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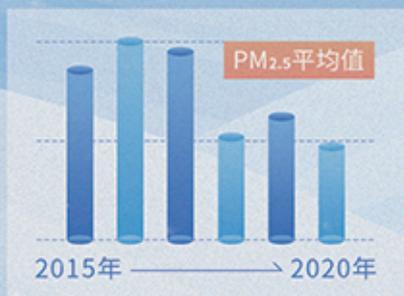
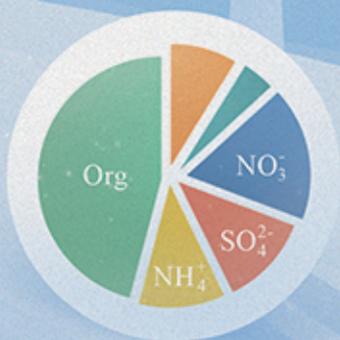
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## 北京冬季奥运会历史同期大气PM<sub>2.5</sub>污染特征分析

刘玥晨, 满睿琪, 裘彦挺, 杨佳炜, 王均睿, 谭瑞, 汤丽姿, 俞颖, 宋锴, 郭松, 陈仕意,  
曾立民, 吴志军, 胡敏



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《环境科学》征订启事(4211) 《环境科学》征稿简则(4312) 信息(3922, 4031, 4107)

# 北京冬季奥运会历史同期大气 PM<sub>2.5</sub> 污染特征分析

刘玥晨, 满睿琪, 裘彦挺, 杨佳炜, 王均睿, 谭瑞, 汤丽姿, 俞颖, 宋锴, 郭松, 陈仕意, 曾立民, 吴志军\*, 胡敏

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**摘要:** 基于2015~2021年的1~3月北京市大气PM<sub>2.5</sub>浓度与化学组成长期观测数据,分析了2022年北京冬季奥林匹克运动会(冬奥会)和北京冬季残疾人奥林匹克运动会(冬季残奥会)历史同期的PM<sub>2.5</sub>污染态势、化学组成特征以及潜在源区。2015~2018年的1~3月重污染[日均 $\rho(\text{PM}_{2.5}) > 75 \mu\text{g}\cdot\text{m}^{-3}$ ]天数以及重污染期间PM<sub>2.5</sub>平均值下降十分显著,之后这两者未发生明显改变。2018~2021年的1~3月每年平均发生重污染23 d,重污染天 $\rho(\text{PM}_{2.5})$ 平均值约为 $120.0 \mu\text{g}\cdot\text{m}^{-3}$ 。2015~2021年的1~3月超长重污染过程(连续重污染超过5 d)平均每年发生2~3次,其中2021年发生3次,且持续时间最长达到8 d。历年冬奥会历史同期发生重污染的天数为2~9 d,春节期间烟花爆竹大量燃放可能是该时期重污染发生的重要原因之一;冬季残奥会历史同期重污染天数一般为1~5 d,但2021年受频繁出现的静稳天气影响,重污染天数高达9 d。在同时段重污染期间,PM<sub>2.5</sub>化学组成均以二次组分为主,例如在PM<sub>2.5</sub>可测组分中,2020年NO<sub>3</sub><sup>-</sup>质量分数高达46%,较同年清洁天(11%)显著增加;SO<sub>4</sub><sup>2-</sup>质量分数为12%~19%,说明当前硫酸盐污染仍不容忽视。北京市1~3月PM<sub>2.5</sub>主要贡献区域包括内蒙古自治区中西部、河北省、天津市、山西省、陕西省、山东省中西部和河南省北部。研究结果将为北京市冬季空气质量持续改善以及2022年冬奥会与冬季残奥会期间北京市环境空气质量保障提供科学依据。

**关键词:** 2022年北京冬季奥林匹克运动会; PM<sub>2.5</sub>; 重污染; 化学组成; 潜在源区

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## Characteristics of PM<sub>2.5</sub> Pollution in Beijing During the Historical Period of the 2022 Olympic Winter Games

LIU Yue-chen, MAN Rui-qi, QIU Yan-ting, YANG Jia-wei, WANG Jun-rui, TAN Rui, TANG Li-zi, YU Ying, SONG Kai, GUO Song, CHEN Shi-yi, ZENG Li-min, WU Zhi-jun\*, HU Min

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**Abstract:** Based on the dataset derived from January to March between 2015 and 2021 in Beijing, the PM<sub>2.5</sub> pollution characteristics and its potential source regions during the historical period of the Beijing 2022 Olympic Winter Games and Paralympic Winter Games were investigated. From 2015 to 2018, both the number of severely polluted days (daily average  $\rho(\text{PM}_{2.5}) > 75 \mu\text{g}\cdot\text{m}^{-3}$ ) and the average PM<sub>2.5</sub> concentrations during severe pollution episodes decreased significantly in the period of January to March. While, neither variable has changed obviously since 2018. On average, severely polluted days occurred 23 times in each year between 2018 and 2021 during the period of January to March, and the average of  $\rho(\text{PM}_{2.5})$  was approximately  $120.0 \mu\text{g}\cdot\text{m}^{-3}$  during such polluted days. From January to March in 2015-2021, the severely polluted event with more than 5 consecutive polluted days occurred 2-3 times in each year, and the severest one lasted 8 d. During the historical period of the Beijing 2022 Olympic Winter Games, severely polluted days took place 2-9 d every year. The large quantities of fireworks during the Spring Festival maybe one of important primary sources of the PM<sub>2.5</sub>. The number of severely polluted days during the historical period of the Paralympic Winter Games ranged from 1 to 5 d, except for 2021 with 9 d owing to the frequent stagnant weather condition. The PM<sub>2.5</sub> chemical composition was dominated by secondary species on severely polluted days during the historical period of the Beijing 2022 Olympic Winter Games and Paralympic Winter Games. Nitrate accounted for 46% of the measurable chemical components of PM<sub>2.5</sub> during severe pollution events in 2020, which was remarkably higher than that during clean days in the same year (11%). The mass fraction of SO<sub>4</sub><sup>2-</sup> ranged from 12% to 19% in 2018-2020, indicating that the contribution of sulfate was much less, but cannot be ignored. The main potential source regions of PM<sub>2.5</sub> in Beijing during the period concerned in this study were central and western Inner Mongolia, Hebei Province, Tianjin City, Shanxi Province, Shaanxi Province, central and western Shandong Province, and northern Henan Province.

**Key words:** Beijing 2022 Olympic Winter Games; PM<sub>2.5</sub>; heavy pollution; chemical composition; potential source regions

2022年北京冬季奥林匹克运动会(冬奥会)于2022年2月4~20日在北京市举办,随后3月4~14日举办2022年北京冬季残疾人奥林匹克运动会(冬季残奥会)。良好的空气质量是冬奥会与冬季残奥会顺利举办的重要保障。近年来,北京市环境空气质量明显改善,以SO<sub>2</sub>和PM<sub>2.5</sub>为代表的污染物浓度持续降低<sup>[1-6]</sup>,NO<sub>x</sub>(NO<sub>x</sub>=NO+NO<sub>2</sub>)和挥发性有机物的排放也得到有效控制<sup>[7]</sup>。有研究表明,二次

无机盐(SO<sub>4</sub><sup>2-</sup>+NO<sub>3</sub><sup>-</sup>+NH<sub>4</sub><sup>+</sup>,SNA)在北京市PM<sub>2.5</sub>中的质量分数逐年增加<sup>[7-9]</sup>,且由于SO<sub>2</sub>浓度降低,NO<sub>3</sub><sup>-</sup>已经取代SO<sub>4</sub><sup>2-</sup>成为对PM<sub>2.5</sub>贡献最高的水溶

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性无机离子<sup>[10~20]</sup>.此外,总有机物的浓度和质量分数呈降低趋势,但二次有机气溶胶在有机物中所占质量分数增加<sup>[7,21,22]</sup>.另一方面,已有研究发现区域传输是北京市 PM<sub>2.5</sub> 污染的重要来源<sup>[23]</sup>.

然而,目前的研究大多集中在对整个冬季 PM<sub>2.5</sub> 化学组成特征的分析<sup>[7,9,24]</sup>,针对近年来,尤其是2018年以后两奥运会历史同期北京市 PM<sub>2.5</sub> 化学组成特征和污染态势等长期变化的详细分析仍然较少.本研究基于2015~2021年北京市 PM<sub>2.5</sub> 物理化学性质的长期测量数据,综合分析了历年来冬奥会和冬季残奥会历史同期 PM<sub>2.5</sub> 的污染态势、化学组成特征和潜在源区等.考虑到冬奥会和冬季残奥会运动员将提前入住奥运村,本研究选取1~3月作为分析时间段.本研究的结果将有助于北京市冬季空气质量的持续改善,并为2022年冬奥会与冬季残奥会期间北京市环境空气质量保障提供科学依据.

## 1 材料与方法

### 1.1 样品采集与分析

观测时间为2015~2021年的1月1日~3月31日,观测地点为北京大学理科教学楼楼顶.采样口距地面高度约为30 m,四周为教学楼,东侧约200 m为中关村北大街.使用Partisol-plus 2025i连续采样器(美国Thermo Fisher)进行PM<sub>2.5</sub>采样,流量为16.7 L·min<sup>-1</sup>,滤膜分别为直径47 mm的Teflon膜与石英膜.采样时长为23 h 59 min(07:01~次日07:00).采样前后,Teflon膜放置在超净室[(20±1)℃,(40±5)%]内平衡24 h.采样后的Teflon膜倒扣于100 mL洁净干燥的烧杯中,加入20 mL去离子水(Milli-Q Gradient纯水机制备,25℃,18.2 MΩ·cm),超声提取30 min.采用离子色谱法(DIONEX ICS2000/ICS2500)分析提取液中的水溶性无机离子(Na<sup>+</sup>、NH<sub>4</sub><sup>+</sup>、K<sup>+</sup>、Mg<sup>2+</sup>、Ca<sup>2+</sup>、Cl<sup>-</sup>、NO<sub>3</sub><sup>-</sup>和SO<sub>4</sub><sup>2-</sup>)<sup>[25]</sup>.基于热光反射法,使用元素碳/有机碳分析仪(美国Sunset Lab.)分析石英膜样品中有机碳(organic carbon, OC)与元素碳(element carbon, EC)含量<sup>[26]</sup>.给定有机物(Org)和OC之间换算系数为1.6,据此算出Org的浓度.PM<sub>2.5</sub>浓度由锥形元件振动微天平监测仪(TEOM,美国Thermo-Fisher Inc.)测定.环境相对湿度(RH)、温度(T)、风向和风速均通过自动气象站(Met one Instrument Inc.)测定.

### 1.2 潜在源分析

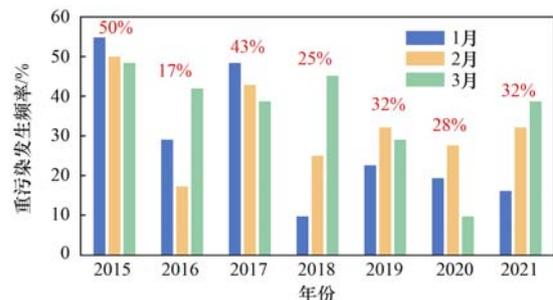
为探究2015~2021年的1~3月北京市PM<sub>2.5</sub>的潜在源区和各源区对PM<sub>2.5</sub>浓度的贡献,利用HYSPLIT-4<sup>[27]</sup>模式,采用总空间方差方法进行北京

市潜在源贡献因子(PSCF)<sup>[28,29]</sup>和浓度权重轨迹(CWT)<sup>[30]</sup>分析.模拟受点为北京大学(39°59'N, 116°18'E),轨迹计算起始高度为500 m,到达受点的时长设置为96 h,研究区域按1°×1°划分网格.PSCF分析法是一种基于气流轨迹分析来识别污染源区的方法,能够解析气流轨迹途经的区域对受点地区污染的贡献,反映某区域污染轨迹所占比例,但它无法区分相同PSCF值的区域对受点PM<sub>2.5</sub>浓度贡献的大小.因此,需进一步采用CWT分析法计算潜在源区气流轨迹浓度权重,分析不同潜在源区的污染程度.PSCF与CWT分析方法详见文献[28~31].

## 2 结果与讨论

### 2.1 PM<sub>2.5</sub>污染态势

根据《环境空气质量标准》(GB 3095-2012)对PM<sub>2.5</sub>污染等级进行了划分:认定日均 $\rho(\text{PM}_{2.5}) \leq 35.0 \mu\text{g}\cdot\text{m}^{-3}$ 时为清洁天,  $35.0 \mu\text{g}\cdot\text{m}^{-3} < \text{日均} \rho(\text{PM}_{2.5}) \leq 75.0 \mu\text{g}\cdot\text{m}^{-3}$ 时为污染天,  $\text{日均} \rho(\text{PM}_{2.5}) > 75.0 \mu\text{g}\cdot\text{m}^{-3}$ 时为重污染天.基于所测PM<sub>2.5</sub>浓度,分别对2015~2021年的1~3月中各月份的重污染发生频率(当月重污染天数与当月总天数之比)进行统计,结果如图1所示.2015~2018年的1月重污染发生频率整体呈下降趋势,重污染天数由17 d降低至3 d,发生频率由55%降低至10%.2018年以后,重污染发生频率有所增加,其中2021年1月为16%.2月重污染发生频率的变化趋势与1月相同.历年冬奥会历史同期发生重污染的天数为2~9 d.2021年2月4~20日(冬奥会历史同时段)的重污染天数为5 d,发生频率为29%.2月12~14日的重污染发生在春节(农历腊月三十至正月初六)期间(图2),烟花爆竹大量燃放可能是该重污染过程发生的重要原因<sup>[32~34]</sup>.根据图2,2016年和2019年冬奥会历史



柱子上方标注数值表示2月重污染发生频率  
图1 2015~2021年的1~3月各月份重污染发生频率

Fig. 1 Frequency of heavy pollution from January to March in 2015-2021

同期均与春节重叠,且均出现重污染过程.而2022年春节与冬奥会也存在重叠日期(2月4~7日),应对该时段可能发生的重污染过程进行防范.除2021年之外,2015~2020年的3月重污染频率整体呈降低趋势.受新冠疫情等因素的影响<sup>[35~37]</sup>,2020年3月重污染发生频率降低为10%,而2021年增高至39%.历年冬季残奥会历史同期重污染天数为1~5 d.但2021年3月4~14日(冬季残奥会历史同时段)的重污染天数高达9 d,占比为82%.该时间段内,NO<sub>x</sub>的平均浓度较高(14.1

$\mu\text{g}\cdot\text{m}^{-3}$ );风向以南风为主,平均风速约为 $1.9\text{ m}\cdot\text{s}^{-1}$ ,风速较小,不利于污染物扩散.高浓度气态前体物叠加静稳天气可能是2021年重污染过程频繁出现的重要原因<sup>[38,39]</sup>.整体而言,近年来北京市全年重污染天数逐年减少<sup>[40]</sup>,2015~2018年的1~3月重污染发生频率降低,但2018年以后未发生显著变化,尤其是在冬奥会与冬季残奥会历史同时段,PM<sub>2.5</sub>重污染频率仍然较高.Lei等<sup>[7]</sup>的研究也指出,2015~2020年的1月和2月的重污染频率在统计上没有显著差异.

年份	4日	5日	6日	7日	8日	9日	10日	11日	12日	13日	14日	15日	16日	17日	18日	19日	20日	重污染天数/d
2015																		8
2016																		4
2017																		9
2018																		4
2019																		2
2020																		6
2021																		5
2022																		/

绿色表示清洁天,黄色表示污染天,红色表示重污染天,蓝色表示2022年春节

图2 2015~2021年冬奥会历史同期(2月4~20日)春节期间(农历腊月三十至正月初六)的污染情况和冬奥会历史同期的重污染天数

Fig. 2 Total number of severely polluted days and pollution degrees during the Spring Festival (from the 30<sup>th</sup> day of the 12<sup>th</sup> month to the 6<sup>th</sup> day of the 1<sup>st</sup> month of the following year in the lunar calendar) in the historical period of the 2022 Olympic Winter Games in 2015-2021

图3为2015~2021年的1~3月重污染天PM<sub>2.5</sub>浓度平均值和最大值的统计结果.从中可知,2016~2017年的1~3月重污染天 $\rho(\text{PM}_{2.5})$ 平均值超过 $140\text{ }\mu\text{g}\cdot\text{m}^{-3}$ ,2018年降低至 $122.7\text{ }\mu\text{g}\cdot\text{m}^{-3}$ ,此后基本保持稳定.除2017年以外,重污染天PM<sub>2.5</sub>最大值整体呈降低趋势.2015年重污染天 $\rho(\text{PM}_{2.5})$ 最大值为 $318.8\text{ }\mu\text{g}\cdot\text{m}^{-3}$ ,2021年降低为 $239.6\text{ }\mu\text{g}\cdot\text{m}^{-3}$ ,降幅为25%.Zheng等<sup>[4]</sup>的研究发现,2005~2017年我国大气人为源污染物的排放量降低了21%~59%.硫酸盐和有机物等化学组分的减少导致PM<sub>2.5</sub>浓度显著降低<sup>[46]</sup>.据文献<sup>[41]</sup>,相比于2018年,北京市2020年全年PM<sub>2.5</sub>滑动平均值同比下降约12.0%,这说明文献<sup>[42]</sup>的实施对我国环境空气质量的改善产生了积极作用<sup>[8,9,28]</sup>.

为进一步分析2015~2021年的1~3月重污染持续时长 $[\rho(\text{PM}_{2.5})$ 连续超过 $75\text{ }\mu\text{g}\cdot\text{m}^{-3}$ 的天数]的变化情况,本研究对不同持续时长的重污染过程的发生频率以及历年持续时间最长的重污染过程的天数进行了统计.根据图4(a),2015年1~3月不同持续时长的重污染过程的发生频率较为相似.2016~2017年和2019~2020年的1~3月均以短时重污染(1~2 d)和超长重污染( $\geq 5$  d)过程为主(总发生频率 $>60\%$ ).2018年1~3月未发生超长重污染

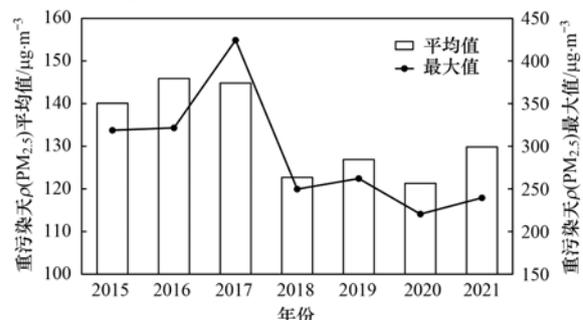


图3 2015~2021年的1~3月重污染天PM<sub>2.5</sub>平均值与最大值

Fig. 3 Average and maximum value of PM<sub>2.5</sub> during severe pollution from January to March in 2015-2021

过程.2021年1~3月以超长重污染为主,发生频率为50%.每年1~3月超长重污染过程平均发生2~3次.除2019年以外,每年冬奥会历史同期均发生了超长重污染过程.另一方面,如图4(b)所示,2015~2021年的1~3月持续时间最长的重污染过程的天数未发生显著改变.2018年最长重污染过程持续时间最短(3 d),2017与2021年最长重污染过程持续时间最长(8 d).在2017年和2021年持续时间最长的重污染过程中,平均风速分别为 $2.0\text{ m}\cdot\text{s}^{-1}$ 和 $1.7\text{ m}\cdot\text{s}^{-1}$ ,风向均以西南为主,环境RH较高,平均RH分别为50%和55%.大气环境长期处于弱南风主导的状态,导致了污染物的累积<sup>[23,25,26]</sup>,

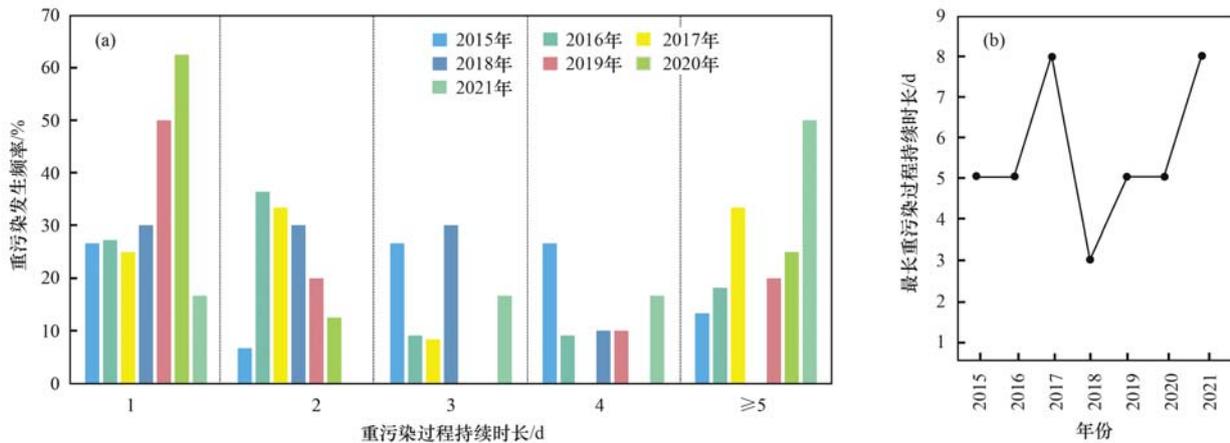


图4 2015~2021年的1~3月不同持续时长重污染过程的发生频率和历年最长重污染过程的持续时长

Fig. 4 Frequency of severe pollution episodes with different durations from January to March in 2015-2021 and the duration of the longest heavy pollution processes in each year

同时高湿条件下颗粒物液态水含量 (aerosol liquid water content, ALWC) 的增加可能进一步加重了污染程度. 因此, 长时间高湿和静稳天气出现时应警惕超长重污染过程的发生.

## 2.2 $PM_{2.5}$ 化学组成特征

2018年后,  $PM_{2.5}$  化学组成及其浓度相较于2017年及以前发生了显著改变<sup>[7]</sup>, 因此本研究针对2018~2020年冬奥会和冬季残奥会历史同期  $PM_{2.5}$  化学组成的变化情况进行了分析. 图5分别为不同污染程度下的历年2月4~20日(冬奥)和3月4~14日(残奥)  $PM_{2.5}$  化学组成的浓度和质量分数.

结果表明, 清洁天、污染天和重污染天  $PM_{2.5}$  化学组成有明显差异. 根据图5(a)和5(b), 清洁天  $PM_{2.5}$  以有机物为主, 且有机物浓度呈逐年增加趋

势. 2018年冬奥会历史同期, 清洁天有机物在  $PM_{2.5}$  可测化学组成中的质量分数为33%, 2020年增加至52%; 2019年冬季残奥会历史同期, 清洁天有机物质量分数为46%, 2020年增加至60%. 在污染期间[图5(d)和5(f)], 有机物在  $PM_{2.5}$  中的质量分数显著降低. 以2020年冬季残奥会历史同期为例, 重污染时有机物质量分数为15%, 相比清洁天减少了45%. 有研究也指出污染期间  $PM_{2.5}$  中有机物质量分数降低<sup>[43~45]</sup>.

重污染时,  $PM_{2.5}$  化学组成以二次无机盐为主. 由图5(b)可知, 清洁天时 SNA 在  $PM_{2.5}$  可测组分中的质量分数最高值为44%, 且  $SO_4^{2-}$  与  $NO_3^-$  浓度相当, 冬奥会与冬季残奥会历史同期  $SO_4^{2-}/NO_3^-$  分别为1.2和1.1. 而在污染[图5(d)]与重污染[图5

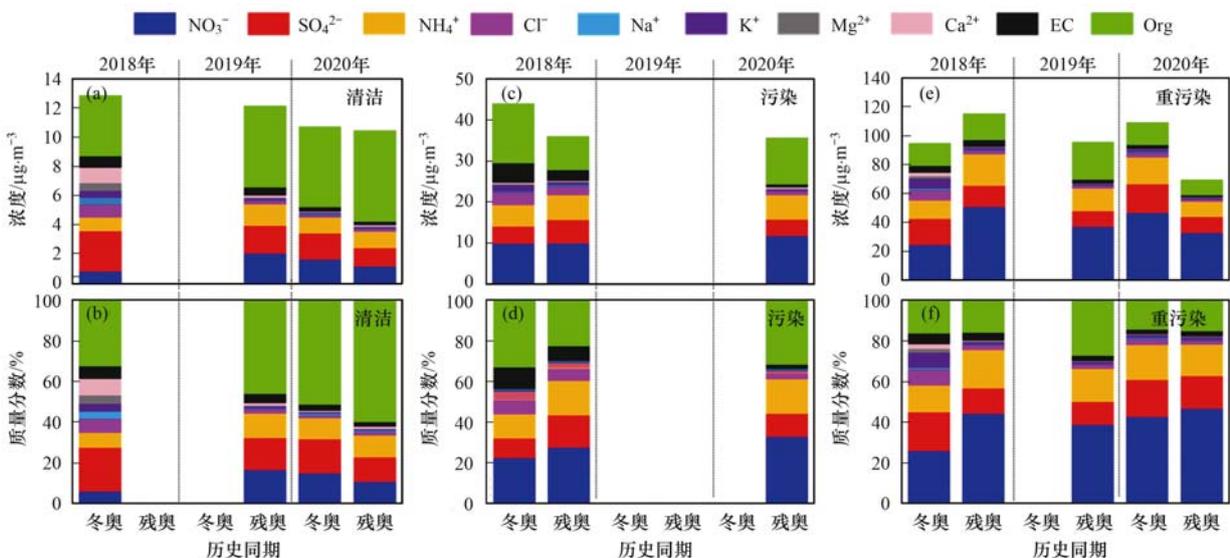


图5 不同污染程度下2018~2020年的2月4~20日(冬奥会历史同期)和3月4~14日(冬残奥会历史同期)的  $PM_{2.5}$  化学组成的浓度和质量分数

Fig. 5 Mass concentration and fraction of  $PM_{2.5}$  chemical compositions in the historical period of the Beijing 2022 Olympic Winter Games and the Paralympic Winter Games in 2018-2020

(f) 时段, SNA 的质量分数最高分别可达 61% 与 78%。此外, 在空气质量大幅改善的前提下, SNA 在 PM<sub>2.5</sub> 中的质量分数呈逐年增加趋势。造成该现象的原因可能是大气氧化性增强和频繁出现的静稳气象条件等<sup>[7]</sup>。高浓度的 NO<sub>3</sub><sup>-</sup> 是近年来 SNA 质量分数升高的主要原因。2020 年的冬季残奥会同期, 清洁天 NO<sub>3</sub><sup>-</sup> 质量分数为 11%, 污染时增加至 33%, 重污染时则高达 46%。同时, SO<sub>4</sub><sup>2-</sup>/NO<sub>3</sub><sup>-</sup> 由 1.1 降低至 0.4, NO<sub>3</sub><sup>-</sup> 替代 SO<sub>4</sub><sup>2-</sup> 成为对 PM<sub>2.5</sub> 贡献最高的水溶性无机离子。由于机动车能够排放大量 NO<sub>3</sub><sup>-</sup> 的气态前体物 NO<sub>x</sub>, 因此机动车排放可能仍然是北京市 PM<sub>2.5</sub> 的重要来源之一。该结论与已有研究相同<sup>[11-14, 16-18]</sup>。尽管相较于 NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup> 并非主导 PM<sub>2.5</sub> 的浓度, 且在重污染时段未显著增加, 但 SO<sub>4</sub><sup>2-</sup> 的质量分数始终大于 10%, 因此当前硫酸盐污染仍不容忽视。近年来, Cl<sup>-</sup> 和 K<sup>+</sup> 在不同污染程度下均表现为明显地降低趋势(例如, 2018~2020 年冬奥会历史同期清洁与重污染时段的质量分数降幅分别为 85% 与 63%), 表明生物质燃

烧排放的 PM<sub>2.5</sub> 减少。Li 等<sup>[9]</sup> 的研究也发现, 2012~2018 年生物质燃烧气溶胶在有机物中的质量分数降低了 67%。

为进一步探究以 NO<sub>3</sub><sup>-</sup> 和 SO<sub>4</sub><sup>2-</sup> 为主的二次污染物在重污染过程中的贡献, 计算了 2015 年以来北京市 1~3 月的硫转化率 (SOR) 和氮转化率 (NOR), 并分析了 SOR 和 NOR 随 PM<sub>2.5</sub> 浓度和 RH 的变化(图 6)。SOR 与 NOR 的计算公式如下:

$$\text{SOR} = [\text{SO}_4^{2-}] / ([\text{SO}_4^{2-}] + [\text{SO}_2]) \quad (1)$$

$$\text{NOR} = [\text{NO}_3^-] / ([\text{NO}_3^-] + [\text{NO}_2]) \quad (2)$$

式中, [M] 表示某物质的量浓度, 单位为 mol·m<sup>-3</sup>。有研究发现, 随着污染程度的加剧, SOR 和 NOR 逐渐上升。重污染过程中污染物二次转化率提高, 表明二次转化是重污染形成的重要原因<sup>[46]</sup>。另一方面, NOR 和 SOR 与 RH 的相关性较好 ( $R > 0.5$ ), 原因可能为重污染时环境 RH 较高, 颗粒物吸湿后 ALWC 增加<sup>[47]</sup>。作为液相化学反应介质, ALWC 与二次无机盐存在正反馈作用<sup>[48, 49]</sup>, 能够促进 SNA 的生成<sup>[50, 51]</sup>。

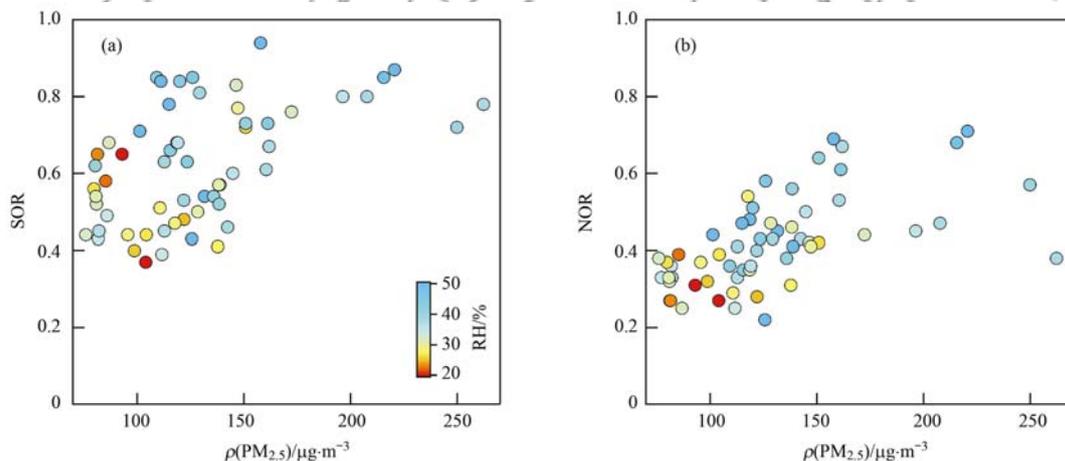


图 6 硫转化率 (SOR) 和氮转化率 (NOR) 随相对湿度 (RH) 和 PM<sub>2.5</sub> 浓度的变化情况

Fig. 6 Sulfur oxidation rate (SOR) and nitrogen oxidation rate (NOR) as a function of PM<sub>2.5</sub>, influenced by the relative humidity (RH)

### 2.3 PM<sub>2.5</sub> 潜在源区分析

当前, 区域传输是北京市 PM<sub>2.5</sub> 污染的重要来源<sup>[23, 52-54]</sup>。按照风向风速, 将 2015~2021 年的 1~3 月重污染时段的天气类型分为静稳天 (风速  $\leq 2 \text{ m}\cdot\text{s}^{-1}$ )、南风主导天 (风速  $> 2 \text{ m}\cdot\text{s}^{-1}$ , 且风向为南) 和北风主导天 (风速  $> 2 \text{ m}\cdot\text{s}^{-1}$ , 且风向为北)。图 7 为重污染期间 PM<sub>2.5</sub> 在不同天气类型下的 PSCF 与 CWT 结果。

静稳天 [图 7(a)] PSCF 大于 0.9 的区域分布范围较广。北京市 PM<sub>2.5</sub> 的主要潜在源区集中在河北省南部、天津市、山东省西部和河南省东北部地区, 并向西北方向延伸至山西省北部、陕西省北部、内蒙古自治区中西部和蒙古国西南区域。甘肃省和河

南省等也有零星地区对北京 PM<sub>2.5</sub> 有明显影响。根据清洁天 CWT [图 7(b)], 蒙古国西南区域、内蒙古自治区中西部、山西省、陕西省、河北省、天津市、河南省、山东省、安徽省北部和江苏省北部日均  $\rho(\text{PM}_{2.5})$  贡献超过  $100 \mu\text{g}\cdot\text{m}^{-3}$ 。

在南风主导天 [图 7(c) 和 7(d)], 对北京市 PM<sub>2.5</sub> 有重要影响的区域明显向东南方向偏移, 主要集中在内蒙古自治区中部、河北省、天津市、辽宁省西南部、山西省、陕西省北部、山东省中西部、河南省东北部、安徽省北部和江苏省西部, 上述地区日均  $\rho(\text{PM}_{2.5})$  贡献均超过  $100 \mu\text{g}\cdot\text{m}^{-3}$ 。

在北风主导天 [图 7(e)], 北京市 PM<sub>2.5</sub> 主要潜在源区包括蒙古国中部、内蒙古自治区中西部、河

北省、陕西省和陕西省. 山东省西部、河南省东部、安徽省北部、江苏省北部和准噶尔盆地的零星地区也为重要潜在源区. 相比于静稳天和南风主导天, 北风主导天时北京市  $\text{PM}_{2.5}$  主要潜在源区在西北方向

的范围扩大. 根据图 7(f), 准噶尔盆地、蒙古国中部、内蒙古自治区中西部、山西省、山西省、河北省、山东省西部、河南省东部和安徽省北部的 CWT 高于  $100 \mu\text{g}\cdot\text{m}^{-3}$ .

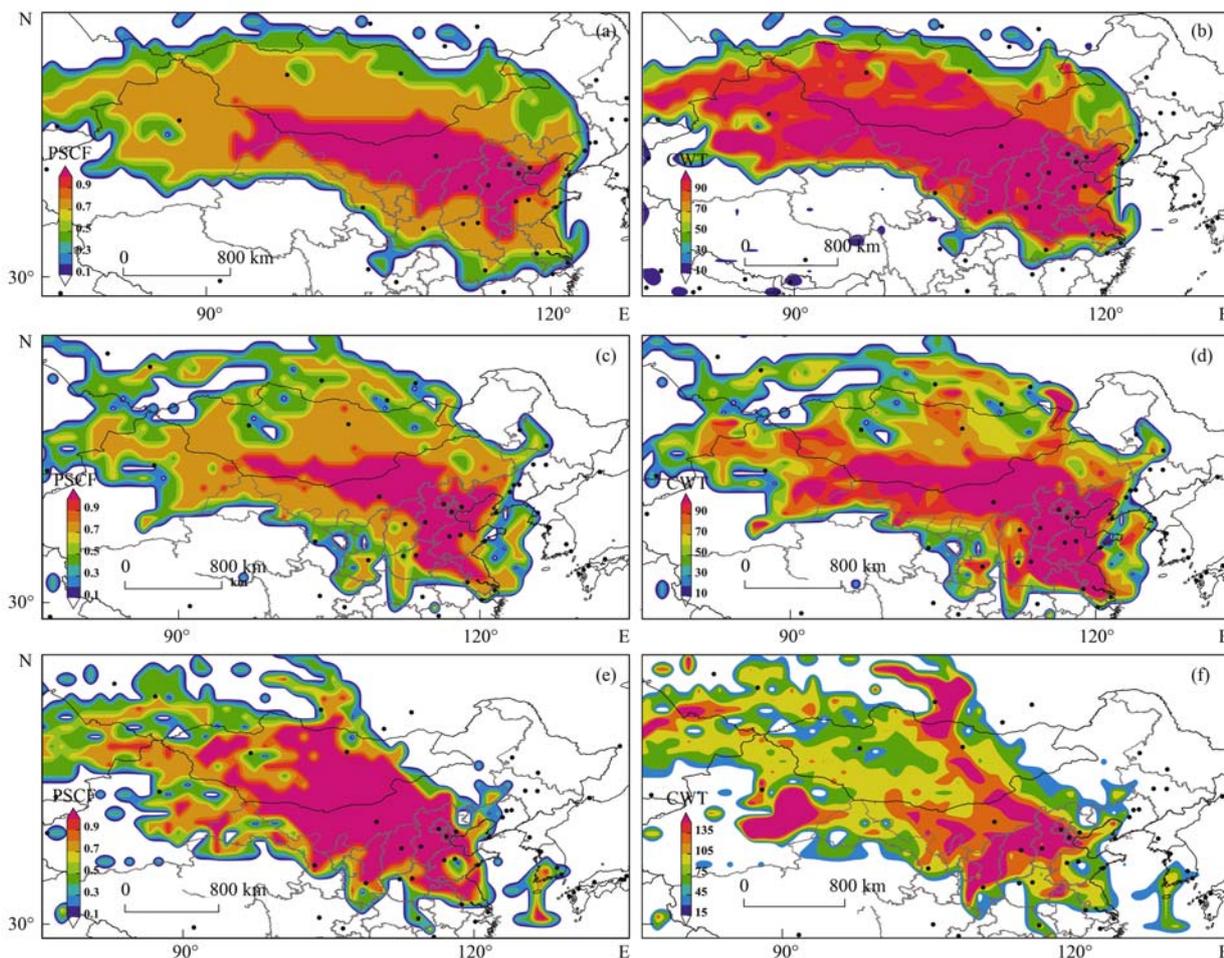


图 7 重污染期间  $\text{PM}_{2.5}$  在不同天气类型下的潜在源贡献因子 (PSCF) 与浓度权重轨迹分布 (CWT)

Fig. 7 Distribution of potential source contribution function (PSCF) and concentration weighted trajectory (CWT) of  $\text{PM}_{2.5}$  in different weather types under severe pollution

综上所述, 内蒙古自治区中西部、河北省、天津市、山西省、陕西省、山东省中西部和河南省北部等地为北京市 1~3 月重污染时的重要潜在源区, 对  $\text{PM}_{2.5}$  浓度贡献显著. 本文的结果与以往研究的结果基本一致<sup>[55~58]</sup>. 例如, 李颜君等<sup>[58]</sup> 研究了 2005~2016 年北京市冬季大气颗粒物潜在源区, 发现内蒙古自治区中部、宁夏部分区域、陕西省西北部及东部、山西省北部、河南省北部、河北省南部、山东省西北部和辽宁省部分区域是主要潜在区域.

### 3 结论

(1) 北京冬奥会历史同期  $\text{PM}_{2.5}$  重污染 [日均  $\rho(\text{PM}_{2.5}) > 75 \mu\text{g}\cdot\text{m}^{-3}$ ] 发生频率仍然较高. 2018 年后, 历年 1~3 月重污染平均发生 23 d, 发生频率为 26%. 其中, 历年来冬奥会历史同期重污染天数为 2~9 d, 冬

季残奥会历史同期重污染天数相对较少, 为 1~5 d.

(2) 2015 后每年 1~3 月超长重污染过程 (重污染连续时长超过 5 d) 平均发生 2~3 次, 且重污染时间最长可达到 8 d. 持续的高湿和静稳天气是超长重污染过程的共同气象特征.

(3) 在冬奥会与冬季残奥会历史同期的重污染时段,  $\text{PM}_{2.5}$  化学组成以二次组分为主. 相较于清洁天, 重污染过程中  $\text{NO}_3^-$  在  $\text{PM}_{2.5}$  可测组分中的质量分数明显增加, 最高可达 46%, 增幅为 340%;  $\text{SO}_4^{2-}$  的质量分数为 12%~19%, 当前硫酸盐污染仍不容忽视.

(4) 2015~2021 年的 1~3 月北京市  $\text{PM}_{2.5}$  的主要贡献区域包括内蒙古自治区中西部、河北省、天津市、山西省、陕西省、山东省中西部和河南省北部等.

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