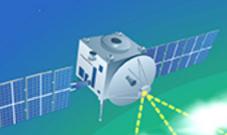


# 4年给到

## **ENVIRONMENTAL SCIENCE**

ISSN 0250-3301 CODEN HCKHDV HUANJING KEXUE

PM<sub>2.5</sub>和O<sub>3</sub>污染协同防控区的遥感精细划定与分析 李沈鑫,邹滨,张凤英,刘宁,薛琛昊,刘婧



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- 主办 中国科学院生态环境研究中心
- ■出版斜学出版社





# 2022年10月

第43卷 第10期 Vol.43 No.10

### ENVIRONMENTAL SCIENCE

第43卷 第10期 2022年10月15日

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# PM<sub>2.5</sub> 和 O<sub>3</sub> 污染协同防控区的遥感精细划定与分析

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(1. 中南大学地球科学与信息物理学院,长沙 410083; 2. 中国环境监测总站,北京 100012)

摘要:针对地面站点监测数据难以支撑大气  $PM_{2.5}$ 与  $O_3$  污染防控区边界划定的问题,融合大气污染浓度遥感估算建模与 GIS 统计分析模型,提出了一种基于  $PM_{2.5}$ 和  $O_3$  浓度遥感估算结果的协同防控区精细划定方法,开展了  $2015\sim2020$  年月和年尺度的全国  $PM_{2.5}$ 与  $O_3$  污染协同防控成效定量分析与防控区精细划定研究.结果表明,  $2015\sim2020$  年,我国  $PM_{2.5}$ 浓度总体下降显著但  $O_3$  浓度基本持平, $PM_{2.5}$ 污染在秋冬超标严重, $O_3$  污染则在春夏;同时  $PM_{2.5}$ 与  $O_3$  浓度变化在空间上的不一致性显著,其中  $PM_{2.5}$ 下降且  $O_3$  上升、 $PM_{2.5}$ 与  $O_3$  均下降、 $PM_{2.5}$ 与  $O_3$  均上升和  $PM_{2.5}$ 上升  $O_3$  下降的面积占比分别为 38.34%、35.12%、15.24% 和 10.89%.遥感精细划定范围显示, $PM_{2.5}$ 和  $O_3$  协同防控区域的边界具有显著动态变化特征,在时间变化上呈现先扩大后缩小的趋势,主体范围集中在"2+26"城市、汾渭平原、长三角北部和山东半岛.以  $PM_{2.5}$ 或  $O_3$  单一防控为主的区域范围较为稳定,辽吉、鄂湘赣、成渝和塔克拉玛干沙漠-河西走廊区域需以  $PM_{2.5}$ 防控为主,珠三角、长三角和环渤海湾部分区域则应以  $O_3$  防控为主.基于卫星遥感手段的  $PM_{2.5}$ 和  $O_3$  协同防控区域边界精细划定方法可更好辅助国家  $PM_{2.5}$ 和  $O_3$  协同防控策略制定需求.

关键词:大气污染; 大气遥感;  $PM_{2.5}$ ; 臭氧 $(O_3)$ ; 协同防控

中图分类号: X51; X87 文献标识码: A 文章编号: 0250-3301(2022)10-4293-12 **DOI**: 10.13227/j. hjkx. 202112075

# Regionalization and Analysis of PM<sub>2.5</sub> and O<sub>3</sub> Synergetic Prevention and Control Areas Based on Remote Sensing Data

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Abstract: Site-based air pollution monitoring data cannot support the regionalization of air pollution prevention and control areas. Faced with this problem, this study proposed a method of regionalizing synergetic prevention and control areas based on multi-source remote sensing data and GIS spatial statistical analysis methods and carried out quantitative analyses of PM<sub>2.5</sub> and O<sub>3</sub> air pollution in China from 2015 to 2020. The results showed that there was an obvious decrease in PM<sub>2.5</sub> concentrations, and O<sub>3</sub> concentrations remained stable; PM<sub>2.5</sub> pollution mostly occurred in autumn and winter, and O<sub>3</sub> pollution occurred in spring and summer. A significant spatial inconsistency was shown between the change rate of PM<sub>2.5</sub> and O<sub>3</sub> concentrations, in which the proportions of PM<sub>2.5</sub> decreasing and O<sub>3</sub> increasing, PM<sub>2.5</sub> and O<sub>3</sub> both decreasing, PM<sub>2.5</sub> and O<sub>3</sub> both increasing, and PM<sub>2.5</sub> increasing and O<sub>3</sub> decreasing accounted for 38.34%, 35.12%, 15.24%, and 10.89%, respectively. The results also showed that the boundary of PM<sub>2.5</sub> and O<sub>3</sub> synergetic prevention and control areas was dynamic during 2015 and 2020, showing a trend of expanding from 2015 to 2018 and then becoming smaller after 2019. Generally, the scope of PM<sub>2.5</sub> and O<sub>3</sub> synergetic prevention and control areas was concentrated in "2 + 26" cities, Fenwei plain, north of the Yangtze River Delta, and Shandong. In contrast, the regional scopes of "PM<sub>2.5</sub> first" and "O<sub>3</sub> first" were relatively stable. Areas of "PM<sub>2.5</sub> first" were mainly carried out in Liaoning-Jilin, Hubei-Hunan-Jiangxi, Chengdu-Chongqing, and Taklimakan-Hexi Corridor, whereas "O<sub>3</sub> first" areas were mainly in specific regions of the Pearl River Delta, Yangtze River Delta, and surrounding areas of Bohai Bay. Remote sensing-based PM<sub>2.5</sub> and O<sub>3</sub> mapping has the advantages of full-coverage and fine spat

Key words: air pollution; atmospheric remote sensing; PM2.5; ozone(O3); synergetic prevention and control

环境污染暴露是世界三大主要疾病负担之一,其中大气细颗粒物(PM<sub>2.5</sub>)和臭氧(ozone,O<sub>3</sub>)暴露导致的健康风险位居当前环境污染引起的疾病负担前列,尤其值得关注<sup>[1-3]</sup>. 近年来,随着我国系列大力治污措施的有效开展<sup>[4]</sup>,全国整体空气质量得到了大幅改善<sup>[5]</sup>,其中 PM<sub>2.5</sub>浓度下降显著,但 O<sub>3</sub> 污染问题日益凸显且与 PM<sub>2.5</sub>在形成机制上存在关联<sup>[6,7]</sup>. 在此背景下,仅单一考虑 PM<sub>2.5</sub>污染浓度划定防控区域的方式已无法满足我国下阶段大气污染精准防控策略的制定与实施,PM<sub>2.5</sub>和 O<sub>3</sub> 污染协同防控区域的划定工作亟待开展<sup>[8]</sup>.

厘清 PM<sub>2.5</sub>和 O<sub>3</sub> 污染的空间分布格局及其时间 演化特征是划定污染重点防控区域的重要前提. 对 于 PM<sub>2.5</sub>和 O<sub>3</sub> 污染协同分析而言,基于地面站点的研究已经揭示,京津冀、长三角和华南等地出现 PM<sub>2.5</sub> 超标日减少、O<sub>3</sub> 超标日增加的"跷跷板"效应<sup>[9]</sup>. 但受限于地面站点空间覆盖范围不足的问题,空间连续的 PM<sub>2.5</sub>与 O<sub>3</sub> 污染演化特征难以通过稀疏站点数据开展分析,也限制了空间精细防控范围划定工作的进一步展开. 在此情况下,大气污染浓度遥感估算方法因具备空间覆盖度广和时空分辨率高的优势,已逐渐

收稿日期: 2021-12-07; 修订日期: 2022-02-24

基金项目: 国家自然科学基金项目(41871317); 湖南省研究生科研 创新项目(CX20200343); 中南大学研究生自主探索创新 项目(2020zzts180)

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成为解决稀疏站点空间代表性不足、获取空间连续 大气污染浓度数据的主要技术手段[10,11].

大气污染浓度遥感估算技术经过近20年的发 展,相关模型方法已由最初的简单比例因子法,发展 到基于机制的半经验法、统计模型与机器学习法以 及半经验半统计的混合模型法[12,13]. 建模变量也逐 步引入了气象条件、土地利用和人口分布等多源要 素. PM25浓度估算结果的空间分辨率也由 10 km 级 (10 km×10 km)<sup>[14,15]</sup>提升到公里级(3 km×3 km、 1 km × 1 km)<sup>[16,17]</sup> 甚至亚公里级(500 m × 500 m)<sup>[18,19]</sup>; O<sub>3</sub> 浓度估算的空间分辨率则多在公里级 到 10 km 级之间<sup>[20,21]</sup>. 理论上, 当前的大气污染浓 度遥感估算结果已为污染防控区域的精细划定提供 了丰富的数据支撑,但综合 PM,,和 O,浓度遥感估 算结果进行协同防控成效分析的研究还较为鲜见, PM,5和O,协同防控区精细划定的相关方法还未见 报道,现有大气污染防控区划定方式还仍以地级市 行政边界为主.

对此,本文在 PM<sub>2.5</sub>和 O<sub>3</sub> 浓度遥感估算建模的基础上,结合 GIS 空间统计分析方法,提出一种基于防控成效空间一致性结果划分不同防控重点(协同防控为主、PM<sub>2.5</sub>防控为主、O<sub>3</sub> 防控为主)区域边界范围的方法,并以我国大陆地区为研究对

象,开展 2015~2020 年  $PM_{2.5}$ 与  $O_3$  污染协同防控成效空间一致性定量分析,进而划定了我国  $PM_{2.5}$ 与  $O_3$  污染协同防控区的精细范围,以期为下一步开展  $PM_{2.5}$ 和  $O_3$  污染协同防控精细治理决策提供支撑.

#### 1 材料与方法

选择中国大陆地区为研究区(包含 23 个省、5 个自治区、4 个直辖市,中国香港、澳门和台湾资料暂缺),重点关注《打赢蓝天保卫战三年行动计划》划分的京津冀及周边地区("2+26"城市)、长三角地区、珠三角地区、汾渭平原和成渝地区这五大重点区域范围(图 1),研究时间段为 2015~2020 年.

#### 1.1 数据收集与预处理

#### 1.1.1 空气质量地面站点浓度数据

空气质量地面站点浓度数据来自中国环境监测总站(http://106.37.208.233;20035/),获取的时间范围为2015年1月1日到2020年12月31日.结合国家《环境空气质量标准》(GB3095-2012)相关规范,对数据进行质量控制.具体过程为:剔除原始数据中小时浓度缺失、为负值的纪录;在日均值计算中,剔除数据在一个自然日24h内低于20h的纪录值;计算月均值时,剔除每月低于27个日浓度平均值(2月至少有25个日浓度平均值)的月份;

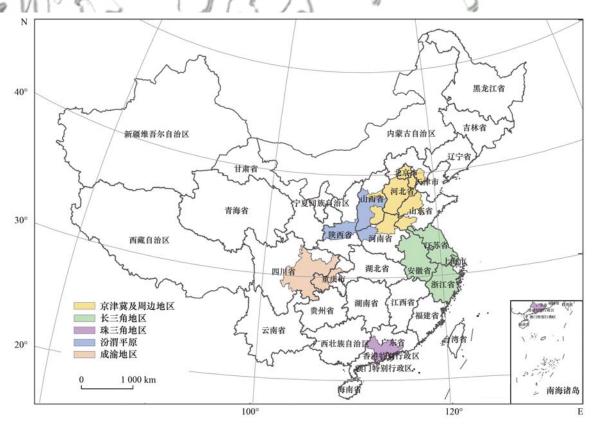


图 1 研究区及重点区域范围示意

Fig. 1 Location of study area and key regions

计算年均值时,剔除少于 324 个日浓度平均值的站点.通过上述处理, $PM_2$ ,引均及年均值取算数平均值, $O_3$  取日最大 8 h 滑动平均值在日历月及日历年的第 90 百分位数(下文简称  $O_3$ \_MDA8\_90).

#### 1.1.2 多源卫星遥感数据

气溶胶光学厚度(aerosol optical depth, AOD) 与地面 PM25浓度具有显著的相关性,因此被广泛应 用于 PM<sub>2.5</sub> 浓度估算. 二氧化氮(NO<sub>2</sub>)和甲醛 (HCHO)作为 O<sub>3</sub> 的前体污染物,通常被用于近地面 0,浓度估算[22].因此,本文采用空间分辨率及覆盖 度较高的 MAICA AOD 产品<sup>[23]</sup>估算 PM<sub>2.5</sub>浓度,OMI NO, 和 HCHO 对流层柱浓度产品估算近地面 O3 浓 度,上述产品获取的时间范围均为2015年1月1日 到 2020 年 12 月 31 日. 其中 MAICA AOD 产品来源 于 NASA Level 1 Atmospheric Archive and Distribution System(LAADS) 网站(http://ladsweb. nascom. nasa. gov/),空间分辨率为1 km×1 km. NO,和 HCHO 柱 浓度数据来自搭载于美国 2004 年发射的 Aura 卫星 上的 OMI 传感器,下载自 NASA GES DISC 数据库 网站(https://disc. gsfc. nasa. gov/),时间分辨率为 逐日,空间分辨率为13~24 km,在预处理过程中, 将目 NO, 和 HCHO 柱浓度数据进行异常值剔除后 融合为月均25 km×25 km分辨率,再使用普通克里 金插值到 10 km × 10 km 分辨率, 年均 NO, 和 HCHO 柱浓度数据则取月平均.

#### 1.1.3 其他建模数据

根据已有研究,气象数据、边界层高度、植被 覆盖指数和地形高程与近地面 PM,5和 O,浓度的生 成以及扩散相关性较大[24,25],因此收集上述数据用 于建立 PM,5和 O,浓度遥感制图模型.其中气象及 边界层高度数据来源于 ERA5 再分析资料(https:// cds. climate. copernicus. eu/)的月均产品,气象要素 包含温度、气压、风速、风向、相对湿度、降雨量和 太阳净辐射量,分辨率为 10 km×10 km,边界层高 度空间分辨率为25 km×25 km; 植被覆盖指数采用 MODIS 归一化植被指数(normalized difference vegetation index, NDVI) 产品 (https://ladsweb. modaps. eosdis. nasa. gov/),空间分辨率为1 km×1 km,时间分辨率为16d;地形高程数据(DEM)来源 于美国宇航局 SRTM 数据 (http://srtm. csi. cgiar. org/),空间分辨率为90 m×90 m. 在数据预处理过 程中,在空间尺度上将所有建模数据通过重采样和 空间插值分别统一到 1 km×1 km(PM,5浓度估算) 和 10 km×10 km(O,浓度估算)分辨率,在时间尺 度上,分别按月和年求平均值得到对应时间尺度合 成数据.

#### 1.2 PM<sub>2.5</sub>和 O, 浓度估算与结果验证

#### 1.2.1 估算模型与验证方法

采用随机森林(random forest, RF)回归建模对研究区月尺度和年尺度上的 PM<sub>2.5</sub>浓度和 O<sub>3\_</sub>MDA8\_90 进行遥感估算. RF 是由 Breiman 提出的一种统计学习理论<sup>[26]</sup>. 其本质是通过集成多个决策树来模拟多重非线性关系,该方法目前已广泛应用至大气污染浓度遥感估算领域<sup>[27-29]</sup>. RF 回归模型主要分为3步:①样本数据随机抽样与训练集生成;②特征变量随机选取与回归树构建;③将②中生成的回归树组成 RF 回归模型,并通过取平均值的方式得到预测值.

本研究采用基于样本、站点和时间的十折交叉验证(10-CV)方法对  $PM_{2.5}$ 和  $O_3$  浓度估算结果进行验证[12,15]. 采用决定系数( $R^2$ )和均方根误差(RMSE)检验模型预测精度,计算公式如下:

$$R^{2} = 1 - \left[ \sum_{i=1}^{n} (y_{i} - \hat{y}_{i}) / \sum_{i=1}^{n} (y_{i} - \bar{y}_{i})^{2} \right]$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_{i} - \hat{y}_{i})^{2}}$$
(2)

式中,  $y_i$  为观测值,  $\bar{y}_i$  为观测值的平均值,  $\hat{y}_i$  为模型的预测值.

#### 1.2.2 验证结果

表 1 显示了采用 RF 构建的 PM<sub>2.5</sub>和 O<sub>3</sub> 浓度估算模型验证结果. 就时间尺度而言,月尺度模型精度优于年尺度模型,基于样本和站点的模型验证精度. 就污染物而言,O<sub>3</sub> 浓度估算模型在月尺度( $R^2$ :0.87~0.92,RMSE:12.16~22.93  $\mu$ g·m<sup>-3</sup>)优于 PM<sub>2.5</sub>模型( $R^2$ :0.71~0.90, RMSE:7.54~12.93  $\mu$ g·m<sup>-3</sup>),但年尺度上略逊于 PM<sub>2.5</sub>浓度估算模型(O<sub>3</sub>,  $R^2$ :0.72~0.88, RMSE:8.48~13.56  $\mu$ g·m<sup>-3</sup>PM<sub>2.5</sub> vs. PM<sub>2.5</sub>,  $R^2$ :0.74~0.89, RMSE:4.81~7.37  $\mu$ g·m<sup>-3</sup>).

#### 1.3 协同防控区划定的 GIS 分析

#### 1.3.1 防控成效空间一致性评价

在防控成效空间一致性评价过程中, 先将  $O_3$  浓度空间分布重采样到与  $PM_{2.5}$  浓度相同空间分辨率  $(1 \text{ km} \times 1 \text{ km})$ ,然后再根据图 2 开展评价. 其中  $\rho(PM_{2.5})_n$  和  $\rho(O_3)_n$  表示该网格基准年(例如 2015年)的  $PM_{2.5}$  和  $O_3$  浓度, $\rho(PM_{2.5})_m$  和  $\rho(O_3)_m$  则表示被评价年(例如 2020年)的  $PM_{2.5}$  和  $O_3$  浓度,  $R(PM_{2.5})$  和  $R(O_3)$ 则是评价期期间  $PM_{2.5}$  和  $O_3$  浓度的变化率.

#### 1.3.2 协同防控区划定

为进一步判定区域防控污染物对象、划分防控等级以及划定防控区范围,本文结合评价年PM<sub>2.5</sub>和 O<sub>3</sub> 污染浓度,以及在基准年与被评价年期间的变化情况进行了防控区划分.首先依据被评价年 PM<sub>2.5</sub>和 O<sub>3</sub> 污染浓度是否超标,将全国范围

按防控污染物对象分为了  $PM_{2.5}$ 和  $O_3$  协同(  $PM_{2.5}$ 和  $O_3$  均超标)、 $PM_{2.5}$ 防控为主(  $PM_{2.5}$ 超标,  $O_3$  达标)和  $O_3$  防控为主(  $O_3$  超标,  $PM_{2.5}$ 达标)这三大类型. 在防控污染物对象大类划定基础上, 再依据被评价年与基准年的浓度变化率升高与降低情况细分防控等级( 表 2 ).

表 1  $PM_{2.5}$ 和  $O_3$  浓度估算模型验证精度

Table 1 Validations of PM<sub>2.5</sub> and O<sub>3</sub> estimation model

					2.0				
时间尺度	检验指标 -	PM <sub>2.5</sub> 制图模型精度			O <sub>3</sub> 制图模型精度				
的同八反	小环 分平 1日 小小	样本数	基于样本	基于站点	基于时间	样本数	基于样本	基于站点	基于时间
月	$R^2$	58 950	0.90	0.89	0.71	56 709	0.92	0.91	0.87
	RMSE/ $\mu$ g·m <sup>-3</sup>		7.54	7.92	12.93		12.16	19.16	22.93
年	$R^2$	7 001	0.89	0.87	0.74	7 288	0.88	0.88	0.72
	RMSE/ $\mu g \cdot m^{-3}$		4.81	5.17	7.37		8.48	8.82	13.56

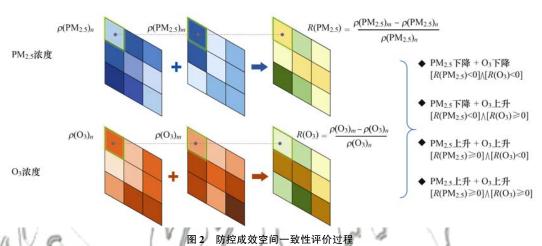


Fig. 2 Process of spatial consistency evaluation of PM<sub>2.5</sub> and O<sub>3</sub> prevention and control effects

表 2  $PM_{3,5}$ 和  $O_{3}$  污染协同防控区域划定条件

Table 2 Conditions of regionalizing PM<sub>2.5</sub> and O<sub>3</sub> collaborative prevention and control area

防控污染物对象	防控等级	约束条件				
例任行采彻州家	奶狂守纵	浓度(ρ)	变化率(R)			
	I级		$[R(PM2.5] \ge 0) \land [R(O3) \ge 0]$			
PM <sub>2.5</sub> 和 O <sub>3</sub> 协同	<b>I</b> 级	$\left[\rho(\operatorname{PM}_{2.5}) > T(\operatorname{PM}_{2.5})\right] \wedge \left[\rho(\operatorname{O}_3) > T(\operatorname{O}_3)\right]$	$\{ [R(PM_{2.5}) < 0] \land [R(O_3) \ge 0] \} \lor$ $\{ [R(PM_{2.5}) \ge 0] \land [R(O_3) < 0] \}$			
	Ⅲ 级		$R(PM_{2.5}) < 0 \land R(O_3) < 0$			
 PM, 5防控为主	I 级	$\lceil \rho(PM_{2.5}) > T(PM_{2.5}) \rceil \land \lceil \rho(O_3) \leq T(O_3) \rceil$	$R(PM_{2.5}) \geqslant 0$			
1 M <sub>2.5</sub> b) 1± /1 ±	Ⅱ 级	$[p(1 M2.5) > I(1 M2.5)] \land [p(O3) \leq I(O3)]$	$R(PM_{2.5}) < 0$			
 0, 防控为主	I 级	$\lceil \rho(PM_{2.5}) \leq T(PM_{2.5}) \rceil \land \lceil \rho(O_3) > T(O_3) \rceil$	$R(O_3) \geqslant 0$			
03 列迁为王	Ⅱ 级	$[p(1 \text{ m}_{2.5}) < I(1 \text{ m}_{2.5})] \land [p(0_3) > I(0_3)]$	$R(O_3) < 0$			

1)按《环境空气质量标准》(GB 3095-2012), $T(PM_{2.5})_{\mp}$ 取 35  $\mu g \cdot m^{-3}$ , $T(O_3)_{\mp}$ 取 160  $\mu g \cdot m^{-3}$ ,该标准未对月或季污染浓度作出规定,故本研究中以日二级标准为参照, $T(PM_{2.5})_{\pm}$ 取 75  $\mu g \cdot m^{-3}$ , $T(O_3)_{\pm}$ 取 100  $\mu g \cdot m^{-3}$ .

#### 2 结果与讨论

#### 2.1 PM, 和 O, 污染浓度时序分析

 $2015 \sim 2020$  年期间,全国整体  $PM_{2.5}$ 年均浓度逐年下降,下降率为 25. 36%,由 39  $\mu g \cdot m^{-3}$ 降至 29  $\mu g \cdot m^{-3}$ ,在 2017 年达到年均浓度二级标准限值.年  $O_{3}$ \_MDA8\_90 则呈现先上升(2018 年达到峰值 137  $\mu g \cdot m^{-3}$ )后下降的趋势,2020 年(127  $\mu g \cdot m^{-3}$ )与 2015 年(128  $\mu g \cdot m^{-3}$ )基本持平.同时,本研究将

PM<sub>2.5</sub>和 O<sub>3</sub> 遥感估算浓度与全国城市空气质量监测结果进行了对比,结果显示遥感估算浓度总体上略低于城市空气质量实时监测数据,但年际总体变化趋势与其基本保持一致[图 3(a)和 3(b)]. 其主要原因在于城市空气质量实时监测站点大多布点在城市建成区区域,该区域空气质量浓度普遍高于非城市区域<sup>[30]</sup>.

图 3(c) 和 3(d) 进一步显示了年尺度不同等级  $PM_{2.5}$  和  $O_3$  浓度超标面积占总体面积的比例.  $PM_{2.5}$ 

二级浓度限值(35  $\mu$ g·m<sup>-3</sup>)以上面积占比总体下降 8 个百分点(40%~32%);  $O_3$  二级浓度限值(160  $\mu$ g·m<sup>-3</sup>)以上面积占比则与其年均浓度呈现出一致的总体基本持平,年际间波动变化的趋势.由于《环境空气质量标准》(GB 3095-2012)中未给定月尺度浓度限值,因此本研究分别以日一级[ $\rho$ (PM<sub>2.5</sub>)为35  $\mu$ g·m<sup>-3</sup>, $\rho$ ( $O_3$ )为100  $\mu$ g·m<sup>-3</sup>]和二级[ $\rho$ (PM<sub>2.5</sub>)为75  $\mu$ g·m<sup>-3</sup>, $\rho$ ( $O_3$ )为160  $\mu$ g·m<sup>-3</sup>]浓度限值标准统计了月尺度超标面积

占比. 结果表明,在一级浓度限值下,PM<sub>2.5</sub>浓度超标面积占比在秋季的 11 月到第二年春季的 3 月期间一般会持续在 70% 以上,而 O<sub>3</sub> 污染超标面积比则在春季 3 月开始上升,到春夏交替的 5 月和 6 月达到峰值(90% 左右),在 9 月和 10 月开始回落[图 3(e)].超二级浓度限值的面积占比则均在 20% 以下[图 3(f)],其中 PM<sub>2.5</sub>浓度超标面积在 12 月和 1 月占比最高,O<sub>3</sub>则在 5~7 月显著高于其他月份,其季节性变化与污染物的形成

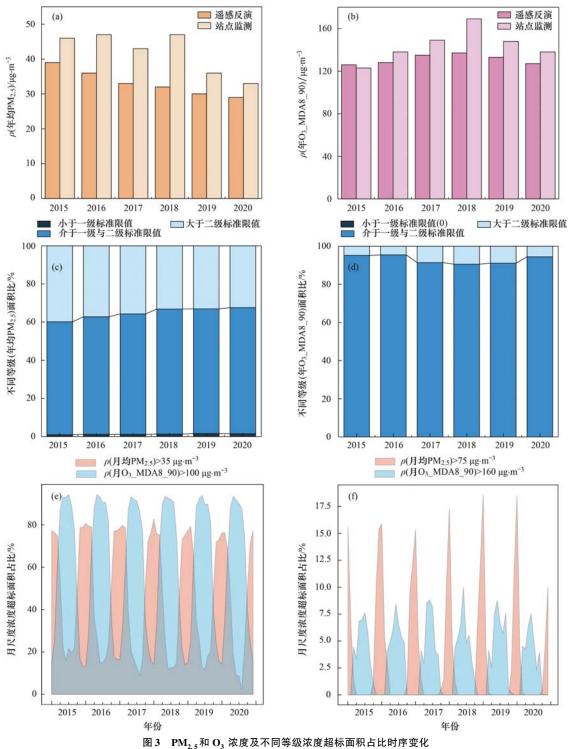


Fig. 3 Temporal variations in PM<sub>2.5</sub> and O<sub>3</sub> concentrations and the proportion of areas with exceeding the standard of different levels

和扩散受气温、湿度、降水和太阳辐射等气象条件影响密切相关<sup>[31,32]</sup>.

#### 2.2 PM,5和 O3污染浓度空间分析

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图 4 展示了 2015 ~ 2020 年 PM<sub>2.5</sub>和 O<sub>3</sub> 浓度空间分布情况. 年均 PM<sub>2.5</sub>浓度高值区域主要在五大重点区域的"2 + 26"城市、汾渭平原、成渝地区和重点区域外的新疆塔克拉玛干沙漠等地区 [图 4 (a)]. 春季, PM<sub>2.5</sub>污染的范围主要在华北平原 [图 4 (c)], 夏季全国 PM<sub>2.5</sub>浓度均处于低值水平 [图 4 (e)], 秋季的污染范围在春季基础上扩大至汾渭、成渝和湖北地区 [图 4(g)], 冬季则覆盖了全国除青藏和云贵高原外的大部分区域 [图 4(i)]. 其中"2 + 26"城市受产业结构、人口密度等因素的影响,一直以来都是我国大气污染防治关注的重点区

域 $^{[33,34]}$ ,汾渭平原、成渝地区因其复杂的地形和不利的气象条件而导致重污染天气频发 $^{[35,36]}$ ,新疆塔克拉玛干沙漠地区的空气质量则主要受沙尘的影响 $^{[37]}$ .年 $O_3$ \_MDA8\_90浓度显示[图4(b)],京津冀鲁豫、长三角和珠三角的 $O_3$ 污染超标情况不容忽视;根据相关研究报道,上述地区的 $NO_x$ 和 $VOCs排放强度(均为<math>O_3$ 的前体污染物)分别是全国平均水平的2.8~4.5倍和4.0~5.3倍,显著高于整个东部地区的平均水平 $^{[38]}$ .除上述需重点关注的区域外,云贵高原在春季也易发生 $O_3$ 污染[图4(d)],新疆、甘肃、宁夏、内蒙和东北地区则在夏季易发生 $O_3$ 污染[图4(f)].

#### 2.3 PM<sub>2.5</sub>和 O<sub>3</sub> 防控成效空间一致性分析 网格尺度的污染浓度变化率显示, 2015~2020

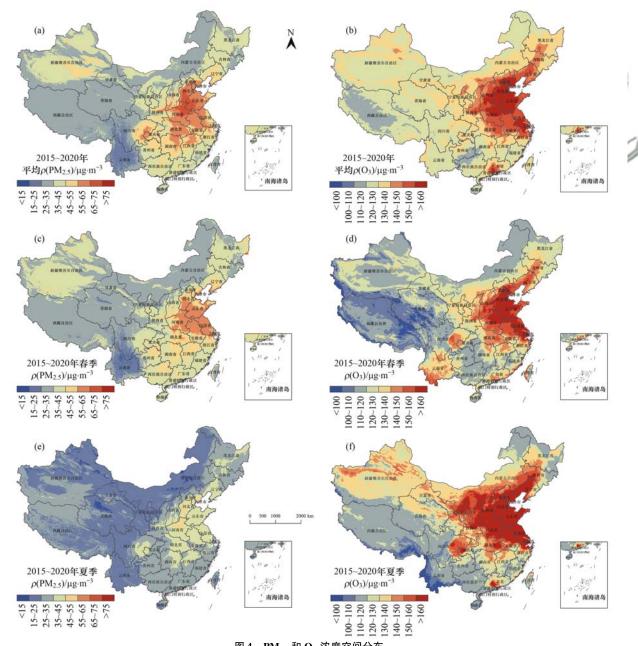


图 4 PM<sub>2.5</sub>和 O<sub>3</sub> 浓度空间分布

Fig. 4 Spatial distribution of PM<sub>2.5</sub> and O<sub>3</sub> concentrations

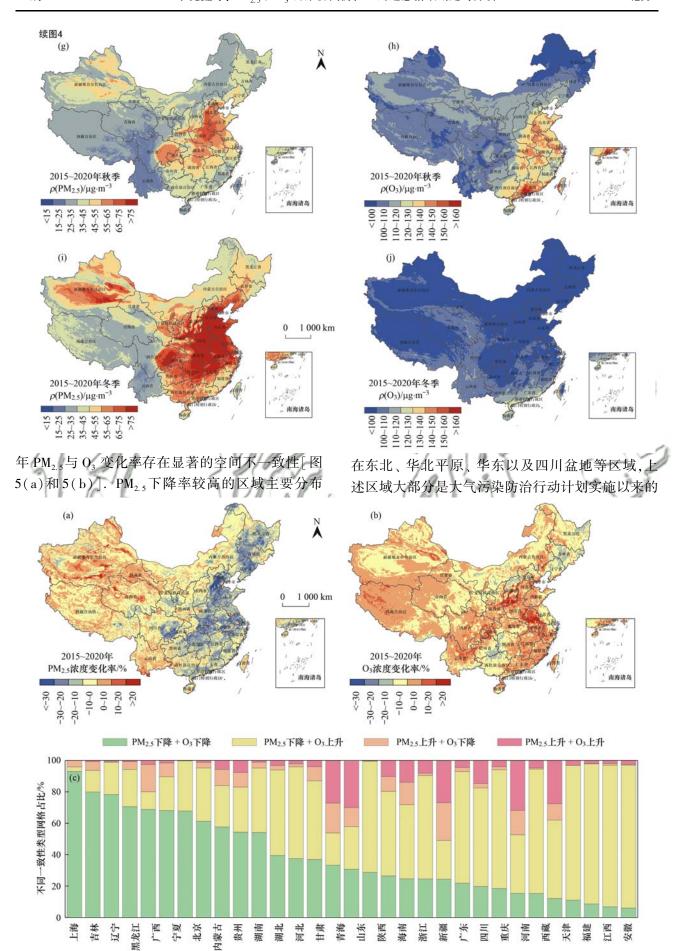


图 5  $PM_{2.5}$ 和  $O_3$  防控成效空间一致性比较 Fig. 5 Comparisons of spatial consistency for the prevention and control effects between  $PM_{2.5}$  and  $O_3$ 

重点防控区域,强有力地减排措施是大气污染得到显著改善的主要原因<sup>[39,40]</sup>.内蒙古、青海、新疆、西藏和云南等地区的 PM<sub>2.5</sub>浓度则出现一定程度上升趋势,其原因主要在于该部分地区的基准浓度 (2015年)较低,因此 PM<sub>2.5</sub>浓度值的小幅变化也会导致大幅的变化率. O<sub>3</sub> 浓度呈下降趋势的范围相对较小,主要分布在东北、西南、西北以及华东部分地区,上升率较高的地区主要在关中平原、川渝地区、苏皖鲁豫交界区域以及华南地区,在空间分布上与 PM<sub>2.5</sub>变化率出现明显的"此消彼长"的趋势.该结果与孟晓艳等<sup>[41]</sup>基于地面监测站点数据开展的重点区域 O<sub>3</sub> 污染状况分析结果一致.

图 5(c)展示了各省份不同一致性类型网格的

占比情况. 共有 11 个省份 PM<sub>2.5</sub>与 O<sub>3</sub> 浓度均下降的 网格占比超过 50%, 其中上海市占比最高, 达到 93.03%, 这与上海在"十三五"期间制定了系列节能 减排措施<sup>[42,43]</sup>, 并超额完成了"十三五"期间制定的 减排与空气质量目标<sup>[44]</sup>密切相关; 其次是东北三省(吉林:79.88%, 辽宁:78.28%, 黑龙江 70.54%). 福建、江西、安徽、天津和河南则呈现出显著的 PM<sub>2.5</sub>与 O<sub>3</sub> 浓度均下降网格占比低, PM<sub>2.5</sub>下降且 O<sub>3</sub> 上升网格占比高的特征, 上述 5 省份 PM<sub>2.5</sub>下降且 O<sub>3</sub> 上升网格占比均在 80% 以上. 部分西部省份(新疆、云南、甘肃、青海和西藏) 受沙尘、基准浓度较低、海拔高度和气象等因素的影响<sup>[45~47]</sup>, 出现较大面积的 PM<sub>2.5</sub>和 O<sub>3</sub> 同时上升的情况.

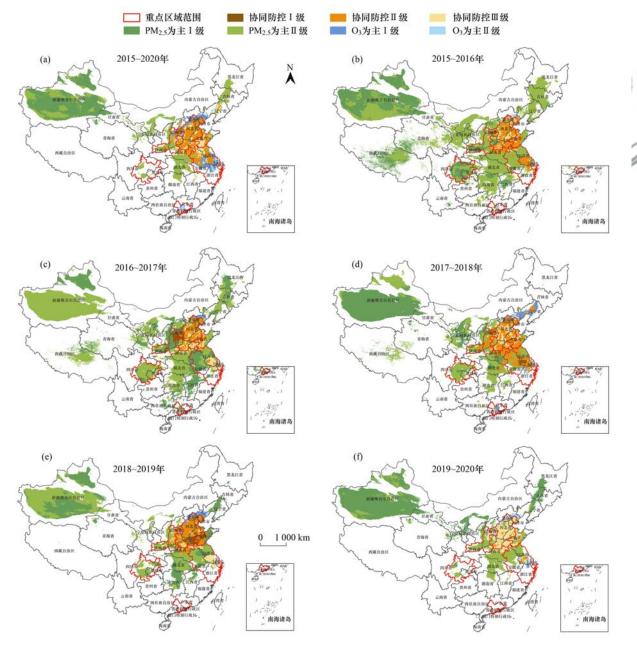


图 6 年尺度协同防控区边界划分结果 Fig. 6 Regionalization of synergetic prevention and control areas at yearly scale

#### 2.4 PM, 5与 O, 协同防控区划定与分析

图 6 展示了年尺度的 PM25和 O3 协同防控区边 界划分结果[图 6(a)]及各边界范围逐年变化情况 [图 6(b)~6(f)]. 总体而言,需开展 PM25与 O3协 同防控的区域主要集中在"2+26"城市、汾渭平原、 长三角地区北部以及山东半岛,其中大部分区域 ("2+26"城市、汾渭平原的关中地区、长三角苏皖 鲁豫交界区域)应以防控等级Ⅱ级为主,江苏及山 东半岛则以Ⅲ级为主. 因气象条件和污染物排放是 形成重污染天气的两大主导因素,且现有研究表明, VOCs 和 NO, 既是 O, 的主要前体物, 也是参与大气 中化学反应生成 PM2.5二次污染物的重要组成部 分[48],因而对于上述协同防控区域而言,大力实施 VOCs 和 NO。减排措施显得至关重要. 协同防控边 界范围也存在时间变化特征,该类型防控区域在 2016年[图 6(b)]主要集中在"2+26"城市、山东 半岛和长三角部分区域,到2017年[图6(c)]向北 扩展至环渤海湾北岸,向西到汾渭平原,向南涵盖河 南和江苏北部,且以Ⅰ级和Ⅱ级防控区域为主. 2018年[图 6(d)],协同防控区域范围进一步向南。 蔓延,这一状况到2019年[图6(e)]出现好转趋势,

空间范围开始缩减,到 2020 年[图 6(f)]防控等级也大部分降为以Ⅲ级为主.与协同防控区域相比,以PM<sub>2.5</sub>或 O<sub>3</sub> 单一防控为主的区域范围总体变化不大.其中以PM<sub>2.5</sub>防控为主的地区主要在东北的辽宁和吉林地区、华中的鄂湘赣地区、西南的成渝地区以及西北的塔克拉玛干沙漠-河西走廊区域;以 O<sub>3</sub> 防控为主的区域范围相对来说面积较小,主要集中在珠三角、长三角以及环渤海湾的部分区域.

分季节划分的协同防控区边界显示,春季[图7(a)]和夏季[图7(b)]重点以 O<sub>3</sub> 防控为主,防控的区域范围除重点区域外,在春季还应重视云南南部,在夏季应关注宁夏北部、内蒙南部和环渤海湾地区;在秋季[图7(c)],除珠三角部分区域需注重O<sub>3</sub> 防控外,整体空气质量情况良好;在以 PM<sub>2.5</sub> 防控为主的冬季[图7(d)],其范围除重点区域外,还应关注豫鄂湘赣地区. 此结果虽然表明 PM<sub>2.5</sub>和 O<sub>3</sub> 污染在同一季节同时发生的情况不显著,但不同季节分别以 PM<sub>2.5</sub>和 O<sub>3</sub> 污染防控为主的区域在地理空间范围上一致性程度较高. 因此上述地区在制定防控策略时可重点考虑先以区域协同防控为主,再对不同季节重点防控的污染物进行针对性施策.

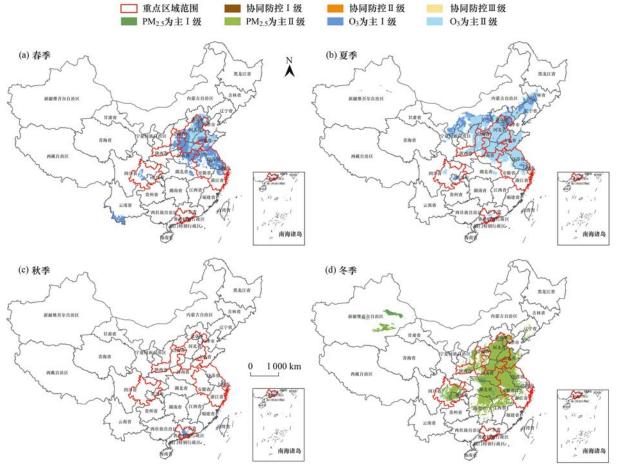


图 7 协同防控区边界分季节划分结果

Fig. 7 Regionalization of synergetic prevention and control areas in different seasons

本文基于遥感数据精细划定的协同防控区域范围在主体上与国家当前划定的重点防控区域一致性程度较高. 二者的主要差异体现在:"2+26"城市区域划定的防控区域范围不足(未能将山东半岛、辽宁、吉林和环渤海湾地区划入),长三角、珠三角防控范围略大. 同时部分地区如华中的豫鄂湘赣地区、西北的塔克拉玛干沙漠-河西走廊区域还暂未被纳入国家重点防控区域. 此外,在月和年尺度上识别出来的重点区域污染区域的基础上,还可进一步考虑针对具体污染事件,融合葵花8号和风云4号等静止卫星数据产品分析日变化特征,分析污染的形成和消亡过程.

#### 3 结论

- (1)2015~2020年,全国整体 PM<sub>2.5</sub>年均浓度逐年下降,下降率为 25.36%,"2+26"城市、汾渭平原、成渝地区和新疆塔克拉玛干沙漠 PM<sub>2.5</sub>污染相对严重; 0<sub>3</sub> 浓度则呈现先上升后下降的趋势, 2020年与 2015年基本持平,京津冀鲁豫、长三角和珠三角地区是 0<sub>3</sub> 污染的重点关注区域.
- (2)全国 PM<sub>2.5</sub>和 O<sub>3</sub> 浓度变化呈现显著的空间不一致性,其中 PM<sub>2.5</sub>下降且 O<sub>3</sub> 上升、 PM<sub>2.5</sub>与 O<sub>3</sub> 均下降、 PM<sub>2.5</sub>与 O<sub>3</sub> 均上升和 PM<sub>2.5</sub>上升 O<sub>3</sub> 下降的面积占比分别为 38.34%、35.12%、15.24%和10.89%.上海、吉林、辽宁和黑龙江 PM<sub>2.5</sub>与 O<sub>3</sub> 均下降面积占比高;福建、江西、安徽、天津和河南则呈现出 PM<sub>2.5</sub>与 O<sub>3</sub> 均下降面积占比低,PM<sub>2.5</sub>下降且 O<sub>3</sub> 上升面积占比高的特征.
- (3)全国 PM<sub>2.5</sub>和 O<sub>3</sub> 协同防控区域边界具有动态变化特征,在时间变化上呈现先扩大后缩小的趋势,主体范围集中在"2+26"城市、汾渭平原、长三角地区的北部和山东半岛.以 PM<sub>2.5</sub>或 O<sub>3</sub> 单一防控为主的区域范围较为稳定,辽吉、鄂湘、成渝和塔克拉玛干沙漠-河西走廊区域需以 PM<sub>2.5</sub>防控为主,珠三角、长三角和环渤海湾的部分区域则应以 O<sub>3</sub> 防控为主.

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Environmental Science (monthly)

Vol. 43 No. 10 Oct. 15, 2022

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