Sustainable Cities and Society 88 (2023) 104299

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Response of dissolved organic carbon in rainwater during extreme rainfall period in megacity: Status, potential source, and deposition flux

Jie Zeng, Guilin Han *, Shitong Zhang, Xuhuan Xiao, Yikai Li, Xi Gao, Di Wang, Rui Qu

Institute of Earth Sciences, China University of Geosciences (Beijing), Beijing 100083, China

ARTICLE INFO

Keywords:
Dissolved organic carbon
Extreme rainfall
Wet deposition
Source identification
Beijing

ABSTRACT

Air pollution and related wet deposition process (rainfall) caused environmental hazards under the climate change, particularly in urban regions, attracting global concern and challenges. Atmospheric dissolved organic carbon (DOC) deposition is not only the major removal pathway of OC from atmosphere, but also a significant influence factor of urban haze pollution and local climate. Although the significance of DOC deposition to carbon budgets is confirmed, the extreme rainfall influenced OC transfers from the atmosphere to land is poorly understood. This study systematically investigated the rainwater DOC in Beijing during the extreme rainfall period of 2021 to explore its status, source, and flux. The results showed that the rainwater DOC concentration level is close to the Asian and global mean level, while the DOC deposition flux was relatively high due to high rainfall amount and rainfall scouring, and the overall declined trend of DOC concentrations was identified. Source identification revealed that human OC emissions (municipal wastes, agricultural and traffic emission) are the primary sources of DOC, whereas ocean and crust source contributed negligibly. This research clarified the extreme rainfall-driven rainwater DOC dynamics in a megacity and supported the evaluation of global carbon budgets.

1. Introduction

With the acceleration of global urbanization, increasing amounts of organic carbon (OC) have been released into the urban atmosphere, causing cities to become the hot spot area of OC emissions. As an important component of fine particles (~30%) (An *et al.*, 2019), OC forms atmospheric particulates and further generates urban haze pollution (Fang *et al.*, 2017). OC alters the urban surface energy balance due to its light-absorbing capabilities (An *et al.*, 2019; Cao *et al.*, 2022), and is thus directly related to local urban climate (Bahadur *et al.*, 2012; Li *et al.*, 2017). Rainwater scouring process is the most major OC removal way from the atmosphere (Formation of dissolved organic carbon, DOC) (Iavorivska *et al.*, 2016; Xing *et al.*, 2019). Therefore, identifying the dynamics and potential sources of rainwater DOC in urban areas is conducive to understand/reveal the urban air pollution and urban local climate change, and supports urban sustainable development and management, which improves evaluation of global carbon budgets (Kieber *et al.*, 2002; Cao *et al.*, 2022).

Climate change is the most influential factor controlling the rainfall process (Shadmehri Toosi *et al.*, 2020), and has typically caused the extreme rainfall event. In addition, extreme rainfall is one of the usual natural hazards which threaten the eco-environment and anthropogenic society (Shadmehri Toosi *et al.*, 2020), and the accompanying frequent inundation has become a severe issue in urban regions (Yamashita *et al.*, 2016). The previous studies of extreme rainfall usually concentrated on the main dangers of inundated regions caused by the rainfall-driven runoff (Hürlimann *et al.*, 2015; Yamashita *et al.*, 2016; Yang *et al.*, 2019) or the influences on municipal water and wastewater system (Arnbjerg-Nielsen *et al.*, 2013; de Sá Silva *et al.*, 2022). For example, the extreme rainfall has resulted in a variety of urban underground infrastructure failures and secondary risks (threaten residents), impeding the sustainable development of city (Jiang & Tan, 2022). However, data on rainwater chemistry (e.g., DOC and ions) during extreme rainfall processes are limited, as well as their provenance, influencing factors, and environmental effects are relatively reported. Therefore, it is necessary to study the extreme rainfall influenced rain components evolution. Actually, precipitation process is the most vital sink processes of air substances, including atmospheric contaminants (Szép *et al.*, 2017; Wei *et al.*, 2019; Keresztesi *et al.*, 2020). Precipitation chemical components are usually altered via the in/below-cloud processes with the scouring of

* Corresponding author.
E-mail address: hanguilin@cugb.edu.cn (G. Han).

https://doi.org/10.1016/j.scs.2022.104299
Received 3 May 2022; Received in revised form 4 October 2022; Accepted 7 November 2022
Available online 8 November 2022

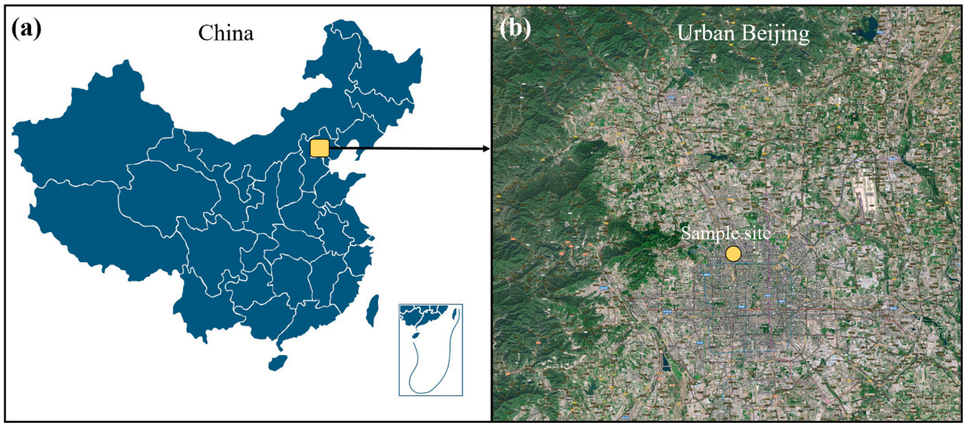

Fig. 1. The position of Beijing (a) and the sample site in urban Beijing (b).

air substances (Chate *et al.*, 2011; Zeng *et al.*, 2020c; Ge *et al.*, 2021; Monteiro *et al.*, 2021). Therefore, rainwater chemical components acts as an effective indicator of the air environment (Han *et al.*, 2019; Zeng *et al.*, 2020a) which further influences the Earth surface hydrochemistry (Wu & Han, 2018; Qin *et al.*, 2020; Wang *et al.*, 2022).

As an important way to get rid of OC from the atmosphere, rainfall deposited about 40% of global OC emissions in the form of DOC (Willey *et al.*, 2000; Kanakidou *et al.*, 2012), making atmospheric DOC deposition as a critical contributor to the global carbon cycle. Accurately quantifying the DOC deposition flux is therefore meaningful in revealing carbon neutrality (Cao *et al.*, 2022). Due to extensive potential human OC emissions, the study of atmospheric DOC deposition is particularly significant in metropolitan areas. For example, the DOC deposition flux in Varanasi (India) has trebled in six years due to biomass burning and industrial emissions (Pandey *et al.*, 2015). Beijing is a well-known megacity around the world and the city with highest urbanization level in China, which has faced numerous atmospheric environmental issues, particularly haze pollution (Sun *et al.*, 2021). The precipitation ions and related deposition fluxes in Beijing were investigated in various studies (Feng *et al.*, 2001; Xu & Han, 2009; Xu *et al.*, 2012; Ge *et al.*, 2021). However, the rainwater DOC dynamics driven by extreme rainfall in Beijing is still infrequently focused.

In 2021, extremely rainfall processes happened in North China, leading to record-breaking rainfall amounts in several cities (Zhang *et al.*, 2021a; Zhong *et al.*, 2021; Liu *et al.*, 2022; Wu *et al.*, 2022b), including Beijing, one of the most typical megacities. Thus, a total of 20 daily-based rainwater samples from this extreme rainfall period (July to August 2021) were collected in this study from the central urbanized area in Beijing (Haidian District). Combined with the atmospheric pollutant concentrations, the rainwater DOC evolution driven by extreme rainfall was clarified via DOC and major ion analysis. The targets of this study were to (1): explore the daily-based DOC concentrations, fluctuations and influencing factors, (2) investigate the major sources of DOC, and (3) evaluate the rainwater DOC flux in extreme rainfall period. This study clarified the extreme rainfall driven rainwater DOC dynamics in a megacity and highlighted the level of DOC deposition flux under the background of extreme rainfall, which would helpful for the megacity environmental management and sustainable development.

2. Methodology

2.1. Study area

As the capital of China, Beijing is situated on the North China plain, about 150 km from Bohai bay (Fig. 1a). It is surrounded by mountains from three sides, with an altitude of 20~2303 m. The climate is belonged to the typical continental monsoon climate in the semiarid climatic zone (Xu & Han, 2009), with the annual precipitation amount of 400~800 mm (Li *et al.*, 2019), the temperature of -3~28°C, and the humidity of 38%~68%. Most of the annual precipitation happens in the rainy season (July and August) (Li *et al.*, 2019). Beijing has a large resident population with a population density of 6602~21888 people/km^2, and car ownerships (~6.57 million) of this city is also huge due to transportation requirements. From the perspective of the whole Beijing city, (Beijing Municipal Bureau of Statistics, 2020), the land use area percentage followed the order of forest (47%), urban area (19%), farmland (13%), garden plot (8%), water area (5%), grassland (5%), transportation land (3%). However, most of the urban area is mainly concentrated in the central urban built-up regions (e.g., Haidian District), and the impervious surface area of urban built-up area accounts for more than 63% (Li & Kuang, 2020), while the forest and farmland mainly distributed in the northwestern mountain regions (Zhang *et al.*, 2021b).

2.2. Sampling

The sample location was selected in the representative municipal region of Beijing City (Haidian District, 39.99°N, 116.35°E, Fig. 1b). Refer to the method of the China Wet Deposition Observation Network, the plastic (polyethylene) sampler set at a site without any potential impacts (e.g., buildings and trees) was used to collect rainwater. To avoid the influence of dry settling, rainwater samples were only collected when rainfall events happened, and the plastic sampler was removed and covered by a plastic lid after the rainfall ended. In addition, the sampler was washed via deionized water and air-dried in a clean room before each sampling to keep the sampling utensil clean. A total of 20 daily-scale based rainwaters were collected manually during extreme rainfall period from July to August 2021. All rainwaters were filtrated by 0.22 μm membrane filters for DOC measurement.

2.3. Measurement and data calculation

The DOC concentration was measured via the Elementar Vario TOC (Elementar, Germany) at the China University of Geosciences (Beijing), referring the measuring methods of the previous study (Liu *et al.*, 2019). The precisions of DOC measurements were better than ±5%, and the detection limitation is 0.05 mg C L^{-1}. Moreover, the major ions of rainwater were determined at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, which were reported in our previous work (Zeng *et al.*, 2022; Zeng *et al.*, 2023). Briefly, anions (Cl^-, F^-, SO_4^{2-}, and NO_3^-) and cations (K^+, Na^+, Ca^{2+}, and Mg^{2+}) were detected by ionic chromatography (Dionex 1100) and ICP–OES (Optima 5300DV). NH_4^+ was measured by the Nessler method

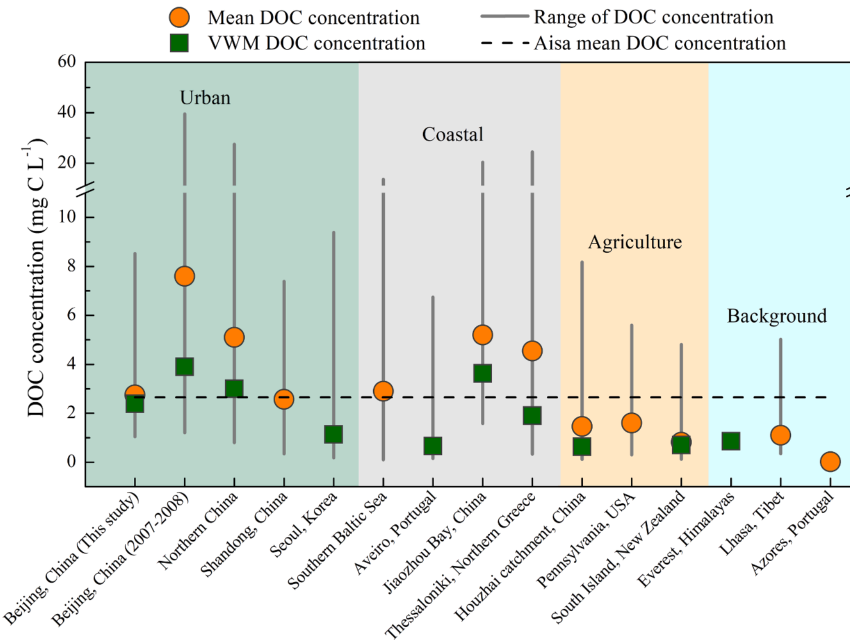

Fig. 2. DOC concentrations of rainwater in Beijing and publications (Kieber *et al.*, 2002; Cerqueira *et al.*, 2010; Pan *et al.*, 2010; Yan & Kim, 2012; Santos *et al.*, 2013; Iavorivska *et al.*, 2016; Li *et al.*, 2016b; Wang *et al.*, 2016; Witkowska & Lewandowska, 2016; Iavorivska *et al.*, 2017; Li *et al.*, 2017; Pantelaki *et al.*, 2018; Xing *et al.*, 2019; Zeng *et al.*, 2020d).

with spectrophotometer. In addition, the atmospheric pollution data (e.g., $PM_{2.5}$ and PM_{10}) and meteorological data (e.g., precipitation amount) were taken from the environmental monitoring station and Weather China (http://www.weather.com.cn/).

The volume-weighted mean (VWM) concentration of DOC in this study is calculated by the equation (Zeng *et al.*, 2020d):

$$C = \frac{\sum C_i P_i}{\sum P_i} \tag{1}$$

where C, C_i, and P_i represents the VWM concentration, sample concentration, and daily rainfall amount, respectively.

Prior to data analyze, the normal distribution of DOC concentrations, major ion concentrations of rainwater and meteorological parameter data were checked via the Kolmogorov–Smirnov (K-S) test. The results revealed that some data (e.g., DOC and Cl^- concentrations) were not normally distributed. Thus, the principal component analysis and Spearman's rank correlation analysis were used to identify the relationships among different parameters.

In addition, to compare the differences between the observed data in this study and the historical data, the historical datasets of different regions (including urban, coastal, agricultural, and background areas) were collected and organized. All the datasets were obtained from published publications, such as Beijing (2007-2008), Northern China, Shangdong Province (China), Seoul (Korea), Southern Baltic Sea, Aveiro (Portugal), Jiazhou Bay (China), Thessaloniki (Greece), Houzhai catchment (China), Pennsylvania (USA), South Island (New Zealand), Everest (Himalayas), Lhasa (Tibet), Azores (Portugal) (Kieber *et al.*, 2002; Cerqueira *et al.*, 2010; Pan *et al.*, 2010; Yan & Kim, 2012; Santos *et al.*, 2013; Iavorivska *et al.*, 2016; Li *et al.*, 2016b; Wang *et al.*, 2016; Witkowska & Lewandowska, 2016; Iavorivska *et al.*, 2017; Li *et al.*, 2017; Pantelaki *et al.*, 2018; Xing *et al.*, 2019; Zeng *et al.*, 2020d). The statistics were performed by SPSS 21.0 (IBM, Armonk, NY, USA).

3. Results and discussion

3.1. Rainwater DOC during extreme rainfall period

3.1.1. Comparisons in different regions

The concentrations of rainwater DOC in this study and other areas (including urban, coastal, agricultural, and background regions) reported in previous studies were summarized. It is clear that the mean value of rainwater DOC concentration (2.75 mg C L^{-1}) was higher than the VWM value (2.38 mg C L^{-1}) (Fig. 2), indicating that the higher DOC concentrations normally occurred along with the condition of lower rainfall amount. This is in agreement with most of the reported observations in the world (Fig. 2). Consequently, the DOC concentrations in this research are about 11.6 to 94.8 times higher than that in remote regions (Everest with a low background DOC concentration of 0.09 mg C L^{-1}) (Li *et al.*, 2016a), with a VWM value of 26.4 times higher, implying the obvious DOC input. Given that the rainwater DOC concentrations were not normally distributed ($p<0.1$, K-S test) and the observed large standard deviation (1.87 mg C L^{-1}), the mean concentration has been obviously influenced by the abnormally high value. Thus, we concluded that the VWM value of rainwater DOC is appropriate for comparison relative to the mean value, which can also be supported by previous studies (Iavorivska *et al.*, 2016; Pantelaki *et al.*, 2018).

From a global perspective (Fig. 2), the VWM concentration of DOC (2.38 mg C L^{-1}) in Beijing rainwater in this study is slightly lower than the average level of rainwater DOC in Asian (2.65 mg C L^{-1}) and worldwide (2.64 mg C L^{-1}) (Iavorivska *et al.*, 2016), but notably higher than that observed in background regions, such as the Everest (Li *et al.*, 2017), Lhasa (Li *et al.*, 2016b), and Azores (Cerqueira *et al.*, 2010) in the remote area of Tibet and ocean. In urban regions, the VWM concentration of rainwater DOC in Beijing is about three fifths of the observed results (~3.9 mg C L^{-1} with large varied range) in previous reports of Beijing during 2007 to 2008, which is lower than Northern China cities (~3 mg C L^{-1}) and similar to the Shandong Province of China (2.57 mg C L^{-1}), but twice of the Seoul in Korea (1.13 mg C L^{-1}) (Pan *et al.*, 2010; Yan & Kim, 2012; Wang *et al.*, 2016) (Fig. 2). Compared to the coastal areas with large variations of rainwater DOC concentrations that easily influenced by ocean factors (Santos *et al.*, 2013; Witkowska &

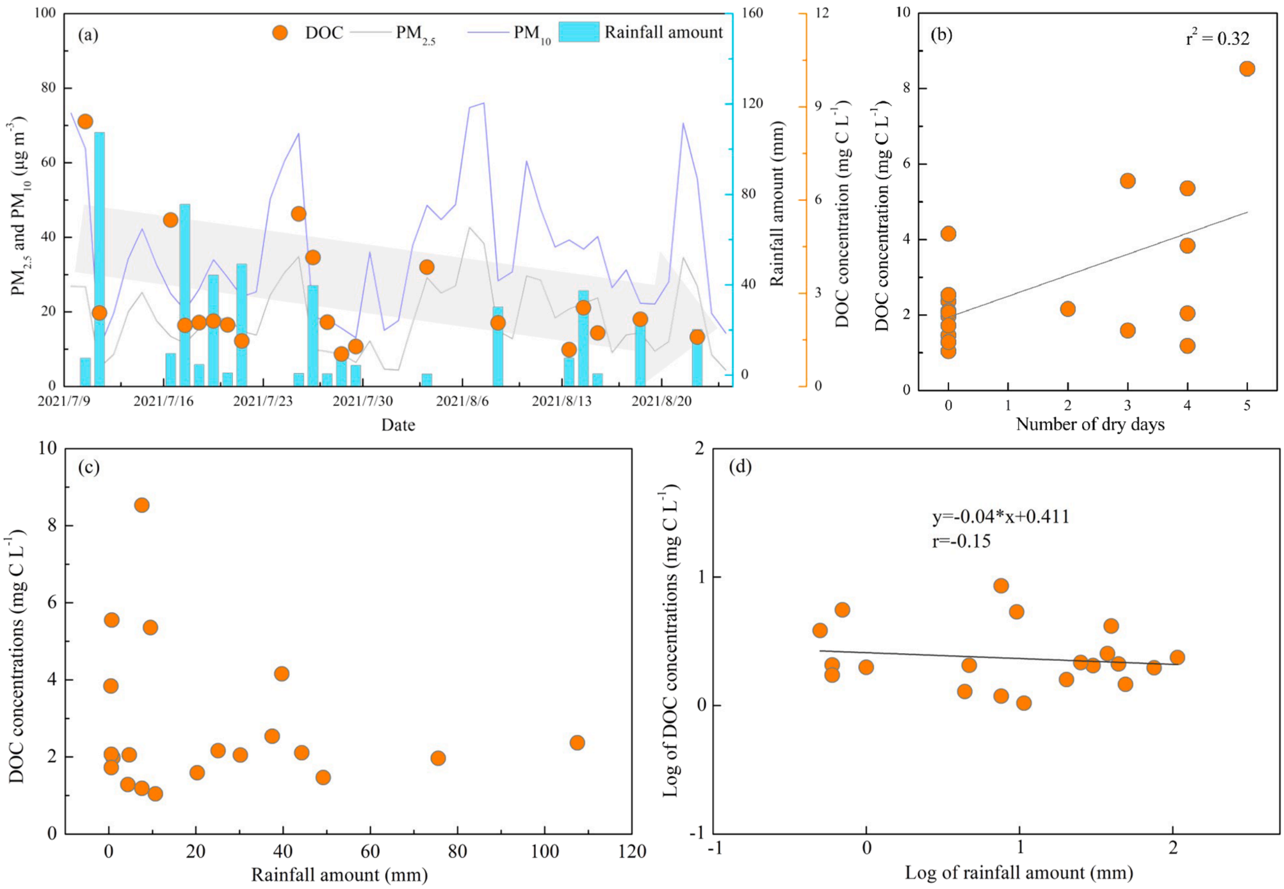

Fig. 3. Fluctuations of (a) DOC, PM_{10} and $PM_{2.5}$ concentrations, and (b) the relationship of DOC concentrations versus the number of dry days. The relationship between (c) Raw DOC concentration data and rainfall amount, and (d) logarithmic DOC concentration and rainfall amount.

Lewandowska, 2016; Pantelaki *et al.*, 2018; Xing *et al.*, 2019) (Fig. 2), the rainwater DOC concentration in Beijing (megacity) is within a middle level. Contrastly, the observed DOC concentration is also significantly higher than that in the agriculture-controlled regions, such as Houzhai catchment (China), South Island (New Zealand) and Pennsylvania (USA) (Kieber *et al.*, 2002; Iavorivska *et al.*, 2017; Zeng *et al.*, 2020d). The compared results indicated that the exogenous OC input significantly contributed to megacity due to the potential emission of pollutants.

3.1.2. Daily fluctuations and controlling factors of DOC

A total amount of 542 mm rainfall occurred during July to August, almost reaching the annual average rainfall amount (Li *et al.*, 2019; Sun *et al.*, 2021). The daily rainfall amount ranged significantly between 0.5 and 107.5 mm (Fig. 3a). Accordingly, the high variability of daily rainwater DOC concentrations was also identified, specifically, an 8.2-fold difference occurred between the highest (8.53 mg C L^{-1}) and lowest (1.04 mg C L^{-1}) concentrations. The highest rainwater DOC concentration was observed on 11th July 2021 (relative low rainfall amount, 7.6 mm), while the lowest was found on 29th July 2021 (Fig. 3a), reflecting the potential influence of precipitation. This phenomenon can also be supported by previous works (Li *et al.*, 2016b; Xing *et al.*, 2019). Notably, there is a decreasing trend (light grey arrow in Fig. 3a) of daily rainfall amount and DOC concentrations during study period. Yet, the relationship between the rainwater DOC concentrations and the number of dry days (maximum 5 days) before each rain event is not distinct (Fig. 3b), reflecting that the impact of dry days on rainwater DOC is negligible. Compared with the previous study in the northwest of downtown Beijing (Yanqing) (Cao *et al.*, 2022), the observation of the influence dry days is similar; that is, the DOC concentrations of bulk deposition (rainwater DOC and dry deposition OC in dry days before corresponding rainfall event) were only ~18% higher than that of rainwater only deposited during long-term monitoring (Cao *et al.*, 2022), suggesting the dominated influencing factor on rainwater DOC concentrations is rainfall amount.

To further explore the precipitation effect, the association between precipitation amount and DOC concentrations was presented in Fig. 3c and the opposite association was found. After logarithmic processing of rainwater DOC concentrations and rainfall amount, the correlation of these two (Fig. 3d) reflected that DOC concentrations in Beijing were partly impacted by the dilution effect, which is also commonly reported in previous researches (Yan & Kim, 2012; Xing *et al.*, 2019). During the rainfall process, the atmospheric OC components can be well scoured (below-cloud scouring) through the initial rain-stage and cause relatively high DOC concentration accompanied by the low rainfall amount. Conversely, the DOC concentrations remain in a lower level due to the subsequent continuous rain-stage (Fig. 3c). The critical value of rainfall amount was about 15 mm. The atmospheric OC components were almost completely scoured when the rainfall amount was up to 15 mm, revealing the in-cloud process with weak dilution effect of DOC (Xing *et al.*, 2019; Zeng *et al.*, 2020d; Monteiro *et al.*, 2021), and long-distance transport of atmospheric OC is thereby regarded as the non-negligible influencing factor of rainwater DOC under this condition (Godoy-Silva *et al.*, 2017). However, if the rainfall amount is <15 mm, the below-cloud process would control the DOC concentrations.

Moreover, the contents of atmospheric suspended OC particles (fine particulate matter) and gaseous soluble OC is also the key factors influencing DOC concentration (Herckes *et al.*, 2002). For example, a previous study in the USA suggested that the short-term and high-intensity discharge of local pollutants and subsequently

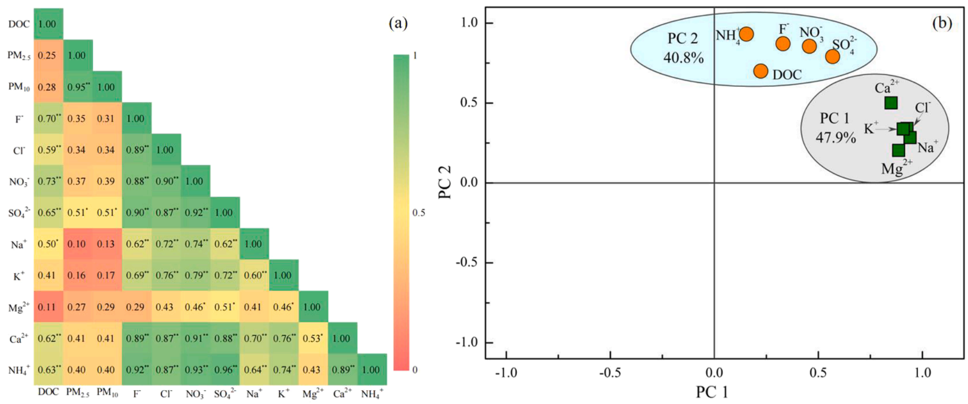

Fig. 4. Spearman rank correlation analysis (a) and principal component analysis (b) of rainwater components. **, significance level $p < 0.01$; *, significance level $p < 0.05$.

photochemical reactions in the atmosphere could promote the rise of rainwater DOC concentration during heavy precipitation events (Iavorivska *et al.*, 2017). As one of the largest cities in China, Beijing has numerous potential emission sources. However, relatively low levels of air $PM_{2.5}$ and PM_{10} concentrations with the $PM_{2.5}/PM_{10}$ ratio of 0.50 (0.25~0.65, secondary air pollutants dominated) were observed during the study period (Fig. 3a), and all days can be defined as the non-episode day ($PM_{2.5}$ concentration < 75 μg m^{-3}) according to the Chinese Air Quality Standards (Zeng *et al.*, 2021). Even so, the co-variation trends of daily $PM_{2.5}$ and PM_{10} concentrations were found in Fig. 3a (significantly correlated in Fig. 4a, R=0.95, p<0.01), but the correlations between rainwater DOC and $PM_{2.5}$ (or PM_{10}) was insignificant (p>0.05). Thus, the influences of atmospheric particles (especially the $PM_{2.5}$) on rainwater DOC is relatively limited, while the gaseous soluble matter in the atmosphere is more probable to be the origin influencing factor of rainwater DOC (Szidat *et al.*, 2006).

3.2. *Sources of rainwater DOC*

3.2.1. *CA and PCA*

The major origins of DOC are generally divided into anthropogenic and natural origins. The nature and human-derived OC in the atmosphere can transport thousands of kilometers (Cao *et al.*, 2009). Moreover, some regional OC emission, such as low molecular weight OC has a short transportation distance and can be fast scoured by rainfall and returned to the Earth surface in wet deposition form (Zhang *et al.*, 2011).

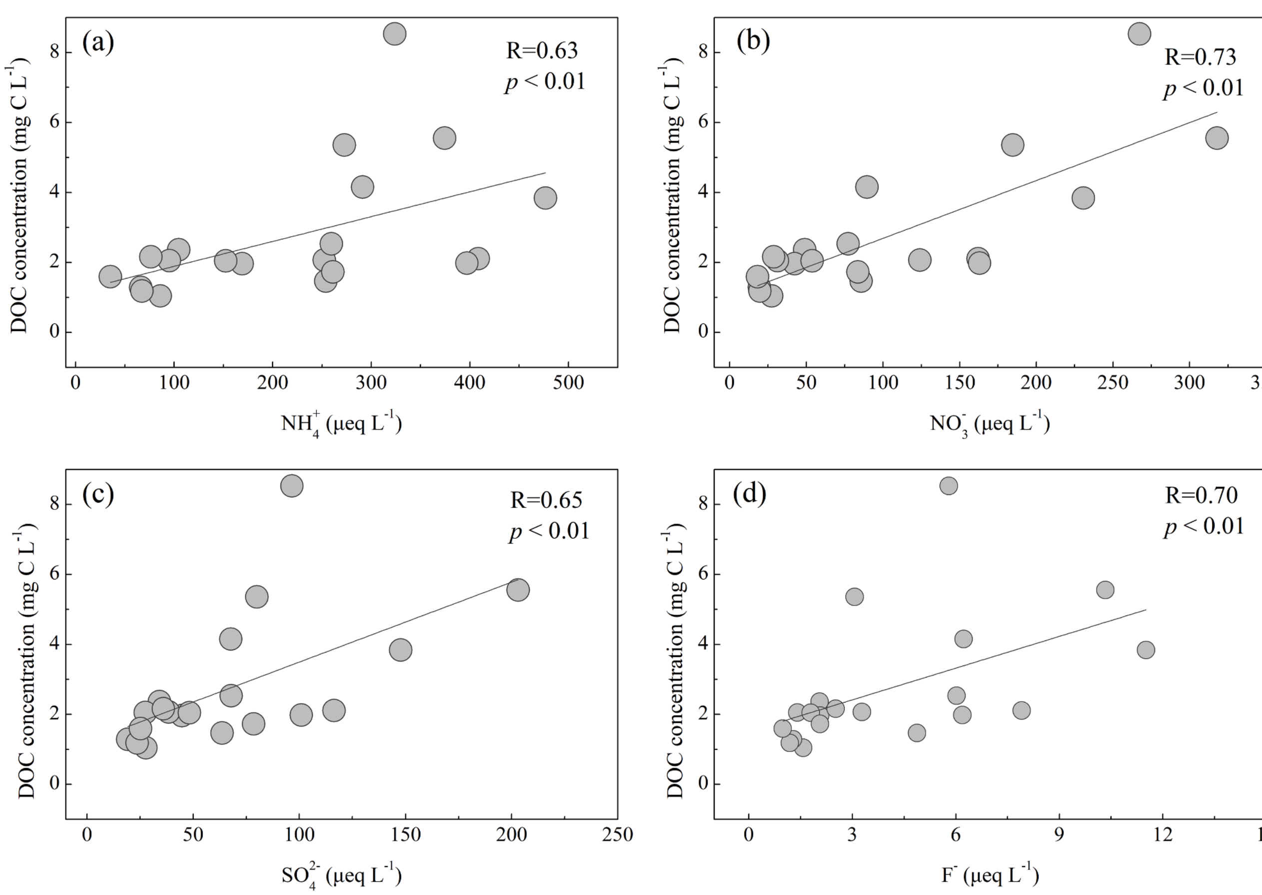

Fig. 5. The relationships between DOC concentrations and typical human-derived ions of rainwater: (a) NH_4^+, (b) NO_3^-, (c) SO_4^{2-}, (d) F^-.

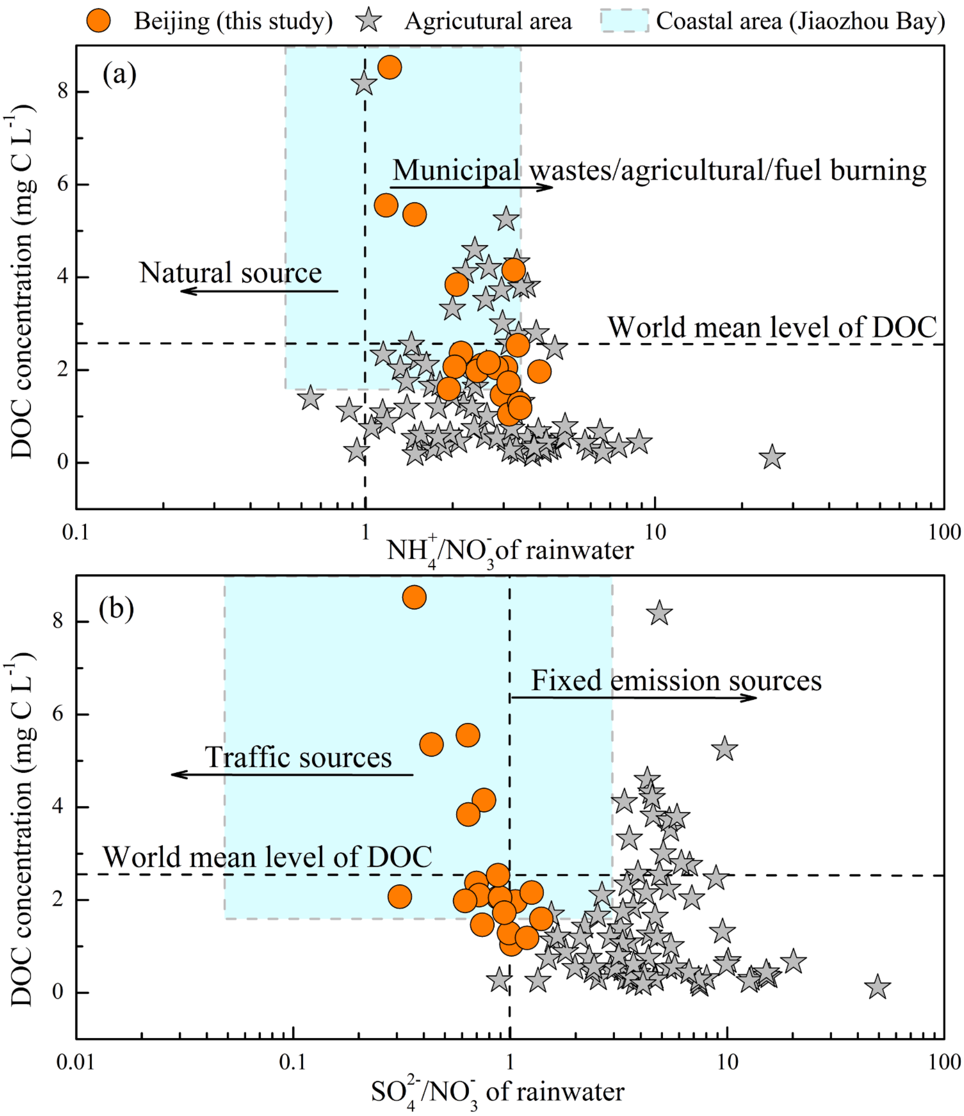

Fig. 6. The relationship between DOC and (a) NH_4^+/NO_3^- and (b) SO_4^{2-}/NO_3^- ratios (equivalent ratio) of rainwater in Beijing, the ion equivalent ratio data and the previously published data of agricultural and coastal areas are from (Xing *et al.*, 2017; Xing *et al.*, 2019; Zeng *et al.*, 2020d; Zeng *et al.*, 2022).

Based on the normal distribution testing results, Spearman's rank correlation analysis (CA) and principal component analysis (PCA), are two widely-used approaches for identifying the sources of atmospheric substances (Han *et al.*, 2019; Cao *et al.*, 2022), were applied to explore the rainwater DOC sources qualitatively. The CA results of DOC and the representative chemical ions of rainwater (F^-, Cl^-, SO_4^{2-}, NO_3^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, and NH_4^+ (Zeng *et al.*, 2022, 2023)) presented that rainwater DOC was significantly correlated with most ions (R=0.50~0.73, $p<0.05$ or 0.01, Fig. 4a). However, more source information of rainwater DOC from CA is relatively not sufficient. In contrast, the PCA results extracted two PCs (eigenvalue is greater than 1), which explained 88.7% of the total variances (Fig. 4b). PC1 (Cl^-, Na^+, K^+, Mg^{2+}, Ca^{2+}) and PC2 (DOC, F^-, SO_4^{2-}, NO_3^-, NH_4^+) explained 47.9% and 40.8% of the total variances, respectively. All the rainwater components presented strong loading values (>0.7) within the corresponding PC. The five ions in PC1 are the most typical crust input ions (e.g., Mg^{2+} and Ca^{2+}) and sea salt input ions (Cl^- and Na^+), while the other four ions in PC2 are the representative human source-derived ions (including SO_4^{2-}, NO_3^-, NH_4^+, and F^-) (Wu *et al.*, 2012; Rao *et al.*, 2017; Zeng *et al.*, 2019; Keresztesi *et al.*, 2020). In combined with high positive loading of rainwater DOC in PC2 (0.70) and weak loading in PC1 (0.22), here we inferred that the rainwater DOC sources were different from the representative sea sources (SS) and crust sources (CS). Therefore, although urban Beijing is only ~150 km away from the Bohai sea (Xu *et al.*, 2012), the contributions of sea sources and crust sources on rainwater DOC were rather limited and negligible.

3.2.2. Possible source identification

In general, the emission of ammonia gas from municipal waste, agricultural soil (organic manure and fertilizer), and fuel combustion is the main origin of dissolved NH_4^+ in rainwater (Lee *et al.*, 2012; Zeng *et al.*, 2020b; Feng *et al.*, 2022). The observed relationship among rainwater NH_4^+ and DOC (Fig. 5a) suggests that ammonia gas related emission acted as an important origin of rainwater DOC in Beijing. Moreover, the characteristic ion ratio of rainwater NH_4^+/NO_3^- (equivalent ratio) is a vital indicator for clarifying the relative contribution of natural and non-natural sources. The rainwater NH_4^+/NO_3^- ratio was generally greater than 1 in anthropogenic emission-controlled regions (e.g., municipal wastes, agriculture emissions and fuel burning) (Wang & Han, 2011; Lee *et al.*, 2012; Zeng *et al.*, 2020d), while $NH_4^+/NO_3^- <1$ indicates the features of the natural region, of which reflected the different controlling role of rainwater nitrogen compositions. In the rainwater NH_4^+/NO_3^- ratio vs DOC plot, all rainwater samples were distributed in the right part of the NH_4^+/NO_3^- =1 line (Fig. 6a),

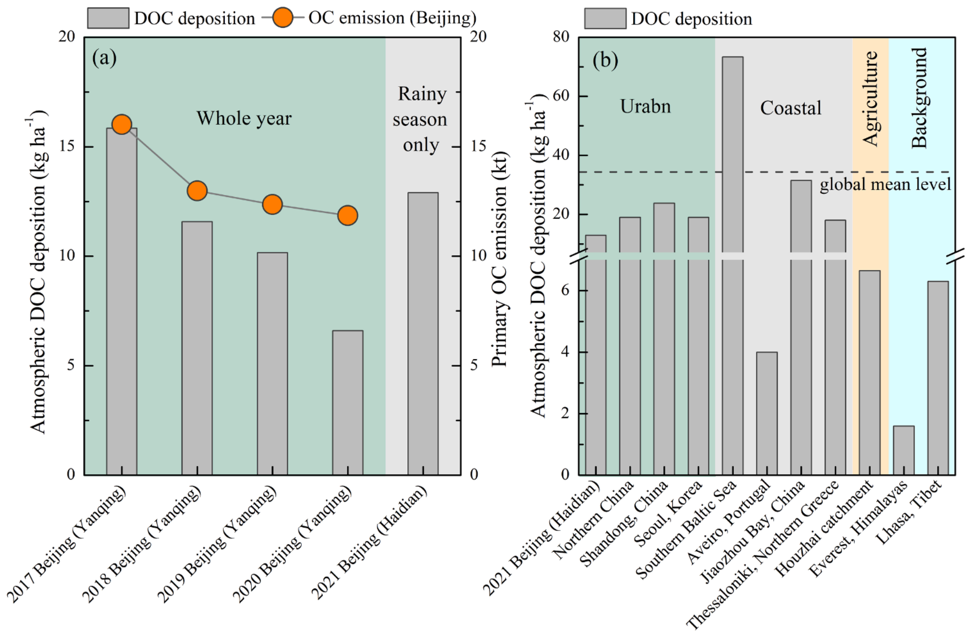

Fig. 7. The rainwater DOC deposition flux in Beijing and the OC emission (a), and the comparisons of DOC deposition flux between this study and other regions. Note: except for 2021 Beijing (Haidian) (this study, rainy season only), all the data here are annual data; The data sources of 2017-2020 Beijing (Yanqing) are (Cao *et al.*, 2022) and the other data sources are same to Fig. 2.

confirming the significant contribution of these typical anthropogenic sources to rainwater DOC. A similar finding was found in the agricultural area, where the agriculture-related soil emission was a dominated contributor of rainwater DOC (Zeng *et al.*, 2020d). Moreover, compared with the coastal city Qingdao, north China (Xing *et al.*, 2019), our findings in Beijing were slightly different, indicating a certain extent of natural source contribution (nattier blue box in Fig. 6a).

Rainwater DOC has been widely verified as a significant sink of atmospheric OC that originated from fossil fuel burning, such as gasoline and coal (Iavorivska *et al.*, 2016; Cao *et al.*, 2022). In Fig. 5b and c, significant positive correlations were found between rainwater DOC and NO_3^- (R=0.73, p<0.01), and between DOC and SO_4^{2-} (R=0.65, p<0.01). These two ions (NO_3^- and SO_4^{2-}) were regarded as the ramification of NO_x and SO_x (via rainfall scouring) released from fossil fuel combustion (Willey *et al.*, 2006; Zeng *et al.*, 2020d). Therefore, the results in Fig. 5b and c indicated that the rainwater DOC has an important fossil fuel burning source similar to the SO_x and NO_x. Moreover, fossil fuel sources mainly include two types: mobile sources (traffic sources, gasoline combustion) and fixed emission origins (coal burning in different human activities) (Han *et al.*, 2010; Godoy-Silva *et al.*, 2017). As shown in the diagram of rainwater SO_4^{2-}/NO_3^- ratio vs. DOC (Fig. 6b), the SO_4^{2-}/NO_3^- ratios of most rainwater samples were smaller than 1, implying that the contributions of mobile (traffic) sources to rainwater components (including DOC) were relatively higher than those of fixed emission sources (Xing *et al.*, 2019). This is well in agreement with the fact of a large number of civil motor vehicles in Beijing, which provide a huge potential for traffic pollutants emission, while the contributions of fixed emission sources were weakened due to the implementation of atmospheric environmental protection policies and managements (Wen *et al.*, 2020; Sun *et al.*, 2021). However, our findings in Beijing were obviously different from those in the agricultural area where few coal-fired activities and vehicles exist (Fig. 6b) (Zeng *et al.*, 2020d). Therefore, the traffic emission-dominated mobile source is another vital contributor of rainwater DOC in study area during the extreme rainfall period. Moreover, although a positive correlation was observed between rainwater DOC and F^- (Fig. 5d), and industrial emission (fluoride-related) is also a potential source of F^- (Khare *et al.*, 2004), but considering the very low concentration of F^- (VWM=0.07 mg L^{-1}), here we concluded that this source contributed finitely to the rainwater DOC. Moreover, although the quantitative source contributions of rainwater DOC were not identified in this work, the previous studies provided potential effective ways to obtain the contribution rates (Li *et al.*, 2016b; Chen *et al.*, 2022; Wu *et al.*, 2022a). For example, the radioactive carbon isotope (^{14}C) and the binary mixing model have been successfully used to quantify the relative contributions of biomass ($f_{biogenic}$) and fossil fuel (f_{fossil}) sources to rainwater DOC (e.g., $f_{biogenic}$=72% and f_{fossil}=28% in rainwater at Tibetan Plateau city) (Li *et al.*, 2016b). The emerging technology of ultrahigh-resolution Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR MS) also has been confirmed to quantitatively characterize the source and formation of rainwater dissolved organic matter at the molecular level (Chen *et al.*, 2022). These quantitative ways warrant future studies to explore rainwater DOC sources, which is also a significant direction for further work.

3.3. Rainwater DOC deposition flux

Based on the total precipitation amount and the VWM concentration of DOC in Beijing (Haidian) in 2021, the rainwater DOC deposition flux was calculated by product of these two (Xing *et al.*, 2019). As shown in Fig. 7a, the DOC deposition flux of the rainy season (only July and August) was 12.9 kg ha^{-1} in Beijing (Haidian) in 2021. Compared with the monitored history results (2017 to 2020) at a monitoring site in Beijing (Yanqing, ~70 km to the sampling site of this study), although the rapid decline of annual rainwater DOC deposition flux (from 15.8 to 6.6 kg ha^{-1}, Fig. 7a) was observed during these years due to the fast decrease (~30%) of human OC emission due to the implementation of clean air policies (Cao *et al.*, 2022). However, this research observed a higher level of rainwater DOC deposition flux (12.9 kg ha^{-1}) within two months (extreme rainfall period). Given that the previous study in the Yanqing site was located in the farmland region (Cultivated land area >39%) (Cao *et al.*, 2022), here we inferred that the variation of land use apart from agriculture was one of the causative factors of increased DOC deposition flux. This can be supported by the fact of a large proportion (63%) of the impervious surface area of urban built-up areas in this study (Li & Kuang, 2020). Moreover, the high efficiency of rainfall scouring effect driven by extreme rainfall amount and the different environmental backgrounds were also the potential causes of high DOC deposition flux level. Therefore, here we hold that the observed DOC deposition can partly reflect the annual flux of downtown Beijing to a certain extent. From a global perspective (Fig. 7b), our rainwater DOC deposition flux is less than half of the global average level (34.0 kg ha^{-1}) (Iavorivska *et al.*, 2016), and is slightly lower than that of the urban areas in northern China, the Shangdong Province, and the Seoul city in Korea (Pan *et al.*, 2010; Yan & Kim, 2012; Wang *et al.*, 2016). However, the rainwater DOC deposition flux is obviously lower than that in some coastal sites, such as the Southern Baltic Sea (73.3 kg ha^{-1}) (Witkowska & Lewandowska, 2016). Unsurprisingly, the rainwater DOC deposition flux in this study is much higher than the agricultural (6.7 kg ha^{-1}) and background sites (1.6~6.3 kg ha^{-1}) (Li *et al.*, 2016b; Li *et al.*, 2017; Zeng *et al.*, 2020d). All the comparisons of rainwater DOC deposition fluxes indicate the high emission intensity of OC in urban Beijing during the study period. Even so, the DOC deposition may be well controlled with the effectively implementation of contaminants reduction managements in future years. This study also points out the importance of updating the global DOC budget under the background of global climate change and fast changes in OC emissions.

4. Conclusion

We investigated the rainwater DOC data in the largest megacity (Beijing) during extreme rainfall period in 2021, to clarify the DOC concentrations, variations, influencing factors, possible sources, and deposition flux. The main findings reflected that the status of rainwater DOC concentration in Beijing was close to that of the Asian and global average, and the DOC deposition flux was higher compared to historical data because of the extremely high rainfall amount and scouring process. Both the rainfall amount and variations of source contributions were the key influencing factors of rainwater DOC, and the long-distance transport of atmospheric OC was also a non-negligible factor. In addition, the possible sources of rainwater DOC were identified by CA and PCA. The anthropogenic emissions were the primary contributors of DOC, while the sea sources and crust sources contributed finitely. Further analysis of DOC and other characteristic ions (and their ratios) of rainwater pointed out that the main OC emission sources were municipal wastes, agriculture emissions and fuel burning (mainly traffic emissions). This work emphasized the significance of DOC deposition in the megacity under the extreme rainfall (climate changes) background, and further clarified the direction of long-term monitoring of rainwater DOC and pollutant reduction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Nos. 41661144029 and 41325010).

References

An, Z., Huang, R.-J., Zhang, R., Tie, X., Li, G., Cao, J., Zhou, W., Shi, Z., Han, Y., Gu, Z., & Ji, Y. (2019). Severe haze in northern China: A synergy of anthropogenic emissions and atmospheric processes. *Proceedings of the National Academy of Sciences, 116*, 8657–8666.

Arnbjerg-Nielsen, K., Willems, P., Olsson, J., Beecham, S., Pathirana, A., Bülow Gregersen, I., Madsen, H., & Nguyen, V.-T.-V. (2013). Impacts of climate change on rainfall extremes and urban drainage systems: a review. *Water Science and Technology, 68*, 16–28.

Bahadur, R., Praveen, P. S., Xu, Y., & Ramanathan, V. (2012). Solar absorption by elemental and brown carbon determined from spectral observations. *Proceedings of the National Academy of Sciences, 109*, 17366–17371.

Cao, J.-J., Xu, B.-Q., He, J.-Q., Liu, X.-Q., Han, Y.-M., Wang, G.-h., & Zhu, C.-s. (2009). Concentrations, seasonal variations, and transport of carbonaceous aerosols at a remote Mountainous region in western China. *Atmospheric Environment, 43*, 4444–4452.

Cao, J., Pan, Y., Yu, S., Zheng, B., Ji, D., Hu, J., & Liu, J. (2022). Rapid decline in atmospheric organic carbon deposition in North China between 2016 and 2020. *Atmospheric Environment*, Article 119030.

Cerqueira, M., Pio, C., Legrand, M., Puxbaum, H., Kasper-Giebl, A., Afonso, J., Preunkert, S., Gelencsér, A., & Fialho, P. (2010). Particulate carbon in precipitation at European background sites. *Journal of Aerosol Science, 41*, 51–61.

Chate, D. M., Murugavel, P., Ali, K., Tiwari, S., & Beig, G. (2011). Below-cloud rain scavenging of atmospheric aerosols for aerosol deposition models. *Atmospheric Research, 99*, 528–536.

Chen, S., Xie, Q., Su, S., Wu, L., Zhong, S., Zhang, Z., Ma, C., Qi, Y., Hu, W., Deng, J., Ren, L., Zhu, D., Guo, Q., Liu, C.-Q., Jang, K.-S., & Fu, P. (2022). Source and Formation Process Impact the Chemodiversity of Rainwater Dissolved Organic Matter along the Yangtze River Basin in Summer. *Water Research, 211*, Article 118024.

de Sá Silva, A. C. R., Bimbato, A. M., Balestieri, J. A. P., & Vilanova, M. R. N. (2022). Exploring environmental, economic and social aspects of rainwater harvesting systems: A review. *Sustainable Cities and Society, 76*, Article 103475.

Fang, W., Andersson, A., Zheng, M., Lee, M., Holmstrand, H., Kim, S.-W., Du, K., & Gustafsson, Ö. (2017). Divergent Evolution of Carbonaceous Aerosols during Dispersal of East Asian Haze. *Scientific Reports, 7*, 10422.

Feng, S., Xu, W., Cheng, M., Ma, Y., Wu, L., Kang, J., Wang, K., Tang, A., Collett, J. L., Fang, Y., Goulding, K., Liu, X., & Zhang, F. (2022). Overlooked Nonagricultural and Wintertime Agricultural NH3 Emissions in Quzhou County, North China Plain: Evidence from 15N-Stable Isotopes. *Environmental Science & Technology Letters, 9*, 127–133.

Feng, Z., Huang, Y., Feng, Y., Ogura, N., & Zhang, F. (2001). Chemical Composition of Precipitation in Beijing Area, Northern China. *Water, Air, and Soil Pollution, 125*, 345–356.

Ge, B., Xu, D., Wild, O., Yao, X., Wang, J., Chen, X., Tan, Q., Pan, X., & Wang, Z. (2021). Inter-annual variations of wet deposition in Beijing from 2014–2017: implications of below-cloud scavenging of inorganic aerosols. *Atmospheric Chemistry and Physics, 21*, 9441–9454.

Godoy-Silva, D., Nogueira, R. F. P., & Campos, M. L. A. M. (2017). A 13-year study of dissolved organic carbon in rainwater of an agro-industrial region of São Paulo state (Brazil) heavily impacted by biomass burning. *Science of The Total Environment, 609*, 476–483.

Han, G., Song, Z., Tang, Y., Wu, Q., & Wang, Z. (2019). Ca and Sr isotope compositions of rainwater from Guiyang city, Southwest China: Implication for the sources of atmospheric aerosols and their seasonal variations. *Atmospheric Environment, 214*, Article 116854.

Han, G., Tang, Y., Wu, Q., & Tan, Q. (2010). Chemical and strontium isotope characterization of rainwater in karst virgin forest, Southwest China. *Atmospheric Environment, 44*, 174–181.

Herckes, P., Lee, T., Trenary, L., Kang, G., Chang, H., & Collett, J. L. (2002). Organic Matter in Central California Radiation Fogs. *Environmental Science & Technology, 36*, 4777–4782.

Hürlimann, M., McArdell, B. W., & Rickli, C. (2015). Field and laboratory analysis of the runout characteristics of hillslope debris flows in Switzerland. *Geomorphology, 232*, 20–32.

Iavorivska, L., Boyer, E. W., & DeWalle, D. R. (2016). Atmospheric deposition of organic carbon via precipitation. *Atmospheric Environment, 146*, 153–163.

Iavorivska, L., Boyer, E. W., Grimm, J. W., Miller, M. P., DeWalle, D. R., Davis, K. J., & Kaye, M. W. (2017). Variability of dissolved organic carbon in precipitation during storms at the Shale Hills Critical Zone Observatory. *Hydrological Processes, 31*, 2935–2950.

Jiang, W., & Tan, Y. (2022). Overview on failures of urban underground infrastructures in complex geological conditions due to heavy rainfall in China during 1994–2018. *Sustainable Cities and Society, 76*, Article 103509.

Kanakidou, M., Duce, R. A., Prospero, J. M., Baker, A. R., Benitez-Nelson, C., Dentener, F. J., Hunter, K. A., Liss, P. S., Mahowald, N., Okin, G. S., Sarin, M., Tsigaridis, K., Uematsu, M., Zamora, L. M., & Zhu, T. (2012). Atmospheric fluxes of organic N and P to the global ocean. *Global Biogeochemical Cycles, 26*.

Keresztesi, Á., Nita, I.-A., Boga, R., Birsan, M.-V., Bodor, Z., & Szép, R. (2020). Spatial and long-term analysis of rainwater chemistry over the conterminous United States. *Environmental Research*, Article 109872.

Khare, Puja, Goel, Ankkur, Patel, Devendra, & Behari, Jairaj (2004). Chemical characterization of rainwater at a developing urban habitat of Northern India. *Atmospheric Research, 69*, 135–145.

Kieber, R. J., Peake, B., Willey, J. D., & Avery, G. B. (2002). Dissolved organic carbon and organic acids in coastal New Zealand rainwater. *Atmospheric Environment, 36*, 3557–3563.

Lee, K.-S., Lee, D.-S., Lim, S.-S., Kwak, J.-H., Jeon, B.-J., Lee, S.-I., Lee, S.-M., & Choi, W.-J. (2012). Nitrogen isotope ratios of dissolved organic nitrogen in wet precipitation in a metropolis surrounded by agricultural areas in southern Korea. *Agriculture, Ecosystems & Environment, 159*, 161–169.

Li, C., Chen, P., Kang, S., Yan, F., Li, X., Qu, B., & Sillanpää, M. (2016a). Carbonaceous matter deposition in the high glacial regions of the Tibetan Plateau. *Atmospheric Environment, 141*, 203–208.
Li, C., Yan, F., Kang, S., Chen, P., Hu, Z., Han, X., Zhang, G., Gao, S., Qu, B., & Sillanpää, M. (2017). Deposition and light absorption characteristics of precipitation dissolved organic carbon (DOC) at three remote stations in the Himalayas and Tibetan Plateau, China. *Science of The Total Environment, 605-606*, 1039–1046.
Li, C., Yan, F., Kang, S., Chen, P., Qu, B., Hu, Z., & Sillanpää, M. (2016b). Concentration, sources, and flux of dissolved organic carbon of precipitation at Lhasa city, the Tibetan Plateau. *Environmental Science and Pollution Research, 23*, 12915–12921.
Li, X., & Kuang, W. (2020). Urban land use /cover change and its impact on urban flood regulation ecosystem service in Beijing. *Acta Ecologica Sinica, 40*, 5525–5533.
Li, Y., Ma, C., & Wang, Y. (2019). Landslides and debris flows caused by an extreme rainstorm on 21 July 2012 in mountains near Beijing, China. *Bulletin of Engineering Geology and the Environment, 78*, 1265–1280.
Liu, J., Han, G., Liu, X., Liu, M., Song, C., Zhang, Q., Yang, K., & Li, X. (2019). Impacts of Anthropogenic Changes on the Mun River Water: Insight from Spatio-Distributions and Relationship of C and N Species in Northeast Thailand. *International Journal of Environmental Research and Public Health, 16*, 659.
Liu, Y., Wu, Q., Jia, H., Wang, Z., Gao, S., & Zeng, J. (2022). Anthropogenic rare earth elements in urban lakes: Their spatial distributions and tracing application. *Chemosphere, 300*, Article 134534.
Monteiro, L. R., Terzer-Wassmuth, S., Matiatos, I., Douence, C., & Wassenaar, L. I. (2021). Distinguishing in-cloud and below-cloud short and distal N-sources from high-temporal resolution seasonal nitrate and ammonium deposition in Vienna, Austria. *Atmospheric Environment, 266*, Article 118740.
Pan, Y., Wang, Y., Xin, J., Tang, G., Song, T., Wang, Y., Li, X., & Wu, F. (2010). Study on dissolved organic carbon in precipitation in Northern China. *Atmospheric Environment, 44*, 2350–2357.
Pandey, J., Singh, A. V., Singh, R., Kaushik, P., & Pandey, U. (2015). Atmospheric deposition coupled terrestrial export of organic carbon in Ganga River (India): linking cross-domain carbon transfer to river DOC. *International Aquatic Research, 7*, 273–285.
Pantelaki, I., Papatzelou, A., Balla, D., Papageorgiou, A., & Voutsa, D. (2018). Characterization of dissolved organic carbon in rainwater of an urban/coastal site in Mediterranean area. *Science of The Total Environment, 627*, 1433–1441.
Qin, C., Li, S.-L., Waldron, S., Yue, F.-J., Wang, Z.-J., Zhong, J., Ding, H., & Liu, C.-Q. (2020). High-frequency monitoring reveals how hydrochemistry and dissolved carbon respond to rainstorms at a karstic critical zone, Southwestern China. *Science of The Total Environment*, Article 136833.
Rao, W., Han, G., Tan, H., Jin, K., Wang, S., & Chen, T. (2017). Chemical and Sr isotopic characteristics of rainwater on the Alxa Desert Plateau, North China: Implication for air quality and ion sources. *Atmospheric Research, 193*, 163–172.
Santos, P. S. M., Santos, E. B. H., & Duarte, A. C. (2013). Seasonal and air mass trajectory effects on dissolved organic matter of bulk deposition at a coastal town in south-western Europe. *Environmental Science and Pollution Research, 20*, 227–237.
Shadmehri Toosi, A., Danesh, S., Ghasemi Tousi, E., & Doulabian, S. (2020). Annual and seasonal reliability of urban rainwater harvesting system under climate change. *Sustainable Cities and Society, 63*, Article 102427.
Sun, S., Liu, S., Li, L., & Zhao, W. (2021). Components, acidification characteristics, and sources of atmospheric precipitation in Beijing from 1997 to 2020. *Atmospheric Environment, 266*, Article 118707.
Szép, R., Mateescu, E., Nechifor, A. C., & Keresztesi, Á. (2017). Chemical characteristics and source analysis on ionic composition of rainwater collected in the Carpathians "Cold Pole," Ciuc basin, Eastern Carpathians, Romania. *Environmental Science and Pollution Research, 24*, 27288–27302.
Szidat, S., Jenk, T. M., Synal, H. A., Kalberer, M., Wacker, L., Hajdas, I., Kasper-Giebl, A., & Baltensperger, U. (2006). Contributions of fossil fuel, biomass-burning, and biogenic emissions to carbonaceous aerosols in Zurich as traced by C-14. *Journal of Geophysical Research-Atmospheres, 111*.
Wang, H., & Han, G. (2011). Chemical composition of rainwater and anthropogenic influences in Chengdu, Southwest China. *Atmospheric Research, 99*, 190–196.
Wang, X., Ge, T., Xu, C., Xue, Y., & Luo, C. (2016). Carbon isotopic (14C and 13C) characterization of fossil-fuel derived dissolved organic carbon in wet precipitation in Shandong Province, China. *Journal of Atmospheric Chemistry, 73*, 207–221.
Wang, Z.-J., Yue, F.-J., Wang, Y.-C., Qin, C.-Q., Ding, H., Xue, L.-L., & Li, S.-L. (2022). The effect of heavy rainfall events on nitrogen patterns in agricultural surface and underground streams and the implications for karst water quality protection. *Agricultural Water Management, 266*, Article 107600.
Wei, J., Huang, W., Li, Z., Xue, W., Peng, Y., Sun, L., & Cribb, M. (2019). Estimating 1-km-resolution PM2.5 concentrations across China using the space-time random forest approach. *Remote Sensing of Environment, 231*, Article 111221.
Wen, Z., Xu, W., Li, Q., Han, M., Tang, A., Zhang, Y., Luo, X., Shen, J., Wang, W., Li, K., Pan, Y., Zhang, L., Li, W., Collett, J. L., Zhong, B., Wang, X., Goulding, K., Zhang, F., & Liu, X. (2020). Changes of nitrogen deposition in China from 1980 to 2018. *Environment International, 144*, Article 106022.
Willey, J. D., Kieber, R. J., & Avery, G. B. (2006). Changing Chemical Composition of Precipitation in Wilmington, North Carolina, U.S.A.: Implications for the Continental U.S.A. *Environmental Science & Technology, 40*, 5675–5680.
Willey, J. D., Kieber, R. J., Eyman, M. S., & Avery, G. B., Jr (2000). Rainwater dissolved organic carbon: Concentrations and global flux. *Global Biogeochemical Cycles, 14*, 139–148.
Witkowska, A., & Lewandowska, A. U. (2016). Water soluble organic carbon in aerosols (PM1, PM2.5, PM10) and various precipitation forms (rain, snow, mixed) over the southern Baltic Sea station. *Science of The Total Environment, 573*, 337–346.
Wu, Q., & Han, G. (2018). δ13CDIC tracing of dissolved inorganic carbon sources at Three Gorges Reservoir, China. *Water science and technology: a journal of the International Association on Water Pollution Research, 77*, 555–564.
Wu, Q., Han, G., Tao, F., & Tang, Y. (2012). Chemical composition of rainwater in a karstic agricultural area, Southwest China: The impact of urbanization. *Atmospheric Research, 111*, 71–78.
Wu, Y., Li, J., Jiang, Z., Liu, S., & Huang, X. (2022a). Shifting of dissolved organic matter components and sources in precipitation into an intensified anthropogenic influenced embayment: Interpretation from spectral characteristics and dual stable isotopes. *Atmospheric Research, 270*, Article 106089.
Wu, Z., Zhang, Y., Zhang, L., Zheng, H., & Huang, X. (2022b). A Comparison of Convective and Stratiform Precipitation Microphysics of the Record-breaking Typhoon In-Fa (2021). *Remote Sensing, 14*, 344.
Xing, J., Song, J., Yuan, H., Li, X., Li, N., Duan, L., & Qi, D. (2019). Atmospheric wet deposition of dissolved organic carbon to a typical anthropogenic-influenced semi-enclosed bay in the western Yellow Sea, China: Flux, sources and potential ecological environmental effects. *Ecotoxicology and Environmental Safety, 182*, Article 109371.
Xing, J., Song, J., Yuan, H., Li, X., Li, N., Duan, L., Qu, B., Wang, Q., & Kang, X. (2017). Chemical characteristics, deposition fluxes and source apportionment of precipitation components in the Jiaozhou Bay, North China. *Atmospheric Research, 190*, 10–20.
Xu, Z., & Han, G. (2009). Chemical and strontium isotope characterization of rainwater in Beijing, China. *Atmospheric Environment, 43*, 1954–1961.
Xu, Z., Tang, Y., & Ji, J. (2012). Chemical and strontium isotope characterization of rainwater in Beijing during the 2008 Olympic year. *Atmospheric Research, 107*, 115–125.
Yamashita, S., Watanabe, R., & Shimatani, Y. (2016). Smart adaptation activities and measures against urban flood disasters. *Sustainable Cities and Society, 27*, 175–184.
Yan, G., & Kim, G. (2012). Dissolved organic carbon in the precipitation of Seoul, Korea: Implications for global wet depositional flux of fossil-fuel derived organic carbon. *Atmospheric Environment, 59*, 117–124.
Yang, L., Smith, J., & Niyogi, D. (2019). Urban Impacts on Extreme Monsoon Rainfall and Flooding in Complex Terrain. *Geophysical Research Letters, 46*, 5918–5927.
Zeng, J., Ge, X., Wu, Q., & Zhang, S. (2021). Three-Year Variations in Criteria Atmospheric Pollutants and Their Relationship with Rainwater Chemistry in Karst Urban Region, Southwest China. *Atmosphere, 12*, 1073.
Zeng, J., Han, G., Wu, Q., & Tang, Y. (2020a). Effects of agricultural alkaline substances on reducing the rainwater acidification: Insight from chemical compositions and calcium isotopes in a karst forests area. Agriculture. *Ecosystems & Environment, 290*, Article 106782.
Zeng, J., Han, G., Zhang, S., & Qu, R. (2023). Nitrate dynamics and source identification of rainwater in Beijing during rainy season: Insight from dual isotopes and Bayesian Model. *Science of The Total Environment, 856*, 159234.
Zeng, J., Han, G., Zhang, S., Xiao, X., Li, Y., Gao, X., Wang, D., & Qu, R. (2022). Rainwater chemical evolution driven by extreme rainfall in megacity: Implication for the urban air pollution source identification. *Journal of Cleaner Production, 372*, Article 133732.
Zeng, J., Yue, F.-J., Li, S.-L., Wang, Z.-J., Qin, C.-Q., Wu, Q.-X., & Xu, S. (2020b). Agriculture driven nitrogen wet deposition in a karst catchment in southwest China. *Agriculture, Ecosystems & Environment, 294*, Article 106883.
Zeng, J., Yue, F.-J., Li, S.-L., Wang, Z.-J., Wu, Q., Qin, C.-Q., & Yan, Z.-L. (2020c). Determining rainwater chemistry to reveal alkaline rain trend in Southwest China: Evidence from a frequent-rainy karst area with extensive agricultural production. *Environmental Pollution, 266*, Article 115166.
Zeng, J., Yue, F.-J., Wang, Z.-J., Wu, Q., Qin, C.-Q., & Li, S.-L. (2019). Quantifying depression trapping effect on rainwater chemical composition during the rainy season in karst agricultural area, southwestern China. *Atmospheric Environment, 218*, Article 116998.
Zeng, J., Yue, F.-J., Xiao, M., Wang, Z. J., Wu, Q., & Qin, C.-Q. (2020d). Dissolved organic carbon in rainwater from a karst agricultural area of Southwest China: Variations, sources, and wet deposition fluxes. *Atmospheric Research, 245*, Article 105140.
Zhang, S., Ma, Z., Li, Z., Zhang, P., Liu, Q., Nan, Y., Zhang, J., Hu, S., Feng, Y., & Zhao, H. (2021a). Using CYGNSS Data to Map Flood Inundation during the 2021 Extreme Precipitation in Henan Province, China. *Remote Sensing, 13*, 5181.
Zhang, Y., Gao, Y., Guo, L., & Zhang, M. (2021b). Numerical analysis of aerosol direct and indirect effects on an extreme rainfall event over Beijing in July 2016. *Atmospheric Research, 264*, Article 105871.
Zhang, Y., Lee, X., Cao, F., & Huang, D. (2011). Seasonal variation and sources of low molecular weight organic acids in precipitation in the rural area of Anshun. *Chinese Science Bulletin, 56*, 1005–1010.
Zhong, S.-X., Zhuang, Y., Hu, S., Chen, Z.-T., Ding, W.-Y., Feng, Y.-R., … Meng, W.-G. (2021). Verification and Assessment of Real-time Forecasts of Two Extreme Heavy Rain Events in Zhengzhou by Operational NWP Models. *Journal of Tropical Meteorology, 27*, 406.