ambient air temperature = 22.5°C. The parametric sensitivity for the total PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content in Xiamen is shown in Fig. 6.

In regard to the total PCDD/F mass concentration parameters (Figs. 5 and 6), when ΔP/P ranged from –20% to 0%, ΔS/S ranged from –74.3% to 0%, but when ΔP/P increased from 0% to +55% and +100%, ΔS/S increased from 0% to +89.1% and +36.5%, respectively in Fuzhou. In the case of Xiamen, when ΔP/P ranged from –20% to 0%, ΔS/S ranged from –41.3% to 0%; when ΔP/P increased from 0% to +45% and +100%, ΔS/S fluctuated from 0% to +38.2% and –18.0%, respectively. In Fuzhou and Xiamen, the effect of the PCDD/F mass concentration on PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content increased first and then decreased with increases in the PCDD/F mass concentration. The results showed that the total PCDD/F mass concentration in the two cities had a significant effect on the total PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content. This may have been because the total PCDD/Fs-WHO$_{2005}$-TEQ concentration depends on the total PCDD/F mass concentration, so a change in the PCDD/F mass concentration has a significant impact on the total PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content.

Figs. 5 and 6 show that the PM$_{2.5}$ concentration was a sensitive parameter for the PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content. In terms of the PM$_{2.5}$ concentration, when ΔP/P ranged from –40% to 0%, ΔS/S ranged from –93.0% to 0%, but when ΔP/P increased from 0% to +50% and +100%, ΔS/S fluctuated from 0% to +38.4% and –9.8%, respectively, in Fuzhou. In the case of Xiamen, when ΔP/P ranged from –35% to 0%, ΔS/S ranged from –95.2% to 0%; but when ΔP/P
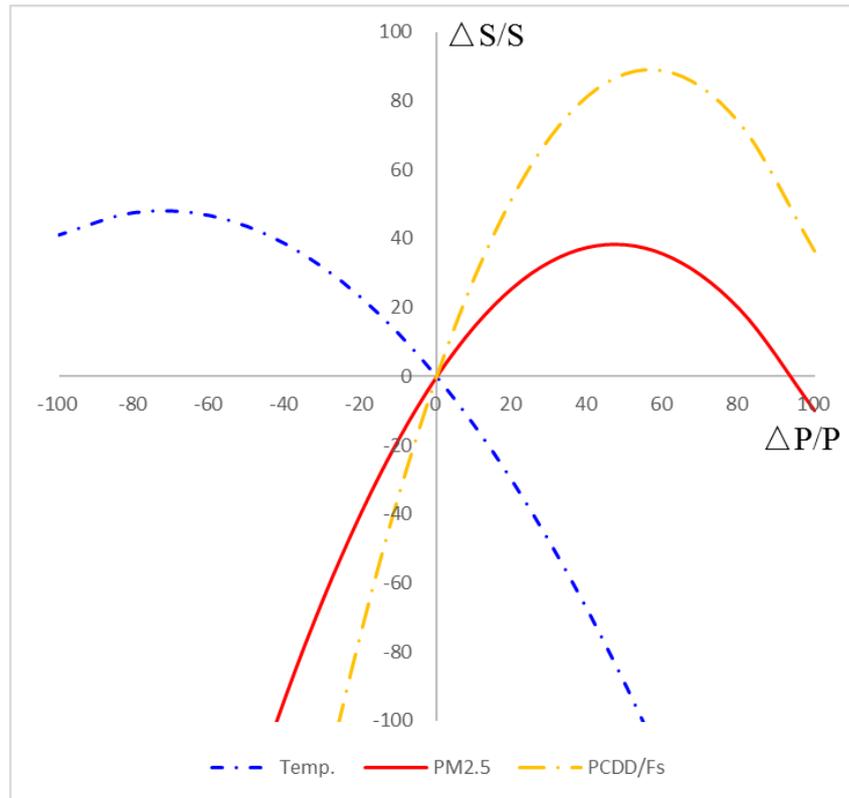
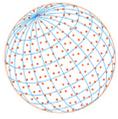**Fig. 5.** Sensitivity analysis for the $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in Fuzhou.
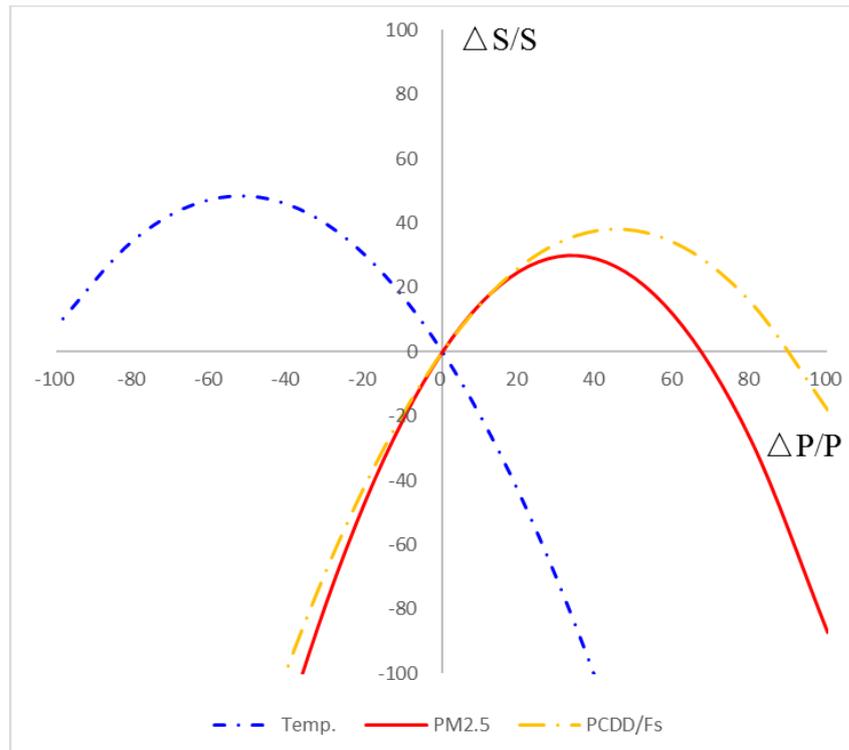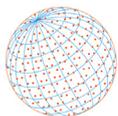

Fig. 6. Sensitivity analysis for the $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in Xiamen.

increased from 0% to +35% and +100%, $\Delta S/S$ fluctuated from 0% to +30.0% and −87.1%, respectively. The PCDD/Fs in $PM_{2.5}$ comprised mainly particulate-bound PCDD/Fs content, where

a higher $PM_{2.5}$ concentration made the air quality worse, which was not conducive to the diffusion and migration of air pollutants. Therefore, when the $PM_{2.5}$ concentration increases, the $PM_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content also exhibits an upward trend. However, when the $PM_{2.5}$ is higher than a specific concentration, the amount of $PM_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content no longer increases but rather decreases, which may be due to a saturation phenomenon.

When the concentration of increases, the effect of the ambient air temperature on the $PM_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content increases first and then decreases. In Fuzhou, when $\Delta P/P$ ranged from −100% to −70% and 0%, $\Delta S/S$ ranged from +41.1% to +48.1% and 0%, but when $\Delta P/P$ increased from 0% to +50%, $\Delta S/S$ fluctuated from 0% to −89.5%, respectively. In the case of Xiamen, when $\Delta P/P$ ranged from −100% to −50% and 0%, $\Delta S/S$ ranged from +8.1% to +48.3% and 0%, but when $\Delta P/P$ increased from 0% to +20%, $\Delta S/S$ decreased from 0% to −44.1%, respectively. Temperature affects the $PM_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content by changing the gas-particle distribution of PCDD/Fs. As the temperature increases, the PCDD/Fs that will cause a larger number of particle phase PCDD/Fs evaporate into the gas phase, and the $PM_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content decreases significantly.

The average sensitivity analysis values of $PM_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content in Fuzhou and Xiamen can be seen in Fig. 7. In terms of the PCDD/F mass concentration, when $\Delta P/P$ ranged from −20% to 0%, $\Delta S/S$ ranged from −57.8% to 0%; but when $\Delta P/P$ increased from 0% to +50% and +100%, $\Delta S/S$ ranged from 0% to +62.8% and +9.3%, respectively. In the case of the $PM_{2.5}$ concentration, when $\Delta P/P$ ranged from −20% to 0%, $\Delta S/S$ ranged from −43.0% to 0%; when $\Delta P/P$ increased from 0% to +40% and +100%, $\Delta S/S$ fluctuated from 0% to +33.3% and −48.5%, respectively. In terms of the ambient air temperature, when $\Delta P/P$ ranged from −100% to −60% and 0%, $\Delta S/S$ ranged from +24.6% to +47.0% and 0%; when $\Delta P/P$ increased from 0% to +20%, $\Delta S/S$ decreased from 0% to −37.2%, respectively.

In conclusion, $PM_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content in Fuzhou and Xiamen was most sensitive to the total PCDD/F mass concentration, followed by the $PM_{2.5}$ concentration and then the ambient air temperature.
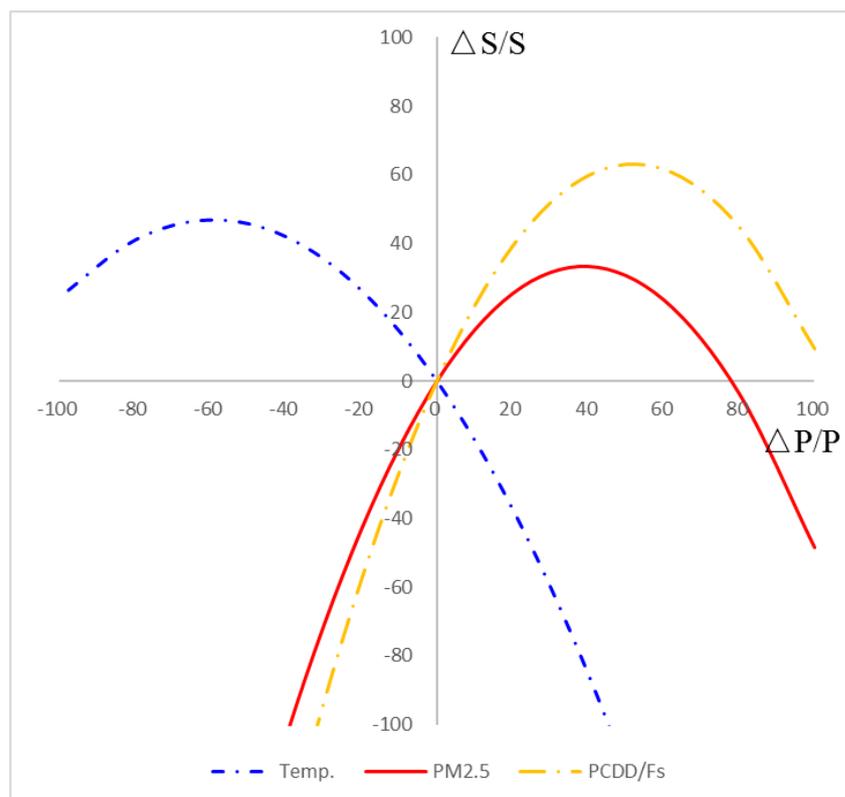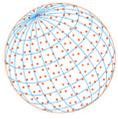

Fig. 7. Average sensitivity analysis for the $PM_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content for Fuzhou and Xiamen.

3.4 PM$_{2.5}$-bound Total PCDD/Fs-WHO$_{2005}$-TEQ content

The PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content in the ambient air of Fuzhou and Xiamen cities from 2018 to 2020 is shown in Fig. 8.

The results shown in the figure indicate that in 2018 in Fuzhou, the PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content ranged between 0.138 and 0.576 ng-WHO$_{2005}$-TEQ g^{-1}, with an average of 0.359 ng-WHO$_{2005}$-TEQ g^{-1}. In 2018, the PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content in spring, summer, fall, and winter were 0.468, 0.148, 0.308 and 0.512 ng-WHO$_{2005}$-TEQ g^{-1}, respectively; the average content in the spring and winter (0.490 ng-WHO$_{2005}$-TEQ g^{-1}) were 69.9% higher than those in summer (0.148 ng-WHO$_{2005}$-TEQ g^{-1}). In 2019, the PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content ranged between 0.109 and 0.551 ng-WHO$_{2005}$-TEQ g^{-1} and averaged 0.344 ng-WHO$_{2005}$-TEQ g^{-1}. In 2019, the average PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ contents in spring, summer, fall and winter were 0.489, 0.135, 0.310 and 0.442 ng-WHO$_{2005}$-TEQ g^{-1}, respectively; the averages in spring and winter (0.466 ng-WHO$_{2005}$-TEQ g^{-1}) were 71.0% higher than in summer (0.135 ng-WHO$_{2005}$-TEQ g^{-1}). In 2020, the PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content ranged between 0.138 and 0.515 ng-WHO$_{2005}$-TEQ g^{-1}, with an average of 0.324 ng-WHO$_{2005}$-TEQ g^{-1}. In
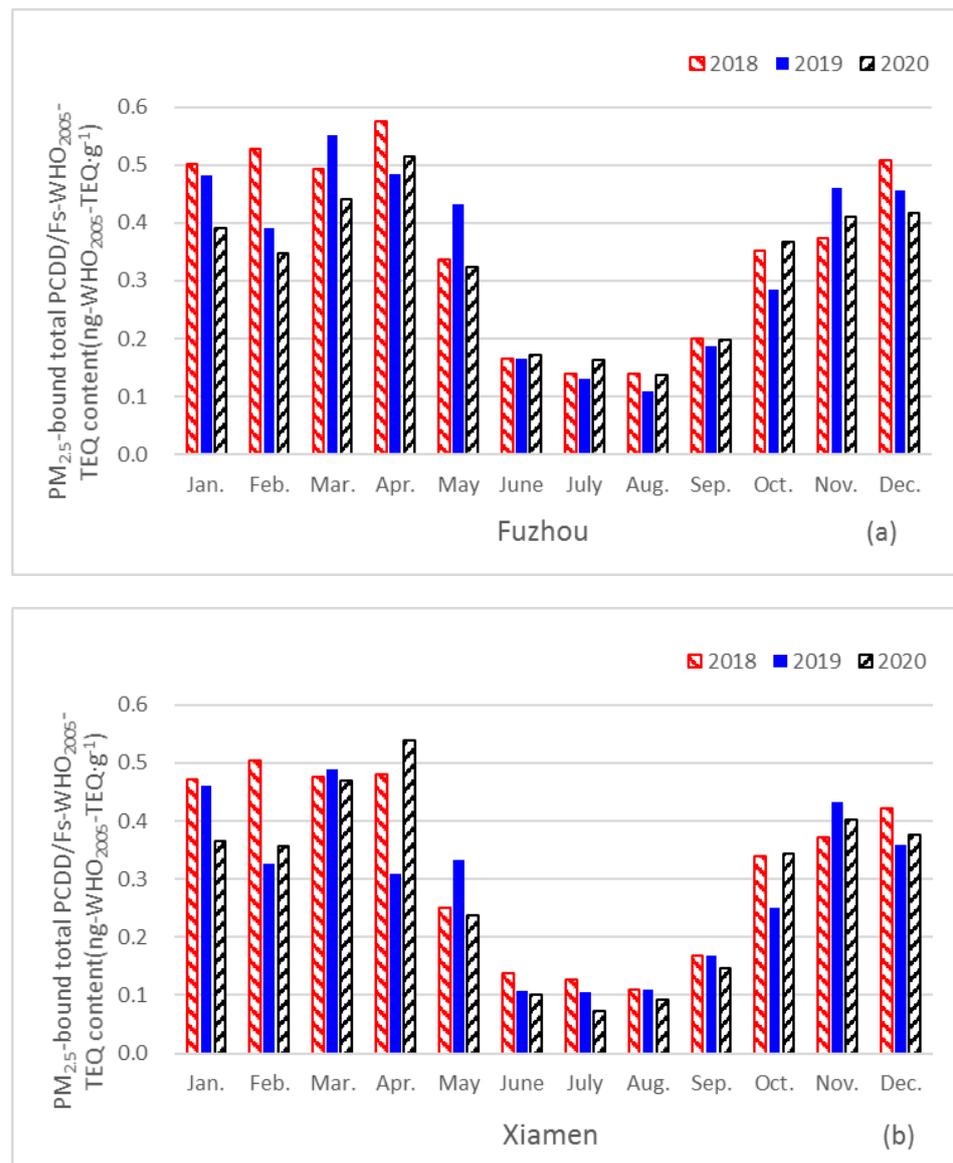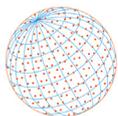

Fig. 8. Monthly PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content in Fuzhou and Xiamen during 2018–2020, respectively.

2020, the average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ contents in spring, summer, fall, and winter were 0.427, 0.158, 0.325, and 0.385 ng-WHO_{2005}-TEQ g^{-1}, respectively; the average in spring and winter (0.406 ng-WHO_{2005}-TEQ g^{-1}) was 61.1% higher than in summer (0.158 ng-WHO_{2005}-TEQ g^{-1}). Overall, the monthly average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in 2020 (0.324 ng-WHO_{2005}-TEQ g^{-1}) was 7.9% lower than that in the period from 2018–2019 (0.352 ng-WHO_{2005}-TEQ g^{-1}). The $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in February 2020 (0.347 ng-WHO_{2005}-TEQ g^{-1}) was 24.4% lower than during 2018–2019 (0.459 ng-WHO_{2005}-TEQ g^{-1}). In 2018–2020, the average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in Fuzhou in the four seasons (spring, summer, autumn, winter) was 0.461, 0.147, 0.315, and 0.446 ng-WHO_{2005}-TEQ g^{-1}, respectively, which was 67.6% higher in spring and winter, on average, (0.454 ng-WHO_{2005}-TEQ g^{-1}) than in summer (0.147 ng-WHO_{2005}-TEQ g^{-1}).

The results showed that in Fig. 8(b), in 2018 in Xiamen, the $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content ranged between 0.110 and 0.504 ng-WHO_{2005}-TEQ g^{-1}, with an average of 0.321 ng-WHO_{2005}-TEQ g^{-1}. In 2018, the average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ contents in spring, summer, fall, and winter were 0.402, 0.125, 0.293, and 0.466 ng-WHO_{2005}-TEQ g^{-1}, respectively; the spring and winter averages (0.434 ng-WHO_{2005}-TEQ g^{-1}) were 71.3% higher than in summer (0.125 ng-WHO_{2005}-TEQ g^{-1}). In 2019, the total $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content ranged between 0.104 and 0.489 ng-WHO_{2005}-TEQ g^{-1} and averaged 0.288 ng-WHO_{2005}-TEQ g^{-1}. In 2019, the average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in spring, summer, fall, and winter was 0.377, 0.107, 0.283 and 0.382 ng-WHO_{2005}-TEQ g^{-1}, respectively; the spring and winter averages (0.380 ng-WHO_{2005}-TEQ g^{-1}) were 71.7% higher than in summer (0.107 ng-WHO_{2005}-TEQ g^{-1}). In 2020, the $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content ranged between 0.073 and 0.539 ng-WHO_{2005}-TEQ g^{-1}, with an average of 0.292 ng-WHO_{2005}-TEQ g^{-1}. In 2020, the $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ contents in spring, summer, fall and winter were 0.415, 0.089, 0.298 and 0.366 ng-WHO_{2005}-TEQ g^{-1}, respectively; the spring and winter averages (0.391 ng-WHO_{2005}-TEQ g^{-1}) were 77.2% higher than in summer (0.089 ng-WHO_{2005}-TEQ g^{-1}). Overall, the monthly average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in 2020 (0.292 ng-WHO_{2005}-TEQ g^{-1}) was 4.1% lower than the average in 2018–2019 (0.304 ng-WHO_{2005}-TEQ g^{-1}). The $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in February 2020 (0.365 ng-WHO_{2005}-TEQ g^{-1}) was 21.6% lower than that in 2018–2019 (0.416 ng-WHO_{2005}-TEQ g^{-1}). In 2018–2020, the average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ contents in Xiamen in the four seasons (spring, summer, autumn, winter) were 0.398, 0.107, 0.291, and 0.405 ng-WHO_{2005}-TEQ g^{-1}, respectively, which were 73.3% higher in the spring and winter (0.401 ng-WHO_{2005}-TEQ g^{-1}) than in the summer (0.107 ng-WHO_{2005}-TEQ g^{-1}).

During 2018, the average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in Fuzhou and Xiamen in the four seasons (spring, summer, autumn, winter) were 0.435, 0.136, 0.301. and 0.489 ng-WHO_{2005}-TEQ g^{-1}, respectively, which was 70.5% higher in spring and winter (0.462 ng-WHO_{2005}-TEQ g^{-1}) than in summer (0.136 ng-WHO_{2005}-TEQ g^{-1}). In 2019, the average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ contents in the two cities in the four seasons (spring, summer, autumn, winter) were 0.433, 0.121, 0.297, and 0.412 ng-WHO_{2005}-TEQ g^{-1}, respectively, which was 71.3% higher in spring and winter (0.423 ng-WHO_{2005}-TEQ g^{-1}) than in summer (0.121 ng-WHO_{2005}-TEQ g^{-1}). In 2020, the average content in the two cities in the four seasons were 0.421, 0.123, 0.311, and 0.375 ng-WHO_{2005}-TEQ g^{-1}, respectively, which was 69.0% higher in the spring and winter (0.398 ng-WHO_{2005}-TEQ g^{-1}) than in the summer (0.123 ng-WHO_{2005}-TEQ g^{-1}). Based on the three years' average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ contents in Fuzhou and Xiamen in the four seasons were 0.430, 0.127, 0.303, and 0.426 ng-WHO_{2005}-TEQ g^{-1}, respectively, which showed that in the summer, the contents were 70.5%, 58.1%, and 70.2% lower than that in spring, autumn, and winter, respectively.

Table 1 shows the $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in atmospheric environments in China. The results of this study were in a similar range compared with those found in other regions.

The results show that the average $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in summer was lower than that in the other three seasons. This is because with the rise in temperature, a large amount of PCDD/Fs evaporates from the particle phase to the gas phase, resulting in a lower content of total PCDD/Fs-WHO_{2005}-TEQ. In addition, the $PM_{2.5}$-bound total PCDD/Fs-WHO_{2005}-TEQ content in Fuzhou and Xiamen in 2020 was lower than that in 2018–2019, especially in
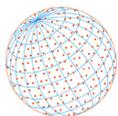
Table 1. PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content in some regions of China (Unit: ng WHO$_{2005}$-TEQ g^{-1}).

City	Content	Reference
Beijing	0.463	Xing *et al.*, 2017
Tianjin	0.501	Xing *et al.*, 2017
Dalian	0.570	Xing *et al.*, 2017
Hohhot	1.000	Xing *et al.*, 2017
Lhasa	0.855	Xing *et al.*, 2017
Urumqi	0.859	Xing *et al.*, 2017
Changchun	0.661	Xing *et al.*, 2017
Handan	0.640	Zhao *et al.*, 2018b
Kaifeng	0.570	Zhao *et al.*, 2018b
Zhangzhou	0.312	Chen *et al.*, 2018
Wuhu	0.440	Wang *et al.*, 2018
Benbu	0.468	Wang *et al.*, 2018
Jinan	0.647	Zhao *et al.*, 2018c
Weihai	0.511	Zhao *et al.*, 2018c
Fuzhou	0.342	This study, 2021
Xiamen	0.300	This study, 2021

February, and the content in both cities was significantly reduced. This may have been related to COVID-19 in 2020, where control measures significantly improved the air quality.

3.5 Total PCDD/Fs-WHO$_{2005}$-TEQ Concentration

The total PCDD/Fs-WHO$_{2005}$-TEQ concentration in Fuzhou and Xiamen in the ambient air, from 2018 to 2020 are shown in Fig. 9.

The results shown in Fig. 9(a) indicate that the average total PCDD/Fs-WHO$_{2005}$-TEQ concentration in Fuzhou in 2018 was 0.0267 pg-WHO$_{2005}$-TEQ m^{-3}; April had the highest concentration (0.0498 pg-WHO$_{2005}$-TEQ m^{-3}), and August had the lowest (0.0171 pg-WHO$_{2005}$-TEQ m^{-3}); the average total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in the four seasons (spring, summer, autumn, winter) of 2018 were 0.0385, 0.0184, 0.0237, and 0.0262 pg-WHO$_{2005}$-TEQ m^{-3}, respectively, which were 52.2% higher in spring (0.0385 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.184 pg-WHO$_{2005}$-TEQ m^{-3}). In Fuzhou, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentration in 2019 was 0.0260 pg-WHO$_{2005}$-TEQ m^{-3}; April had the highest concentration (0.0365 pg-WHO$_{2005}$-TEQ m^{-3}), and August had the lowest (0.0171 pg-WHO$_{2005}$-TEQ m^{-3}). In Fuzhou, in the four seasons (spring, summer, autumn, winter) of 2019, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentrations were 0.0337, 0.0184, 0.0275, and 0.0243 pg-WHO$_{2005}$-TEQ m^{-3}, respectively; which were 45.2% higher in spring (0.0337 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.0184 pg-WHO$_{2005}$-TEQ m^{-3}). In Fuzhou in 2020, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentration was 0.0230 pg-WHO$_{2005}$-TEQ m^{-3}; April had the highest concentration (0.0326 pg-WHO$_{2005}$-TEQ m^{-3}), and August had the lowest (0.0181 pg-WHO$_{2005}$-TEQ m^{-3}); the average total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in the four seasons (spring, summer, autumn, winter) of 2020 were 0.0281, 0.0202, 0.0237, and 0.0201 pg-WHO$_{2005}$-TEQ m^{-3}, respectively, which were 28.3% higher in spring (0.0281 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.0202 pg-WHO$_{2005}$-TEQ m^{-3}). In 2018–2020, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in Fuzhou in the four seasons (spring, summer, autumn, winter) were 0.0334, 0.0190, 0.0250, and 0.0235 pg-WHO$_{2005}$-TEQ m^{-3}, respectively, which were 43.2% higher in spring (0.0334 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.0190 pg-WHO$_{2005}$-TEQ m^{-3}).

It can be seen that the total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in the ambient air of Fuzhou exhibit seasonal changes, with the highest concentrations in spring and the lowest concentrations in summer. This may be related to atmospheric inversion in winter. When a temperature inversion occurs due to the weakening of the wind, the atmosphere is in a stable state, and the upper and lower levels of air do not exchange easily. At this time, if a large amount of waste gas is discharged into the atmosphere, it is difficult to diffuse the polluted gas due to interference from the inversion layer, so the concentration of polluted gas in the atmosphere increases, thereby increasing the
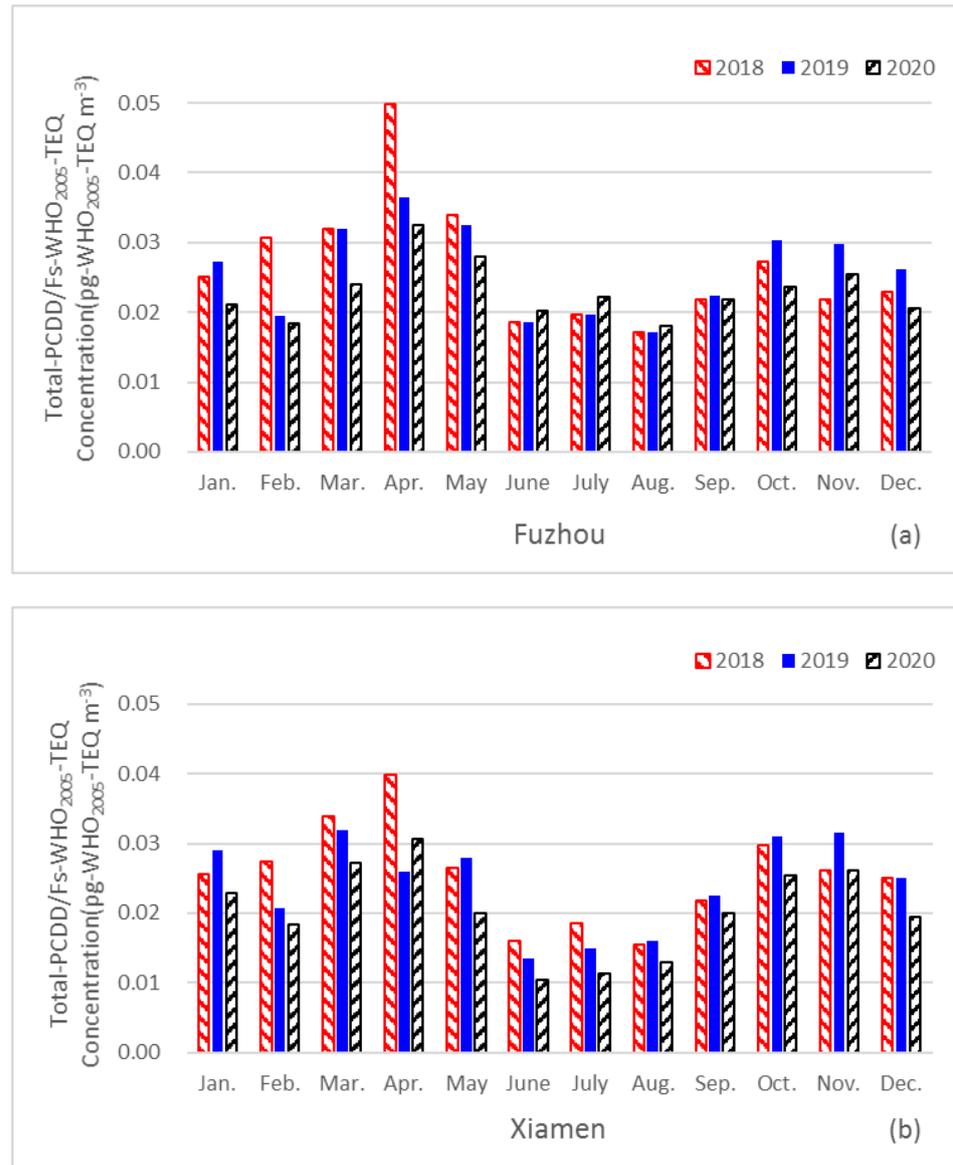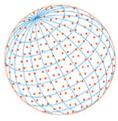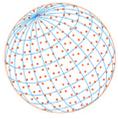
Fig. 9. Monthly total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in Fuzhou and Xiamen in 2018, 2019, and 2020, respectively.

intensity of the air pollution. In addition, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentration in 2020 (0.0326 pg-WHO$_{2005}$-TEQ m^{-3}) was 12.7% lower than the average in 2018–2019 (0.0326 pg-WHO$_{2005}$-TEQ m^{-3}), especially in February. In February 2020, Fuzhou formulated control measures, including home quarantine and suspension of work and production, to focus COVID-19 prevention and control. Therefore, the total PCDD/Fs-WHO$_{2005}$-TEQ concentration in February 2020 was 26.7% lower than that in February of 2018 and 2019, indicating a significant improvement in atmospheric quality due to COVID-19 control measures.

The results shown in Fig. 9(b) indicate that the average total PCDD/Fs-WHO$_{2005}$-TEQ concentration in Xiamen in 2018 was 0.0255 pg-WHO$_{2005}$-TEQ m^{-3}; April had the highest concentration (0.0399 pg-WHO$_{2005}$-TEQ m^{-3}), and August had the lowest (0.0155 pg-WHO$_{2005}$-TEQ m^{-3}); the average total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in the four seasons (spring, summer, autumn, winter) in 2018 were 0.0334, 0.0167, 0.0259, and 0.0260 pg-WHO$_{2005}$-TEQ m^{-3}, respectively, which were 50.0% higher in spring (0.0334 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.167 pg-WHO$_{2005}$-TEQ m^{-3}). In Xiamen, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentration in 2019 was 0.0242 pg-WHO$_{2005}$-TEQ m^{-3}; April had the highest concentration (0.0319 pg-WHO$_{2005}$-TEQ m^{-3}), and August had the lowest (0.0134 pg-WHO$_{2005}$-TEQ m^{-3}).In Xiamen, in the four seasons (spring, summer,

autumn, winter) of 2019, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentrations were 0.0286, 0.0148, 0.0283, and 0.0249 pg-WHO$_{2005}$-TEQ m^{-3}, respectively, which were 48.1% higher in spring (0.0286 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.0148 pg-WHO$_{2005}$-TEQ m^{-3}). In Xiamen in 2020, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentration was 0.0204 pg-WHO$_{2005}$-TEQ m^{-3}; April had the highest concentration (0.0306 pg-WHO$_{2005}$-TEQ m^{-3}), and August had the lowest (0.0103 pg-WHO$_{2005}$-TEQ m^{-3}); the average total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in the four seasons (spring, summer, autumn, winter) of 2020 were 0.0259, 0.0115, 0.0239, and 0.0203 pg-WHO$_{2005}$-TEQ m^{-3}, respectively, which were 55.4% higher in spring (0.0259 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.0115 pg-WHO$_{2005}$-TEQ m^{-3}). In addition, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentration in 2020 was 17.9% lower than the averages in 2018 and 2019, especially in February. In February 2020, the control measures in Xiamen resulted in total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in February 2020 being 23.2% lower than in previous years. From 2018–2020, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in Xiamen in the four seasons (spring, summer, autumn, winter) were 0.0293, 0.0144, 0.0260, and 0.0237 pg-WHO$_{2005}$-TEQ m^{-3}, respectively, which were 51.0% higher in spring and winter (0.0293 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.0144 pg-WHO$_{2005}$-TEQ m^{-3}).

A comparison of the monthly total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in Fuzhou and Xiamen showed that the monthly total PCDD/Fs-WHO$_{2005}$-TEQ concentrations were the highest in spring and lowest in summer. The average total PCDD/Fs-WHO$_{2005}$-TEQ concentration in 2020 was significantly lower than that in 2018–2019, especially in February, which was closely related to the implementation of COVID-19 control measures. In addition, the average total PCDD/Fs-WHO$_{2005}$-TEQ concentration in Xiamen was lower than that in Fuzhou, indicating that the air quality in Xiamen was better during the period under observation.

3.6 PM$_{2.5}$ Concentration

Fig. 8 shows the average PM$_{2.5}$ concentrations in the ambient air in Fuzhou and Xiamen during the period between 2018 and 2020.

As shown in Table 2, the average PM$_{2.5}$ concentration of Fuzhou in 2018 was 23 μg m^{-3}; the highest monthly average occurred in April (35 μg m^{-3}), and the lowest concentration was in August (15 μg m^{-3}); the average PM$_{2.5}$ concentrations in the four seasons (spring, summer, autumn, winter) of 2018 were 29.3, 16.7, 19.0, and 27.0 μg m^{-3}, respectively, which were 40.8% higher in spring and winter (28.2 μg m^{-3}) than in summer (16.7 μg m^{-3}). In Fuzhou, the average PM$_{2.5}$ concentration in 2019 was 24 μg m^{-3}; the highest monthly average value occurred in January (30 μg m^{-3}), and the lowest concentration was in August (17 μg m^{-3}). In Fuzhou, in the four seasons (spring, summer, autumn, winter) of 2019, the average PM$_{2.5}$ concentrations were 27.3, 18.3, 23.0, and 27.3 μg m^{-3}, respectively; which were 32.9% higher in spring and winter (27.3 μg m^{-3}) than in summer (18.3 μg m^{-3}). In Fuzhou during 2020, the average PM$_{2.5}$ concentration was 20.6 μg m^{-3}; the highest monthly average value occurred in January (28 μg m^{-3}), and the lowest concentration was in August (14 μg m^{-3}); the average PM$_{2.5}$ concentrations in the four seasons (spring, summer, autumn, winter) of 2020 were 24.0, 15.3, 18.3, and 24.7 μg m^{-3}, respectively, which were 37.0% higher in spring and winter (24.3 μg m^{-3}) than in summer (15.3 μg m^{-3}). In 2018–2020, the average PM$_{2.5}$ concentrations in Fuzhou in the four seasons (spring, summer, autumn, winter) were 26.9, 16.8, 20.1, and 26.3 μg m^{-3}, respectively, which were 37.0% higher in spring and winter (26.6 μg m^{-3}) than in summer (16.8 μg m^{-3}). Compared with the average annual PM$_{2.5}$ concentrations in Fuzhou in the period from 2018–2019 (23.5 μg m^{-3}), the PM$_{2.5}$ concentration in 2020 (20.6 μg m^{-3}) decreased by 12.4%. In particular, the monthly average PM$_{2.5}$ concentration in Fuzhou in February 2020 (23.0 μg m^{-3}) was 19.3% lower than that in the period from 2018–2019 (28.5 μg m^{-3}).

As shown in Table 2, the average PM$_{2.5}$ concentration in Xiamen in 2018 was 22.8 μg m^{-3}; the highest monthly average value occurred in March (30 μg m^{-3}), and the lowest concentration was in June (16 μg m^{-3}); the average PM$_{2.5}$ concentrations in the four seasons (spring, summer, autumn, winter) of 2018 were 26.7, 16.7, 21.3, and 26.3 μg m^{-3}, respectively, which were 37.1% higher in spring and winter (26.5 μg m^{-3}) than in summer (16.7 μg m^{-3}). In Xiamen, the average PM$_{2.5}$ concentration in 2019 was 24.0 μg m^{-3}; the highest monthly average value occurred in December (31 μg m^{-3}), and the lowest concentration was in July (15 μg m^{-3}). In Xiamen, in the four seasons (spring, summer, autumn, winter) of 2019, the average PM$_{2.5}$ concentrations were
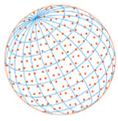
Table 2. Monthly minimum, maximum, and average PM$_{2.5}$ concentrations in Fuzhou and Xiamen in the period from 2018-2020 (Unit: μg m^{-3}).

City		Fuzhou			Xiamen		
Year	Month	Mix	Max	Average	Min	Max	Average
2018	Jan.	8.0	63.0	27.0	11.0	54.0	27.0
	Feb.	12.0	73.0	33.0	11.0	63.0	28.0
	Mar.	9.0	66.0	29.0	11.0	86.0	30.0
	Apr.	18.0	74.0	35.0	15.0	46.0	29.0
	May	9.0	45.0	24.0	7.0	33.0	21.0
	June	6.0	29.0	18.0	7.0	29.0	16.0
	July	4.0	33.0	17.0	7.0	40.0	17.0
	Aug.	5.0	35.0	15.0	4.0	35.0	17.0
	Sep.	6.0	33.0	16.0	5.0	31.0	18.0
	Oct.	9.0	33.0	22.0	14.0	40.0	24.0
	Nov.	8.0	28.0	19.0	6.0	35.0	22.0
	Dec.	3.0	57.0	21.0	7.0	57.0	24.0
2019	Jan.	13.0	67.0	30.0	9.0	55.0	30.0
	Feb.	5.0	80.0	24.0	9.0	97.0	26.0
	Mar.	13.0	46.0	28.0	13.0	50.0	30.0
	Apr.	9.0	56.0	29.0	13.0	50.0	27.0
	May	7.0	48.0	25.0	10.0	48.0	25.0
	June	4.0	33.0	20.0	10.0	30.0	16.0
	July	5.0	39.0	18.0	5.0	29.0	15.0
	Aug.	7.0	41.0	17.0	6.0	32.0	16.0
	Sep.	6.0	33.0	18.0	8.0	30.0	19.0
	Oct.	8.0	48.0	27.0	14.0	50.0	29.0
	Nov.	11.0	40.0	24.0	12.0	45.0	24.0
	Dec.	10.0	53.0	28.0	12.0	60.0	31.0
2020	Jan.	3.0	61.0	28.0	5.0	68.0	30.0
	Feb.	3.0	44.0	23.0	5.0	42.0	21.0
	Mar.	4.0	54.0	24.0	10.0	69.0	24.0
	Apr.	11.0	42.0	27.0	11.0	40.0	23.0
	May	9.0	42.0	21.0	5.0	29.0	17.0
	June	7.0	27.0	16.0	4.0	15.0	8.0
	July	6.0	28.0	16.0	5.0	33.0	11.0
	Aug.	6.0	28.0	14.0	4.0	32.0	13.0
	Sep.	6.0	34.0	18.0	8.0	37.0	19.0
	Oct.	9.0	24.0	17.0	12.0	27.0	17.0
	Nov.	7.0	43.0	20.0	10.0	42.0	18.0
	Dec.	7.0	55.0	23.0	8.0	48.0	21.0

27.3, 15.7, 24.0, and 29.0 μg m^{-3}, respectively; which were 44.4% higher in spring and winter (28.2 μg m^{-3}) than in summer (15.7 μg m^{-3}). In Xiamen in 2020, the average PM$_{2.5}$ concentration was 18.5 μg m^{-3}; the highest monthly average value occurred in January (30 μg m^{-3}), and the lowest concentration was in June (8 μg m^{-3}); the average PM$_{2.5}$ concentrations in the four seasons (spring, summer, autumn, winter) during 2020 were 21.3, 10.7, 18.0, and 24.0 μg m^{-3}, respectively, which were 52.9% higher in spring and winter (22.7 μg m^{-3}) than in summer (10.7 μg m^{-3}). In the period from 2018–2020, the average PM$_{2.5}$ concentrations in Xiamen in the four seasons (spring, summer, autumn, winter) were 25.1, 14.3, 21.1, and 26.4 μg m^{-3}, respectively, which were 44.4% higher in spring and winter (25.8 μg m^{-3}) than in summer (14.3 μg m^{-3}). Compared with the average annual PM$_{2.5}$ concentrations in Xiamen in the period from 2018–2019 (23.4 μg m^{-3}), the PM$_{2.5}$ concentration in 2020 (18.5 μg m^{-3}) decreased by 20.9%. In particular, the monthly average PM$_{2.5}$ concentration in Xiamen in February 2020 (21.0 μg m^{-3}) was 19.3% lower than that in 2018–2019 (27.0 μg m^{-3}).

According to the above results, it is clear that the PM$_{2.5}$ concentration in urban ambient air has
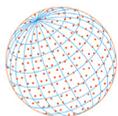
seasonal variations, and the average PM$_{2.5}$ concentration in spring and winter is significantly higher than that in summer. This may be because the lower ground temperature in winter enhances the stability of the atmosphere, reduces the diffusion capacity of pollutants, and reduces vertical convection in the atmosphere, where atmospheric pollutants gather on the ground (Zhao *et al.*, 2018c). In addition, the PM$_{2.5}$ concentration in Fuzhou and Xiamen decreased by 12.4% and 20.9%, respectively, in 2020 compared with in 2018–2019, especially by 19.3% and 22.2% in February. This may have been due to the COVID-19 outbreak, where control measures have resulted in significant environmental improvements.

4. CONCLUSIONS

The results of this study can be summarized as follows:

1. The average sensitivity analysis of the dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in Fuzhou and Xiamen showed that the total PCDD/F mass concentration was the factor most positively correlated with the deposition flux. When $\Delta P/P$ ranged from –50% to 0%, $\Delta S/S$ ranged from –66.0% to 0%; when $\Delta P/P$ increased from 0% to +50%, $\Delta S/S$ increased from 0% to +66.0%, respectively. The second factor that was positively correlated with the deposition flux was the PM$_{2.5}$ concentration: When $\Delta P/P$ ranged from –50% to 0%, $\Delta S/S$ ranged from –63.3% to 0%; when $\Delta P/P$ increased from 0% to +50% and +100%, $\Delta S/S$ fluctuated from 0% to +20.8 and –0.9%, respectively.

2. Ambient air temperature is less sensitive to dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ: When $\Delta P/P$ ranged from –50% to –17% and 0%, $\Delta S/S$ ranged from –17.0% to +5.6% and 0%; when $\Delta P/P$ increased from 0% to +50%, $\Delta S/S$ decreased from 0% to –84.5%, respectively. This could have been because temperature affects the dry deposition flux of total PCDD/Fs-WHO$_{2005}$-TEQ by changing the gas-particle distribution of PCDD/Fs. As the temperature increases, the PCDD/Fs that will cause a larger amount of particle- phase PCDD/F mass to evaporate into the gas phase.

3. In the period from 2018–2020, the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in Fuzhou in the four seasons (spring, summer, autumn, winter) were 364.0, 206.9, 271.7, and 256.2 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively, which were 43.2% higher in spring than in summer. In Xiamen, the average dry deposition fluxes of total PCDD/Fs-WHO$_{2005}$-TEQ in the four seasons (spring, summer, autumn, winter) were 319.0, 156.3, 283.4, and 258.2 pg WHO$_{2005}$-TEQ m^{-2} month^{-1}, respectively, which were 51.0% higher in spring than in summer.

4. The average sensitivity analysis of the PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ content in Fuzhou and Xiamen showed that the total PCDD/F mass concentration was the factor most positively correlated with the deposition flux: When $\Delta P/P$ ranged from –20% to 0%, $\Delta S/S$ ranged from –57.8% to 0%; but when $\Delta P/P$ increased from 0% to +50% and +100%, $\Delta S/S$ increased from 0% to +62.8% and +9.3%, respectively. The second factor positively correlated with the deposition flux was the PM$_{2.5}$ concentration: When $\Delta P/P$ ranged from –20% to 0%, $\Delta S/S$ ranged from –43.0% to 0%; when $\Delta P/P$ increased from 0% to +40% and +100%, $\Delta S/S$ fluctuated from 0% to +33.3% and –48.5%, respectively. This was followed by the temperature, which had a relatively small effect, where when $\Delta P/P$ ranged from –100% to –60% and 0%, $\Delta S/S$ ranged from +24.6% to +47.0% and 0%; when $\Delta P/P$ increased from 0% to +20%, $\Delta S/S$ decreased from 0% to –37.2%, respectively.

5. During the period form 2018–2020, the average PM$_{2.5}$-bound total PCDD/Fs-WHO$_{2005}$-TEQ contents in Fuzhou and Xiamen in the four seasons (spring, summer, autumn, winter) were 0.430, 0.127, 0.303 and 0.426 ng-WHO$_{2005}$-TEQ g^{-1}, respectively, which showed that summer was 70.5%, 58.1% and 70.2% lower than that in spring, autumn and winter, respectively.

6. The average total PCDD/Fs-WHO$_{2005}$-TEQ concentrations in Fuzhou in 2018–2020 in the four seasons (spring, summer, autumn, winter) were 0.0334, 0.0190, 0.0250, and 0.0235 pg-WHO$_{2005}$-TEQ m^{-3}, respectively, which were 43.2% higher in spring (0.0334 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.0190 pg-WHO$_{2005}$-TEQ m^{-3}). In Xiamen, the average concentrations in the four seasons (spring, summer, autumn, winter) were 0.0293, 0.0144, 0.0260, and 0.0237 pg-WHO$_{2005}$-TEQ m^{-3}, respectively, which were 51.0% higher in spring and winter (0.0293 pg-WHO$_{2005}$-TEQ m^{-3}) than in summer (0.0144 pg-WHO$_{2005}$-TEQ m^{-3}).
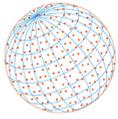
7. The average PM$_{2.5}$ concentrations in Fuzhou in 2018–2020 in the four seasons (spring, summer, autumn, winter) were 26.9, 16.8, 20.1, and 26.3 µg m^{-3}, respectively, which were 37.0% higher in spring and winter (26.6 µg m^{-3}) than in summer (16.8 µg m^{-3}). In Xiamen, the average PM$_{2.5}$ concentrations in the four seasons (spring, summer, autumn, winter) were 25.1, 14.3, 21.1, and 26.4 µg m^{-3}, respectively, which were 44.4% higher in spring and winter (25.8 µg m^{-3}) than in summer (14.3 µg m^{-3}).

REFERENCES

Ahlborg, U.G., Brouwer, A., Fingerhut, M.A., Jacobson, J.L., Jacobson, S.W., Kennedy, S.W., Kettrup, A.F., Koeman, J.H., Poiger, H., Rappe, C., Safe, S.H., Seegal, R.F., Tuomisto, J., van den Berg, M. (1992). Impact of polychlorinated dibenzo-p-dioxins, dibenzofurans, and biphenyls on human and environmental health, with special emphasis on application of the toxic equivalency factor concept. Eur. J. Pharmacol. 228, 179–199. https://doi.org/10.1016/0926-6917(92)90029-C

Anezaki, K., Kashiwagi, N. (2021). Daily variations and factors of atmospheric PCDD/Fs in post-harvest paddy fields: PCDD/F source estimation using a Bayesian semi-factor model. Chemosphere 268, 129292. https://doi.org/10.1016/j.chemosphere.2020.129292

Chen, S., Cui, K., Zhao, Y., Yin, Z., Chao, H.R., Chang-Chien, G.P. (2018). Sensitivity analysis of atmospheric PM$_{2.5}$-bound content and dry deposition of total PCDD/Fs-TEQ: In the case of Xiamen and Zhangzhou, China. Aerosol Air Qual. Res. 18, 3096–3114. https://doi.org/10.4209/aaqr.2018.11.0393

Chi, K.H., Hsu, S.C., Lin, C.Y., Kao, S.J., Lee, T.Y. (2011). Deposition fluxes of PCDD/Fs in a reservoir system in northern Taiwan. Chemosphere 83, 745–752. https://doi.org/10.1016/j.chemosphere.2011.02.069

Chung, M.C., Tsai, M.H., Que, D.E., Bongo, S.J., Hsu, W.L., Tayo, L.L., Lin, Y.H., Lin, S.L., Gou, Y.Y., Hsu, Y.C., Hou, W.C., Huang, K.L., Chao, H.R. (2019). Fine particulate matter-induced toxic effects in an animal model of *Caenorhabditis elegans*. Aerosol Air Qual. Res. 19, 1068–1078. https://doi.org/10.4209/aaqr.2019.03.0127

Du, P.R., Du, R., Lu, Z.D., Ren, W.S., Fu, P.Q. (2018). Variation of bacterial and fungal community structures in PM$_{2.5}$ collected during the 2014 APEC summit periods. Aerosol Air Qual. Res. 18, 444–455. https://doi.org/10.4209/aaqr.2017.07.0238

Ghosh, S., Gupta, T., Rastogi, N., Gaur, A., Misra, A., Tripathi, S.N., Paul, D., Tare, V., Prakash, O., Bhattu, D. (2014). Chemical characterization of summertime dust events at Kanpur: Insight into the sources and level of mixing with anthropogenic emissions. Aerosol Air Qual. Res. 14, 879–891. https://doi.org/10.4209/aaqr.2013.07.0240

Goldman, L.R., Hayward, D.G., Flattery, J., Hardy, M.E., Patterson, D.G., Jr., Needham, L.L., Siegel, D., Chang, R., Stephens, R.D., Kizer, K.W. (1989). Serum, adipose and autopsy tissue and PCDF levels, in people eating dioxin contaminated beef and chicken eggs. Chemosphere 19, 841–848. https://doi.org/10.1016/0045-6535(89)90419-0

Huang, C.J., Chen, K.S., Lai, Y.C., Wang, L.C., Chang-Chien, G.P. (2011). Characterization of atmospheric dry deposition of polychlorinated dibenzo-p-dioxins/dibenzofuran in a rural area of Taiwan. Aerosol Air Qual. Res. 11, 448–459. https://doi.org/10.4209/aaqr.2011.03.0033

Kimbrough, R. D., Falk, H., Stehr, P., Fries, G. (1984). Health implications of 2, 3, 7, 8-tetrachloro-dibenzodioxin (TCDD) contamination of residential soil. J. Toxicol. Environ. Health 14, 47–93. https://doi.org/10.1080/15287398409530562

Lee, K.L., Lee, W.J., Mwangi, J.K., Wang, L.C., Gao, X., Chang-Chien, G.P. (2016). Atmospheric PM$_{2.5}$ and depositions of polychlorinated dibenzo-p-dioxins and dibenzofurans in Kaohsiung area, Southern Taiwan. Aerosol Air Qual. Res. 16, 1775–1791. https://doi.org/10.4209/aaqr.2016.04.0168

Li, M., Hu, M., Guo, Q., Tan, T., Du, B., Huang, X., He, L., Song Guo, S., Wang, W., Fan, Y., Xu, D. (2018). Seasonal source apportionment of PM$_{2.5}$ in Ningbo, a coastal city in southeast China. Aerosol Air Qual. Res. 18, 2741–2752. https://doi.org/10.4209/aaqr.2018.01.0011

Maciejczyk, P., Jin, L., Hwang, J.S., Guo, X., Zhong, M., Thurston, G., Qu, Q., Zhang, J., Sun, Q., Chen, L.C. (2018). Association of cardiovascular responses in mice with source-apportioned PM$_{2.5}$ air pollution in Beijing. Aerosol Air Qual. Res. 18, 1839–1852. https://doi.org/10.4209/aaqr.2017.11.0504
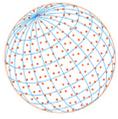
Mari, M., Sánchez-Soberón, F., Audí-Miró, C., van Drooge, B.L., Soler, A., Grimalt, J.O., Schuhmacher, M. (2016). Source apportionment of inorganic and organic PM in the ambient air around a cement plant: Assessment of complementary tools. Aerosol Air Qual. Res. 16, 3230–3242. http://doi.org/10.4209/aaqr.2016.06.0276

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

Polezer, G., Tadano, Y.S., Siqueira, H.V., Godoi, A.F.L., Yamamoto, C.I., de André, P.A., Pauliquevis, T., Andrade, M.d.F., Oliveira, A., Saldiva, P.H.N., Taylor, P.E., Godoi, R.H.M. (2018). Assessing the impact of $PM_{2.5}$ on respiratory disease using artificial neural networks. Environ. Pollut. 235, 394–403. https://doi.org/10.1016/j.envpol.2017.12.111

Qiu, J., Tang, M., Peng, Y., Lu, S., Li, X., Yan, J. (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. https://doi.org/10.4209/aaqr.2019.11.0610

Safe, S. (1990). Polychlorinated biphenyls (PCBs), dibenzo-p-dioxins (PCDDs), dibenzofurans (PCDFs), and related compounds: environmental and mechanistic considerations which support the development of toxic equivalency factors (TEFs). Crit. Rev. Toxicol. 21, 51–88. https://doi.org/10.3109/10408449009089873

Safe, S. (1993). Development of bioassays and approaches for the risk assessment of 2, 3, 7, 8-tetrachlorodibenzo-p-dioxin and related compounds. Environ. Health Perspect. 101, 317–325. https://doi.org/10.1289/ehp.93101s3317

Schröder, S., San-Román, M.F., Ortiz, I. (2021). Dioxins and furans toxicity during the photocatalytic remediation of emerging pollutants. Triclosan as case study. Sci. Total Environ. 770, 144853. https://doi.org/10.1016/j.scitotenv.2020.144853

Sheu, H.L., Lee, W.J., Su, C.C., Chao, H.R., Fan, Y.C. (1996). Dry deposition of polycyclic aromatic hydrocarbons in ambient air. J. Environ. Eng. 122, 1101–1109. 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

Suryani R., C., Lee, W.J., Mutiara M.P., E., 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

Tuomisto, J. (2011). The toxic equivalency principle and its application in dioxin risk assessment, in: The AH Receptor in Biology and Toxicology, John Wiley & Sons, Ltd, pp. 317–330. https://doi.org/10.1002/9781118140574.ch23

Viluksela, M., Stahl, B.U., Birnbaum, L.S., Schramm, K.W., Kettrup, A., Rozman, K.K. (1998). Subchronic/ chronic toxicity of a mixture of four chlorinated dibenzo-p-dioxins in rats. Toxicol. Appl. Pharm. 151, 57–69. https://doi.org/10.1006/taap.1998.8384

Wang, W., Cui, K., Zhao, R., Zhu, J., Huang, Q., Lee, W.J. (2018). Sensitivity analysis of $PM_{2.5}$-bound total PCDD/Fs-TEQ Content: In the case of Wuhu City, China. Aerosol Air Qual. Res. 18, 407–420. https://doi.org/10.4209/aaqr.2017.11.0507

Wang, Y., Qian, L., Yu, Z., Chun, T., Long, H., Wu, X., Li, J. (2020). Inhibition behavior of PCDD/Fs congeners by addition of N-containing compound in the iron ore sintering. Aerosol Air Qual. Res. 20, 2568–2579. https://doi.org/10.4209/aaqr.2019.12.0660

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

Xing, J., Cui, K., Tang, H., Lee, W.J., Wang, L.C., Zhu, J., Huang, Q. (2017). Part II: $PM_{2.5}$ and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) in the ambient air of northern China. Aerosol Air Qual. Res. 17, 2010–2026. https://doi.org/10.4209/aaqr.2017.06.0211
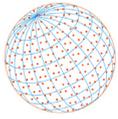
Yin, Z., Cui, K., Chen, S., Zhao, Y., Chao, H.R., Chang-Chien, G.P. (2019). Characterization of the air quality index for Urumqi and Turfan cities, China. Aerosol Air Qual. Res. 19, 282–306. https://doi.org/10.4209/aaqr.2018.11.0410

Zhao, R., Cui, K., Wang, W., Wang, L.C., Wang, Y.F. (2018a). Sensitivity analyses for the atmospheric dry deposition of total PCDD/Fs-TEQ for Handan and Kaifeng cities, China. Aerosol Air Qual. Res. 18, 1255–1269. https://doi.org/10.4209/aaqr.2018.03.0109

Zhao, R., Cui, K., Wang, W., Wang, L.C., Yan, P. (2018b). Atmospheric $PM_{2.5}$ and total PCDD/Fs-WHO_{2005}-TEQ level: A case of Handan and Kaifeng cities, China. Aerosol Air Qual. Res. 18, 994–1007. https://doi.org/10.4209/aaqr.2018.02.0040

Zhao, Y., Cui, K., Chen, S., Yin, Z., Chao, H.R., Chang-Chien, G.P. (2018c). Atmospheric $PM_{2.5}$, total PCDD/Fs-WHO_{2005}-TEQ level and wet deposition: Cases of Jinan and Weihai cities, China. Aerosol Air Qual. Res. 18, 3081–3095. https://doi.org/10.4209/aaqr.2018.11.0395

Zhu, J., Tang, H., Xing, J., Lee, W.J., Yan, P., Cui, K. (2017). Atmospheric deposition of polychlorinated dibenzo-p-dioxins and dibenzofurans in two cities of southern China. Aerosol Air Qual. Res. 17, 1798–1810. https://doi.org/10.4209/aaqr.2017.05.0177