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基于四维通量法的佛山臭氧污染输送量化

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摘要: 定量输送过程对大气污染事件的贡献程度一直是目前区域大气污染防治的突出难点和重要需求. 对此, 基于 WRF-Chem 模式对佛山典型区域性臭氧(O_3)污染事件开展模拟, 应用四维通量法分别量化周边区域对佛山市臭氧及其前体物的输送通量, 厘清臭氧直接输送和前体物输送的贡献, 发现周边区域对佛山市输送的 O_3 总通量平均值为 $120.3 \text{ t} \cdot \text{h}^{-1}$; 挥发性有机化合物(VOCs)总通量平均值为 $30.2 \text{ t} \cdot \text{h}^{-1}$; 其对应的臭氧生成潜势(OPF)为 $114.8 \text{ t} \cdot \text{h}^{-1}$. 通过统计各 O_3 污染事件的输送通量, 发现污染期间输入佛山 O_3 通量最大的城市为广州(贡献率为 44%); 输入 VOCs 通量最大的城市为肇庆(贡献率为 48%). 分析输送 VOCs 排放导致的 O_3 生成潜势发现含氧挥发性有机物(OVOCs)对 OPF 的贡献最大, 在“最大输入事件”中占比为 47%. 甲醛、二甲苯、醛类、丙酮和苯酚类等 OVOCs 和芳香烃是对 OPF 贡献前 5 的物种, 贡献量占总 OPF 的 50% 以上, 主要来自工业溶剂源.

关键词: 佛山; 臭氧污染; 区域输送; 四维通量法; WRF-Chem 模式

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Quantification of Ozone Pollution Transport Based on Four-dimensional Flux Method in Foshan, China

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Abstract: Quantifying the contribution of transport processes to air pollution events has been a prominent challenge and an important need in regional air pollution prevention and control. The WRF-Chem model was used to simulate a typical regional ozone (O_3) pollution event in Foshan, and the four-dimensional flux method was applied to quantify the transport fluxes of ozone and its precursors from the surrounding areas to Foshan and to clarify the contributions of the direct transport of ozone and transport of precursors. The average ozone flux from the surrounding areas to Foshan was $120.3 \text{ t} \cdot \text{h}^{-1}$, the volatile organic compound (VOCs) flux was $30.2 \text{ t} \cdot \text{h}^{-1}$, and the corresponding ozone formation potential (OPF) was $114.8 \text{ t} \cdot \text{h}^{-1}$. By counting the transport fluxes of each ozone pollution event, it was found that the city with the largest ozone flux into Foshan during the pollution period was Guangzhou (contributed 44%); the city with the largest input VOCs flux was Zhaoqing (contributed 48%). The analysis of ozone generation potential due to transported VOCs emissions found that oxygenated volatile organic compounds (OVOCs) contributed the most to OPF, accounting for 47% of the “maximum input events.” OVOCs and aromatic hydrocarbons such as formaldehyde, xylenes, aldehydes, acetone, and phenols were the top five species contributing to the OPF, contributing more than 50% of the total OPF, mainly from industrial solvent sources.

Key words: Foshan; ozone pollution; regional transport; four-dimensional flux method; WRF-Chem model

近年来珠江三角洲(珠三角)区域的 O_3 污染愈加严重^[1~5], 并呈现明显的区域性^[6~10]. 区域性 O_3 污染事件是由强太阳辐射下的局部光化学反应、大范围不利于扩散的天气条件和 O_3 及其前体物的输送共同造成的, O_3 前体物的本地排放和 O_3 及其前体物的区域输送都对 O_3 浓度有很大影响^[11~16]. 目前人们对光化学反应生成 O_3 的机制认识已相对完善^[17~19], 对影响 O_3 污染的天气分型的运用也相对广泛^[20~23]. 然而, 对于 O_3 的区域输送研究, 前人多直接用 O_3 浓度差异结果表示输送过程的影响, 尚未厘清具体物质输送对 O_3 污染的影响^[24, 25].

当前学界尝试使用了多种 O_3 区域输送的表征方法开展这一过程的量化工作^[26, 27]. 如 Wang 等^[28] 通过潜在源分析发现, 在海洋气团影响下江苏省的

排放对浙江省 O_3 的体积分数贡献为 $100 \times 10^{-9} \sim 200 \times 10^{-9}$; 李杰等^[29]通过污染物来源和过程追踪技术发现中国南部光化学反应生成的 O_3 对朝鲜半岛和日本的贡献达 $5 \sim 10 \mu\text{L} \cdot \text{m}^{-3}$. 伍永康等^[30]利用 O_3 源解析技术(ozone source apportionment technology, OSAT)量化了东莞和深圳受惠州传输贡献, 分别为 26% 和 44%. 上述这些工作虽然量化了

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输送过程对区域间 O_3 污染的贡献,但没有区分 O_3 前体物输送和 O_3 直接输送对区域间 O_3 污染的影响,对区域 O_3 污染防治攻坚的指导价值有限。

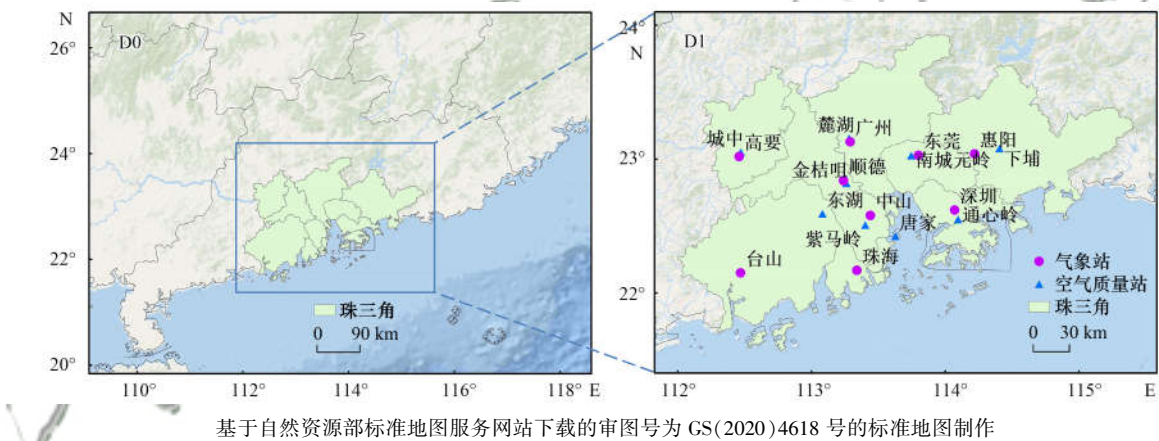
佛山市位于广东省珠江三角洲地区,是粤港澳大湾区的重要组成城市. 由于正处于城市化、工业化快速发展时期,佛山市近年来 O_3 污染问题突出. 2021 年佛山市 O_3 年评价浓度居珠三角城市之首, O_3 污染事件已成为影响当地空气质量的关键因素^[31,32]. 关于佛山市 O_3 污染的研究主要集中在对 O_3 及其前体物的污染特征分析和来源解析,有研究发现佛山为挥发性有机化合物 (volatile organic compounds, VOCs) 敏感区^[33], 针对 VOCs 开展治理有利于当地 O_3 污染防治^[34]. 关于 O_3 和前体物 VOCs 的输送通量及其对当地 O_3 污染影响需要进一步深入研究. 本研究联用数值模拟和四维通量法,选取佛山市典型 O_3 污染事件,量化不同天气型下佛

山地区 O_3 及其前体物 VOCs 的区域输送通量,以期 为佛山市 O_3 污染精准防控提供决策依据。

1 材料与方法

1.1 模式设置

本研究采用区域大气化学传输模式 WRF-Chem (V4.1.2),模拟佛山市及其周边城市的 O_3 浓度时空分布. 如图 1 所示,研究区域位于我国华南地区 (D0),模型网格范围覆盖整个珠三角 (D1),水平分辨率为 $3\text{ km} \times 3\text{ km}$,模式顶气压设置为 100 hPa,垂直方向上划分为 30 层. 模式气象场采用全球 $1^\circ \times 1^\circ$ 再分析资料 (FNL) 驱动,化学初始和边界条件来自于 Mozart 全球模式结果. 人为排放数据来源于 2016 年中国月平均多分辨率排放清单 (MEIC). WRF-Chem 物理参数化方案和化学方案具体设置如表 1 所示。



基于自然资源部标准地图服务网站下载的审图号为 GS(2020)4618 号的标准地图制作

图 1 模拟区域和观测站点

Fig. 1 Simulation area and observation sites

表 1 WRF-Chem 模拟物理和化学参数化方案设置

Table 1 WRF-Chem simulation physical and chemical parameterization scheme settings

组成	过程	参数化方案
物理参数设置	微物理	Lin
	长波辐射	RRTM
	短波辐射	Dudhia
	近地面层	Monin-Obukhov
	陆面过程	Noah-MP
	城市冠层	UCM
	行星边界层	YSU
	积云	Grell 3D Ensemble
化学参数设置	光解	Madronich
	气相化学	RACM
	气溶胶化学	MOSAIC

1.2 污染物与气象观测资料

本研究使用的气象观测数据为 2019 ~ 2021 年珠三角内中国地面气象站逐小时观测资料 (<https://data.cma.cn>), 共计有 9 个气象站点; 污染物数据

采用国家环境空气质量监测网环境空气质量监测点的常规污染物观测数据 (<http://113.108.142.147:20032>), 包括珠三角内佛山 (FS)、广州 (GZ)、中山 (ZS)、江门 (JM)、肇庆 (ZQ)、东莞 (DG)、深圳 (SZ)、惠州 (HZ) 和珠海 (ZH) 这 9 个城市的空气质量监测站点. 气象和环境空气质量监测站点分布见图 1.

1.3 四维通量法

四维通量法定义为特定时间内垂直通过特定面积给研究对象所输送的污染物的物理量, 该方法采用微元法计算不同污染物的输送通量, 运用“闭合绘线法”解决了输送过程中最关键的方向问题, 其原理见文献^[35]对四维通量的介绍. 四维通量法具有普遍适用性、计算过程更接近现实和计算结果更精确等优点, 已经在 $PM_{2.5}$ 区域输送通量研究方面有成功的应用^[36]. 本研究主要关注地面到 2 km 高度范围周边城市输送到佛山市的 O_3 及其前体物的通

量,对佛山市 O₃ 污染影响为正贡献时,将其定义为输入事件;对佛山市 O₃ 污染影响为负贡献时,将其定义为输出事件,本研究重点对“最大输入事件”开展特征分析.

1.4 污染天气型分类

本研究参考颜丰华等^[37]对污染天气型的分型方法,采用主观分型方法对佛山市 2019 ~ 2021 年 O₃ 污染事件大气环流形势开展分析,将天气型归纳为高压控制型 (high-pressure control, HC)、高压出海型 (high-pressure sea, HS) 和热带低压型 (tropical depression, TD) 共 3 类,天气型分类结果与司徒淑聘等^[38]和高晓荣等^[39]的研究相近.

2 结果与讨论

2.1 模拟验证结果与天气型分类

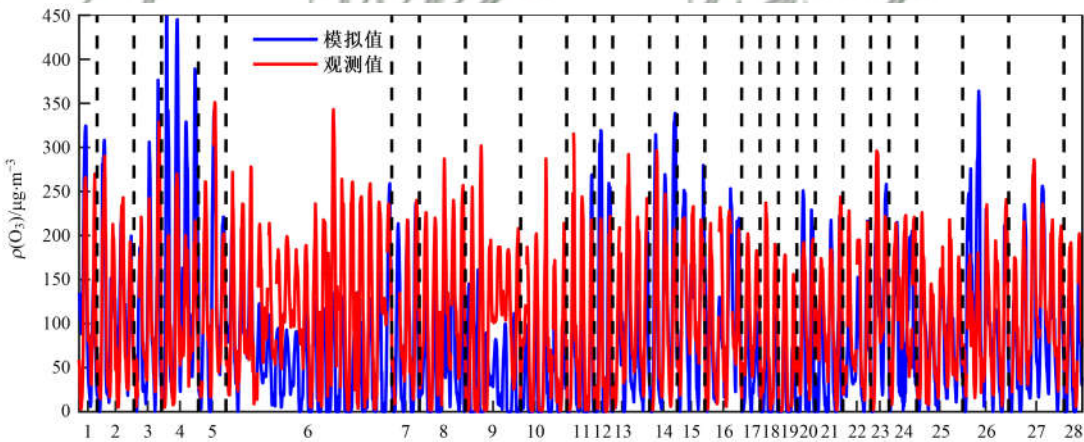
2.1.1 模拟结果验证

基于观测数据 (OBS) 和模拟数据 (SIM),采用评价标准包括平均绝对偏差 (MAE)、均方根误差 (RMSE) 和相关系数 (*R*) 共 3 个评价模型性能的指标,具体结果见表 2. 在本次模拟结果中,温度、气压

和相对湿度的模拟效果较好,相关系数均在 0.7 以上. 风速模拟存在低估现象,偏差为 0.1 m·s⁻¹. O₃ 模拟结果相比观测有所低估,但其相关系数为 0.71, O₃ 变化趋势效果较好;如图 2 所示,模型虽然在部分污染事件中低估了 O₃ 浓度峰值,但是可以捕捉到污染事件的发生. 综上所述,本次模拟能较好地反映佛山市及其周边城市的气象条件和 O₃ 污染状况.

2.1.2 O₃ 污染事件天气型分类特征

对 2019 ~ 2021 年期间佛山市合计发生 149 d O₃ 污染日和 28 次 O₃ 污染事件 (O₃ 连续 2 d 或以上超标) 进行统计,并对 O₃ 污染开展天气主观分型. 如图 3 所示,诱发佛山市 O₃ 污染的天气型以 HC 为主,发生频率为 54%, TD 和 HS 发生频率分别为 37% 和 9%. 按污染日当天主导风向对这 3 类污染天气型进一步细分,发现 HC 天气型时南风、东北风和西北风主导的污染天数发生频率分别占 20%、61% 和 19%; TD 天气型时南风、东北风和西北风主导的污染天数发生频率分别占 24%、56% 和 20%; HS 天气型发生的污染则 67% 为南风主导,偏



1. 2019-05-11 ~ 2019-05-12, 2. 2019-08-05 ~ 2019-08-08, 3. 2019-08-20 ~ 2019-08-22, 4. 2019-09-06 ~ 2019-09-09, 5. 2019-09-11 ~ 2019-09-13, 6. 2019-09-18 ~ 2019-10-02, 7. 2019-10-10 ~ 2019-10-12, 8. 2019-10-19 ~ 2019-10-23, 9. 2019-11-01 ~ 2019-11-06, 10. 2019-11-09 ~ 2019-11-13, 11. 2019-11-15 ~ 2019-11-17, 12. 2019-11-23 ~ 2019-11-24, 13. 2020-04-27 ~ 2020-04-30, 14. 2020-08/21 ~ 2020-08-23, 15. 2020-08-28 ~ 2020-08-30, 16. 2020-09-01 ~ 2020-09-04, 17. 2020-10-11 ~ 2020-10-12, 18. 2020-10-26 ~ 2020-10-27, 19. 2020-12-27 ~ 2020-12-28, 20. 2021-02-06 ~ 2021-02-07, 21. 2021-02-21 ~ 2021-02-23, 22. 2021-04-21 ~ 2021-04-23, 23. 2021-04-30 ~ 2021-05-01, 24. 2021-06-06 ~ 2021-06-07, 25. 2021-07-23 ~ 2021-07-27, 26. 2021-09-10 ~ 2021-09-13, 27. 2021-09-25 ~ 2021-09-30, 28. 2021-10-04 ~ 2021-10-05

图 2 O₃ 模拟值和观测值时序对比

Fig. 2 Time-series comparison of simulated and observed ozone values

表 2 模式验证结果

Table 2 Model validation results

项目	OBS	SIM	MAE	RMSE	<i>R</i> (无量纲)
温度/℃	28.9	26.3	3.1	4.1	0.75
相对湿度/%	65.3	72.6	12.5	15.5	0.71
风速/m·s ⁻¹	2.3	2.2	1.0	1.4	0.46
气压/hPa	1 006.8	1 008.7	2.8	3.5	0.89
ρ(O ₃)/μg·m ⁻³	108	84	50	66	0.71

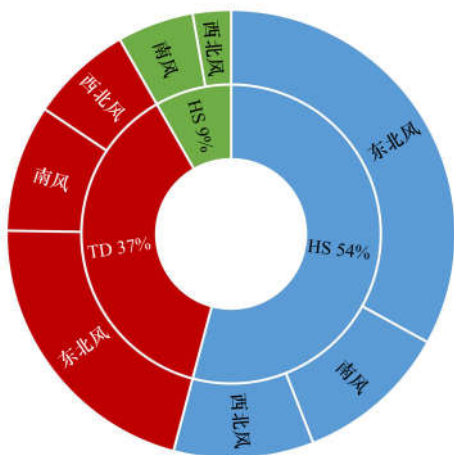


图3 O₃污染事件主导天气型和风向分布

Fig. 3 Distribution of dominant weather patterns and wind directions for O₃ pollution events

北风发生频率为33%。佛山市在不同大气环流类型控制下,整体以主导风向为东北风时O₃污染发生率较其他主导风向高。

2.2 不同风向及天气型条件下O₃污染事件输送通量特征

2.2.1 不同风向条件下O₃污染事件输送通量特征

在污染事件发生时,周边城市对佛山市O₃影响整体呈正贡献,输入的O₃总通量平均值为120.3 t·h⁻¹[图4(a)],其中以广州输入的贡献量最大,输入的通量为52.9 t·h⁻¹(贡献率为44%),其次为肇庆,输入通量为51.4 t·h⁻¹(贡献率为43%)。在污染事件发生时,周边城市对佛山市输入的VOCs总通量平均值为30.2 t·h⁻¹,所造成的臭氧生成潜势

(ozone formation potentials, OFP)为114.8 t·h⁻¹;其中以肇庆输入的贡献量最大,输入的VOCs通量为14.5 t·h⁻¹(贡献率为48%),对应的OFP为54.0 t·h⁻¹(贡献率为47%),其次为广州,对应的VOCs通量和OFP分别为12.7 t·h⁻¹(贡献率为42%)和46.9 t·h⁻¹(贡献率为41%)。

不同主导风向条件会直接影响周边城市对佛山市的污染物输送贡献^[40~42]。在东北风条件下[图4(b)],由于广州处于佛山市上风向地区,该地区对佛山市O₃及其前体物输送量的贡献最大,O₃输送通量贡献率为69%,VOCs输送通量的贡献率为90%,VOCs对应的OFP贡献率为87%;在南风条件下[图4(c)],佛山市上风向城市为江门和中山,其中江门为该风向条件下对佛山市O₃污染影响最大的城市,O₃输送通量、VOCs输送通量及对应的OFP贡献率分别可达83%、80%和79%;在西北风条件下[图4(d)],肇庆作为佛山市上风向地区对其O₃和VOCs输送通量的贡献率最大,O₃输送通量、VOCs输送通量及对应的OFP贡献率分别可达74%、66%和62%。在不同风向条件下,上风向城市为该地区的主要污染贡献城市,但在东风条件下广州市为佛山市上风向城市时,其向佛山市输送的VOCs及其对应的OFP贡献率大于其他风向下上风向城市的输送量。因此,应加强关注广州市VOCs输送对佛山市的影响。

2.2.2 不同天气型下O₃污染事件输送通量特征

不同污染天气型分类在大气环流形势方面具有

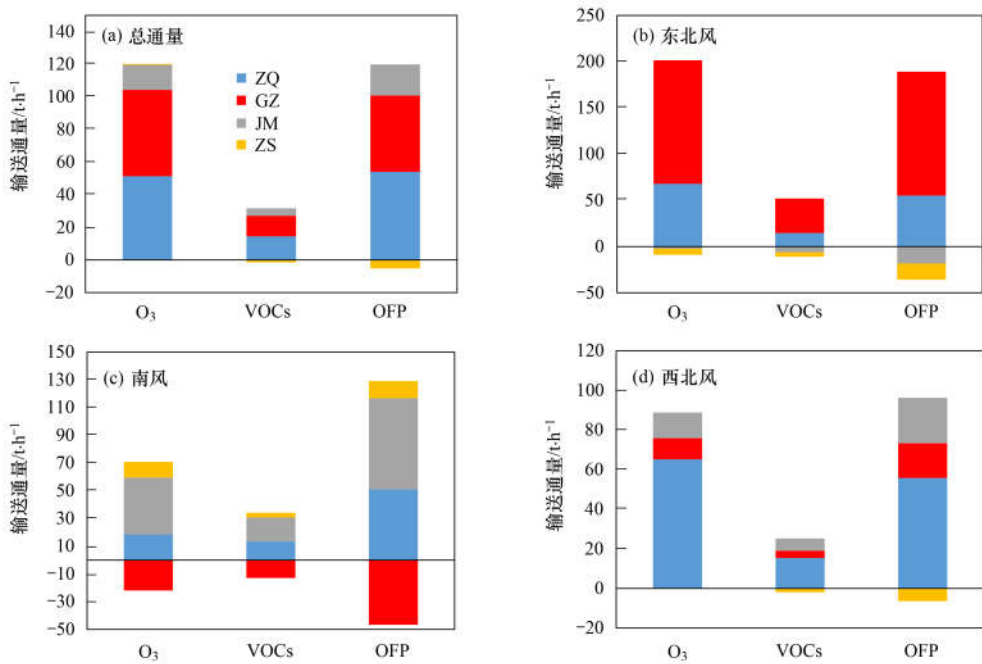


图4 不同风向条件下周边城市对佛山市的O₃及其前体物通量贡献情况

Fig. 4 Contribution of O₃ and its precursor fluxes from surrounding cities to Foshan under different wind conditions

不同特征,因此在不同天气型下周边城市对佛山市的污染物贡献存在较大差异^[43,44].在污染事件出现频率最高的 HC 天气型下[图 5(a)], O_3 总输入通量为 $125.0 \text{ t} \cdot \text{h}^{-1}$,VOCs 总输入通量为 $23.6 \text{ t} \cdot \text{h}^{-1}$,对应的 OFP 为 $95.2 \text{ t} \cdot \text{h}^{-1}$.肇庆为贡献最大的城市, O_3 和 VOCs 输送通量贡献率分别可达 44% 和 47%;其次为广州市, O_3 和 VOCs 输送通量贡献率分别可达 39% 和 40%.

在 TD 天气型下[图 5(b)], O_3 总输入通量为 $108.8 \text{ t} \cdot \text{h}^{-1}$,VOCs 总输入通量为 $24.3 \text{ t} \cdot \text{h}^{-1}$,对应的 OFP 为 $89.7 \text{ t} \cdot \text{h}^{-1}$;广州为贡献最大的城市, O_3 和 VOCs 输送通量贡献率分别可达 55% 和 62%.值得注意的是,TD 天气型下虽然 VOCs 输送量多于 HC 天气型下,但其 OFP 会比 HC 天气型下低 6%,不同天气型下的污染事件所生成的 VOCs 物种占比及贡献差异可能是造成这一现象的主要原因.

在 HS 天气型下[图 5(c)], O_3 总输入通量为 $146.0 \text{ t} \cdot \text{h}^{-1}$,VOCs 总输入通量为 $82.5 \text{ t} \cdot \text{h}^{-1}$,对应的 OFP 为 $300.0 \text{ t} \cdot \text{h}^{-1}$,肇庆为贡献最大的城市, O_3 和 VOCs 输送通量贡献率分别可达 32% 和 52%.虽然 HS 污染天气型发生频率占比低(8%),但其控制下周边 O_3 和 VOCs 的输入通量最大,因此在该天气型下对周边城市 O_3 污染的防控不容忽视.

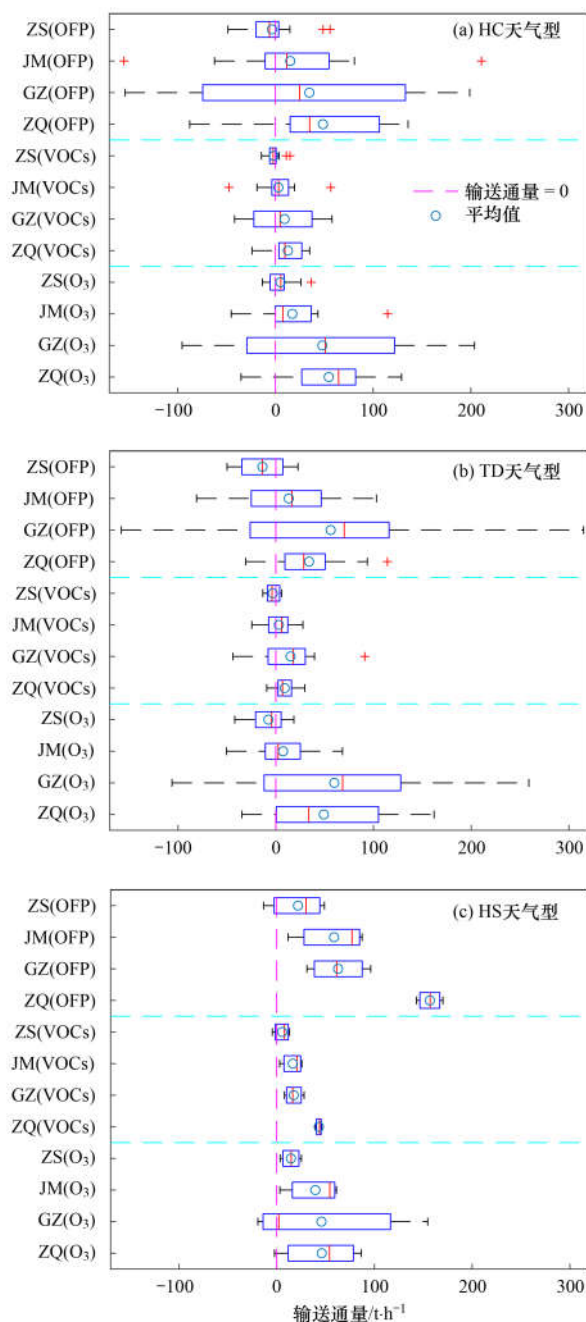
2.3 佛山市 O_3 “最大输入事件”输送特征

2.3.1 最大输入污染案例筛选

对 2019 ~ 2021 年佛山市全部 O_3 污染事件的 O_3 及其前体物输送通量进行排序(图 6),结果显示在 2020 年 10 月 26 ~ 27 日, O_3 总输送通量为 $431.1 \text{ t} \cdot \text{h}^{-1}$,VOCs 总输送通量为 $128.3 \text{ t} \cdot \text{h}^{-1}$,为研究时段内的“最大输入事件”.结合天气型分析可以看到,该次事件为 TD 天气型下的大气环流控制,其中广州输送的 O_3 通量为 $259.0 \text{ t} \cdot \text{h}^{-1}$ (贡献率为 60%),VOCs 通量为 $91.1 \text{ t} \cdot \text{h}^{-1}$ (贡献率为 71%),广州为本次污染事件输送贡献最大的城市.

2.3.2 佛山市 O_3 “最大输入事件”垂直分布特征

为深入探究佛山市“最大输入事件” O_3 及其前体物的输送特征,对该事件 O_3 和 VOCs 输入通量在边界层内外的时空分布情况开展分析.由于“最大输入事件”发生时广州为佛山市上风向城市,因此主要探究了该事件发生时广州输入佛山的 O_3 及 VOCs 通量的垂直分布情况.由图 7(a)可知, O_3 输入通量高值主要分布在 10:00 ~ 20:00 期间 900 hPa 高度以上,输入通量最大可达 $106.7 \text{ t} \cdot \text{h}^{-1}$,从地面到 950 hPa 高度 O_3 输送通量较小,输入通量接近于 $20.0 \text{ t} \cdot \text{h}^{-1}$,与 Zhang 等^[45]观测到的 O_3 浓度峰值垂



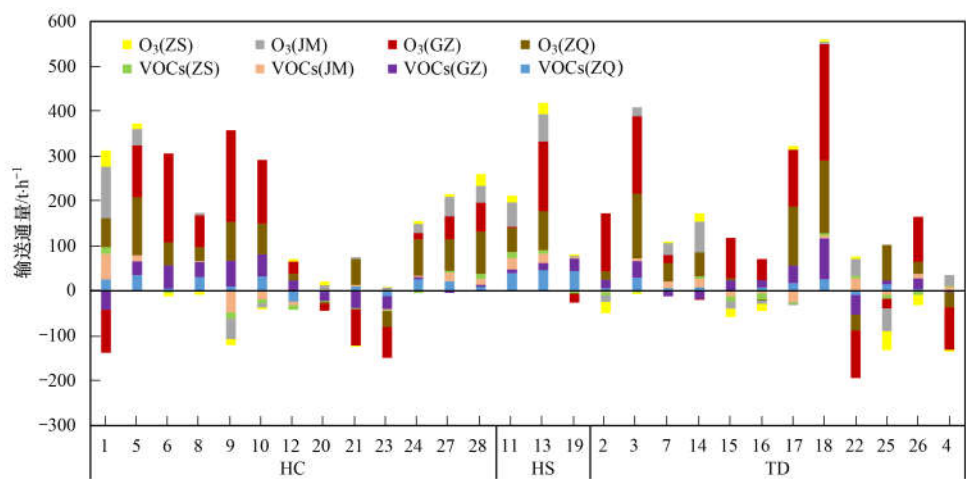
红色加号和红色实线分别表示离群值和中值

图 5 不同天气型下周边城市对佛山市的 O_3 及其前体物通量贡献情况

Fig. 5 Contribution of O_3 and its precursor fluxes to Foshan from neighboring cities under different weather patterns

直分布结果具有一致性.而 O_3 前体物 VOCs 通量输送特征相反[图 7(b)],输送通量高值主要集中在 00:00 ~ 12:00 期间 900 hPa 高度以下,输入通量最大可达 $32.7 \text{ t} \cdot \text{h}^{-1}$.但白天随着边界层的抬升,VOCs 在 12:00 ~ 18:00 期间 950 hPa 高度以上的边界层内部也出现了较明显输送情况,这与 Geng 等^[46]发现的 VOCs 垂直分布特征相近.

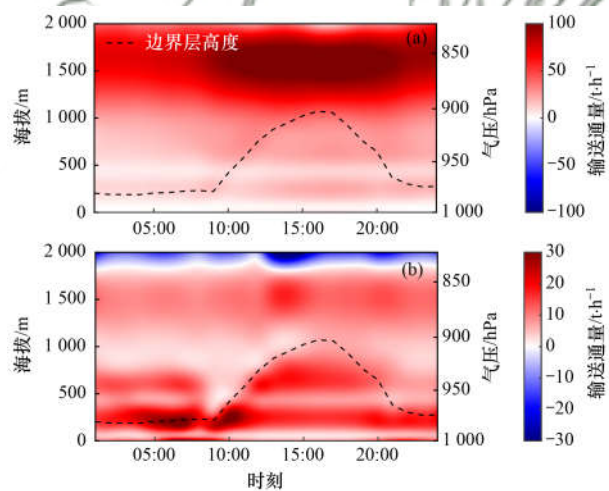
从“最大输入事件”发生时 O_3 输送通量在污染全时段的小时平均值垂直分布可知[图 8



1. 2019-05-11 ~ 2019-05-12, 2. 2019-08-05 ~ 2019-08-08, 3. 2019-08-20 ~ 2019-08-22, 4. 2019-09-06 ~ 2019-09-09, 5. 2019-09-11 ~ 2019-09-13, 6. 2019-09-18 ~ 2019-10-02, 7. 2019-10-10 ~ 2019-10-12, 8. 2019-10-19 ~ 2019-10-23, 9. 2019-11-01 ~ 2019-11-06, 10. 2019-11-09 ~ 2019-11-13, 11. 2019-11-15 ~ 2019-11-17, 12. 2019-11-23 ~ 2019-11-24, 13. 2020-04-27 ~ 2020-04-30, 14. 2020-08/21 ~ 2020-08-23, 15. 2020-08-28 ~ 2020-08-30, 16. 2020-09-01 ~ 2020-09-04, 17. 2020-10-11 ~ 2020-10-12, 18. 2020-10-26 ~ 2020-10-27, 19. 2020-12-27 ~ 2020-12-28, 20. 2021-02-06 ~ 2021-02-07, 21. 2021-02-21 ~ 2021-02-23, 22. 2021-04-21 ~ 2021-04-23, 23. 2021-04-30 ~ 2021-05-01, 24. 2021-06-06 ~ 2021-06-07, 25. 2021-07-23 ~ 2021-07-27, 26. 2021-09-10 ~ 2021-09-13, 27. 2021-09-25 ~ 2021-09-30, 28. 2021-10-04 ~ 2021-10-05

图 6 各 O₃ 污染事件发生期间佛山市 O₃ 及 VOCs 输送通量分布

Fig. 6 Distribution of transport fluxes of O₃ and its precursors in Foshan during each O₃ pollution event



(a) “最大输入事件”O₃ 输送通量,
(b) “最大输入事件”VOCs 输送通量

图 7 O₃ 及其前体物输送垂直分布日变化

Fig. 7 Spatial and temporal characteristics of the vertical distribution of O₃ and its precursor transport

(a)], 污染全时段 O₃ 输入平均通量最高值在 820 hPa 高度附近, 输送通量平均值为 88.0 t·h⁻¹; VOCs 平均通量输送最高值在 980 hPa 高度附近, 通量为 27.5 t·h⁻¹. 16:00 ~ 17:00 为 O₃ 输送通量峰值时段, 该时段 O₃ 及 VOCs 通量最大值分布不变, O₃ 和 VOCs 最高输送通量变大, 分别可达 104.6 t·h⁻¹ 和 69.1 t·h⁻¹ [图 8(b)], 值得注意的是在 O₃ 输送峰值时段, 近地面 VOCs 的输送通量显著升高, 这可能是造成污染事件持续

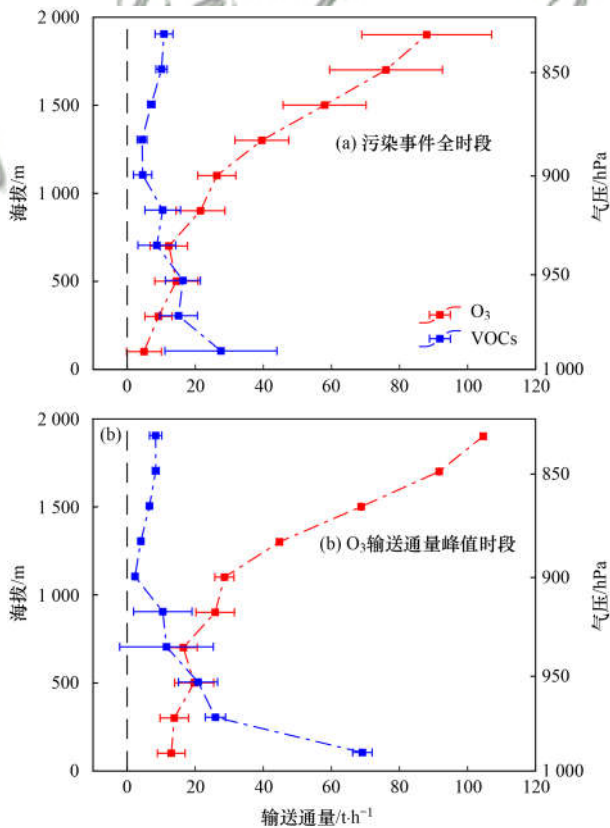


图 8 O₃ 及其前体物输送垂直分布特征

Fig. 8 Vertical distribution characteristics of O₃ and its precursor transport

的重要原因。
2.4 佛山市 O₃ “最大输入事件”前体物 OFP 解析
为厘清不同 VOCs 种类对 OFP 输送通量的贡

献,本研究统计了“最大输入事件”发生时不同 VOCs 种类的 OFP(图 9),VOCs 对应的 OFP 输送通量总贡献为 $306 \text{ t} \cdot \text{h}^{-1}$. 其中,含氧挥发性有机物(oxygenated volatile organic compounds, OVOCs)对 OFP 的通量贡献最大,贡献量为 $143 \text{ t} \cdot \text{h}^{-1}$,贡献率为 47%;其次是芳香烃类,贡献量为 $77 \text{ t} \cdot \text{h}^{-1}$,贡献率为 25%。“最大输入事件”发生时,对 OFP 生成贡

献最大的前 5 物种为:甲醛、二甲苯、醛类、丙酮和苯酚类,贡献量(贡献率)分别为: $58 \text{ t} \cdot \text{h}^{-1}$ (19%)、 $39 \text{ t} \cdot \text{h}^{-1}$ (13%)、 $32 \text{ t} \cdot \text{h}^{-1}$ (10%)、 $23 \text{ t} \cdot \text{h}^{-1}$ (8%) 和 $21 \text{ t} \cdot \text{h}^{-1}$ (7%),这些物种主要来自工业溶剂源. 因此,当发生污染输入时,对佛山及周边城市工业溶剂源开展针对性减排,能够有效缓解佛山市的 O_3 污染.

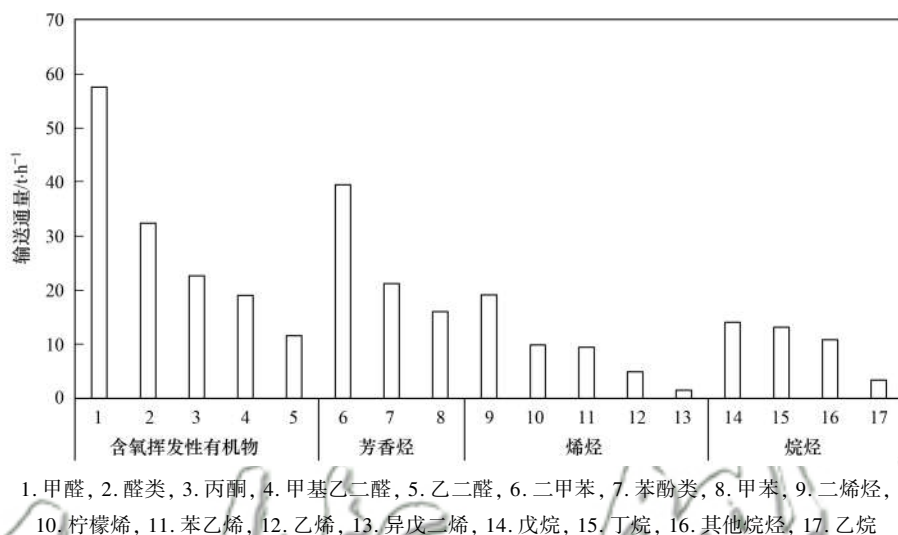


图 9 输入事件不同 VOCs 种类 OFP 分布情况

Fig. 9 OFP distribution of different VOCs types for input event

3 结论

(1) 通过统计近 3 年的 O_3 污染事件输送通量,发现周边区域在不同污染事件对佛山市输送的 O_3 总通量平均值为 $120.3 \text{ t} \cdot \text{h}^{-1}$;前体物 VOCs 总通量平均值为 $30.2 \text{ t} \cdot \text{h}^{-1}$;其对应的 O_3 生成潜势(OFP)为 $114.8 \text{ t} \cdot \text{h}^{-1}$.

(2) 污染期间对佛山市输入 O_3 通量最大的城市为广州;输入 VOCs 通量最大的城市为肇庆. 周边地区对佛山市 O_3 及其前体物输送量的贡献在东北风条件下最大, O_3 输送通量贡献率为 69%,VOCs 输送通量的贡献率为 90%,VOCs 对应的 OFP 贡献率为 87%.

(3) “最大输入事件”发生时, O_3 输入通量高值主要分布在白天 900 hPa 高度以上;前体物 VOCs 通量输送特征则与 O_3 相反,高值集中在夜间 900 hPa 高度以下,其中 OVOCs 是对 OFP 贡献最大的 VOCs 种类.

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