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## 北京城区$PM_{2.5}$各组分污染特征及来源分析

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# 基于空气质量监测数据的钢铁行业污染源识别方法

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**摘要**：京津冀及周边地区等重点区域已经建立具有高时空分辨率特点的空气质量监测网，但监测数据主要用于环境空气质量评价，在大气污染来源识别中应用较少.采用特征雷达图中的双重归一化算法对区域上2018～2019年秋冬季空气质量监测数据中的$SO_2$、$NO_2$、CO、$PM_{2.5}$和粗颗粒物($PM_{10}$与$PM_{2.5}$的浓度差值)这5种因子进行分析，识别出偏$SO_2$、偏$NO_2$、偏CO、偏$PM_{2.5}$、偏粗颗粒物、偏$SO_2$-CO、偏$NO_2$-CO和偏$PM_{2.5}$-CO这8种典型污染特征.以偏$SO_2$-CO特征为例，结合污染特征时空分布、主要污染源排放特征和$PM_{2.5}$源解析，判断该特征下对空气质量影响最突出的污染源，并将该方法用于一次典型污染过程的分析.结果表明，研究时段内偏$SO_2$-CO特征的平均占比为7.6%.① 偏$SO_2$-CO特征在非采暖期占比较采暖期高出11.5个百分点，空间上主要分布在唐山、安阳和长治等钢铁企业集中的城市；② 和区域内电厂、机动车、民用燃煤、建材行业等排放源相比，钢铁行业$SO_2$和CO排放量同高，是各行业平均水平的1.3倍和4.0倍；③ 唐山、安阳和长治的$PM_{2.5}$源解析表明，偏$SO_2$-CO特征时段内钢铁源对$PM_{2.5}$的贡献分别为48.6%、36.9%和40.2%，高于燃煤源和二次源等其他污染源的贡献，其它时段下$PM_{2.5}$主要源自燃煤或扬尘排放；④ 在由唐山市东部钢铁企业排放所导致的污染过程中，市区的偏$SO_2$-CO特征和钢铁排放示踪元素同步变化.综上，偏$SO_2$-CO特征可用于识别钢铁行业污染源排放对空气质量的影响.典型污染过程分析表明，特征雷达图中的双重归一化算法拓展了空气质量监测数据的应用，为快速识别钢铁行业排放对空气质量的影响提供了一种新的方法.

**关键词**：空气质量监测；京津冀及周边地区；污染特征；来源解析；钢铁行业
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# Method of Identifying Air Pollution from Iron and Steel Industry Based on Ambient Air Quality Monitoring Data Analysis

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**Abstract**: An air quality monitoring network with high temporal and spatial resolution has been established in Beijing-Tianjin-Hebei (BTH) and the surrounding area. However, those data are mainly used for ambient air quality assessment and are rarely applied for identifying air pollution sources. In this study, a data analysis method referring to the characteristic radar chart (CRC) was used to analyze air pollution characteristics in BTH and the surrounding area based on air monitoring data, including $SO_2$, $NO_2$, CO, $PM_{2.5}$, and coarse particulate matter ($PM_{10}$ minus $PM_{2.5}$) mass concentration. Eight pollution characteristics were identified, which included characteristics dominated by $SO_2$, $NO_2$, CO, $PM_{2.5}$, or coarse particulate matter and characteristics co-dominated by $SO_2$-CO, $NO_2$-CO, or $PM_{2.5}$-CO. As an example, to illustrate the major cause of the pollution characteristic co-dominated by $SO_2$-CO, we combined the analysis of the spatio-temporal distribution pattern of this pollution characteristic, emission intensity of major pollution sources, and $PM_{2.5}$ source apportionment. The results showed that the percentage of days with the pollution characteristic co-dominated by $SO_2$-CO in the study region and period was 7.6%. ① The occurrence frequency of the pollution characteristic co-dominated by $SO_2$-CO in the non-heating season was 11.5% higher than that in the heating season. This pattern mainly existed in cities where the iron and steel industry were densely located, e.g., in Tangshan, Anyang, and Changzhi. ② Furthermore, the iron and steel industry had higher $SO_2$ and CO emission intensity, which were 1.3 times and 4.0 times the average intensity of major sectors, including coal-fired power plants, vehicular exhaust, residential coal combustion, etc. in BTH and the surrounding area. ③ According to $PM_{2.5}$ source apportionment, the contributions of the iron and steel industry to $PM_{2.5}$ when the pollution characteristic was co-dominated by $SO_2$-CO were 48.6%, 36.9%, and 40.2% in Tangshan, Anyang, and Changzhi, respectively. In the other period, $PM_{2.5}$ was mainly from coal-burning or fugitive dust emissions. ④ The pollution characteristic co-dominated by $SO_2$-CO and the tracer elements of the iron and steel industry changed simultaneously during the pollution episode in east Tangshan. In summary, the pollution characteristic co-dominated by $SO_2$-CO can indicate the impact of iron and steel industry emissions on air quality. This method expands the application of air quality monitoring data and provides a new tool for the instant identification of iron and steel industry pollution.

**Key words**: air quality monitoring data; Beijing-Tianjin-Hebei and the surrounding area; pollution characteristics; source apportionment; iron and steel industry

$PM_{2.5}$是影响我国秋冬季空气质量的首要污染物，在重点地区$PM_{2.5}$污染尤为突出[1].钢铁行业排放量大，是影响空气质量的重要排放源之一，在京津冀及周边地区，钢铁行业对$SO_2$、$NO_x$和一次$PM_{2.5}$的排放量贡献占比分别为8.8%、9.9%和4.1%[2].因此，快速识别钢铁行业排放对空气质量的影响，对开展精细化治理工作十分重要.

基于观测数据的污染源排放识别方法包括比值法、示踪物法和受体模式源解析法等[3].比值法可减少气象影响，判断污染源排放的相对强弱.对于常规

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污染物,通常根据 $PM_{2.5}/PM_{10}$[4] 和 $NO_2/SO_2$[5] 判断扬尘排放和机动车/燃煤排放的相对强度. 对于颗粒物组分,通常根据 $NO_3^-/SO_4^{2-}$[6] 和 OC/EC[7,8] 判断不同排放源的贡献强度. 此外,$PM_{2.5}$ 中某些组分具有特定的来源,可作为某些排放源的示踪物,如用 Mg、Al 和 Ca 等表征扬尘源排放[9,10],As、W、OC 和 $Cl^-$ 表征燃煤源排放[11,12],V 和 Ni 用来表征移动源排放[13],Fe、Zn、Pb 和 Ca 来表征钢铁源排放[14,15]. 然而,仅根据示踪物浓度变化难以量化污染源的贡献强度,因此,基于多元数据的主因子分析、化学质量平衡模型和正定矩阵因子分析等来源解析方法相继发展并应用于大量研究中[16,17].

空气污染通常具有区域性的特点,而颗粒物组分站点有限,基于颗粒物组分数据的分析方法仅能反映出有限的空间信息[18,19]. 目前,我国在重点地区已建成高时空分辨率的环境空气质量监测网,环境空气质量监测数据能够全面和客观地阐述空气污染的时空变化特点[20,21],然而,以上数据大多用于环境空气质量的评价与考核,很少用来分析空气污染成因和来源,这是由于常规污染物的来源复杂,而比值法仅反映出有限的污染信息,因此亟待开发出基于环境空气质量监测数据来分析空气污染来源的多元分析方法[22~24].

本研究基于京津冀及周边地区("2+26"城市)2018~2019 年秋冬季国控与非国控的环境空气质量监测数据,使用特征雷达图中的双重归一化算法[25]来识别空气污染特征,以偏 $SO_2$-CO 特征为例,从污染特征时空分布、重点污染源排放特征和 $PM_{2.5}$ 源解析方面综合研判该特征下对空气质量影响最突出的污染源,并将该方法应用于典型污染过程的排放源识别. 本研究通过拓展环境空气质量监测数据的应用,以期为快速识别钢铁行业排放对空气质量的影响提供了一种新的方法.

## 1 材料与方法

### 1.1 研究区域和数据来源

研究区域为"2+26"城市,研究时段为 2018~2019 年秋冬季(2018 年 10 月 1 日~2019 年 3 月 31 日),研究时段包括非采暖期(2018 年 10 月 1 日~2018 年 11 月 14 日和 2019 年 3 月 16 日~2019 年 3 月 31 日)和采暖期(2018 年 11 月 15 日~2019 年 3 月 15 日). 国控与非国控空气质量监测数据来自中国环境监测总站的全国空气质量监测数据应用平台(http://123.127.175.60/),$PM_{2.5}$ 组分数据来自中国环境监测总站的京津冀及周边综合立体观测数据共享平台(http://123.127.175.60:8765),地面气象数据来自中央气象局的国家气象科学数据中心(http://data.cma.cn/),研究区域与各站点分布如图 1 所示,Dao 等[26]的研究对 $PM_{2.5}$ 组分监测站点的采样和分析方法进行了详细解释.

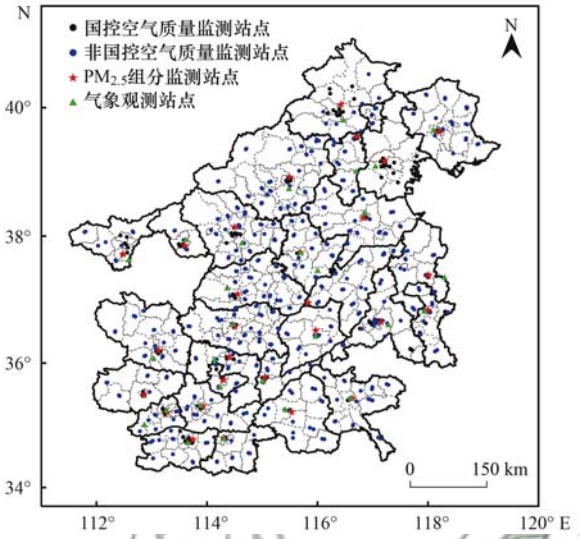


**图 1 研究区域和站点分布示意**

Fig. 1 Study areas and station distribution

### 1.2 数据处理方法

由于空气质量监测数据之间离散程度不同,且受气象条件影响下,不同污染物之间的浓度波动存在共线性现象,为消除不同污染物浓度变异程度的差异和由气象条件变化带来的污染物浓度的共线性波动[27],段菁春等[25]对监测数据进行了两次归一化处理,建立了特征雷达图来分析时间序列上不同排放源对空气质量的影响. 本研究借鉴其思路,采用特征雷达图中双重归一化算法的数据处理方法,对空气质量监测数据中的 $SO_2$、$NO_2$、CO、$PM_{2.5}$ 和粗颗粒物($PM_{10}$ 与 $PM_{2.5}$ 的浓度差值)这 5 项因子进行污染特征分析,具体方法如下.

步骤一,求特定城市、特定时间下污染物的归一化值:

$$Z_{ijk} = c_{ijk} \Big/ \sum_{k=1}^{5} c_{ijk} \tag{1}$$

式中,$Z_{ijk}$ 为 $i$ 城市在 $j$ 时刻下第 $k$ 种污染物归一化值,$c_{ijk}$ 为 $i$ 城市在 $j$ 时刻下第 $k$ 种污染物原始浓度.

步骤二,求一定空间和时间范围内污染物的特征值上下限和特定城市、特定时间下污染物的特征值:

$$Z_k = \text{average}\left(\sum_{i=1}^{n}\sum_{j=1}^{m} Z_{ijk}\right) \tag{2}$$

$$\sigma_k = \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{m}(Z_{ijk} - Z_k)^2/(n \times m)} \tag{3}$$

$$\text{MAX}_k = (Z_k + \sigma_k)/Z_k \tag{4}$$

$$\text{DNV}_{ijk} = Z_{ijk}/Z_k \tag{5}$$

式中，$Z_k$ 为一定城市和一定时间范围内第 $k$ 种污染物归一化值的平均值，$\sigma_k$ 为第 $k$ 种污染物归一化值的标准差，$MAX_k$ 为一定空间和时间范围内第 $k$ 种污染物的特征值上下限，$DNV_{ijk}$ 为 $i$ 城市在 $j$ 时刻下第 $k$ 种污染物的特征值，当 $DNV_{ijk}$ 不小于 $MAX_k$，则认为 $i$ 城市在 $j$ 时刻下污染特征由污染物 $k$ 主导，若多个污染物的 $DNV_{ijk}$ 均不小于各自的 $MAX_k$，则认为此时污染特征由多种污染物共同主导.

在实际应用中，该算法所识别的污染特征主要受两个因素影响，一是基准时段的选取，过短的基准时段易导致归一化值的标准偏差增大，不利于污染特征的识别，段菁春等[24]的研究中，通常选取30 d以上的数据以保证分布的正态性；二是 $MAX_k$ 的选取，过大的 $MAX_k$ 不易于识别污染特征，而 $MAX_k$ 过小时，易导致大于 $MAX_k$ 的 $DNV_{ijk}$ 与 $DNV_{ijk}$ 总体无明显差异. 本研究中，各城市在不同特征下的 $DNV_{ijk}$ 与 $DNV_{ijk}$ 总体的大小比较均通过 Mann-Whitney U 检验，因此，在通过假设检验的前提下，也可根据实际情况来调整 $MAX_k$ 的选取方式.

### 1.3　主成分分析

主成分分析法（principal component analysis，PCA）是一种通过正交变化来对多维数据进行特征提取或降维的统计方法[28,29]，在 $PM_{2.5}$ 的来源解析中，通常根据主成分中因子负载的大小和污染源特征元素来推断可能的污染源类型[30,31]. 本研究对偏 $SO_2$-CO 特征影响时段和非偏 $SO_2$-CO 特征影响时段的 $PM_{2.5}$ 组分开展主成分分析，判断不同特征下污染来源的差异.

## 2　结果与讨论

### 2.1　污染特征的识别结果

5 个污染因子最多可组合出 31 种污染特征，当某污染特征在任一城市内的占比超过 5% 时，认为环境中存在该污染特征. 基于这一识别方法，本研究共识别出 8 种典型污染特征，分别为偏 $SO_2$、偏 $NO_2$、偏 CO、偏 $PM_{2.5}$、偏粗颗粒物、偏 $SO_2$-CO、偏 $NO_2$-CO 和偏 $PM_{2.5}$-CO 特征，区域内各污染特征的平均占比为 18.2%、6.5%、8.8%、13.4%、10.8%、7.6%、1.6% 和 3.3%（图 2）. 以往的研究通常以单一污染物的浓度变化或相关比值来分析污染特征或推断排放来源[1,19,20]，而就多污染物协同变化的研究相对较少. 因此，本研究选取多元指标中分布最广和占比最高的偏 $SO_2$-CO 特征，结合污染特征时空分布、重点污染源排放特征和 $PM_{2.5}$ 组分解析，判断该特征下对空气质量影响最突出的污染源.

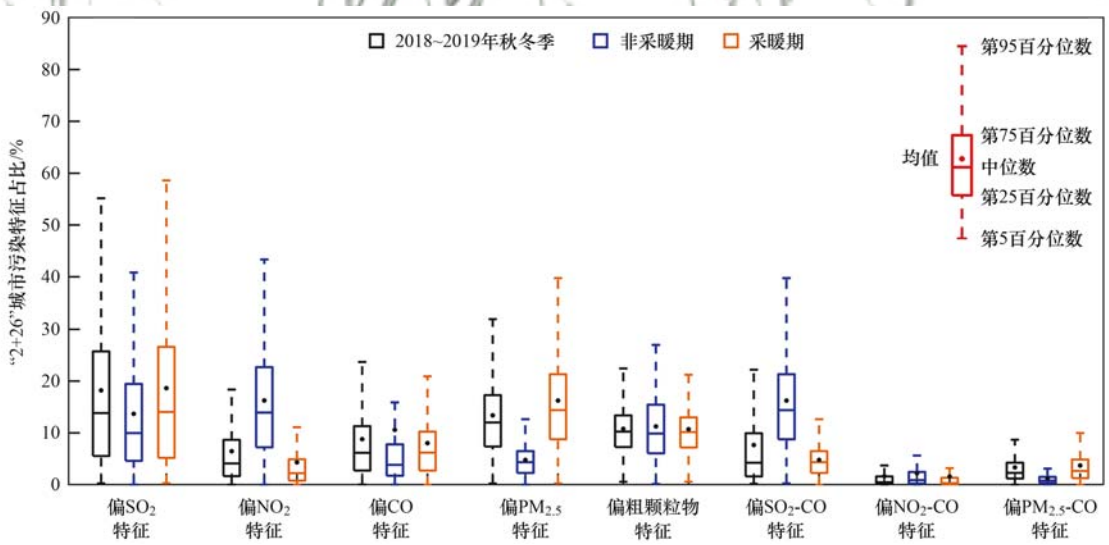


**图 2　"2 +26"城市 8 种污染特征在 2018 ~ 2019 年秋冬季、非采暖期和采暖期的占比分布**

Fig. 2　Ratio distribution of eight pollution characteristics in "2 +26" cities during the autumn-winter season in 2018-2019, non-heating season, and heating season

### 2.2　偏 $SO_2$-CO 特征的污染来源

#### 2.2.1　偏 $SO_2$-CO 特征的时空分布特征

从污染特征的时间分布上看，"2 +26"城市偏 $SO_2$-CO 特征在非采暖期的占比较采暖期高出 11.5 个百分点（图 2），而 Zhang 等[32]的研究表明，民用散煤用量与环境温度体现出负相关性，在采暖期的民用燃煤用量显著高于非采暖期，偏 $SO_2$-CO 特征在不同时段的占比与燃煤用量之间不存在正相关性. 从空间分布上看，图 3 中偏 $SO_2$-CO 特征主要出现在钢铁企业集中分布的地区，在唐山、安阳、邯郸和长治，偏 $SO_2$-CO 特征在钢铁企业集中分布地区的占比较其他区县高出 14.9、15.2、25.4 和 18.1 个百分点. 因此，偏 $SO_2$-CO 特征可能受到钢铁行业排放的影响.

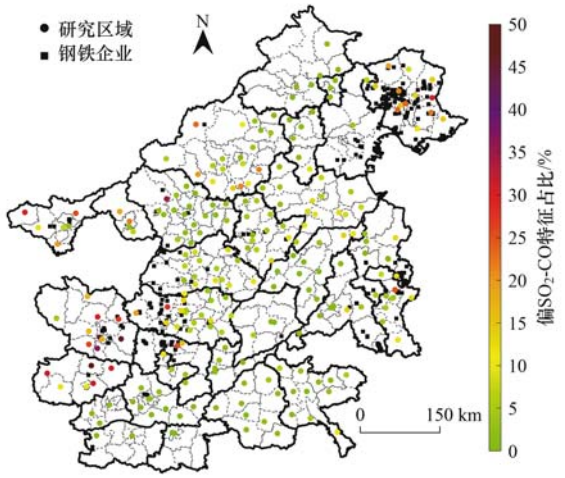


**图 3 “2 +26”城市 2018 ~ 2019 年秋冬季偏 $SO_2$-CO 特征的占比和钢铁企业分布情况**

Fig. 3 Ratio distribution of pollution characteristic co-dominated by $SO_2$-CO during autumn-winter season in 2018-2019 and location of iron and steel factories in “2 +26” cities

**2.2.2** 主要污染源排放特征

从“2 +26”城市主要排放源的相对排放强度上看,图 4 中钢铁行业的 $SO_2$ 和 CO 排放强度是各行业平均水平的 1.3 倍和 4.0 倍[33],且其他污染物的排放强度均低于行业平均水平. 因此,钢铁企业排放是导致环境中 $SO_2$ 和 CO 浓度快速增加的重要原因,典型钢铁厂排放时,周边 1 km 的 $SO_2$ 浓度增加了 15.3 $\mu g \cdot m^{-3}$,CO 浓度增加了 2.7 $mg \cdot m^{-3}$[34]. 与之相比,虽然民用燃煤 $SO_2$ 和 CO 排放强度是区域均值的 3.0 倍和 1.8 倍,但民用燃煤排放的污染物更加复杂,$PM_{2.5}$ 的排放强度是区域均值的 1.7 倍,在多种污染物的共同影响下,环境中不易出现偏 $SO_2$-CO 特征[35]. 因此,钢铁行业排放可能是导致环境中偏 $SO_2$-CO 特征出现的主要原因.

**2.2.3** 偏 $SO_2$-CO 特征时段与非偏 $SO_2$-CO 特征时段内 $PM_{2.5}$ 组分差异

为明确偏 $SO_2$-CO 特征可指示的行业来源,对

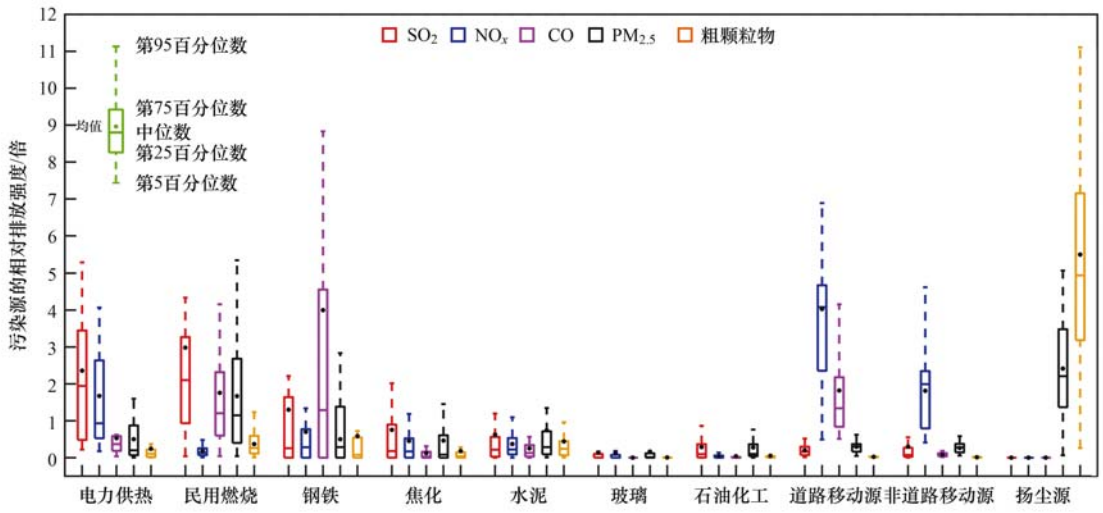


**图 4 “2 +26”城市主要行业的相对排放强度**

Fig. 4 Relative emission intensity of the major sectors of “2 +26”

唐山、安阳和长治这 3 个典型城市在偏 $SO_2$-CO 特征和非偏 $SO_2$-CO 特征时段内的颗粒物组分进行对比,如图 5 所示,偏 $SO_2$-CO 特征时段内 3 个典型城市 Fe、Zn、Pb 和 $Cl^-$ 等元素在 $PM_{2.5}$ 中的占比均高于非偏 $SO_2$-CO 特征时段,Fe 高出 1.03、0.63 和 0.52 个百分点,Zn 高出 0.20、0.11 和 0.03 个百分点,Pb 高出 0.16、0.06 和 0.08 个百分点,$Cl^-$ 高出 1.40、1.61 和 2.40 个百分点. 作为铁矿石的主要成分,Fe 是钢铁行业排放的重要示踪元素[36]; 由于我国多产贫矿、铁矿杂质较多,冶炼前需洗选,而铅锌铁镶嵌体因其具有颗粒细小、含量多变的特点,普通洗选过程无法筛出,因此 Pb 和 Zn 是钢铁粉尘的示踪元素[36,37]; $Cl^-$ 主要来自煤炭燃烧和脱硫剂的使用,NaCl 是脱硫剂[$Ca(OH)_2$ 和 NaCl]中的重要成分,由于脱硫阶段水的循环使用,脱硫液中 $Cl^-$ 持续累积,导致烟气中 $Cl^-$ 含量较高[38,39]. 从 $PM_{2.5}$ 组分上看,偏 $SO_2$-CO 特征时段内 $PM_{2.5}$ 中钢铁行业的示踪元素要高于非偏 $SO_2$-CO 特征时段.

**2.2.4** 偏 $SO_2$-CO 特征时段与非偏 $SO_2$-CO 特征时段内 $PM_{2.5}$ 的来源解析

为进一步确定典型城市 $PM_{2.5}$ 的主要来源,对偏 $SO_2$-CO 特征和非偏 $SO_2$-CO 特征时段内 $PM_{2.5}$ 组分开展主成分分析,结果见表 1 和表 2. 从各组分的因子负载上看,在偏 $SO_2$-CO 特征时段内,唐山市主成分 1 中 $Ca^{2+}$、$Cl^-$、Fe 和 Zn 因子负载在 0.7 ~ 1 之间,可指示钢铁行业的排放[40,41],主成分 2 中 As、

**表 1　偏 $SO_2$-CO 特征时段内唐山、安阳和长治市 $PM_{2.5}$ 因子负载矩阵**[1)]

Table 1　Factor loading matrix of $PM_{2.5}$ during pollution characteristics co-dominated by $SO_2$-CO in Tangshan, Anyang, and Changzhi

| 组分 | 唐山市 | | | 安阳市 | | | 长治市 | | |
|---|---|---|---|---|---|---|---|---|---|
| | PC1 | PC2 | PC3 | PC1 | PC2 | PC3 | PC1 | PC2 | PC3 |
| OC | 0.6 | **0.6** | −0.8 | 0.3 | **0.9** | −0.1 | 0.6 | **0.6** | 0.2 |
| EC | 0.8 | 0.4 | −0.3 | 0.4 | **0.8** | −0.2 | 0.3 | **0.9** | −0.2 |
| $Na^+$ | 0.6 | −0.5 | −0.4 | 0.8 | 0.3 | 0.0 | 0.6 | **0.6** | 0.1 |
| $K^+$ | 0.4 | −0.6 | **0.6** | 0.1 | **0.5** | 0.2 | 0.7 | −0.3 | 0.3 |
| $Mg^{2+}$ | **0.9** | 0.3 | 0.3 | 0.7 | −0.6 | −0.3 | 0.7 | −0.5 | **0.4** |
| $Ca^{2+}$ | **1.0** | −0.1 | −0.2 | **0.8** | 0.0 | 0.2 | **0.9** | −0.2 | −0.3 |
| $Cl^-$ | **0.9** | −0.5 | 0.0 | 0.1 | **0.7** | −0.3 | 0.7 | **0.6** | 0.2 |
| $NO_3^-$ | −1.0 | 0.0 | −0.1 | −0.7 | 0.1 | **0.8** | −0.5 | 0.3 | **0.5** |
| $SO_4^{2-}$ | −0.9 | 0.4 | 0.1 | −0.4 | −0.4 | **0.8** | −0.3 | 0.5 | **0.7** |
| Mn | −0.1 | **0.6** | 0.3 | **0.8** | −0.6 | −0.1 | **0.8** | 0.5 | −0.2 |
| Fe | **0.9** | 0.1 | **0.3** | **0.8** | 0.3 | 0.3 | **0.9** | 0.0 | −0.3 |
| Zn | 0.7 | −0.5 | **0.5** | 0.7 | −0.3 | −0.4 | **0.9** | 0.1 | −0.3 |
| As | −0.1 | **0.7** | 0.3 | −0.6 | **0.5** | −0.4 | −0.1 | **0.7** | −0.4 |
| Se | 0.3 | **0.7** | −0.1 | 0.3 | −0.4 | 0.1 | 0.1 | −0.5 | −0.2 |
| Pb | 0.0 | −0.6 | **0.5** | **0.8** | −0.7 | 0.2 | **0.8** | −0.2 | **0.4** |
| Al | **0.8** | 0.0 | 0.2 | 0.3 | 0.3 | **0.4** | 0.6 | −0.4 | 0.2 |
| S | −0.4 | **0.7** | **0.3** | −0.2 | −0.2 | **0.3** | −0.5 | 0.4 | **0.6** |
| Si | 0.8 | 0.6 | 0.2 | **0.8** | 0.4 | **0.3** | 0.0 | −0.4 | 0.2 |
| 特征值 | 9.2 | 4.7 | 2.3 | 7.0 | 4.5 | 2.6 | 7.6 | 4.8 | 2.3 |
| 方差贡献/% | 48.6 | 24.5 | 12.3 | 36.9 | 23.4 | 13.5 | 40.2 | 25.1 | 12.0 |
| 污染来源 | 钢铁源 | 燃煤源 | 其他 | 钢铁源 | 燃煤源 | 二次源 | 钢铁源 | 燃煤源 | 二次源 |

1)黑体字表示主成分中因子负载排名前五的元素，下同

**表 2　非偏 $SO_2$-CO 特征时段内唐山、安阳和长治市 $PM_{2.5}$ 因子负载矩阵**

Table 2　Factor loading matrix of $PM_{2.5}$ during pollution characteristics co-dominated by non-$SO_2$- CO in Tangshan, Anyang, and Changzhi

| 组分 | 唐山市 | | | 安阳市 | | | | 长治市 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PC1 | PC2 | PC3 | PC1 | PC2 | PC3 | PC4 | PC1 | PC2 | PC3 |
| OC | −0.2 | 0.3 | −0.9 | **0.8** | 0.2 | 0.1 | **0.8** | 0.8 | 0.4 | 0.0 |
| EC | 0.3 | **0.9** | −0.2 | 0.6 | 0.1 | 0.0 | **0.9** | 0.8 | −0.1 | 0.1 |
| Na | −0.3 | **0.9** | −0.2 | −0.3 | −0.1 | **0.9** | −0.1 | 0.1 | −0.1 | 0.2 |
| $K^+$ | **0.8** | 0.2 | −0.1 | −0.2 | 0.2 | −0.1 | **0.3** | 0.5 | 0.6 | −0.5 |
| $Mg^{2+}$ | **0.9** | 0.2 | −0.2 | 0.1 | **0.6** | 0.0 | 0.2 | **0.8** | 0.5 | −0.2 |
| $Ca^{2+}$ | −0.3 | **0.9** | −0.3 | 0.4 | −0.2 | **0.7** | −0.4 | 0.7 | 0.1 | **0.7** |
| $Cl^-$ | −1.0 | −0.3 | 0.1 | −0.3 | −0.7 | **0.9** | −0.1 | −0.6 | 0.7 | **0.9** |
| $NO_3^-$ | −0.9 | −0.1 | 0.1 | −0.8 | −0.3 | **0.9** | 0.2 | −0.5 | −0.2 | **0.8** |
| $SO_4^{2-}$ | 0.3 | 0.2 | 0.0 | **0.7** | 0.3 | 0.2 | 0.2 | 0.1 | **1.0** | 0.0 |
| Mn | **0.8** | 0.0 | **0.8** | 0.3 | **0.8** | 0.0 | −0.1 | **1.0** | 0.0 | −0.2 |
| Fe | 0.1 | 0.8 | **1.0** | 0.2 | **0.4** | 0.0 | 0.0 | 0.3 | **0.8** | −0.5 |
| Zn | 0.1 | **0.9** | **0.1** | **0.7** | 0.0 | −0.2 | 0.2 | **0.9** | −0.2 | −0.3 |
| As | 0.0 | 0.0 | **0.2** | **0.7** | 0.0 | −0.2 | **0.3** | 0.1 | **0.9** | −0.3 |
| Se | −0.5 | 0.0 | **0.8** | 0.1 | 0.0 | **0.3** | **0.6** | 0.0 | 0.2 | −0.8 |
| Pb | **0.9** | −0.3 | 0.1 | 0.1 | **0.9** | 0.0 | 0.0 | 0.1 | **1.0** | −0.2 |
| Al | −0.9 | 0.0 | −0.3 | **0.6** | −0.2 | 0.3 | 0.1 | **1.0** | −0.3 | **0.9** |
| S | **0.9** | −0.3 | 0.1 | 0.1 | **0.9** | −0.1 | −0.1 | −0.4 | **0.9** | −0.1 |
| Si | −0.3 | **0.9** | 0.1 | 0.2 | 0.0 | 0.2 | −0.2 | **0.8** | 0.2 | **0.3** |
| 特征值 | 9.3 | 6.3 | 2.6 | 6.2 | 4.1 | 2.7 | 1.9 | 9.1 | 4.8 | 4.7 |
| 方差贡献/% | 40.0 | 28.8 | 13.1 | 23.8 | 19.4 | 14.9 | 9.4 | 40.7 | 54.0 | 23.7 |
| 污染来源 | 扬尘源 | 燃煤源 | 钢铁源 | 燃煤源 | 扬尘源 | 二次源 | 交通源 | 燃煤源 | 燃煤和扬尘源 | 二次源 |

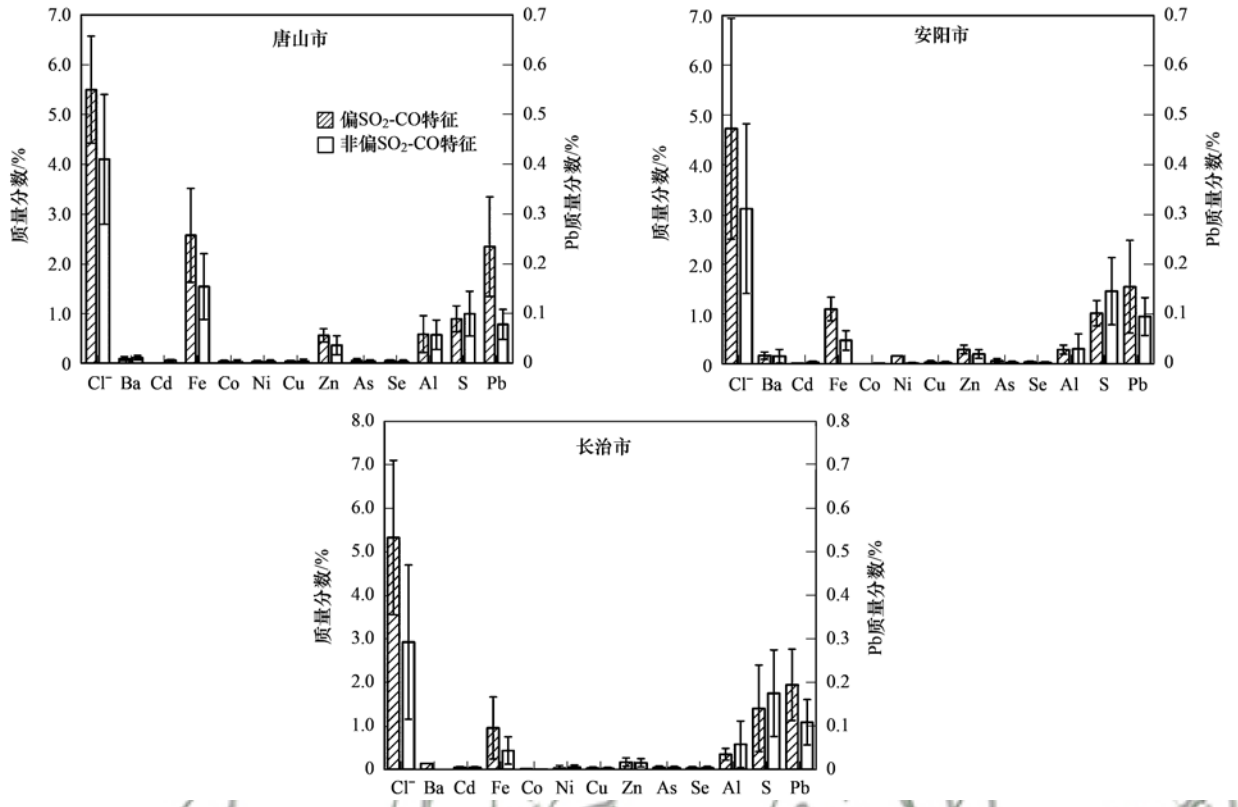


**图 5 唐山、安阳和长治偏 $SO_2$-CO 特征时段与非偏 $SO_2$-CO 特征时段内 $PM_{2.5}$ 组分的质量分数**

Fig. 5 Mass ratio of $PM_{2.5}$ components when pollution characteristics co-dominated by $SO_2$-CO and non-$SO_2$-CO in Tangshan, Anyang, and Changzhi

Se、OC、EC、$SO_4^{2-}$ 和 S 因子负载在 0.4 ~ 0.7 之间,可指示燃煤排放[11,42],偏 $SO_2$-CO 特征时段内唐山市钢铁源和燃煤源对 $PM_{2.5}$ 分别贡献了 48.6% 和 24.5%; 安阳市主成分 1 中 $Ca^{2+}$、Fe、Zn 和 Pb 因子负载在 0.7 ~ 0.8 之间,可指示钢铁行业排放,主成分 2 中 As、OC 和 EC 因子负载在 0.5 ~ 0.9 之间,可指示燃煤排放,主成分 3 中 $NO_3^-$ 和 $SO_4^{2-}$ 因子负载均为 0.8,可视为二次源[29],偏 $SO_2$-CO 特征时段内安阳市钢铁源、燃煤源和二次源对 $PM_{2.5}$ 分别贡献了 36.9%、23.4% 和 13.5%; 长治市主成分 1 中 $Ca^{2+}$、$Cl^-$、Fe、Zn 和 Pb 因子负载在 0.7 ~ 0.9 之间,可指示钢铁排放,主成分 2 中 OC、EC 和 As 因子负载在 0.6 ~ 0.9 之间,可指示燃煤排放,主成分 3 中 $NO_3^-$ 和 $SO_4^{2-}$ 因子负载为 0.5 和 0.7,可视为二次源,偏 $SO_2$-CO 特征时段内长治市钢铁源、燃煤源和二次源对 $PM_{2.5}$ 分别贡献了 40.2%、25.1% 和 12.0%. 相比之下, 3 个城市在非偏 $SO_2$-CO 特征时段内主要污染源为燃煤或扬尘源[43~45]. 从行业来源解析结果上看,钢铁行业排放是偏 $SO_2$-CO 特征时段内典型城市最主要的排放源.

### 2.3 典型污染过程分析

特征雷达图中的双重归一化算法具有时空分辨率高的特点,可以快速分析当前污染特征,判断对空气质量影响最为突出的污染源. 以 2018 年 11 月 22 ~ 24 日唐山市的一次 $PM_{2.5}$ 污染过程为例,唐山市区 $PM_{2.5}$ 浓度从 48 μg·m$^{-3}$ 增至 135 μg·m$^{-3}$,$SO_2$ 和 CO 同步增加,两者相关系数达 0.977, $SO_2$ 和 CO 小时峰值浓度分别为 186 μg·m$^{-3}$ 和 8.2 mg·m$^{-3}$ (图 6); 从污染特征上看, 23 日凌晨,市区东部的开平区和古冶区率先出现偏 $SO_2$-CO 特征,随后在偏东风影响下,唐山市区和丰南区相继出现偏 $SO_2$-CO 特征,因此,唐山市区的污染主要来自东部钢铁企业的排放. 从 $PM_{2.5}$ 组分上看, 23 日唐山市区的 $Cl^-$ 浓度较 22 日增加了 123.3%,Fe 和 Zn 浓度分别增加了 138.8% 和 570.0%,而 EC 浓度降低了 7.7%,OC 浓度增加了 2.1%,碳质组分浓度变化不明显(图 7),这同样说明唐山市区在这一时段受到钢铁企业的传输影响[46].

典型案例分析可以看出,该算法可快速识别大气污染特征. 但由于本算法采用的变量在环境中来源复杂,因此,在实际应用中,仍需结合当地和上游地区的产业结构、空间分布和风场变化,从多角度共同判断主要污染源. 相较于传统方法,本算法进一步拓展了空气质量监测数据的应用,为快速识别钢铁

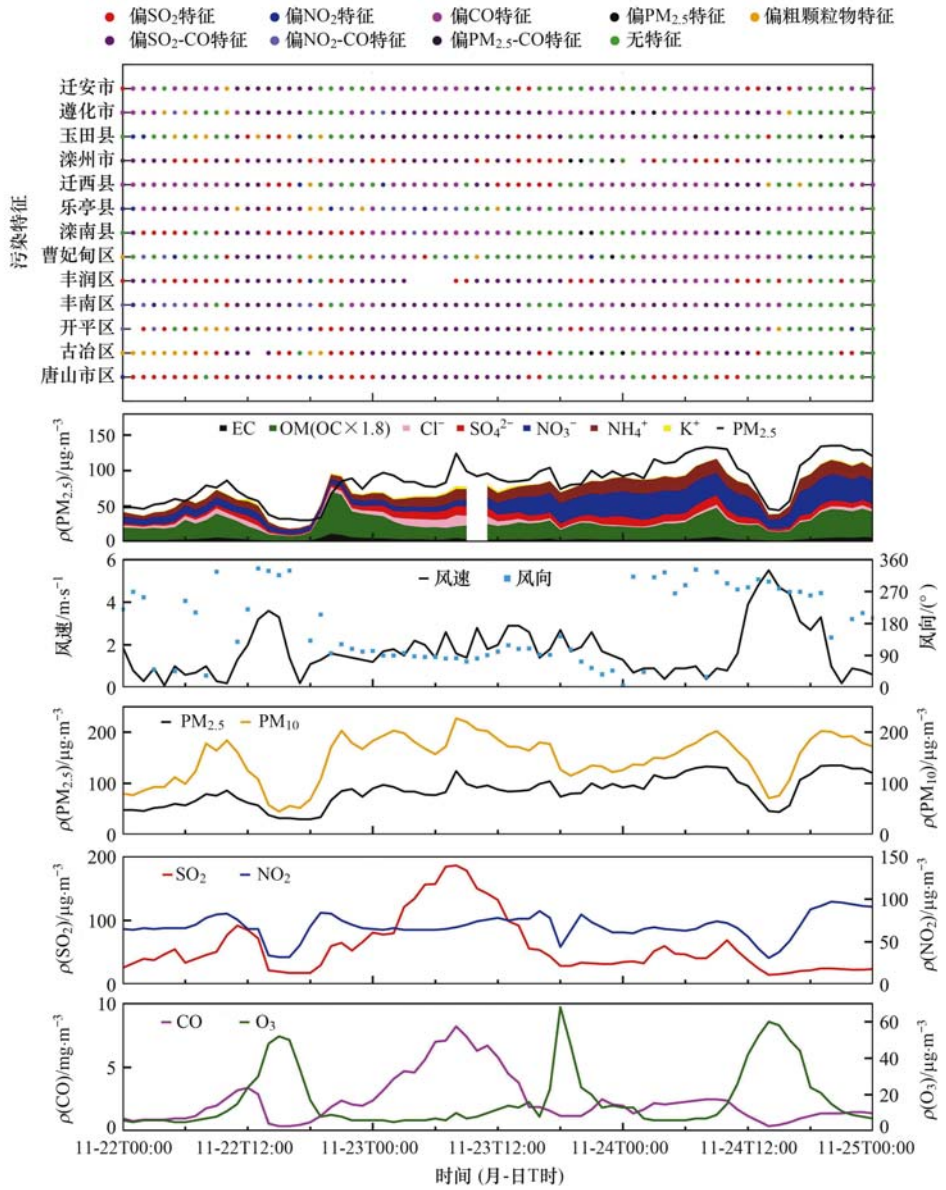


**图 6　唐山市 2018 年 11 月 22～25 日常规污染物浓度、风速风向、$PM_{2.5}$组分浓度和周边区县污染特征的变化**

Fig. 6　Changes in the concentration of conventional pollutants, wind speed and direction, $PM_{2.5}$ component concentration, and pollution characteristics of surrounding districts in Tangshan from November 22-25, 2018

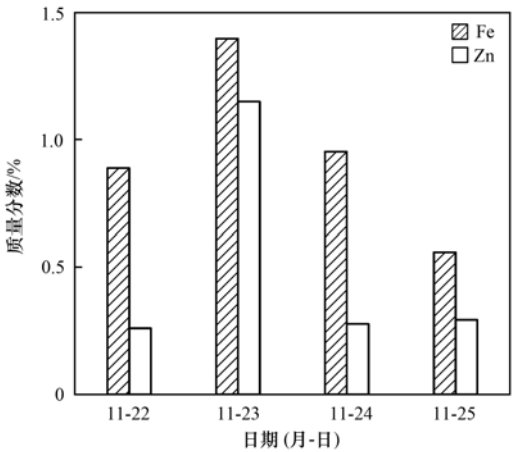


**图 7　唐山市 2018 年 11 月 22～25 日 Fe 和 Zn 在 $PM_{2.5}$ 中的质量分数**

Fig. 7　Mass ratio of Fe and Zn in $PM_{2.5}$ on November 22-25, 2018 in Tangshan

行业排放对空气质量的影响提供了一种新的方法.

## 3　结论

（1）基于“2 +26”城市 2018～2019 年秋冬季环境空气质量监测数据,采用特征雷达图中的双重归一化算法可识别 8 种典型污染特征,分别为偏 $SO_2$、偏 $NO_2$、偏 CO、偏 $PM_{2.5}$、偏粗颗粒物、偏 $PM_{2.5}$-CO、偏 $SO_2$-CO 和偏 $NO_2$-CO 特征. 其中,偏 $SO_2$-CO 特征平均占比为 7.6%,在多元指标特征中占比最高,分布最广.

（2）时间分布上,偏 $SO_2$-CO 特征在非采暖期占比较采暖期高出 11.5 个百分点；空间分布上,偏 $SO_2$-CO 特征主要分布在钢铁企业集中的地区,唐山、安阳、邯郸和长治市的钢铁企业数量大的区县

较当地其他区县偏 $SO_2$-CO 特征占比高出 14.9、15.2、25.4 和 18.1 个百分点；重点污染源排放上，钢铁行业的 $SO_2$ 和 CO 排放强度是各行业平均水平的 1.3 倍和 4.0 倍.

（3）$PM_{2.5}$组分分析表明，在偏 $SO_2$-CO 特征时段内，唐山、安阳和长治的 Fe、Zn、Pb 和 $Cl^-$等钢铁行业示踪元素均高于其他时段，钢铁行业对当地 $PM_{2.5}$的贡献为 48.6%、36.9% 和 40.2%. 而在其他时段内，$PM_{2.5}$排放源主要为燃煤或扬尘源. 因此，钢铁行业的排放是导致偏 $SO_2$-CO 特征出现的重要原因.

（4）典型污染过程分析表明，特征雷达图中的双重归一化算法拓展了环境空气质量监测数据的应用，为快速识别钢铁行业排放对空气质量的影响提供了一种新的方法.

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