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Chemically enhanced transboundary ozone pollution suppresses city-level emission control benefits

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Abstract:

Severe ozone pollution persists in summertime of 60 cities in North China Plain and Fenwei Plain, which requires a fundamental change in the current mitigation strategy. Herein, we investigate how city-level ozone pollution would be affected by self- and collaborative mitigation actions among and beyond the 60 cities, by a modeling analysis of the daily maximum 8-h average ozone for summer (June-July-August). We find that a local uniform 20% cut in anthropogenic emissions would decrease ozone by merely 2.6% and even worsen ozone over two cities. Owing to cross-city ozone transport, the implementation of a range of city-specific emission cuts from 10% to 30% resulted in ozone changes that were essentially the same as those obtained from a uniform 20% cut. By contrast, a 20% emission cut across the entire country would decrease ozone in the 60 cities by 4.5% with no ozone deterioration in any city. Furthermore, owing to the transitioned ozone chemical regime and extended ozone chemical lifetime, the transboundary ozone from outside the two plains would be enhanced by emission reductions in the 60 cities (e.g., an increase by 68% with complete removal of emissions), leading to a significant suppression (about 23%) on the expected benefit. Nationwide collaborative action is essential for more effective city-level ozone mitigation.

Keywords: City-level ozone mitigation; Transboundary ozone pollution; Nonlinear chemical reactions

Introduction

As an important worldwide environmental threat, ambient ozone pollution harmfully impacts public health [1, 2], crop production [3], and the surface ecosystem [4]. Despite substantial mitigation progress in developed regions, such as Europe and the United States, city-level ozone reduction remains a challenging task. In many cities in developing regions, the threat of ozone pollution has been increasingly pervasive [5]. Although city-level ozone mitigation is closely tied to achievements of the second (zero hunger) and third (good health and wellbeing) sustainable development goals of the United Nations, the effective and efficient control of city-level ozone pollution remains an unresolved issue.

Over past decades, the observed increase in surface summertime ozone pollution in cities in the North China Plain and Fenwei Plain (NCP+FP) has been substantially higher than those observed in other cities worldwide [5]. Furthermore, NCP+FP is characterized by its dense population and intensive agricultural activity. Thus, the Government of China has determined that ozone pollution must be reduced. For example, China's 14th Five-Year Plan (FYP, 2021–2025) sets a specific target of at least a 10% reduction in ozone precursor emissions. To date, in NCP+FP cities, emission control has been conducted by the Government, which implemented collaborative "2+26" (simultaneous emission control in its 2+26 cities) and "one city one policy" (city-specific emission control policies) programs. In 2021, the "2+26" program was extended to "60 cities" in the entire NCP+FP. Although these policies were adopted based on the success in $PM_{2.5}$ mitigation, they did not lead to ozone reductions in most cities [6]. Besides anthropogenic emissions [7], massive emissions from natural sources (i.e., soil NO_x [2], biogenic volatile organic compounds (VOCs) [8]) further complicates ozone mitigation. Therefore, the effectiveness of current ozone mitigation policies must urgently be investigated to develop more effective strategies. Such an exploration could also serve as an important reference for other cities worldwide struggling with similar ozone threats.

Many previous studies on ozone mitigation of NCP+FP cities have attempted to design specific local emission reduction pathways for its individual cities or city clusters, such as Beijing [9], Jinan (a city in the North China Plain) [10], Xi'an (a city in the Fenwei Plain) [11] and Beijing-Tianjin-Hebei and surrounding areas [12-14]. An implicit assumption behind these studies is that the absolute benefit of local emission reduction would be determined by local

emission control strategies and not be influenced by transboundary pollution. Previous and ongoing ozone mitigation policies in NCP+FP cities have been designed based on this assumption. However, these studies and policies have simplified impacts of transboundary transport.

In recent years, other studies have attempted to directly quantify the transboundary contribution on ozone pollution for individual cities or city clusters, such as Beijing [15], the North China Plain [16-18], and Xi'an. Another study [19] that focused on deep emission cuts (40%) by the mid-21st century preliminary found that compared with only local emission control, nationwide emission control could be helpful for mitigating ozone in Beijing–Tianjin–Hebei and Yangtze River Delta regions. However, all these studies implicitly assumed that the amounts of ozone contributed by local and transboundary (from outside the city or NCP+FP) sources could be (or approximately) linearly added. In fact, transported pollutants could also affect ozone chemical formation and alter the efficacy of the local control measures, as one previous study [20] has found that internationally transported pollutants could affect China's locally emitted pollution from $PM_{2.5}$ perspective. In all previous studies focusing on transboundary impacts on local ozone pollution, the embedded chemical interaction mechanism has not been mentioned and the authentic influence of the transboundary transport on ozone mitigation of NCP+FP cities remains unquantified. When local emissions are cut, transboundary ozone contribution, including its chemical interactions with locally emitted pollutants, might change. Thus, exact effects of transboundary transport between NCP+FP cities and from outside NCP+FP on the effectiveness of city- or region-specific ozone mitigation policies remain unclear.

Therefore, by focusing on summertime (June-July-August) ozone mitigation in NCP+FP (Figure S1), we examine the effectiveness of collaborative emission control among and beyond its 60 cities. September and January, representative of fall and winter, are included for sensitivity analysis. We employ average daily maximum 8-h average (MDA8) ozone, consistent with current regulation and ozone-related public health estimation [21]. We employ the nested GEOS-Chem model to simulate surface ozone after comprehensively evaluated, including surface measurements for simulated ozone (S5.1 in Supplementary Material) and NO_2 (S5.2), observations collected from literatures for simulated NMVOCs (S5.3), satellite datasets for simulated ozone chemical regime (S5.4), and ground-based Multi-Axis Differential Optical Absorption Spectroscopy observations for simulated NO_2 vertical profiles (S5.5). We combine

two groups of nested GEOS-Chem simulations, with the first for 2015 through 2020 focusing on historical transboundary transport (0.5° latitude × 0.625° longitude), and the second for a representative year of 2019 when ozone exposure and ozone-related premature deaths peaks [6] (0.25° latitude × 0.3125° longitude). For 2019, we have more detailed scenarios and analyses in the main text are mainly based them. More information about model set-up and scenario design is in S1, S2 and Table S1, with emission datasets in S4 of Supplementary Material. As a sensitivity test, WRF-Chem is also employed to test the consistency between multi-models (S3).

In this study, we, first, examine the effects of local ozone mitigation strategies within NCP+FP by assigning either a uniform or city-specific reduction ratio to each of the 60 NCP+FP cities. Then, we quantify the effects of nationwide emission control on city-level ozone mitigation over NCP+FP. Furthermore, we examine how transboundary transport from outside NCP+FP could be chemically enhanced with local emission reduction, explore the underlying chemical mechanism, and reveal the corresponding suppression impact on the effectiveness of local emission reduction.

Collaborative city-level emission control within NCP+FP

Ozone pollution is severe over NCP+FP. Figure 1a shows simulated MDA8 ozone concentrations in summertime 2019 in BASE simulation. The regional average MDA8 ozone is 80.1 ppbv, and the highest value reaches 94.0 ppbv. Most cities exceed the Chinese standard (160 μg/m³, which is equivalent to 82.3 ppbv at 298.15 K and 1013.25 hPa), and the rest exceed the guideline of the World Health Organization (100 μg/m³, equivalent to 51.5 ppbv). This is also the case on the ozone pollution from 2015 through 2020 (Figure S2).

A uniform 20% reduction in anthropogenic emissions (LCx20 in Table S1) over NCP+FP could only slightly mitigate ozone pollution (by 2.6% on regional average). Note that the natural emissions (i.e., natural (nonfertilizer) soil NO_x, biogenic NMVOCs) keep constant. Owing to nonlinearity of ozone chemical reactions, such a uniform emission cut even worsens ozone pollution over two northeastern cities of NCP+FP (Figure 1b). This deterioration is more severe in June and August, especially in September (Figure S3). Here, we follow previous studies [2, 22] to analyze the ozone chemical regime using the ratio of hydrogen peroxide (H_2O_2) to nitric acid (HNO_3) concentrations (referred to as H_2O_2/HNO_3 hereafter). In BASE (Figure S4), the

average H_2O_2/HNO_3 is below 0.2 around Tangshan and Tianjin, indicating a NO_x-saturated regime, in which excess NO_x emissions would suppress ozone formation and could further titrate ozone [23]. This is consistent with those in previous observational and model-based studies [2, 24] and explains ozone deterioration in Figure 1b. The simulated chemical regime is also validated using satellite observations with high spatial consistency (Figure S5); more information about this validation is in S5.4 of Supplementary Material.

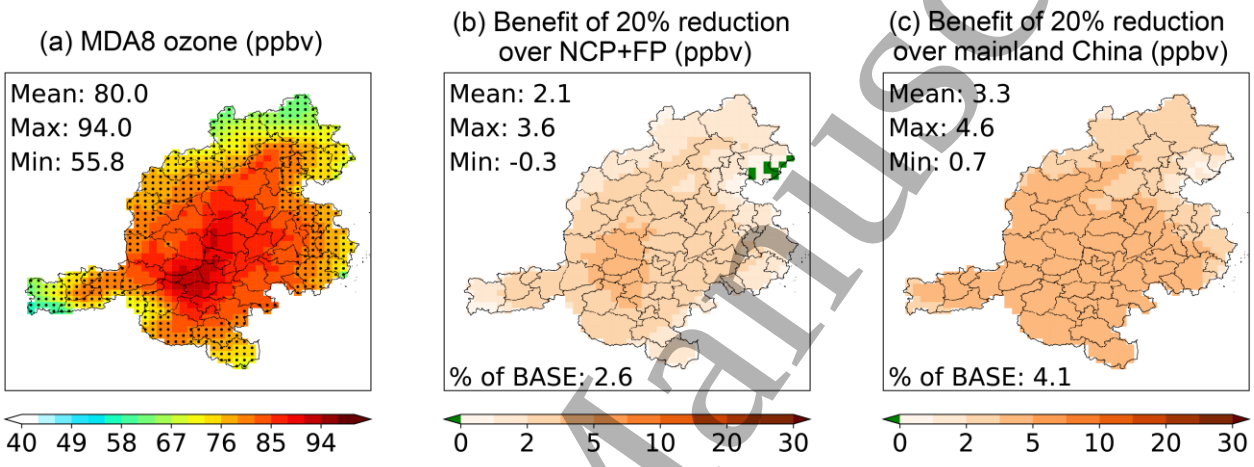

Figure 1: Ozone pollution under moderate emission cut. Panel (a) shows MDA8 ozone pollution in summer 2019. Dots represent grid cells in which MDA8 ozone mixing ratios (ppbv) exceed WHO guidelines but are below Chinese standards. Panels (b) and (c) show decline in MDA8 ozone with 20% reduction in anthropogenic emissions over only NCP+FP cities and all cities of mainland China, respectively, in summertime 2019. Inset in the top left corner shows mean, maximum, and minimum values over NCP+FP. Insets in the bottom of (b) and (c) show regional average benefits expressed as percentage of total MDA8 ozone in BASE simulation.

Furthermore, to examine the effects of "one city, one policy" initiative, we assign city-specific reduction ratios to NCP+FP cities (Figure 2a) in LCxHIGH and LCxLOW scenarios. In LCxHIGH scenario, city with the highest anthropogenic emissions of ozone precursors (expressed as NO_x+NMVOCs) is assigned with highest reduction ratio, and it is the opposite in LCxLOW, as detailed in Supplementary Material S1 and Table S1. Figure 2b-c show relative differences in anthropogenic emissions (of NO_x and NMVOCs), H_2O_2/HNO_3, ozone production efficiencies (OPEs; calculated by dividing ozone chemical production rate by NO_x emissions [2]), ozone chemical lifetimes (estimated by dividing ozone mass by ozone chemical loss rate), and MDA8 ozone for all 60 cities in LCxHIGH and LCxLOW compared to those in LCx20, respectively. Note we use chemical production and loss rates of O_x (comprising ozone and

species with which ozone rapidly cycles [25]) from GEOS-Chem to approximate those of ozone, since 95% of O_x is ozone.

As shown in Figure 2a and b, city-level changes in MDA8 ozone for LCxHIGH and LCxLOW are essentially the same as those in LCx20. The detailed changes in these three scenarios compared to BASE are shown in Figure S6. For cities that are assigned higher reduction ratios than in LCx20, additional mitigation benefits are suppressed via the transitioned chemical regime which shifts toward NO_x-sensitive situation (increasing H_2O_2/HNO_3) and enhanced ozone formation from residual (from residue anthropogenic plus natural emissions) and transboundary transported precursors (increasing OPE). Additionally, the chemical lifetime of ozone is extended. Taking Tangshan (an industrial city indicated by dark purple) in LCxHIGH for example, compared to LCx20, its NO_x and NMVOCs are additionally reduced by about 11.5% and 12.0% respectively, which are accompanied with H_2O_2/HNO_3 increased by 6.1%, OPE increased by 10.3% and lifetime of O_3 enhanced by 3.9% (Figure S6 and Figure 2b). Increased OPE is generally because when anthropogenic NO_x and NMVOCs are additionally reduced, the total ratio of NMVOCs to NO_x (anthropogenic + natural) would increase due to massive biogenic VOCs emissions.

We tracked the changes in ozone chemical reactions (detail information in S2 of Supplementary Material and Table S2). As shown in Figure S6, the hydroxyl radical would react more with NMVOCs accelerating ozone formation [26]. The extended ozone lifetime is due to the decreasing chemical loss with NO_x and NMVOCs resulting from the emissions reduction. Thus, ozone locally formed and transported from other cities could stay in the atmosphere for longer periods and thus compensated for the decline in ozone. Therefore, the MDA8 O_3 change over Tangshan is only 0.1% compared to LCx20 (Figure S6). Conversely, cities that are assigned lower reduction show opposite trends.

Overall, while city-level emissions in LCxHIGH and LCxLOW scenarios differ from those in the LCx20 by up to ±10%, the resulting relative differences in MDA8 ozone concentrations remain within ±1.0% for the summer average (Figure 2) and for each summer month as well as September (Figure S8).

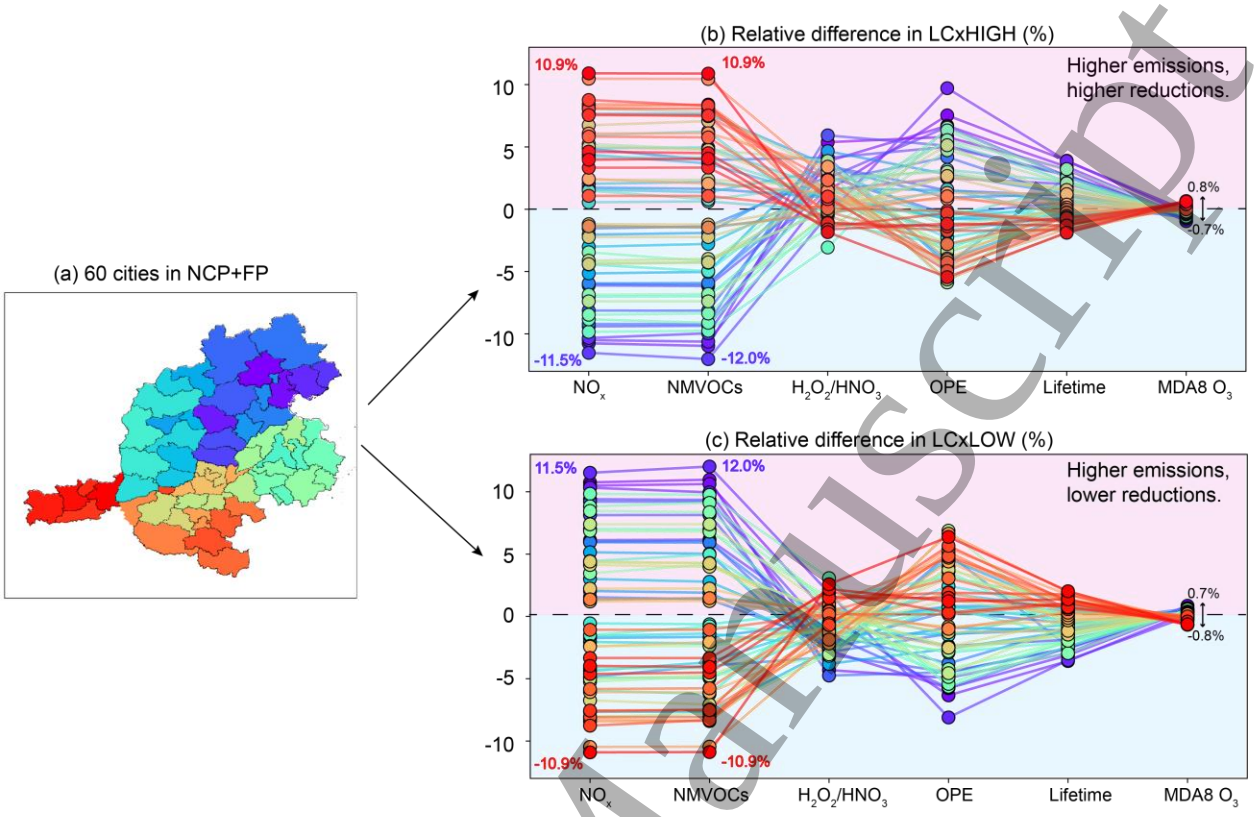

Figure 2: Ozone mitigation benefits of city-specific mitigation pathways are suppressed by cross-city transboundary transport. Panel (a) shows 60 cities included in NCP+FP with each color indicating a specific city. Panel (b) shows relative differences in LCxHIGH scenario compared to uniform 20% reduction in emissions (LCx20) of each city in NCP+FP. In LCxHIGH scenario, city with the highest anthropogenic emissions of ozone precursors (expressed as NO_x+NMVOCs) is assigned with highest emission reduction ratio. Panel (c) is similar to panel (b) but indicates LCxLOW scenario in which city with lowest NO_x+NMVOCs emissions is assigned highest emission reduction ratio. More information of LCxHIGH, LCxLOW, and LCx20 scenarios is detailed in Section S1 in Supplementary Material and Table S1.

As sensitivity tests, we further employed another air quality model WRF-Chem to simulate ozone pollution over NCP+FP under LCx20 and LCxHIGH scenarios (detailed in Supplementary Material S3). The WRF-Chem simulations were conducted only for June 2019 to save compute costs, with the same emission set-ups as those in GEOS-Chem simulations. As shown in Figure S9, the relative differences in MDA8 ozone between LCx20 and LCxHIGH remain within ±1.5% (Figure S9c), suggesting the feature is robust among air quality models.

This result means that even if cities had specific emission reduction plans, ozone mitigation benefits beyond a universal emission cut would be suppressed by the nonlinear ozone chemistry and cross-city transboundary transport.

Benefits of nationwide emission control for mitigating ozone over NCP+FP (468)

Transboundary ozone attributable to anthropogenic sources over the rest of mainland China substantially contributes to ozone pollution over NCP+FP and is quantified based on the difference between BASE and NLCx100 scenarios. In summertime 2019, averaged over NCP+FP, the transboundary MDA8 ozone is approximately 8.5 ppbv (Figure 3). According to tagged ozone simulations (detailed in Supplementary Material S2), the transboundary MDA8 ozone consists about 9.4 ppbv produced outside of NCP+FP (direct contribution; Figure S10a) and about -0.9 ppbv which is due to the transported precursors (indirect contribution; Figure S10b). The latter implies a suppression effect on local ozone production process. The transboundary contribution for each summer month and September ranges from 5.3 ppbv to 9.5 ppbv (Figure S11). On summertime average, over cities in southern NCP+FP, the transboundary ozone could reach 23.6 ppbv and account for 33.2% of the total MDA8 ozone. Furthermore, the transboundary anthropogenic ozone (8.5 ppbv) is approximately four times higher than the ozone mitigation benefit of a 20% reduction in local emissions (2.1 ppbv) and is close to the half of the ozone mitigation benefit of a 100% cut in local emissions (20 ppbv, Figure 5a). The minimum city-level transboundary MDA8 ozone (4.9 ppbv) is higher than the maximum ozone mitigation benefit of a 20% local reduction (3.5 ppbv), as shown in Figure S12. Summertime transboundary MDA8 ozone over 2015-2020 ranges from 6.9 ppbv to 9.0 ppbv, with the proportion to total MDA8 ozone from 8.8% to 11.5% (Figure S13).

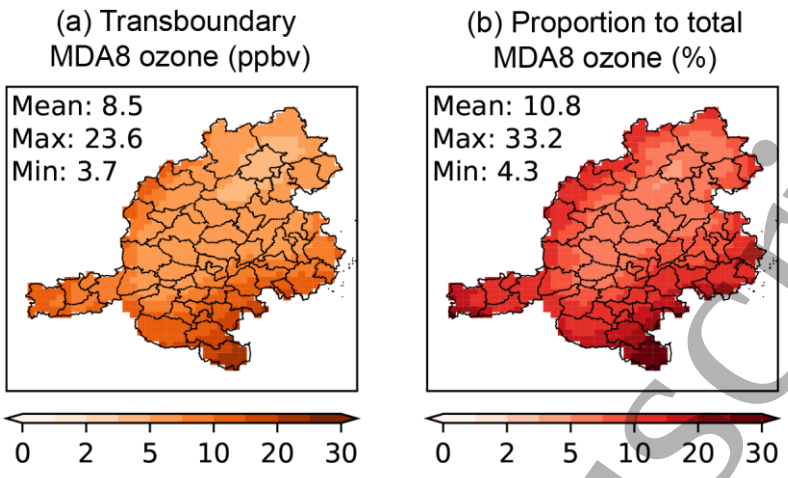

Figure 3: Anthropogenic transboundary ozone in NCP+FP cities. Panel (a) shows transboundary MDA8 ozone contributed by anthropogenic sources from rest of mainland China outside NCP+FP in summertime 2019. Panel (b) shows proportions of (a) to total MDA8 ozone in summertime 2019. Inset shows mean, maximum, and minimum values over NCP+FP.

Furthermore, we examine the effect of collaborative 20% emission reductions beyond NCP+FP cities (i.e., over the entire country) by contrasting the BASE and ALLx20 simulations (Table S1). The ozone benefit is 3.6 ppbv (Figure 1c), which is 72% more beneficial than the effect of a 20% cut within only NCP+FP (Figure 1b). Furthermore, in contrast to Figure 1b, collaborative 20% emission reductions mitigate ozone pollution with no city exhibiting deteriorated ozone pollution for summer average (Figure 1c) and each summer month (Figure S3). In September, it could also contribute to reducing the area of ozone degradation (Figure S3). Thus, for effectively reducing city-level ozone pollution and avoiding the NO_x reduction trap [23], transboundary ozone must be controlled.

Transboundary ozone chemically enhanced by local emission reduction within NCP+FP

Figure 4 shows average anthropogenic transboundary MDA8 ozone concentrations at different anthropogenic emission levels in NCP+FP cities, including no emission reduction (BASE) and uniform 20% (LCx20) and 100% (LCx100) emission. In the latter two scenarios, anthropogenic emissions outside NCP+FP cities are identical to those in BASE. With local emissions reduced, the transboundary ozone is enhanced, for the regional average, by 68% in the LCx100 compared to the BASE scenario (from 8.5 to 14.3 ppbv). For each summer month (Figure S15 and S14), the enhancement percentage to BASE transboundary ozone is 57%, 69%,

and 80% respectively, and can reach 94% in September. Spatially, the enhanced transboundary ozone can reach 9.7 ppbv (Figure S14c) over southern cities. The enhancement is even larger than the BASE transboundary ozone over many cities with its ratio to BASE transboundary ozone larger than 100% (the right column of Figure S14). According to tagged ozone results (Figure S10), direct and indirect contributions increase by 0.7 ppbv and 5.0 ppbv respectively, with about 86% of enhanced transboundary ozone attributable to the indirect part.

The enhancement of transboundary MDA8 ozone is attributable to the nonlinearity in ozone chemical reactions. First, by reducing all the local anthropogenic emissions, the local ozone chemical regime shifts toward a NO_x-sensitive regime, as indicated by the H_2O_2/HNO_3 ratio (represented by solid-colored circles in Figure 4) increasing from 0.87 to 3.9. Therefore, residual (e.g., nonfertilizer-related soil emissions [27]) and transboundary transported precursors could form ozone more efficiently, as indicated by the nearly quadrupled OPE (represented by circles with respect to the right *y*-axis), due to enhanced reactions with NMVOCs species (Figure S16). Additionally, the lifetime of ozone on regional average is extended by 71% (represented by the circle size in Figure 4), due to the decreasing chemical losses with NO_x and NMVOC species (Figure S16). Consequently, ozone produced locally and transported from outside NCP+FP could linger in the atmosphere for longer periods and be transported over greater distances.

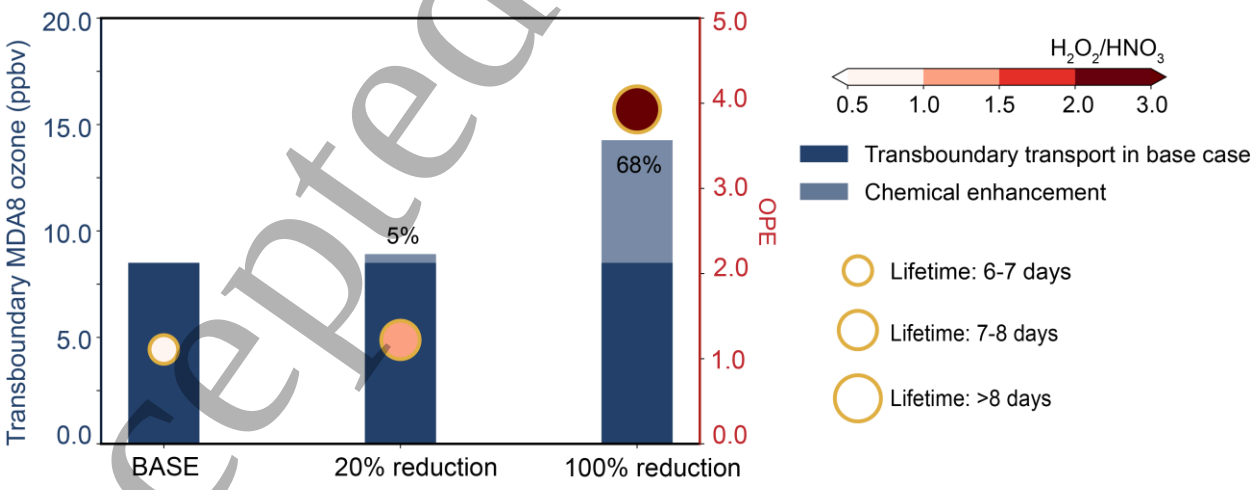

Figure 4: Transboundary MDA8 ozone concentrations chemically enhanced by local emission reductions. Bars represent transboundary anthropogenic MDA8 ozone concentrations for no local emission reductions (BASE) and uniform 20% (LCx20) and 100% (LCx100) local emission cuts in all NCP+FP cities in summertime 2019. Light-blue bars indicate enhanced

transboundary ozone concentrations in addition to BASE transboundary ozone, and percentages represent ozone concentrations proportionally enhanced relative to BASE transboundary ozone. Circles (corresponding to right *y*-axis) represent regional average OPE near surface. Circle colors and sizes depict H_2O_2/HNO_3 ratios and ozone chemical lifetimes, respectively.

A sensitivity test with other reduction ratios (LCxothers in Table S1) shows that the chemical enhancement in transboundary MDA8 ozone is ubiquity (Figure S17 and S18). With the deepening of local emissions reduction, the enhanced transboundary ozone would increase, with the enhanced percentage to BASE transboundary ozone increasing from 1.2% under LCx5, to 1.9% under LCx10, to 4.1% under LCx20, to 57.1% under LCx100.

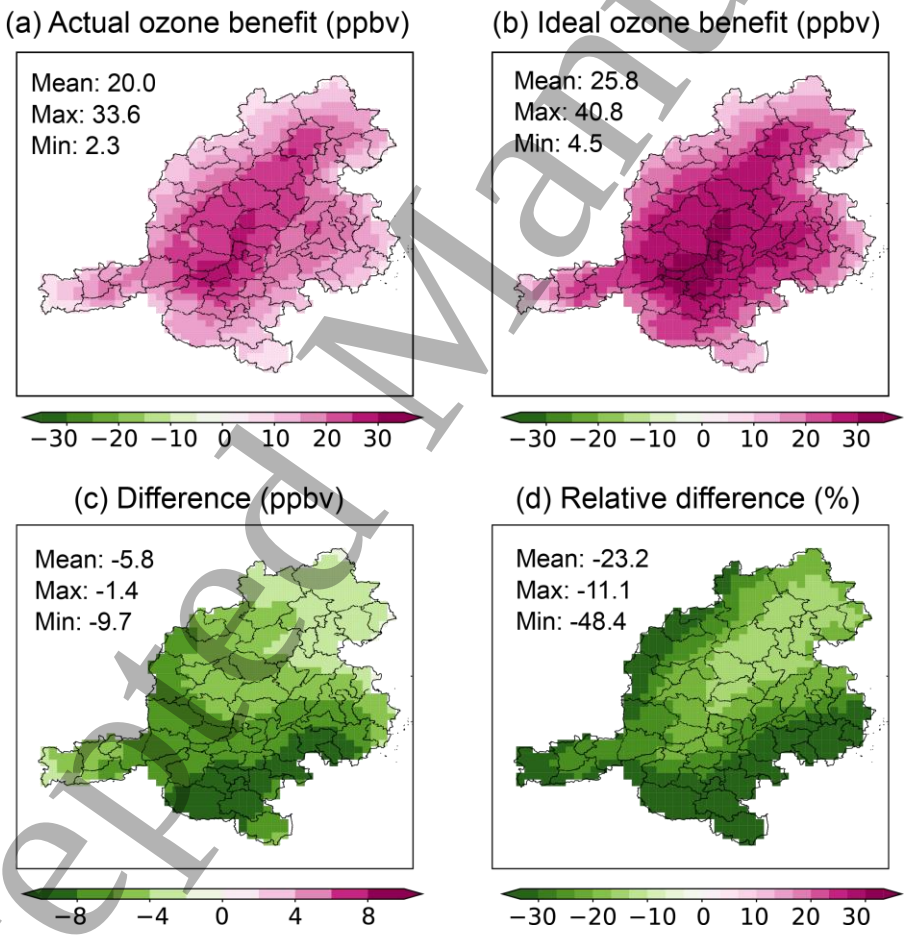

Figure 5: Suppression of ozone mitigation benefit of local emission control owing to chemically enhanced transboundary transport. Panel (a) shows modeled decline in MDA8 ozone concentrations caused by 100% local emission reductions with the anthropogenic emissions outside NCP+FP turned on. This is referred to as actual ozone mitigation benefit of local emission cuts. Panel (b) is similar to panel (a) but with anthropogenic emissions outside NCP+FP completely removed. This is referred to as ideal ozone mitigation benefit of local

emission cuts. Panel (c) shows difference between actual and ideal benefits. Panel (d) shows relative difference (%) in (c) compared to (b). Inset shows regional average, maximum, and minimum values over NCP+FP.

Note that there are significant differences between the chemically enhanced transboundary MDA8 ozone revealed by this study and the NO_x reduction trap (i.e., NO_x titration effect) [23, 28, 29] in terms of chemical mechanisms. The enhancement in transboundary MDA8 ozone is significant over cities where is NO_x-sensitive regime (Figure S5). Controlling the transboundary transport would be helpful for avoiding the NO_x reduction trap in city-level ozone mitigation pathway (Figure 1c).

The historical transboundary enhancement from 2015 through 2020 under LCx100 is always significant (Figure S19), with the percentage ranging from 70.0% to 84.6%.

Owing to the unintended enhanced transboundary ozone, ozone mitigation benefits of local emission reductions are suppressed. Figure 5a shows the modeled decline in MDA8 ozone when all the local anthropogenic emissions are removed and all emissions outside NCP+FP remain constant. This is referred to as the "actual benefit" of local emission cuts. Figure 5b is similar to Figure 5a but with anthropogenic emissions outside NCP+FP completely removed. This is referred to as the "ideal benefit" of local emission cuts. The average regional actual and ideal benefits are 20.0 and 25.8 ppbv respectively, indicating that the benefits by local emission reductions are suppressed by as much as 5.8 ppbv. The suppression reaches 9.7 ppbv around southern cities in NCP+FP (Figure 5c). The proportion of the suppression relative to the ideal benefit is approximately 23% on average and nearly 50% over southern NCP+FP (Figure 5d). The suppression effect is significant for each month (Figure S20).

The suppression effects with other local reduction ratios are shown in Figure S21 and Figure S22. Although the suppression effect is relatively small with mild reductions (i.e., 0.1 ppbv under LCx5), it still could suppress upto 20% (18.4%-23.7%; right column in Figure S21 and S22) of the ideal benefit. In January, representative for wintertime, transboundary transport would enhance the ozone deterioration from 1.2 ppbv (Figure S23b) to 1.5 ppbv (Figure S23a). It means that transboundary transport from outside NCP+FP could enhance the ozone deterioration in winter by 41% on regional average (Figure S23d).

This implies that regardless of the season, whether in the early or later stages of emission reduction, transboundary ozone and its chemical enhancement are crucial for the effective ozone mitigation.

Conclusions and implications

Overall, this study suggests local collaborative city-level emission control within NCP+FP might not be ideal for mitigating ozone pollution. Even implementing a range of city-specific emission cuts based on their anthropogenic emission levels, the additional benefits compared to those of uniform emission cuts would be suppressed by cross-city transboundary transport and the nonlinearity of ozone chemical processes. The sole local emission control could be inadequate for mitigating ozone. It is since when local emissions are reduced, transboundary ozone from outside NCP+FP would be chemically enhanced and further compromise the effectiveness of local emission reductions, owing to the transitioned chemical regime and extended lifetime of ozone. The absolute benefits resulting from local emission reduction would be expressed due to the existence of transboundary transport, whether in the early or later stages of emission control. Thus, collaborative emission control must be implemented both within and beyond NCP+FP for more successful ozone mitigation in NCP+FP cities.

China's carbon neutrality pathway is expected to be accompanied by massive changes in nationwide economic [30] and energy-consumption structures [30], and end-of-pipe control technologies [31]. Combined with the increasing emphasis on ozone pollution, this will lead to substantial changes in both the total amount and spatial distribution of emissions [32]. Additionally, climate change will influence the natural emissions [27], chemical formation of ozone [33], and regional transboundary transport pathways. Driven by these multiple factors, transboundary ozone transport and its chemical enhancement will likely significantly change in future. Therefore, further studies on the temporal evolution of transboundary ozone in future for ozone polluted cities and city clusters will provide useful information for improving ozone mitigation strategies in a timely manner as a support and supplement for China's carbon neutrality pathway.

According to this study, even for city clusters that have very high local anthropogenic emissions, transboundary transport from other regions, including the interactions with locally emitted pollutants, is important for local ozone mitigation. This finding has global relevance. In

the United States, the Ozone Transport Commission [34], which comprises 13 states, aims to mitigate ozone pollution in northeastern and mid-Atlantic cities. In Europe, the Gothenburg Protocol [35] sets emission ceilings for major pollutants in member nations. The extent of success for these collective mitigation efforts depends on how its transboundary pollution interacts with locally released pollution. Cities in developing countries, such as India, face similar issues[36]. In cities that have high emissions but less financial and/or technological capabilities, external aids could be mutually beneficial by reducing the amount of pollution exerted upon and transported from these less affordable places.

This study has several limitations. First, it mainly focuses on summer. Although we have included September and January for sensitivity analysis, systematic exploration in other months would be supportive for month-specific policies for ozone control. Second, although this study only explores the unidirectional transboundary impact exerted upon NCP+FP, the reverse transboundary transport also originates from NCP+FP. Owing to different pollution levels, emission amounts, topographical conditions, etc., transboundary impacts could be different for each pair of cities/regions.

To that end, the importance of transboundary ozone and its chemical enhancement in conjunction with local emission control, as found in this study, sheds light on collaborative efforts required for mitigating ozone in China and can be valuable for other regions that face similar challenges of severe ozone pollution [1].

Conflict of interest

The authors declare that they have no conflict of interest.

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Data availability

Data presented in this paper are available upon request to the corresponding author.

Author contribution

LC led the study. LC designed the study with input from JTL. HK provided the satellite-based NO_x emission data. LC wrote the manuscript with input from JTL and ST. All authors commented on the manuscript.

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