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Role of export industries on ozone pollution and its precursors in China

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This study seeks to estimate how global supply chain relocates emissions of tropospheric ozone precursors and its impacts in shaping ozone formation. Here we show that goods produced in China for foreign markets lead to an increase of domestic non-methane volatile organic compounds (NMVOCs) emissions by 3.5 million tons in 2013; about 13% of the national total or, equivalent to half of emissions from European Union. Production for export increases concentration of NMVOCs (including some carcinogenic species) and peak ozone levels by 20–30% and 6–15% respectively, in the coastal areas. It contributes to an estimated 16,889 (3,839–30,663, 95% CI) premature deaths annually combining the effects of NMVOCs and ozone, but could be reduced by nearly 40% by closing the technology gap between China and EU. Export demand also alters the emission ratios between NMVOCs and nitrogen oxides and hence the ozone chemistry in the east and south coast.

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Ozone (O_3) in the troposphere is an important air pollutant detrimental to human health and ecosystem productivity[1]. In the past few decades, the entire Northern Hemisphere has seen significant increases in tropospheric O_3 pollution, especially in the East and South Asia[2]. Since China started to include O_3 to its national monitoring network in 2013, the recorded hourly O_3 increased by 16–27% from 2013 to 2017[3]. The O_3 exposure metrics (cumulative O_3 concentration) increased even more by 57–77%[3]. The present extent of O_3 pollution, in terms of the exposure of humans and vegetation, is greater in China than in any other developed region of the world with comprehensive O_3 monitoring[3].

Globally, there are continuous efforts to capture the dynamics of tropospheric O_3 pollution, and its causes and impacts. As a secondary pollutant, O_3 in the troposphere is not directly emitted by human activities. Rather, it is formed from precursor emissions of non-methane-volatile organic compounds (NMVOCs), nitrogen oxide (NOx), carbon monoxide (CO) and others under photochemical reactions[4]. Studies have shown that the spatial distribution of precursor emissions dominates global tropospheric O_3[5]. This can be attributed to the variations of photochemical reaction rates, convection and precursor sensitivities that affect the effectiveness of O_3 formation in different latitudes. The process of globalisation has connected countries better than ever and relocated a large amount of precursor emissions. More and more production activities have shifted from developed to developing countries. Among the later ones, China is undoubtedly the largest export economy[6]. Millions of tonnes of goods associated with O_3 precursor emissions are produced domestically and shipped and consumed elsewhere in the world.

Several studies have been conducted to investigate how the role of the world's factory has contributed to the domestic pollution and greenhouse gas emissions in China[7–10]. For example, Zhang et al.[7] studied how international trade has contributed to the global distribution of fine particulate matter ($PM_{2.5}$) pollution, and showed that around 10–20% of the premature mortality attributable to $PM_{2.5}$ in China was attributed to the demand of export. However, the impact of export on O_3 pollution in China is still largely unknown. Tropospheric O_3 distinguishes with $PM_{2.5}$ in terms of their precursors, formation regimes and sensitivities to other environmental factors such as sunlight and temperature. Indeed, there is a contrasting trend of O_3 and $PM_{2.5}$ in China. In contrast to the above-mentioned increase in O_3, $PM_{2.5}$ in eastern China has seen an annual decrease of around 7% from 2013 to 2017[11,12]. It suggests that knowledge and experiences in $PM_{2.5}$ are not necessarily applicable to O_3.

An understanding of the role of export industries in China's O_3 pollution might open up new opportunities to tackle the persistent growth of O_3 and its precursors in China. In addition to the rise of ambient O_3 levels in China, its precursor—NMVOCs—is also growing persistently in contrast to the sharp decrease in NOx and other primary pollutants[13,14]. The persistent growth of NMVOCs is mainly due to the increase in emissions from industrial processes and solvent use (+36%), while the NMVOCs from transport had decreased by 21% from 2010 to 2017[14]. In addition to the contribution of O_3 formation, some NMVOC species, such as benzene, toluene, ethylbenzene and xylenes (BTEX in short), have well-documented influences on the central nervous system and immune functions[15]. The debate about the priority of controlling NMVOCs or NOx to reduce O_3 in China led to policies asking for stronger reduction of NOx, delaying sector-wide NMVOC control[14,16]. However, there is agreement that controlling NMVOCs has not only its own merit (e.g., toxicity), but would help to alleviate the local/urban O_3 increases following NOx policy[4]. Among China's top export goods, many of them are associated with intensive NMVOC emissions,

including but not limited to vehicle parts, wood furniture, coke, integrated circuits, shoes and leather products. It is therefore important to understand the role of international export in China's O_3 formation and its precursors, and to explore new opportunities to curb the worrying growth of O_3 and NMVOCs in China.

Studies in China can also partly reveal how the global supply chain has shaped the O_3 formation in the low- and mid-latitudes of the Northern Hemisphere. Since 1980, a large proportion of O_3 precursor emissions have shifted from developed to developing regions. While the absolute change of O_3 in the world from 1980 to 2010 has been investigated[5], it is not clear how the emissions embodied in and relocated by the global supply chain have contributed to the present O_3 pollution, especially those in the exporting countries. Exporting countries might not only see an increase in the emissions of O_3 precursors, but a shift of the O_3 formation chemistry due to disproportionate changes of NMVOCs and NOx emissions[4,17]. As a vast country across a wide range of latitudes, the role of export industries in China has important implications for other countries.

Therefore, we present a consumption-based study on the tropospheric O_3 pollution in China with a focus on export. We utilise China's 2012 multiregional input–output (MRIO) table, the Global Trade Analysis Database (GTAP) and an air-quality model to estimate the contribution of export demand on O_3 precursors and its formation in China. Health burden associated with ambient O_3 and BTEX is estimated, followed by possible pathways to reduce the export footprint and aid the O_3 pollution control in China. Implications for other countries in southern Asia and Africa as the new receptors of China's export capacities are discussed.

Results and discussion

Scale of precursor emissions and change in chemistry. The demand of export increases not only the production activities related to direct export products, but also the activities from power supply sectors, transportation and others to support the production of export goods. Nationally, export explains 13%, 15% and 10% of the NMVOCs, NOx and CO emissions in 2013, respectively. As the world's largest exporter for a lot of VOC-relevant products, the contribution from export industries to national NMVOC emissions was not as high as expected. However, it does not mean that we can downplay the role of export. Though being dwarfed by China's total emission budget, export-driven NMVOC emissions (3,794 kt in 2013) were equivalent to half the emissions of the European Union (EU, including EU-27 and UK)[18]. If such emissions were generated by a single country, it would be ranked as the 10th largest NMVOC emitter in the world[19].

The impact of export is highly uneven in China. Over 65% of China's astonishingly high export-related gross domestic product (GDP) comes from Guangdong, Fujian, Yangtze River Delta and Shandong (see Supplementary Fig. 1). As a result, the export-driven NMVOC emissions originate mainly from these regions. Around 18–26% NMVOC emissions from human activities in these areas were indeed associated with demand of export rather than local or domestic demand (Fig. 1a). Considering only the trade-relevant emissions, export emissions in Guangdong, Fujian, Shanghai, Shandong and Zhejiang indeed amounted to 44%, 41%, 36%, 33% and 30% of the emissions driven by interregional trade within China, respectively. In addition, it should be noted that NMVOCs as a group include hundreds of species. Among the export-related emissions in the above areas, around 20–35% were in the forms of BTEX, which have well-documented influences on the central nervous system and immune functions. Benzene and
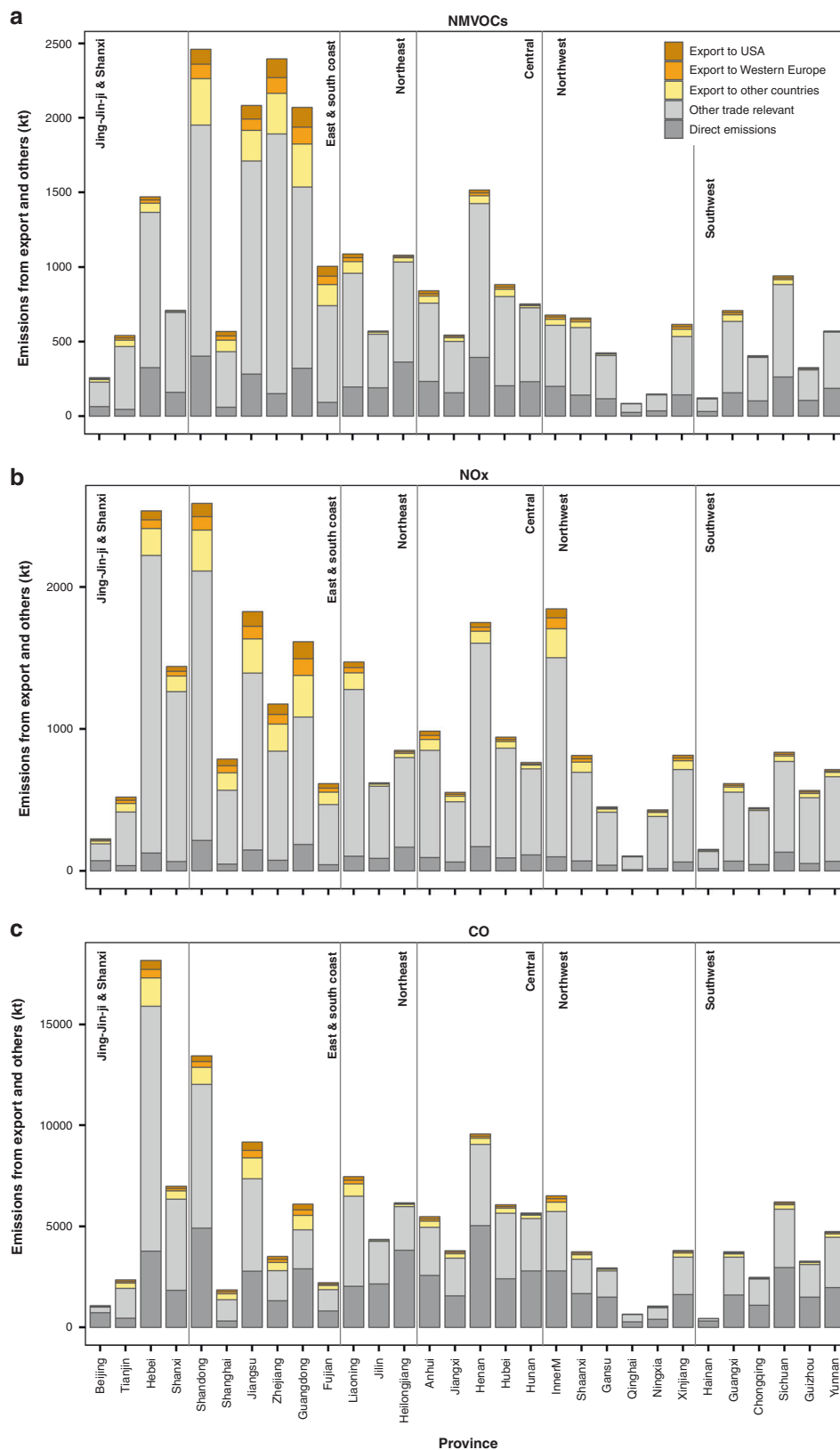
Fig. 1 China's provincial emissions driven by export and domestic demands in 2013. a NMVOCs. Export-driven emissions stood out in the east and south coast, e.g., Shandong, Jiangsu, Zhejiang and Guangdong. Demands from the United States (USA) and western Europe explained nearly half the export-relevant emissions. **b** NOx. Export contributed to 15% national sum of NOx emissions. Export-embodied emissions were notable in the east and south coast, as well as other inland provinces such as Inner Mongolia and Hebei. **c** CO. About 10% CO emissions in China were driven by export. Impacts of export were highlighted in Hebei, Shandong and Jiangsu. Source data are provided as a Source Data file.
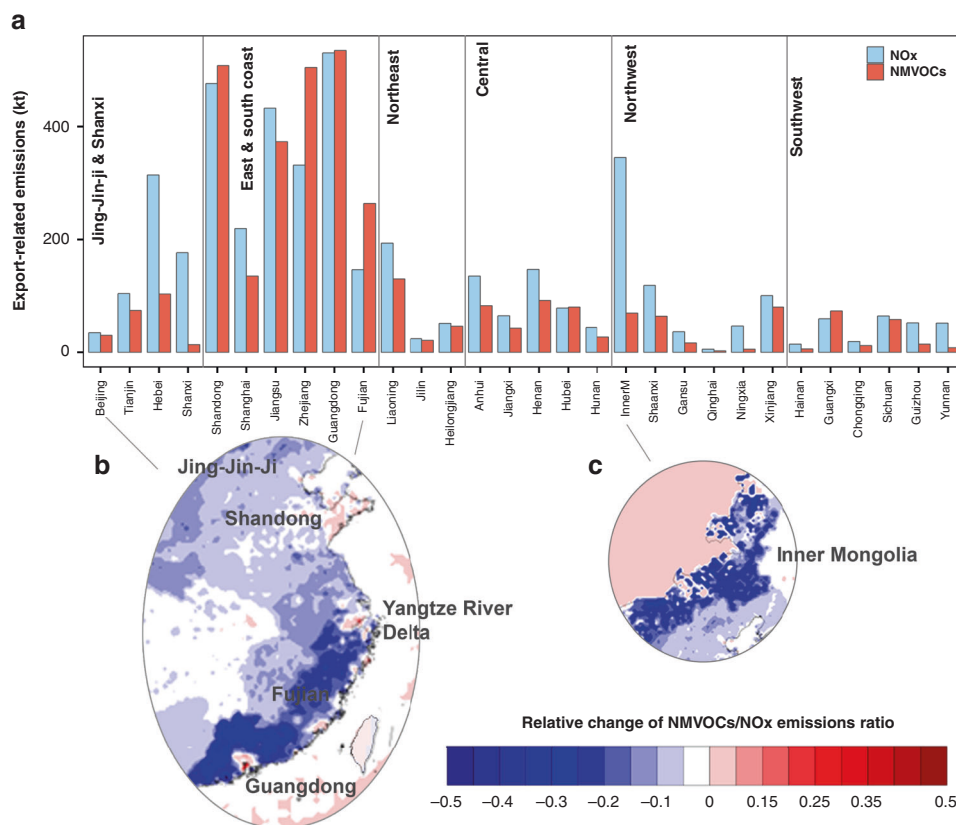
Fig. 2 Relative emissions of NMVOCs and NOx alerted by export demand. a Absolute value of NOx (in blue) and NMVOCs (in red) related to export demand by provinces. **b** Relative change in the ratio between anthropogenic NMVOCs to NOx emissions in the east and south coast in July. Blue indicates that export demand decreases the NMVOC/NOx ratio and red for increase. Export generally increased the NMVOC/NOx ratio in urban areas or industrial sites, but decreased the ratio in rural areas. **c** Export significantly decreased the NMVOC/NOx ratio in the Inner Mongolia since export demand in this province was largely associated with activities from power supply sectors to support the production of export goods with intensive NOx emissions. The relative changes in other provinces are generally less than 10% and not shown here. Source data are provided as a Source Data file.

ethylbenzene are even classified as Group 1 and Group 2B carcinogens by the International Agency for Research on Cancer (IARC)[20,21], respectively. The impact of export on the environmental concentration of BTEX will be explored in the next section. Regarding NOx and CO, the contributions of export were generally higher in the coastal areas of export industry hubs as well as some inland provinces such as Inner Mongolia and Hebei (Fig. 1b, c). This reflects the emission characteristics of NMVOCs, NOx and CO and the industry layout of China. In addition to common sources such as transportation, NOx and CO emissions are generally from fossil fuel combustion from the energy-intensive and heavy industrial sectors, while NMVOC emissions are emitted from miscellaneous non-combustion processes of light industries. As light industries thrive in the east and south coast, but heavy industries in the northern and inland provinces, the NMVOC emissions from export in coastal provinces generally outweighed those of NOx emissions, and vice versa for northern and inland provinces (Fig. 2a).

Tropospheric O_3 distinguishes from other air pollution partly because of its non-linear relationship with NMVOCs and NOx emissions. The emission ratio of NMVOCs and NOx largely determines the O_3 formation chemistry and hence the effectiveness of air pollution mitigation strategy[4,17]. By altering the emissions of NMVOCs and NOx disproportionately across the country (Fig. 2a), the demand of export has shaped the O_3 chemistry in the ground level in a hidden way. For the vast majority of China, export decreased the NMVOCs to NOx emission ratios by around 5–10%. In the suburban and rural areas

along the coast and some energy-supplying inland provinces such as Inner Mongolia (Fig. 2b, c), export had nearly cut down the NMVOC/NOx ratio by 50%. The urban and industrial areas in the export industry hubs, such as Guangdong, Fujian, Yangtze River Delta and Shandong, were a few exceptions that saw an increase in NMVOC/NOx ratio (Fig. 2b). These areas are largely overlapped with China's O_3 hotspots[3] and are governed by a NMVOC-limited or transitional regime[4,11,22]. Activities to support export have indeed made the O_3 regime less NMVOC-sensitive. For the other vast areas with decreased NMVOC/NOx ratio, however, they are governed by a NOx-limited regime[22], and the O_3 sensitivity to NOx emissions would be even higher without the export demand. Considering the rise of South–South trade, there is an emerging trend of production activities relocating from China and India to other developing countries[9]. If such relocations are significant enough, China should prepare for the changes in not only the scale of O_3 precursor emissions but also the O_3 chemistry. The current NMVOC-limited or transitional regime in the urban and industrial areas along the coast would be more limited by NMVOC emissions, while the NOx-limited regime in the majority of China would be enhanced.

Changes in primary and secondary pollution due to export demands. All the export-relevant emissions of NMVOCs, NOx and CO were excluded from the air-quality model (Case 1, detailed settings can be found in Supplementary Note 1) and compared with base case to study the impact of export demands
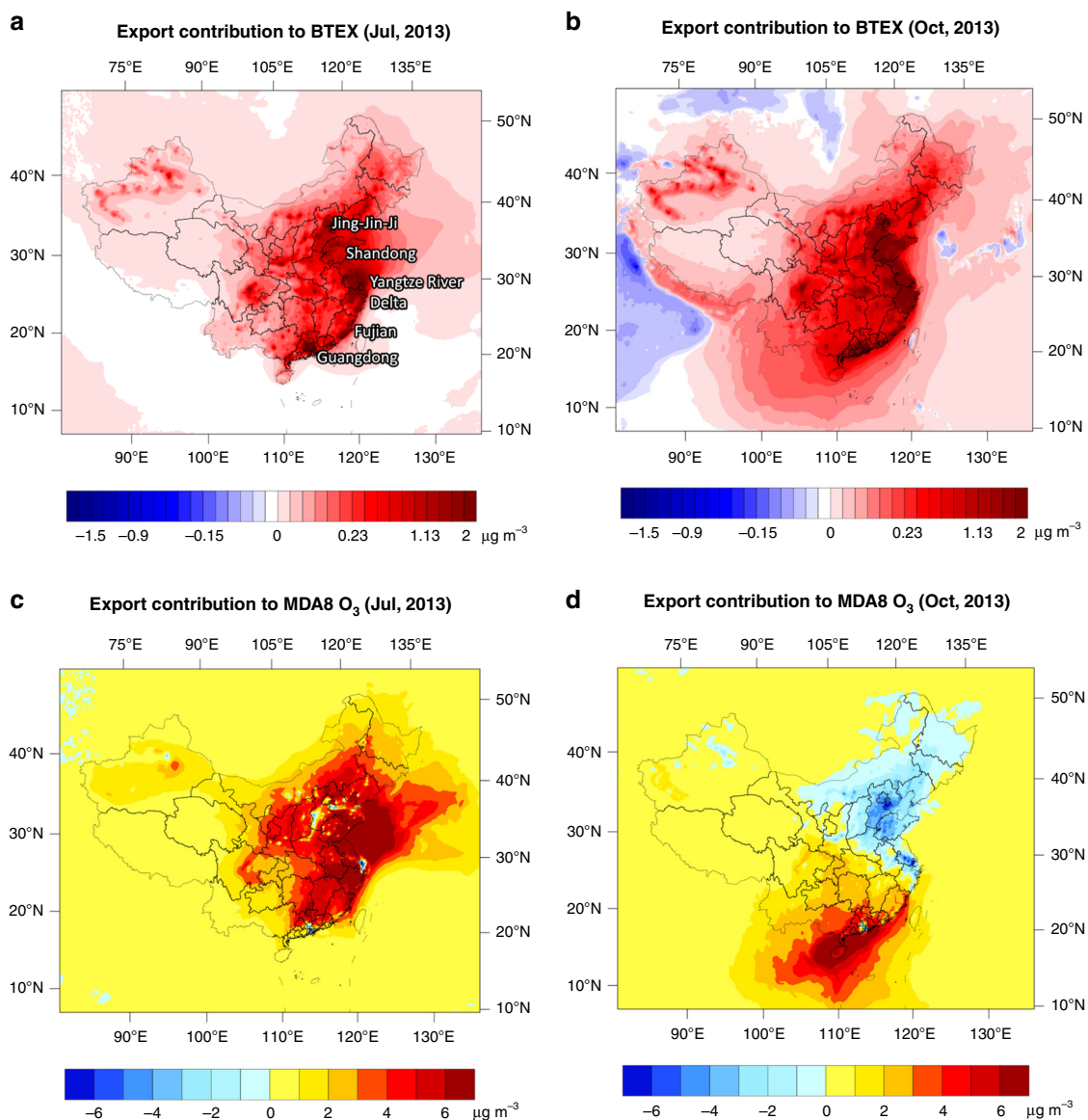
Fig. 3 Export contributions to ambient BTEX and O₃ concentrations in China. a, b Export increased the BTEX concentrations all year round in China, especially in the North China Plain and coastal areas (>0.5 μg m⁻³). **c** Export elevated the peak O₃ level in July by 2–6 μg m⁻³, varying from provinces. **d** Effects from export were mixed in October. While export emissions still contributed positively to the O₃ formation in south China, it inhibited peak O₃ by 1–3 μg m⁻³ in the vast areas north to the Yangtze River Delta, especially the Jing-Jin-Ji area (3–5 μg m⁻³). Source data are provided as a Source Data file.

on the ambient concentrations of BTEX and O₃. As primary pollutants, changes in BTEX concentrations due to export were consistent across different seasons (Fig. 3a, b). The coastal areas in China had suffered from an increase in BTEX concentrations of 20–30% annually. It resulted in an estimated 15,707 (3488–28,671, 95% CI) premature deaths per year, considering only the short-term environmental exposure.

The effects of export on China's O₃ concentration varied from seasons and latitudes. In July, which is the typical O₃ season in the north China and the Yangtze River Delta, the impact of export was generally consistent across the country. It had elevated the maximum daily 8-h average (MDA8) O₃ in the vast majority of China by 2–3 μg m⁻³ (Fig. 4c). The effect of export stood out in the coastal areas of Shandong, Jiangsu, Zhejiang and Fujian with an increase of more than 6 μg m⁻³, or 6–20% peak O₃ level by anthropogenic causes. In October, the impact of export-related emissions varied. Similar increase in O₃ was observed in southern China (red and orange areas in Fig. 4d). In the vast areas north to

the Yangtze River Delta, instead of increase, export-related emissions had inhibited the O₃ level (blue areas in Fig. 4d). Inhibition from export emissions was most notable around the Jing-Jin-Ji area, Shandong and Zhejiang (3–5 μg m⁻³). Similar inhibition effects are observed for the other non-O₃ seasons, such as January and April (see Supplementary Fig. 2).

Such inhibition effects are mainly attributed to the temporal and spatial variations of O₃ formation regimes in China. In July, the vast majority of China is governed by a NOx-limited chemistry with a few exceptions in very limited areas of Jing-Jin-Ji, Yangtze River Delta and Guangdong. Under the NOx-limited regime, the increase in NOx and NMVOC emissions introduced by export demand could lead to a growth of maximum O₃ concentration. As the temperature dropped from July to October, biogenic NMVOC emissions declined dramatically and drove the O₃ regime towards NMVOC-sensitive. This is especially true for northern provinces where temperature dropped more significantly than that in the south. On top of this, the demand of
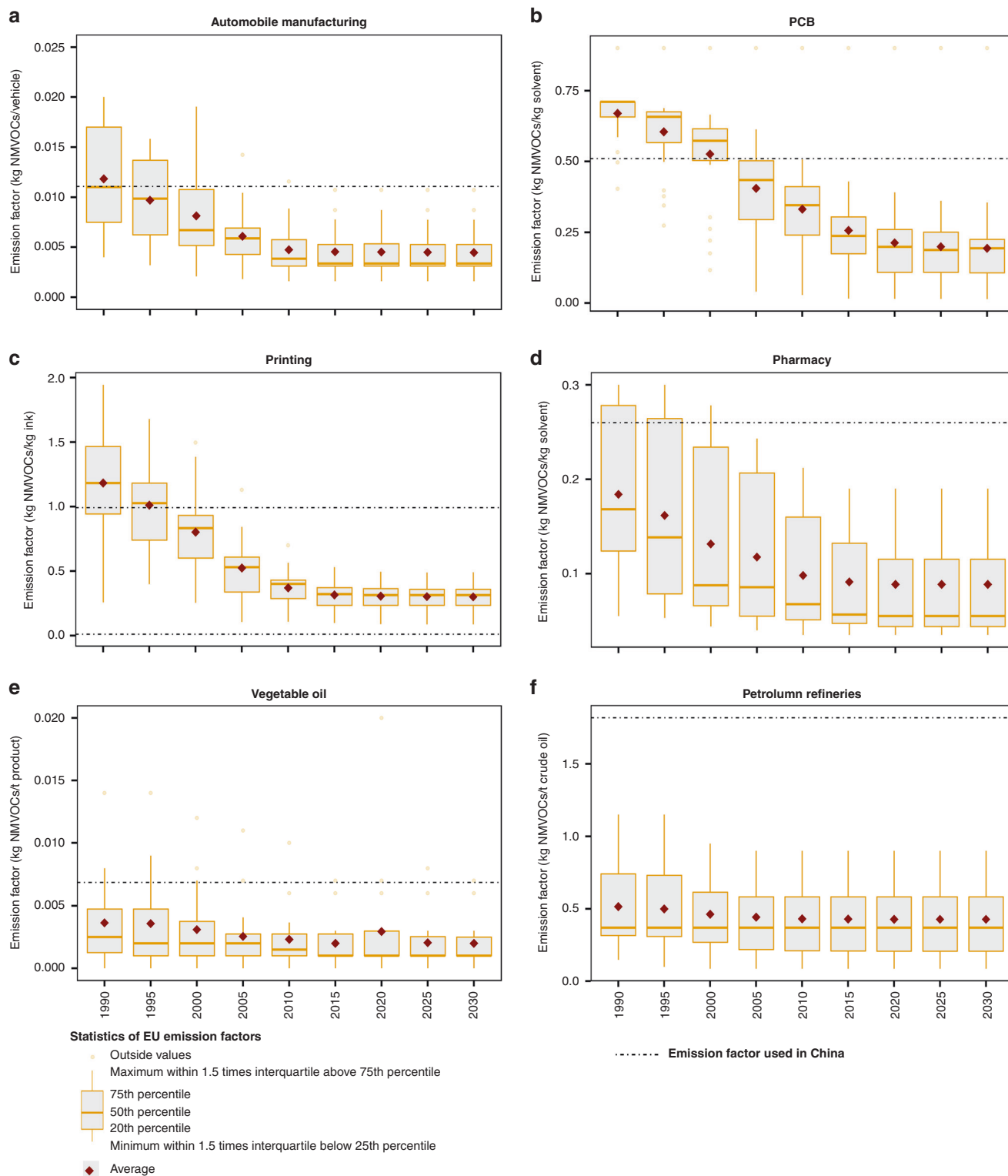
Fig. 4 Gaps of NMVOC emission intensities between China and EU. Boxplots represent the distribution of European levels in every 5 years from 1990 to 2030. The dotted line denotes the level of China in 2013. Intensities of China fall within the range of EU for most sectors, e.g., **a** automobile manufacturing, **b** PCB, **c** printing, **d** pharmacy and **e** vegetable oil. For **f**, petroleum refineries, intensities in China were symmetrically higher than in Europe. For evaluation of emission-reduction potentials, relative change in Europe was adopted instead of absolute value. Source data are provided as a Source Data file.

exports had pumped more NOx than NMVOC emissions in the atmosphere in most areas (as discussed in the last section). With a NMVOC-limited regime, an increase in NOx emissions could result in the decline of OH radical pool to react with NMVOCs and consequently inhibited the formation of O_3.

To sum up, emissions from export contributed positively to the peak O_3 level in the O_3 seasons, but help alleviate the low-level O_3 in other months. In this sense, export contributed to the exceedance rates of MDA8 O_3 in China, but its health burden would be less. Given the limited evidence that a threshold exists

for the association between exposure to O_3 and the risk of death[23–26], low-level O_3 could pose negative health impacts. By alleviating the low-level O_3 in non-O_3 seasons, part of the health burden introduced by export was offset and resulted in annualised premature deaths of 1182 (351–1,992, 95% CI).

Closing the gap in emission intensity. The adverse impact from export activities can be potentially eased by either decreasing the quantity of export goods or cutting down the emissions emitted per unit of goods ('emission intensity'). The ongoing US–China trade war and the emerging South–South trade overshadow the future of China's export industries. While it is difficult to predict precisely how the export industries will develop, we analysed the emission-reduction potentials of China's export industries and their impacts on the whole production capacity under static conditions (the 2013 productivities). Given the fact that NOx and CO emissions have been reduced aggressively under the clean-air actions in China[14], the focus was on NMVOC emissions from export-relevant industries. Specifically, they are the 20 industrial sectors with high volumes of export goods (Table 1). Considering the availabilities of sectoral emission factors and the corresponding technical coefficients, NMVOC emission levels per unit of goods produced in China were compared with those in the EU as estimated in the GAINS model[27], which were assumed to represent the cleaner production practices with proven and affordable technologies[28]. For most industrial sectors, the emission intensities in China around 2013 were comparable to the upper bound of the EU around 2000, as shown in Fig. 4a–e. Following the experience in EU, NMVOC levels can be substantially cut down. For example, it has been shown that implementation of improved management practices in degreasing sector could lead to 41% lower emissions, while more advanced techniques, such as cold cleaner and the combination of sealed degreasers and activated carbon adsorption, can reduce emissions by well over 90%. For a few sectors such as petroleum refineries and rubber-tyre production, the emission levels in China are systematically higher than those in the EU. This might be attributed to the different compositions of products or poorer management along the production line that leads to higher NMVOC emissions.

By benchmarking the emission levels in China with those attainable in EU by 2030, reduction potential for China's export

Table 1 Potentials of emission reductions and abatement cost.

Sources	NMVOC emission factors			NMVOC-reduction potentials (ton)[a]	Annualised abatement cost (million $)	Industrial output in 2013 (million $)
	China in 2013	Possible low level	Unit			
Petroleum refinery	1.82[b]	1.08[c]	kg t^{-1} product	353,972	0	NA[p]
Extraction of edible oil	6.88[d]	2.29[c]	kg t^{-1} product	256,444	0	NA[p]
Tyre	0.6[e]	0.44[c]	kg piece^{-1}	176,464	0	NA[p]
Wood-furniture making	0.92[f]	0.49[c]	kg piece^{-1}	252,913	0	NA[p]
Extraction of oil	1.42[b]	0.93[c]	kg t^{-1} product	105,982	0	NA[p]
Paint manufacturing	15[b]	11[c]	kg t^{-1} product	38,170	35	53,226 (0.24%)
Ink manufacturing	50[b]	36[c]	kg t^{-1} product	9459	9	
Dye manufacturing	81[b]	58[c]	kg t^{-1} product	20,575	19	
Carbon-black manufacturing	52[b]	37[c]	kg t^{-1} product	69,036	64	
Glue manufacturing	11[g]	8[c]	kg t^{-1} product	15,742	15	NA[p]
Printing	993[f]	301[c]	kg t^{-1} ink	396,216	501	167,718 (0.30%)
Shoe making	0.028[f]	0.020[c]	kg pair^{-1}	37,087	56	106,140 (0.05%)
Printed circuit board	0.22[h]	0.09[c]	kg m^{-2} product	29,019	55	22,548 (0.24%)
Metal coating (small devices)	0.20[b]	0.08[c]	kg piece^{-1}	67,305	127	NA[p]
Metal coating (large devices)	0.40[b]	0.15[c]	kg piece^{-1}	216	0.4[o]	NA[p]
Pharmacy	260[i]	125[c]	kg t^{-1} product	354,546	977	359,629 (0.27%)
Automobile manufacturing						
Bikes	0.3[b]	0.12[c]	kg VEH^{-1}	4290	26	853,225 (0.13%)
Small vehicles	2.43[b]	0.972[c]	kg VEH^{-1}	19,208	115	
Other vehicles	21.2[b]	8.48[c]	kg VEH^{-1}	152,106	911	
Motorbikes	1.8[b]	0.72[c]	kg VEH^{-1}	13,470	81	
Coking	2.1[j]	0.427[k]	kg t^{-1} coal charged	1,128,867	NA	NA[p]
Polymeric coating	0.182[b]	0.009[l]	kg m^{-2} surface	818,404	NA	NA[p]
Polymers and resins						
Polyethylene	7.85[m]	2.00[k]	kg t^{-1} product	68,679	NA	NA[p]
Polypropylene	3.00[b]	0.35[n]	kg t^{-1} product	33,019	NA	NA[p]
Polyvinyl chloride	0.7448[b]	0.1[k]	kg t^{-1} product	9865	NA	NA[p]
Polystyrene	2.92[b]	0.15[k]	kg t^{-1} product	5817	NA	NA[p]

[a]Reduction potentials estimated based on the activity level in 2013.
[b]Emission factor from MEP, P.R. China[49].
[c]Value is estimated based on the EU-average emission-factor trajectory.
[d]Weighted average of the emission factors of corn oil, cottonseed oil, peanut oil and soybean oil from MEP, P.R. China[49].
[e]Average factor of MEP, P.R. China (2014)[49] and previous studies[43,47,50,51].
[f]From a field survey in the Pearl River Delta[52]. The factor of printing is the average of offset printing, rotogravure printing and letterpress printing.
[g]Local factor unavailable. Factor from EMEP/EEA[53].
[h]From a field survey in the Pearl River Delta[54].
[i]Emission factor from Zheng et al.[14].
[j]Local factor unavailable. Factor from US EPA (2008)[55] was adopted[50,56,57], which was based on the higher bound of emission level in an earlier study by Economic Commission for Europe (ECE)[58].
[k]Based on the lower bound of emission level by ECE[58].
[l]By carbon adsorption units using activated carbon, 95% of NMVOCs from this process can be removed[55].
[m]Average of high- and low-density polyethylene emission factors from MEP, P.R. China[49].
[n]Factor from US EPA (2008)[55].
[o]The value might be underestimated since only the activity-level data of the cutting machine was available from the national statistics.
[p]The industrial outputs for these sectors were not available since they were integrated with other sectors in China's official statistical systems.

industries was estimated. For those sectors with emission intensities within the EU range, the average level across the EU countries (instead of the median or country with the lowest value) was used as a reference for the possible low level that can be achieved. For the few sectors with systematically higher emission levels, a relative change was adopted instead of an absolute value. It is estimated that 57% of NMVOC emissions from export industries (excluding transport and other supporting activities) could be reduced (1165 kt). When these 1165 kt of NMVOCs were excluded from export industries and NOx and CO remained constant (Case 2, detailed settings can be found in Supplementary Note 1), a nationwide decrease in BTEX and MDA8 O_3 is observed, especially along the coastal areas (see Supplementary Fig. 3a–d). The export footprint in terms of health burden can be reduced by 37% by saving 6,520 (1396–11,954, 95% CI) premature deaths associated with the exposure of BTEX and MDA8 O_3 on an annual basis.

In reality, the assumption that cleaner production practices in a sector are only applied to export goods is frail and hardly plausible. If a shoe-making factory decided to upgrade its technology and resource management, it is more plausibly done for the whole production line rather than only for the shoes for export. Expanding the efforts from export sectors to the whole production capacity, a reduction of 4437 kt of NMVOCs would be expected, i.e., 58 and 17% of industrial and total anthropogenic NMVOC emissions in China, respectively. Considering the challenges in controlling NMVOC emissions (+11% from 2010 to 2017) and the rising relative contribution from industry, such decreases entail significances in China's NMVOC control. As shown in Fig. 5a, b, the reduced NMVOC emissions would lead to more than 0.5 µg m^{-3} decrease of BTEX concentration in most areas (Case 3, detailed settings can be found in Supplementary Note 1). For Jing-Jin-Ji, Shandong, Yangtze River Delta and Guangdong, the decrease was more than 1 µg m^{-3}, accounting for

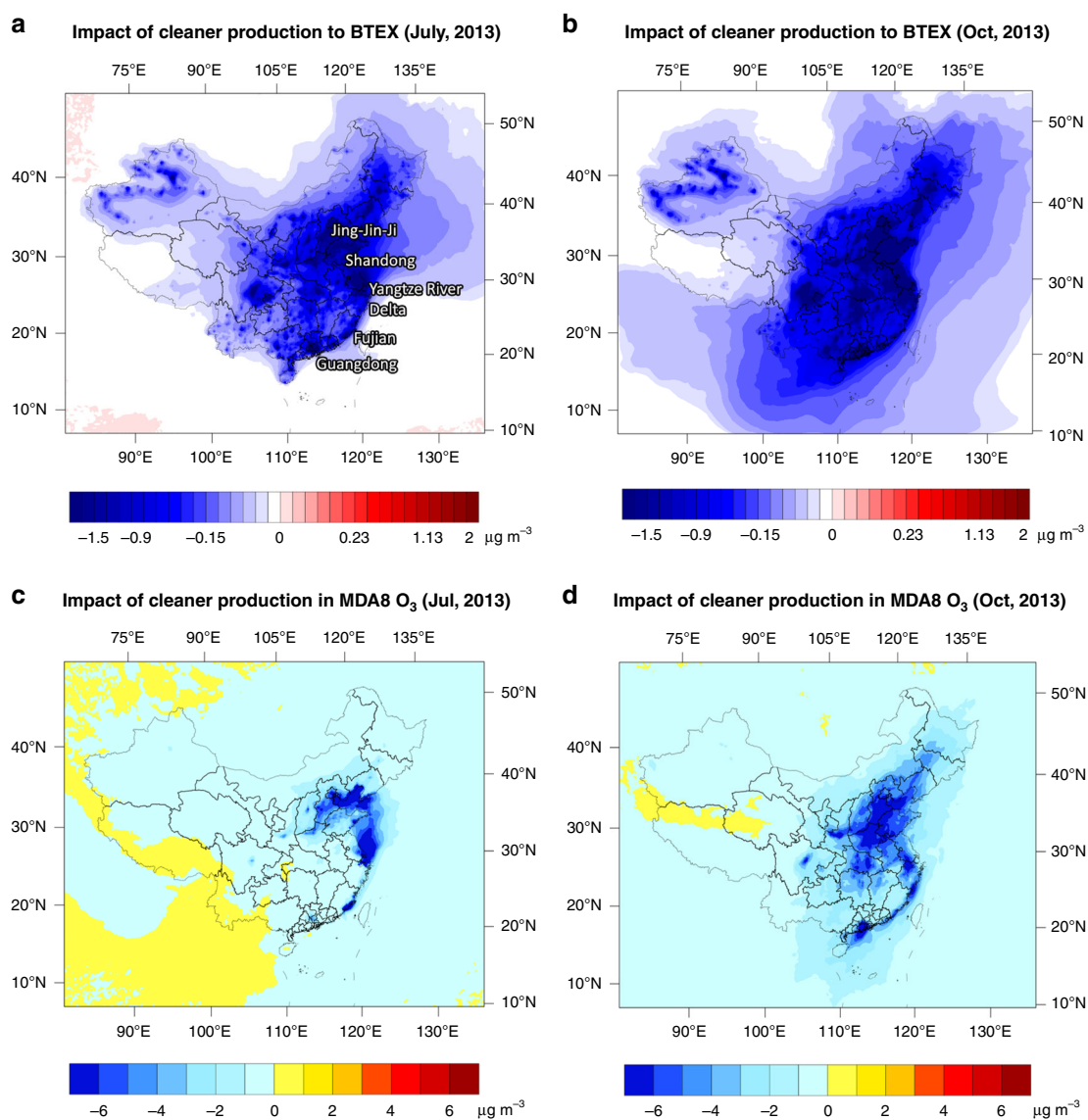**Fig. 5 Efficacy of cleaner production manners in whole production capacities. a, b** BTEX decreased by more than 0.5 µg m^{-3} in most areas when emission intensities of NMVOCs from key industrial sectors were lowered to European references under the 2013 emission rates. Coastal areas and the North China Plain experienced a decrease of 20–35% (>1 µg m^{-3}). **c, d** Cleaner production manners also resulted in a nationwide decrease in MDA8 O_3 under the 2013 emission rates, especially for the east and south coast and the North China plain (2–8 µg m^{-3} in O_3 seasons). Source data are provided as a Source Data file.

20–35% of the BTEX concentration in 2013. Similarly, a nationwide decrease of peak O_3 in both O_3 and non-O_3 seasons was observed, especially for the east and south coast and north China plain (2–8 $\mu g\,m^{-3}$ in O_3 seasons, Fig. 5b, c). To put such reductions in context, one should note the challenge to reduce peak O_3 level. Considering the Yangtze River Delta as an example, an 8 $\mu g\,m^{-3}$ decrease in MDA8 O_3 would require a reduction of either 35% of NOx emissions or 32% of NMVOC emissions[11]. For Pearl River Delta (PRD), it would be a reduction of either 45% of NOx or NMVOC emissions[11]. Nationally, such reductions could save 28,309 people (6236–51,495, 95% CI) dying prematurely from diseases associated with BTEX and MDA8 O_3 per year.

The costs for introducing such low-emission practices were estimated at 0.05–0.3% of the annual industrial output, varying across sectors (Table 1). For pigment-manufacturing and shoe-making industries, emissions can be cut down by around 30% with annualised costs of 0.24% and 0.05%, respectively. Regarding printing, PCB, pharmacy and automobile manufacturing, sectoral emission reduction of 50–70% can be achieved with annualised cost from 0.13 to 0.3%. Negative unit costs were estimated for few sectors such as tyre manufacturing, wood-furniture making and extraction of edible oil. It is because the value of saved or recovered solvent (e.g., hexane in vegetable oil-producing process) offsets the investment and additional operating costs of control technologies. The recovery of these NMVOCs does not only reduce the emissions, but also increases the output and revenue. Since prices of solvents, pollution-discharge fees, labour costs and other input material costs are generally lower in China, negative costs estimated here might be overstated. Nevertheless, the 'true' costs for these sectors should not be excessive and decrease over time. Therefore, we assume that the costs are relatively low and set them as zero in Table 1.

The estimated cost is comparable to a study in the PRD, South China[29]. Costs for adsorption by activated carbon and a switch from low-solvent to solvent-free paints were estimated as $501 and $13317 per ton of abated NMVOCs in that study, respectively. The cost for solvent substitution is much higher. Estimated costs in this paper fall within the above range, varying from $923 to $5992 per ton of NMVOCs; the upper bound is lower than that of the previous study since a mix of technological means is adopted in each sector. For instance, a combination of process modification, solvent substitution, adsorption and incineration techniques are adopted in the automobile- manu-facturing sector. As a result, the average cost would be lower than a sole measure of solvent substitution.

Efforts from homeland and abroad to reduce O_3 and its pre-cursors. By filling the gap of consumption-based O_3 study, this study reveals the responsibilities of global consumers and opportunities for future efforts from homeland and abroad to address the tropospheric O_3 problem. China exports goods to 140 countries or regions in the world[30]. Among them, export to USA alone accounted for 22%, 20% and 20% of the NMVOCs, NOx and CO emissions embodied in China's export goods, respectively. Western European countries (see the country list in Sup-plementary Table 1) together explained around 20% of the export-driven NMVOCs, NOx and CO emissions in China. Another share of 20% was associated with the demands in developed regions in Asia and Pacific. Consumption in the above three regions each entails approximately 3700 premature deaths per year in China due to the elevation of BTEX and MDA8 O_3.

The export footprint can be reduced by more responsible consumption and production. By reducing the disposal of products within their service lives and increasing recycling, a large part of the consumption of electrical equipment, metal devices, furniture, shoes and leather products and others can be avoided. This might be especially applicable for the developed countries that together accounted for over 60% of the export goods from China and excess consumption exists. Many consumers are not fully aware of the environmental footprints of the products they consumed or only focus on the CO_2 footprints. To enable a fundamental shift in demand side, a transparent system in the embodied environmental impacts of products should be established. From the perspective of production, there exist great potentials in reducing the export footprints by accelerating technology transfer. Emissions of O_3 precursors in production per unit of export goods in China are still consistently higher than those in European countries with stricter emission standards. With the proven and affordable technologies, export footprint can be reduced by ~40%. Analysis of mitigation costs indicates that NMVOCs from export sectors can be reduced by around 60% at the expense of less than 0.3% of the annual industrial output. The price competiveness of export goods would not be seriously undermined. Despite the current setback of technology transfer under the clean development mechanism (CDM), global traders should be made aware of the significant benefits of cleaner production technology and management in terms of environmental impacts, and explore the potential for future collaboration.

Even for the world's top exporting countries like China, production for the domestic market still needs to be addressed to achieve substantial reduction of NMVOC emissions and O_3. The direct and indirect consumption of urban and rural households in China contributes about 40% of NMVOC emissions. With increasing household income and consumption, that contribution is expected to grow further. Policies addressing household products and consumer behaviour should be formulated. Long-term attainment of O_3 across the country would also call for further NO_x reduction of >50%[30]. As demand from abroad accounted for about 15% of China's NO_x emissions in 2013, strategies targeting domestic demand driving NO_x emissions and end-of-pipe treatment would be the key to halve NOx emission and consequently bring ambient O_3 to a safe level nationwide.

This study reveals the complex interplay between exogenous demands and the formation of tropospheric O_3 in China. Due to the non-linear relationship between NMVOCs, NOx and O_3 and the other contributing factors such as sunlight and temperature, export emissions have mixed impacts on the tropospheric O_3. They have inhibited the O_3 formation in non-O_3 seasons, especially in the areas with higher latitude and notable seasonal changes of sunlight and temperature (e.g., the North China Plain). Such a relationship should be investigated in other countries to reveal how the global supply chain has shaped the tropospheric O_3 globally.

Another concern is the emerging trend of the relocation of global supply chain and whether it will exacerbate the existing O_3 pollution in the low- and mid-latitudes. A few factors are driving the relocation of the global supply chain. One is the rise of South–South trade, and it is reported that some of China's export capacities had moved out to other emerging economies[9]. The other is the ongoing US–China trade war. A large proportion of industrial products characterised by high NMVOC emission intensity are subject to recently increased tariffs, such as paints, dyes, glues, adhesives, wood furniture, man-made textiles, machinery, electronics, vehicles and parts, ships and boats[31]. These two factors might be accelerated under the COVID-19 crisis due to the disruptions to supply chains, and more companies are working through alternative sourcing strategies. While a small amount of the capacities might move back to developed economies, south Asian and African countries will be

the major receptors of the relocated export capacities. For lower-latitude areas in these regions, the inhibition effects observed in latitudes similar to China's North China Plain might not be applicable. A full-year increase in O_3 might be observed, and the health burden would be much higher than what we reported here for China. Tropospheric O_3 and its precursors in these exporting countries should be monitored closely to avoid severe disruptions in human health and crop yields[32].

Methods

This study was conducted applying a validated air-quality modelling platform with emission inputs from environmentally extended input–output (EEIO) analysis and emission-reduction scenarios. First, consumption-based emission inventories for NMVOCs, NOx and CO were developed from EEIO analysis. Emissions relevant to final demands including export were revealed. Second, export-relevant emissions were excluded from the air-quality model (Case 1) and compared with the base case to study the contribution of export demand on China's O_3 formation. Another two cases were then constructed to study the effectiveness of NMVOC reductions from merely the export industrial capacities (Case 2) and the whole capacities (Case 3). Finally, O_3 health-exposure relationship was applied to study the health cost or benefit from the above cases.

Environmentally extended input–output analysis. China's MRIO table for 30 provinces and 30 sectors was linked to the GTAP database to study the impact of export and the originating countries with the established methods for EEIO analysis[8,33]. The total outputs of sectors in a given economy (X) can be understood as the sum of the intermediate input to other sectors (Z) and the finished goods for final consumers (Y). For the global economy with M regions and N industries in each region, x_i^r represents the total output of industry i in country r and can be expressed as

$$x_i^r = \sum_{s=1}^{M} \sum_{j=1}^{N} z_{ij}^{rs} + \sum_{s=1}^{M} y_i^{rs}, \tag{1}$$

where $z_{ij}^{rs}(r, s = 1, 2, ..., M; i,j = 1, 2, ... N)$ represents the intermediate product sold from industry i in country r to industry j in country s, y_i^{rs} represents the finished goods sold from industry i in country r to the final consumers in country s.

A technical coefficient $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$ is defined as the input from sector i in region r needed to produce one unit of output from sector j in region s. Equation (1) can therefore be formulated as follows:

$$X = (I - A)^{-1} F, \tag{2}$$

where X, A, F and I are the matrices of x_i^r, a_{ij}^{rs}, y_i^{rs} and an identity matrix, respectively.

To calculate the O_3 precursor emissions embodied in goods and services, emission intensity (i.e., O_3 precursor emissions per unit of economic output) is introduced. The NMVOCs, NOx and CO emissions embodied in goods and services can be calculated as

$$C = h(I - A)^{-1} F, \tag{3}$$

where C is the matrix showing the emissions embodied in goods and services used for different final demands, and h is a vector of emission intensity by sector and region.

Air-quality modelling platform. The study domain for this work is mainland China, with a spatial resolution of 27×27 km. The air-quality modelling platform coupled the Weather Research and Forecast (WRF) model[34], SparseMatrix Operator Kernel Emissions (SMOKE) model[35] and CMAQ model[36]. The Weather Research and Forecast (WRF) model v3.9 was used to provide meteorological data. The platform reproduced the O_3 pollution in January, April, July and October of 2013, representing the peak O_3 months (July and October) in the northern and southern China and supporting the health-risk analysis, respectively. Model performances were evaluated by ambient O_3 measurements (see Supplementary Note 2). The correlation coefficient (R) between the modelling result and observations was between 0.50 and 0.78 for 1-h average or maximum daily 8-h average, similar to those of previous studies in China[37–39]. Detailed model configurations and validation of CMAQ and WRF are shown in Supplementary Tables 2 and 3 and Fig. 4. Bulk emission inventories from the EEIO analysis were processed by the emission-processing module with localised temporal and spatial surrogates to have the model-ready emission inputs for simulation and analysis.

Health-impact estimation. Epidemiological studies on the detrimental effects of BTEX and ambient O_3 on population health are emerging in China. The concentration-response functions from studies within China are prioritised in this study. The number of premature deaths due to a change in ambient BTEX and O_3

concentration was estimated as follows:

$$\Delta M = \sum_{i=1}^{15321} POP_i \times M_i \times CRF \times \Delta X_i, \tag{4}$$

where i is the number of 15321 grids (27×27 km) in accordance with the modelling platform, POP_i is the number of people in Grid i, M_i is the baseline cause-specific mortality in Grid i, CRF is the concentration-response function from epidemiological studies, ΔX_i is the change of BTEX or O_3 concentration in Grid i. Baseline cause-specific mortality for the year of 2013 was obtained from the burden of disease study in China[25] and the statistical yearbooks[40]. Since mortality data are only available at the provincial level, grids within the same province adopted the provincial value. CRF is pollutant- and disease-specific. For BTEX, the short-term increments of environmental benzene (1 µg m^{-3}) and TEX (1 µg m^{-3}) are associated with 4.1% (0.7–7.7%, 95% CI) and 0.44% (0.13–0.77%, 95% CI) increases in circulatory mortality[15]. For O_3, the pooled CRF associated with a 10 µg/m^3 increase in O_3 concentrations from eight epidemiological studies in China is 0.60% (0.22–0.97%, 95% CI) and 0.51% (0.03–0.98%, 95% CI) for cardiovascular and respiratory diseases, respectively[25].

Data sources. The MRIO table was adopted from previous studies[7,8,33]. It was developed based on the 2012 Chinese national and provincial single-region input–output tables. The table has been demonstrated and used to study the driving demands and trade-related contributions to greenhouse gases[8,33,41], and some of the air pollutants in China[7]. GTAP version 9 was used, which described bilateral trade between 140 regions for 57 sectors. The production-based emission inventories of NMVOCs, NOx and CO for China were developed based on the established methodologies, and the best available local emission factors[14,42–47], for the base year of 2013. For China, anthropogenic NMVOC emissions from stationary combustion, on-road and non-road mobile sources, industrial processes, industrial and household solvent use, biomass burning and others (such as gas stations and dry cleaning) were estimated. Activity-level data were collected from national and provincial statistical yearbooks. As for other countries in the world, NMVOC emissions were taken from the Emissions Database for Global Atmospheric Research (EDGAR) v4.3.2 database[19]. Biogenic VOC emissions were estimated by Model of Emissions of Gases and Aerosols from Nature (MEGAN)[48]. It should be noted that there was a 1-year gap in the MRIO table (in 2012) and production-based emission inventories (in 2013). The MRIO tables heavily rely on the statistics of trade flow, which is only available for 2007, 2010 and 2012 in provincial levels. But nationwide measurements on ambient O_3 in China were not available until 2013. To enable the validation of the modelling platform, the reference year of emission inventories was set for 2013 instead of 2012. Nevertheless, the 1-year gap should not undermine the reliability of this study since we assume no dramatic change of trade characteristics from 2012 to 2013. Cause-specific mortality rate was obtained from China Health and Family Planning Statistical Yearbook[40].

Data availability

The China Multi-Regional Input–Output Table 2012 can be downloaded from the China Emission Accounts and Datasets (CEADS) website (http://www.ceads.net/)[8,9]. Source data are provided with this paper.

Code availability

Code used in this study is provided in a repository in Github (https://github.com/JmmOo/Consumption-based-study-on-O3-and-its-precursors-in-China).

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Author contributions

J.O., Z.W., Z.K., J.Z. and D.G. designed the study. J.O. and Z.W. prepared emission profiles, performed analysis and prepared the paper. J.G. built the simulation platform. S.Z., C.L. and P.L. supported the emission inventory development. J.M., Z.M., H.Z. and Y.S. supported the EEIO analysis. Z.K., J.Z. and D.G. jointly coordinated and supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

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