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IOP Publishing Environ. Res. Commun. 2 (2020) 065006 https://doi.org/10.1088/2515-7620/ab9dbd

Environmental Research Communications

OPEN ACCESS

RECEIVED
27 March 2020

REVISED
12 June 2020

ACCEPTED FOR PUBLICATION
17 June 2020

PUBLISHED
30 June 2020

PAPER

Modelling public health benefits of various emission control options to reduce NO_2 concentrations in Guangzhou

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Keywords: air pollution, urban air quality, public health, exposure, air quality limit values, emission control

Supplementary material for this article is available online

Abstract

The local government of the megacity of Guangzhou, China, has established an annual average NO_2 concentration target of 40 $\mu g\ m^{-3}$ to achieve by 2020. However, the *Guangzhou Ambient Air Quality Compliance Plan* does not specify what constitutes compliance with this target. We investigated a range of ambition levels for emissions reductions required to meet different possible interpretations of compliance using a hybrid dispersion and land-use regression model approach. We found that to reduce average annual-mean NO_2 concentration across all current monitoring sites to below 40 $\mu g\ m^{-3}$ (i.e. a compliance assessment approach that does not use modelling) would require emissions reductions from all source sectors within Guangzhou of 60%, whilst to attain 40 $\mu g\ m^{-3}$ everywhere in Guangzhou (based on model results) would require all-source emissions reduction of 90%. Reducing emissions only from the traffic sector would not achieve either interpretation of the target. We calculated the impacts of the emissions reductions on NO_2-atttributable premature mortality to illustrate that policy assessment based only on assessment against a fixed concentration target does not account for the full public health improvements attained. Our approach and findings are relevant for NO_2 air pollution control policy making in other megacities.

1. Introduction

In response to rapidly increasing levels of air pollution, governments at all levels in China have implemented a range of laws, policies, and plans. For example, in 2014 China's National People's Congress (NPC) Standing Committee passed a new Environmental Protection Law (Zhang *et al* 2016a), and in 2018 amended the Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution (Ministry of Ecology and Environment of the People's Republic of China 2018). As a result of the efforts being put into curbing emissions by both national and local governments, substantial improvements in Chinese air quality have been reported in recent years (Li *et al* 2015, Zhang *et al* 2016b, Huang *et al* 2018, Liu *et al* 2018, UN Environment 2019), although other researchers have argued that despite increased political focus on the issues, further measures are needed for more profound improvement (Kostka 2016, Shi *et al* 2019).

Guangzhou is an example of many cities in China that do not currently meet the Chinese air quality standards (GB 3095-2012) (Ministry of Ecology and Environment 2012). Consequently, as required under both the Chinese national laws cited above the Guangzhou Municipal People's Government has developed the Guangzhou Ambient Air Quality Compliance Plan (2016–2025) (People's Government of Guangzhou Municipality 2017). Of the six Chinese priority air pollutants (SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO and O_3), nitrogen dioxide (NO_2) is of particular concern at the urban and sub-urban scale. Exposure to ambient concentrations of NO_2 is associated with premature mortality and other public health burdens (WHO 2013, Faustini *et al* 2014, Crouse *et al* 2015). The Chinese air quality standard for NO_2 is currently set equal to the World Health

Organization (WHO) air quality guideline, at 40 μg m^{-3} as an annual average, and the Guangzhou aspiration is to achieve this by 2020 (and also to achieve an annual average NO_2 concentration of 38 μg m^{-3} by 2025) (People's Government of Guangzhou Municipality 2017).

NO_2 derives primarily from NO_x (NO and NO_2) emitted from road transport, domestic, commercial and industrial combustion, and shipping (MEIC 2016, Fu *et al* 2017, Liu *et al* 2017, Ding *et al* 2018). Due to the ubiquitous nature of combustion sources and the relatively short lifetime of NO_2, its concentrations are highly spatially variable (Beirle *et al* 2011, Cyrys *et al* 2012, Gurung *et al* 2017). However, although the Guangzhou Ambient Air Quality Compliance Plan states that the NO_2 target needs to be met in all areas in Guangzhou, it is not defined how compliance is to be evaluated, for instance whether this includes at locations without monitoring stations. Furthermore, because the ultimate aim of setting an NO_2 concentration target is to alleviate the negative impacts on health, the estimation of potential city-wide population health gains from policy interventions that target NO_2 emission reductions from local sources also requires highly spatially resolved NO_2 concentration data.

Estimation of NO_2 at non-monitored locations requires some form of modelling. However, modelling NO_2 (and other pollutant) concentrations at high spatial resolution for Chinese cities such as Guangzhou presents a considerable challenge, both because of the geographical scale of the domain (for example, Guangzhou has an area >7000 km^2), and the relative paucity of data needed as inputs to models (He *et al* 2018). The two main approaches to urban-scale air pollution modelling are dispersion models that endeavour to explicitly simulate physical-chemical processes at urban scale (Visscher 2013), and land-use regression (LUR) models that are based on empirical spatial statistics (Briggs *et al* 1997, Jerrett *et al* 2005). Applications of either approach in China have so far been limited by the city size and data availability (He *et al* 2018).

We recently developed and demonstrated a hybrid modelling approach that addresses some of the limitations of applying a dispersion or land-use regression model in isolation (He *et al* 2019). In our hybrid approach, a dispersion model is used to derive NO_2 concentrations at a set of 'virtual' receptor locations—strategically chosen to represent geographical areas, the expected NO_2 concentration range and population weighting—which are then used as input to generate an LUR model to map annual-average NO_2 concentrations across the entire domain. An advantage of this method is that it is possible to derive spatially-explicit maps of NO_2 concentrations for the whole domain under alternative future emissions scenarios that are underpinned by process-based dispersion simulations.

The aim of the current study is two-fold. First, we apply our modelling approach (He *et al* 2019) to investigate the ability of a range of example emission reduction scenarios to meet the Guangzhou Ambient Air Quality Compliance Plan target of 40 μg m^{-3} annual-average NO_2 concentration. Since it is not clear what constitutes compliance with the target, we present results that illustrate the emissions reductions required for modelled concentrations to meet the following interpretations of a 40 μg m^{-3} target:

- Target Interpretation 1: the average of the annual average concentrations at all current NO_2 monitoring sites meets the target (TI1).
- Target Interpretation 2: the annual average concentration at all current NO_2 monitoring sites meet the target (TI2).
- Target Interpretation 3: the population-weighted annual average concentration in Guangzhou meets the target (TI3).
- Target Interpretation 4: the annual average concentration everywhere in Guangzhou meets the target (TI4).

Secondly, we use our modelled NO_2 concentrations to determine the changes in population exposure to NO_2, and the associated population premature mortality avoided. We use these data to illustrate that the use of a concentration threshold as a policy metric can fail to convey to policy-makers and the public the extent of population health gain achieved across a range of potential emissions reductions even where reductions fail to deliver the concentration target (and the continuing public health gain for reductions that go beyond meeting the concentration target).

Our study does not set out to simulate real-world proposed policy measures, but to illustrate an approach to identifying the scale of the mitigation challenge to achieve city-wide concentration standards set under existing policy targets and what their associated potential health gains may be. Economic costs and benefits are not evaluated.

Whilst the results are based on consistent model results for the specific situation in Guangzhou, they provide relevant evidence to decision makers designing effective air pollution control policies in other fast-growing megacities in China and elsewhere globally.

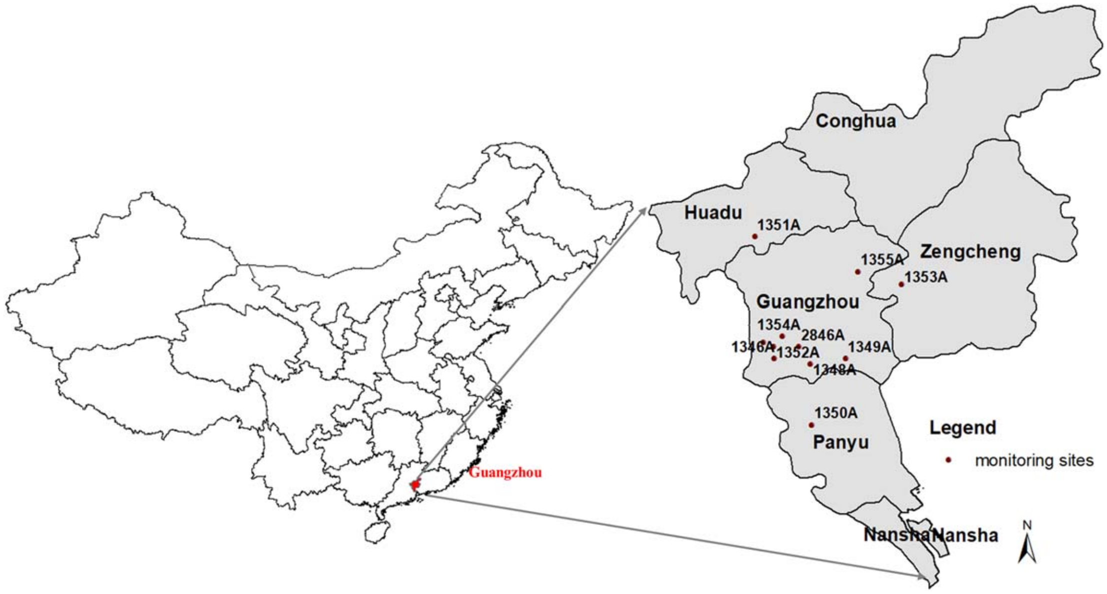

Figure 1. The location of Guangzhou in China and the locations of the 11 monitoring sites (red dots) within the six districts of the city. The labels are the Guangzhou codes for the monitoring sites. Shapefiles of the city-wide and district administrative boundaries were obtained from the GADM database (GADM 2019).

2. Method

2.1. A hybrid modelling approach

The city of Guangzhou (population 14 million) is located on the north side of the Pearl River Delta (figure 1) and comprises six districts in a total area of 7434 km^2. As described by He *et al* (2019), the size of the city and lack of some data limit the application of domain-wide air pollution dispersion modelling. Similarly, the eleven monitoring sites that measure NO_2 concentrations are too few to develop spatially representative NO_2 concentrations using a LUR approach. To overcome these challenges we developed a hybrid model, described by He *et al* (2019), which uses a combination of both dispersion and LUR modelling. The ADMS-Urban dispersion model v4.1 (CERC 2017) is used to derive NO_2 concentrations at 83 receptor locations across Guangzhou systematically selected to represent the anticipated concentration range (from background to roadside) in each of the six districts, with additional location weighting according to population density (since the overall focus is estimation of population NO_2 exposure). The NO_2 concentrations at these selected receptors locations are then used to develop a LUR model for NO_2 concentrations across the whole city domain. The LUR model is built with the 84 potential predictor variables listed in supplementary information (SI) table S1 available online at stacks.iop.org/ERC/2/065006/mmedia. The final LUR model variables and the evaluation statistics for the LUR model for 2017 ('base case') NO_2 concentrations, as reported previously in He *et al* (2019), are summarised in SI tables S2 and S3, respectively. The spatial resolution of the final modelled NO_2 concentrations is 25 m.

We use the same method here to develop spatial maps of NO_2 concentration for each of the emissions reductions scenarios described in the following section. The use of the dispersion model means that NO_2 concentrations at the set of 83 receptor locations for different emissions reductions scenarios are derived from a process-based model. The variables selected for the subsequent LUR models for the different scenarios are listed in SI table S4. Because road length was used as a proxy of traffic, and therefore cannot reflect the proportion change of traffic emission, the final model might underestimate the impacts of traffic emission reduction.

The ADMS-Urban model was also used to derive NO_2 concentrations at each of the 11 NO_2 monitor locations in order to address target interpretations TI1 and TI2 of compliance with a Guangzhou NO_2 target.

2.2. Modelling scenarios

To explore the scale of emissions reductions required to meet the Guangzhou NO_2 concentration target of 40 μg m^{-3}, the following different scenarios were simulated using ADMS-Urban to derive concentrations at the 83 pre-selected receptor locations.

(1) Base case: 2017 emissions

(2) Scenarios A_x: reductions of NO_x and VOCs emission in all source sectors equally by 10% decrements (x) between 10% and 90%

(3) Scenarios B_x: reductions of NO_x and VOCs emission in the road transport sector by 10% decrements (x) between 10% and 90%

Road traffic NO_x emissions comprise 21.3% of all NO_x emissions (including shipping) in the model domain for Guangzhou (MEIC 2016) but transport is the dominant (i.e. comprises >45%) land-based NO_x emission source in the majority of the individual grid cells (SI figures S1 and S2 and table S5). Changes in road traffic emissions only were explicitly modelled in ADMS-Urban (CERC 2017), so the B_x scenarios were undertaken to demonstrate the change of NO_2 concentration if interventions focusing only on reductions of NO_x and VOCs emissions from road traffic were to be implemented.

Under the base case scenario (2017), the total annual NO_x and VOCs emissions are 180.2 kt and 357.3 kt, respectively (SI table S6). When comparing outcomes from the two sets of scenarios it is important to note that emissions reductions are substantially larger under the A_x scenarios than the B_x scenarios. For example, in scenario B_{90}, the 90% reductions in emissions from road transport result in reductions of about 34 kt NO_x and 45 kt VOC. In scenario A_{90}, the 90% reductions in emissions across all sectors corresponds to reductions in NO_x and VOC of 162 kt and 322 kt respectively (SI table S6).

We included emissions reductions in VOC as well as NO_x in the model simulations since VOC are the other class of primary emissions that can impact on the gas-phase NO_x chemistry. The same percentage reductions in VOC and NO_x were applied, although equal reductions of each is probably not a realistic outcome of particular policy measures. However, the VOC reductions imposed in the model scenarios in fact impact relatively little on the results of our study which investigates the impacts of emissions reductions in the Guangzhou domain on intraurban levels of NO_2 in the Guangzhou domain. We demonstrate this by conducting a sensitivity simulation with the dispersion model of NO_2 concentrations at the 11 monitoring sites in Guangzhou for a scenario with 50% reduction in NO_x emissions but baseline VOC emissions. The results from this simulation are compared in SI figure S3 with those for the simulation with baseline NO_x and VOC emissions and for the scenario where both NO_x and VOC emissions are reduced by 50%. Figure S3 shows that the inclusion or not of 50% VOC emissions reductions alongside the 50% reductions in NO_x emissions has very little impact on the NO_2 concentrations at these locations (across a range of absolute NO_2 concentrations) compared with the change in NO_2 concentrations brought about by the reductions in NO_x emissions. The average change (increase) in NO_2 concentration for the scenario with 50% NO_x emissions reduction and no VOC reductions compared with the scenario where both VOC and NO_x emissions are reduced by 50% is only 1.1 μg m^{-3}, which equates to only a 2.5% change in the mean of the NO_2 concentrations across the 11 sites under these scenarios (43 μg m^{-3}). In comparison, the 50% reduction in the NO_x emissions causes an average change across the 11 sites of more than 18 μg m^{-3}.

Meteorological variability can have a significant influence on air quality by affecting the advection, diffusion and deposition of air pollutants, although less so for annual average concentrations compared with shorter averaging times. The magnitude of inter-annual meteorological variability on annual average NO_2 in Guangzhou was explored by also running the dispersion model for the 11 monitoring sites using the Guangzhou meteorology for each of the years 2013 to 2016. Emissions were maintained at the 2017 base case year. The ranges in the annual averages of the meteorological variables input into the dispersion model across these five years are shown in SI table S7.

2.3. Health burden calculation

Total premature deaths attributable to the simulated concentrations of NO_2 across the whole Guangzhou domain under each scenario were calculated as described by Walton *et al* (2015), using the association with all-cause premature mortality of 2.45% (95% CI: 2.34%, 2.58%) per 10 μg m^{-3} NO_2 from Zhang *et al* (2011). The association is taken to be linear across the NO_2 concentration range here. The number of deaths in 2017 in Guangzhou was 60 900 (Guangzhou Municipal Public Security Bureau 2016). Population density data at 100 m × 100 m (for the year 2015) was obtained from WorldPop (WorldPop 2019). The population-weighted average concentration (E) for NO_2 across the whole of Guangzhou was calculated as follows,

$$E = \frac{1}{Pop}\sum_i C_i Pop_i \tag{1}$$

where C_i and Pop_i are the concentration and the number of people in each cell i of the concentration map.

The attributable deaths from exposure to ambient NO_2 in Guangzhou was calculated by multiplying the attributable fraction (AF) by number of all-cause deaths (equations (2)–(4)), where RR refers to relative risk.

$$RR = 1.0245^{(E/10)} \tag{2}$$

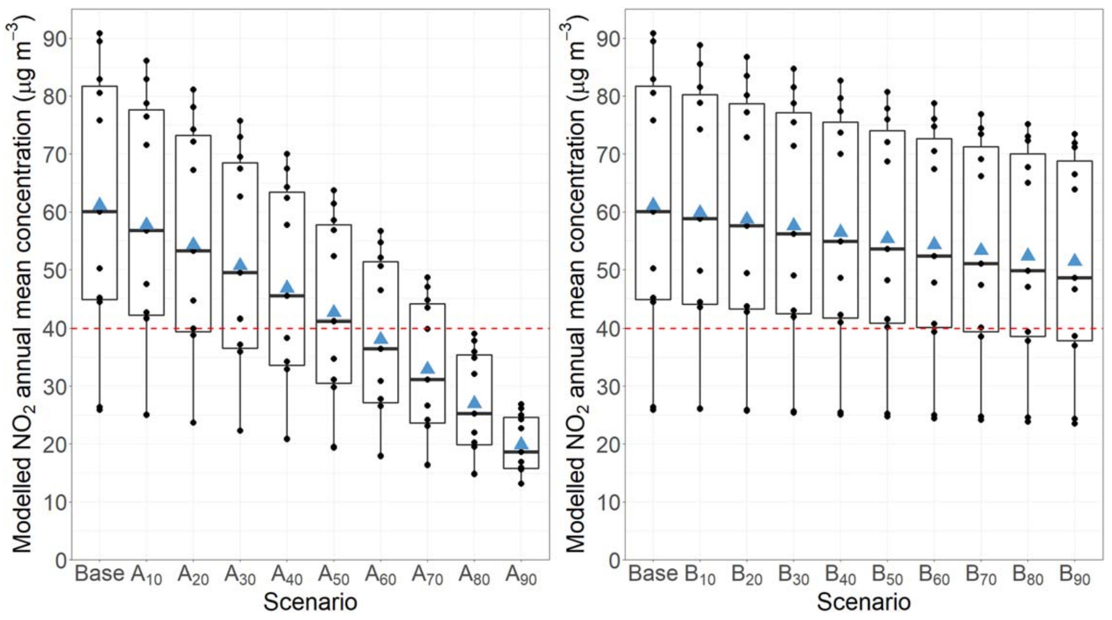

Figure 2. Modelled NO_2 concentrations at the 11 monitoring sites under (left) emissions reduction scenarios A_x, in which emissions are reduced by 10%–90% across all sectors equally, and (right) emissions reduction scenarios B_x, in which only traffic emissions are reduced by 10%–90%. The box plots summarise the range in NO_2 concentrations across the 11 sites, which are shown individually as the black dots, whilst the blue triangle shows the average concentration across all 11 sites. The horizontal red line on each panel demarcates 40 μg m^{-3}, the WHO NO_2 guideline and Guangzhou 2020 target.

$$AF = (RR - 1)/RR \tag{3}$$

$$\text{Attributable death} = \text{the number of deaths} \times AF \tag{4}$$

In common with studies of this kind, population data at residential address was used. An assessment of the impact of work location on population level of exposure requires additional information on population distributions at different times (Reis *et al* 2018).

3. Results

3.1. Modelled NO_2 concentration changes at monitoring sites

The Guangzhou Ambient Air Quality Compliance Plan does not specify whether modelling is to be used for compliance assessment. Without modelling, compliance can only be evaluated using the monitor data. The NO_2 concentrations simulated using the ADMS-Urban dispersion model at the 11 monitoring sites for the base case and the 18 emissions reduction scenarios are summarized in figure 2. For comparison, the NO_2 concentrations simulated at the 11 monitor sites for the base case for the five meteorological years tested are shown in SI figure S4. The latter figure shows that NO_2 concentrations at a given receptor varied relatively little for the different meteorological scenarios (at most a few μg m^{-3}) compared with the changes associated with the emissions reduction scenarios shown in figure 2.

As expected, concentrations at monitoring sites under A_x scenarios are lower than those under B_x scenarios because absolute emissions reductions are larger when applied to all sectors than when applied only to road transport (figure 2). It is notable that the range in NO_2 concentrations across the 11 sites gets smaller as emissions reductions become greater. Concentrations at sites with the highest concentrations, which are located nearer to main roads, fall off faster than at sites with the lowest concentrations, which are background sites. This is because NO_2 concentrations are strongly influenced by local NO_x emission sources, so locations closer to strong sources, particularly roads, are more immediately impacted by reductions in emissions from those sources. This effect is greater for the A_x emissions reduction scenarios (figure 2) since these also include reductions in domestic and other local NO_x sources, not just traffic sources. As a consequence of the relatively greater effect of emissions reductions on higher concentration locations, there is a smaller reduction in the average NO_2 concentrations for the scenarios with smaller reductions in emissions (toward the left side of each panel in figure 2) compared with the reductions in the average NO_2 concentration when emissions reductions are already substantial (toward the right side of each panel in figure 2).

Figure 2 suggests that to attain an average annual-average NO_2 concentration across all monitoring sites of 40 μg m^{-3} (TI1) would require a 60% reduction of emissions in all sectors (A_{60}). (We note here that since our

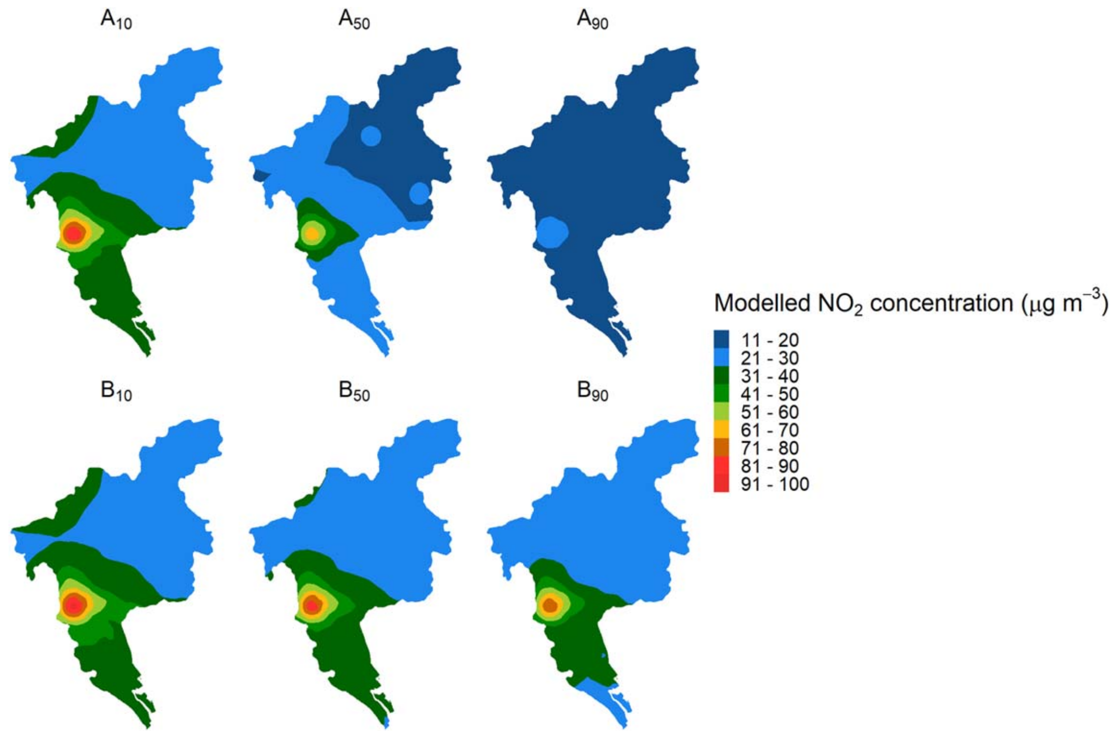

Figure 3. Hybrid dispersion-LUR modelled maps of annual-average NO_2 concentrations in Guangzhou under the A_{10}, A_{50}, A_{90}, B_{10}, B_{50}, and B_{90} emission reduction scenarios. Highest concentrations occur in Guangzhou city centre.

emissions reductions scenarios go in 10% increments it is more strictly accurate to state that TI1 would be reached with a scenario somewhere between A_{50} and A_{60}, and likewise for other statements below referring to emissions reductions required to meet certain target interpretations.) To attain 40 μg m^{-3} or less at all 11 monitoring sites individually (TI2) would require an 80% reduction from all emitting sectors (A_{80}). Figure 2 further suggests that neither of the Target Interpretations 1 or 2 are attainable if interventions aiming at emission reductions only from road transport are implemented.

3.2. Spatial assessment of NO_2 concentration changes

The data presented in section 3.1 show modelled concentrations of NO_2 under emissions reductions scenarios only for the 11 locations in Guangzhou that currently have NO_2 monitoring, yet compliance with the Guangzhou NO_2 target may be required at non-monitor locations. Furthermore, 11 monitoring locations in a city the size of Guangzhou cannot capture the full extent of variation in population exposure to NO_2. Our hybrid dispersion-LUR model maps of the spatial variation in NO_2 concentration across Guangzhou for six examples of the 18 emissions reductions scenarios are shown in figure 3. For all scenarios, concentrations of NO_2 remain highest in the city centre where most people live and lowest in the north of the city domain. Figure 4 illustrates the spatial patterns in change in NO_2 concentration against the base-case scenario for the same emissions reduction scenarios presented in figure 3. As the finer spatial structure of the changes in NO_2 concentration cannot be visualised in figure 4, figure 5 shows a magnification of the changes in NO_2 concentration in the city centre for the A_{50} and B_{50} scenarios (using a different colour scale compared with figure 4).

The A_x scenarios show more substantive reductions in annual average concentrations of NO_2 (figures 3 and 4) than the B_x scenarios, given the larger absolute emissions reductions applied in the former set. In terms of the spatial variation, the modelled annual average NO_2 concentrations under the A_{90} scenario ranged from 13.0 to 27.8 μg m^{-3} while under the B_{90} scenario they ranged from 20.0 to 78.4 μg m^{-3} (figure 3). In the base case they ranged from 21.5 to 99.7 μg m^{-3} (He *et al* 2019). Figure 5 illustrates the substantial spatial structure to the changes in NO_2 concentration that is difficult to discern in the maps of figure 4 that present the changes for the entire Guangzhou city area. The NO_2 reductions are greatest near roads in both A and B scenarios but figure 5 illustrates that the A scenarios also lead to larger reductions in NO_2 away from roads than the B scenarios. Nevertheless, these simulations suggest that only the most stringent emissions reduction scenario simulated (A_{90}) would result in NO_2 concentrations of less than 40 μg m^{-3} in all locations, including in the city centre, i.e. would meet Target Interpretation TI4. This target interpretation would not be achieved even with complete elimination of road traffic emissions, without reductions in other sources as well.

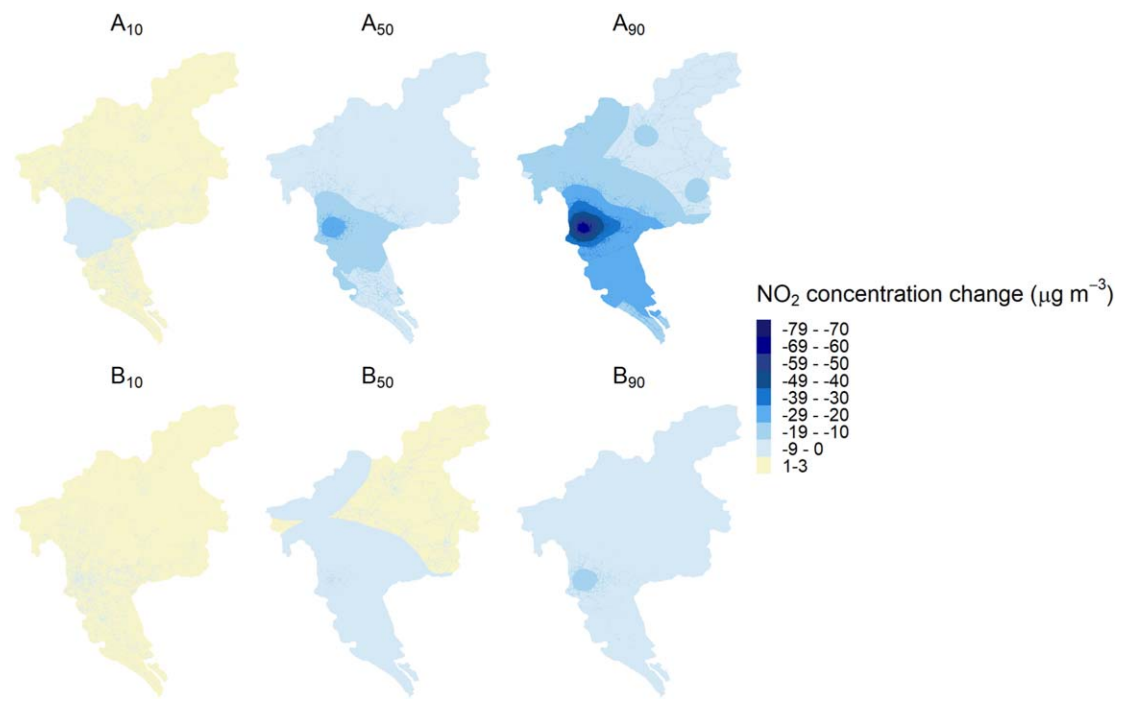

Figure 4. Changes in modelled annual-average NO_2 concentrations in Guangzhou for the A_{10}, A_{50}, A_{90}, B_{10}, B_{50}, and B_{90} emission reduction scenarios compared with the 2017 base case.

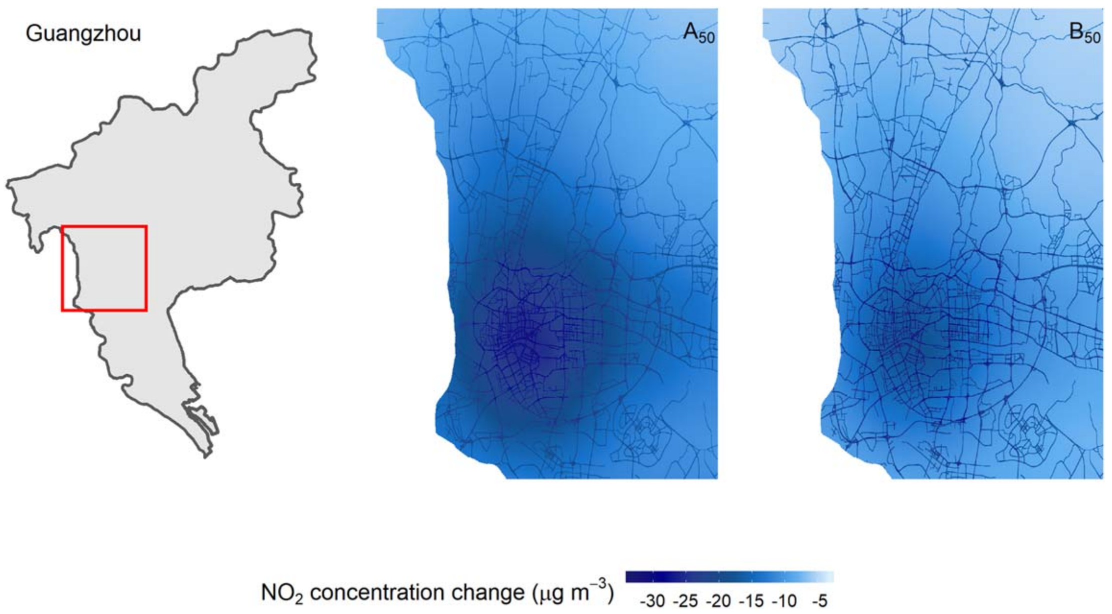

Figure 5. Changes in modelled annual-average NO_2 concentrations in Guangzhou for the A_{50} (centre) and B_{50} (right) emissions reduction scenarios compared with the 2017 base case for a magnification of the city centre area (shown by the red box on the map) to illustrate the spatial gradients in NO_2 change. Note that the colour scale is different to that used in figure 4 for the equivalent maps for the whole of Guangzhou. The road network is apparent from the spatial gradients in the NO_2 concentration changes.

Figure 4 shows that under small and moderate emissions reductions the annual average NO_2 concentration are simulated to increase slightly in some areas of Guangzhou. This is most apparent for the B_{10} scenario, under which the maximum simulated increase in NO_2 concentration is 2.59 $\mu g\ m^{-3}$. There are two explanations for the small increases in NO_2 when emissions are reduced. First, it reflects errors in simulated NO_2 concentration inherent in the two different LUR models being subtracted; when the effect of emissions reductions in an area are small the subtraction of surfaces of roughly similar concentration can lead to a positive value. These positive values of a couple of $\mu g\ m^{-3}$ provide an indication of model surface uncertainty. There is also potentially an

Table 1. Summary for selected emissions reduction scenarios of population-weighted annual-average NO_2 concentration, the percentage of people living at locations with annual average NO_2 concentration >40 $\mu g\ m^{-3}$, the number of NO_2-attributable premature deaths, and the number of NO_2-attributable lives saved compared with the base case. The ranges given for the numbers of attributable premature deaths reflect the confidence interval given for the health response coefficient used in the calculation. The data for all emissions reductions scenarios is given in SI table S8.

Scenario	Population-weighted NO_2 concentration ($\mu g\ m^{-3}$)	Proportion of population at locations with NO_2 concentration >40 $\mu g\ m^{-3}$ (%)	Number of NO_2-attributable premature deaths	Reduction in number of NO_2-attributable premature deaths cf base case
Base	52.5	60.0	7270 [6960–7620]	n.a.
Emission reductions—all sources				
A_{10}	49.9	58.6	6932 [6642, 7273]	338 [318, 347]
A_{50}	36.8	37.8	5195 [4974, 5454]	2075 [1986, 2165]
A_{90}	18.0	0	2594 [2481, 2727]	4676 [4479, 4893]
Emission reductions—traffic sources only				
B_{10}	51.7	63.4	7167 [6868, 7519]	103 [92, 101]
B_{50}	47.5	53.5	6615 [6337, 6941]	655 [623, 679]
B_{90}	43.5	48.6	6087 [5831, 6389]	1183 [1129, 1231]

atmospheric chemistry contribution. Where NO_x emissions are large, the concentrations of O_3 are low, and rate of oxidation of NO emissions to NO_2 is suppressed; therefore as the NO_x emissions are initially lowered more O_3 is available to convert NO to NO_2. The effect is proportionally greater where NO_2 concentrations are lower.

3.3. Modelled potential health gains of different emission changes

Table 1 presents, for each scenario, the population-weighted NO_2 concentration, the percentage of the Guangzhou population living at locations where NO_2 concentration exceeds 40 $\mu g\ m^{-3}$, the estimated number of NO_2-attributable premature deaths, and the number of NO_2-attributable premature deaths avoided compared with the base case. (Calculations of premature deaths are subject to uncertainty in the health response coefficient as well as that in simulated NO_2 concentrations.) Under A_x scenarios, the number of premature deaths avoided is almost three times that of the equivalent percentage emissions reductions under B_x scenarios, which is due to the greater absolute emission reductions in A_x scenarios than in B_x scenarios. Under the A_x scenarios, no part of the population is exposed to concentrations exceeding 40 $\mu g\ m^{-3}$ when the emissions reductions reach 90% (table 1). Under the B_x scenarios, even for the B_{90} scenario nearly half (48.6%) of the population resides in locations where modelled NO_2 concentrations still exceed 40 $\mu g\ m^{-3}$. The corresponding population-weighted NO_2 concentration for A_{90} and B_{90} emissions reduction scenarios are 18.0 $\mu g\ m^{-3}$ and 43.5 $\mu g\ m^{-3}$ respectively. However, although the population-weighted NO_2 concentration for the A_{90} emissions reduction scenario is less than 40 $\mu g\ m^{-3}$, the modelled number of NO_2-attributable premature deaths under A_{90} is still 2594 [2481, 2727].

4. Discussion

4.1. Interpretation of NO_2 policy targets

We have found that different interpretations of the Guangzhou Municipal People's Government's target to attain an NO_2 concentration of 40 $\mu g\ m^{-3}$ can lead to different amounts of emissions reduction required. These are illustrated in figure 6.

If modelling is not used, then compliance can only be assessed via the concentrations measured at the 11 sites in Guangzhou that monitor levels of NO_2 (our target interpretations TI1 and TI2). Our simulations suggest that the scenario in which NO_x emissions from all source sectors are reduced by 80% (the A_{80} scenario) would achieve the goal of reducing NO_2 concentrations at all monitor sites to $\leqslant$40 $\mu g\ m^{-3}$ (TI2). The slightly smaller reductions in emissions required to reach this interpretation of the target, compared with the A_{90} scenario that is required to satisfy the interpretation that NO_2 concentrations must not exceed 40 $\mu g\ m^{-3}$ everywhere (TI4), and which can only be evaluated through modelling, is because there are no monitors at the 'hotspots' simulated in the spatial model to have the highest concentrations. If an interpretation of the target is that the average NO_2 concentration across the 11 monitor sites is to be $\leqslant$40 $\mu g\ m^{-3}$ (TI1), then this is met with the A_{60} scenario. A population-weighted concentration of $\leqslant$40 $\mu g\ m^{-3}$ (TI3) is met under scenario A_{50}, but this scenario still leaves 37.8% of the Guangzhou population living in locations where NO_2 concentration exceeds 40 $\mu g\ m^{-3}$ (table 1 and figure 6).

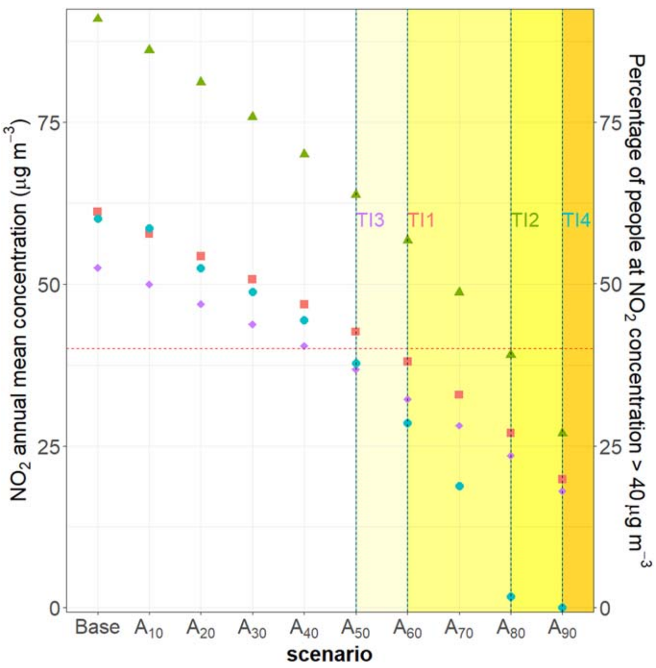

Figure 6. Changes as a function of the A set of emissions reduction scenarios in different metrics of quantifying NO_2 concentration and associated population health gains in Guangzhou. Red squares show the average NO_2 concentration for the 11 monitor sites. Green triangles show the maximum NO_2 concentration across the 11 monitor sites. Purple diamonds show the population-weighted NO_2 concentration. Blue dots show the percentage of population in locations where NO_2 exceeds 40 μg m^{-3}. The horizontal red line demarcates 40 μg m^{-3}, the WHO NO_2 guideline and Guangzhou 2020 target. The four vertical dotted lines marked TI*n* indicate at what point of A_x scenario emission reductions each of our four target interpretations (TI) of the Guangzhou target of 40 μg m^{-3} are met. TI1, the average concentration at the 11 monitoring sites is below 40 μg m^{-3}, is met under scenario A_{60} (and greater emissions reductions). TI2, the concentration at all 11 monitoring sites is below 40 μg m^{-3}, is met under scenario A_{80} (and greater emissions reductions). TI3, the population-weighted concentration is below 40 μg m^{-3}, is met under scenario A_{50}. TI4, the concentration everywhere is below 40 μg m^{-3}, is met only under scenario A_{90}. The yellow-orange shadings indicates the scenarios under which a given TI is met.

Our simulations illustrate the substantial challenge to reduce NO_2 concentrations to 40 μg m^{-3}, whatever way compliance with this target may be assessed, via actions on emissions sources in Guangzhou alone. Although NO_2 concentrations reduce more rapidly with emissions reductions at locations where the concentrations are high initially, because these are the locations closest to local emissions of NO_x (e.g. heavily trafficked roads), huge efforts are still required to reduce these 'hotspot' concentrations to $\leqslant$40 μg m^{-3}. These hotspots also tend to be the places where most people live. None of the scenarios reducing emission from road traffic sector alone (the B_x scenarios) can achieve any of the four interpretations of the 40 μg m^{-3} target (table 1). Thus only substantial overall emissions reductions across all sectors will be viable to make progress towards attaining the limit values. In fact, our simulations show that only a scenario in which NO_x emissions from all source sectors are reduced by 90% (the A_{90} scenario) results in annual average NO_2 concentrations $\leqslant$40 μg m^{-3} everywhere in Guangzhou. As noted already, the difference in response between all-sector emissions reductions and transport-only emissions reduction reflects the different absolute reductions in NO_x (and VOC) between these two sets of scenarios. Also, a proportion of the NO_2 concentrations in these simulations is due to import of NO_2 from outside the Guangzhou domain, which is not impacted by emissions reductions applied within the domain. Figures 2 and 3 indicate that even with almost total Guangzhou emissions reductions there is simulated to be ~12 μg m^{-3} NO_2 at locations in the domain most remote from NO_x sources. We also note again a limitation in our LUR modelling arising from lack of traffic intensity data on specific road links.

Specific interventions targeted at very high concentration areas (for example, a city centre) may be a more practical approach to avoid such locations dominating the overall attainment of limit values. Whilst applying a given percentage emission reduction within a city centre zone would not reduce the NO_2 concentration in the city centre more than applying that emission reduction domain wide, such targeted reductions may well be more economically and technically efficient in terms of absolute 'unit' of NO_2 metric gained per absolute reduction in NO_2 emissions. The actual mitigation scenario(s) followed in practice needs to strike a balance between the amount of emissions reductions needed in an area of given size, whilst also taking account of other essential factors such as cost, technical practicality and societal acceptance. Designing and modelling all such aspects of emissions reductions is challenging. Overall behavioural change (Vardoulakis *et al* 2018) and measures attenuating negative health impacts (Lucock et al 2017, Stevens et al 2019) should also be explored alongside traditional policy interventions aiming to reduce NO_2 concentration levels.

4.2. Utility of NO_2 concentration threshold as a policy target

Given the scale of the emissions reductions required that are illustrated by our model simulations, one could argue that a 40 μg m^{-3} objective for NO_2 concentration over a megacity is unattainable through actions in that city alone, as long as internal combustion engines and combustion in stationary sources are the predominant source of NO_x emissions in cities. For example, since the 1980s, the UK government has committed to reducing NO_2 concentration; but despite the continuous improvement, in many larger cities in the UK it is still a challenge to meet the current limit value for annual average NO_2 concentrations of 40 μg m^{-3} (Carnell et al 2019). The same is true for many cities across other European countries (Fuller 2018).

On the other hand it is important to remember that NO_2 concentration targets within cities are driven by the desire to improve adverse health outcomes associated with NO_2, and in this context using a specific concentration target to assess progress towards improvement in air quality can underplay the actual extent of gains made in improving population health outcome. For example, it is important to note that, even for our 'softer' interpretations of attainment of the Guangzhou target (TI1 and TI3), substantial reductions in the number of NO_2-attributable premature deaths compared to the base case are anticipated: 2703 [2589, 2824] for TI1 and 2075 [1986, 2165] for TI3. These represent reductions in attributable mortality of 37% and 29%, respectively, relative to the 7270 NO_2-attributable deaths associated with the base case (in comparison, the reductions in NO_2-attributable premature deaths for TI2 and TI4 are 3905 [3741, 4084] and 4676 [4479, 4893] respectively), but with substantially less stringent emissions reductions than needed to attain TI2 or TI4.

The use of a concentration threshold as a policy target to deliver health protection against NO_2 has further shortcoming in that the 40 μg m^{-3} concentration does not constitute a no-effect threshold for NO_2, and in fact current epidemiological evidence is that there is no zero-effect threshold for exposure to NO_2 (Beelen et al 2014, COMEAP 2018). In other words, there are health gains if concentrations go down in locations irrespective of whether the concentrations are above or below the target value. Therefore what is fundamentally relevant in relation to potential policy measures is not the change in proportion of locations with NO_2 concentrations $\leqslant$40 μg m^{-3}, nor the change in the numbers of people in locations with NO_2 concentrations $\leqslant$40 μg m^{-3}, but by how much the cumulative population exposure changes. Quantification of the latter shows that there are greater rates of population health gain as emissions are reduced than is implied by considering only the rates of change of number of people with NO_2 exposure brought below 40 μg m^{-3}. This point is clearly illustrated in figure 7 for our Guangzhou example emissions reduction scenarios. The gradient of the plot of the number of NO_2-attribuable deaths saved (compared to base case) for the set of A emissions reduction scenarios is steeper than the plot of the percentage of population at locations with $NO_2 \leqslant 40$ μg m^{-3}. The message is particularly obvious for the smallest emissions reduction scenario simulated (the A_{10} scenario), which makes almost no difference to the number of people in locations with concentrations $\leqslant$40 μg m^{-3} compared with the base case (and which might therefore be deemed to be having no effect), but yet delivers health gains of 338 attributable deaths avoided. The need to consider cumulative population health exposure rather than progress against a concentration target is again graphically apparent in figure 7 at the other end of the scale of emissions reductions: further emissions reductions beyond the A_{90} scenario will not lead to more people living at locations with NO_2 concentration $\leqslant$40 μg m^{-3}, since 100% of the population would then already do so, but further emissions reductions would continue to deliver additional NO_2-attributable deaths avoided.

The use of attainment of a specific concentration as a policy target actually has the potential to promote a detrimental effect on policy ambition levels (Fuller and Font 2019), since there might be a perception that once a 40 μg m^{-3} is reached that is 'job done'; or worse, to encourage the perception that it doesn't matter if previously low concentrations are allowed to increase as long as they still remain below 40 μg m^{-3}. This may lead to situations where compliance may be achieved, but more pronounced public health impacts could be attained at lower cost, or irrespective of individual locations being in exceedance. The data we present for our example modelling in Guangzhou illustrate the quantitative evidence on population health gain for different scenarios (as opposed to evidence just on NO_2 concentrations) that needs to be fed into policy decisions related to costs and benefits associated with attaining a concentration target in any large city.

The reduction scenarios investigated here only represent reductions in emissions within the Guangzhou city domain. Emissions reductions in the region surrounding Guangzhou will contribute to lowering background NO_2 concentrations coming into Guangzhou, which would likely enable the city to attain air quality limit values for NO_2 with less additional emissions reductions within Guangzhou itself than simulated here. In addition, emissions reductions within Guangzhou will have the additional benefit of lowering NO_2 concentrations, with consequent gains in health, in areas surrounding and downwind of Guangzhou, in addition to the health gains calculated here for Guangzhou alone. As studies in both Europe and China have pointed out, joint emissions

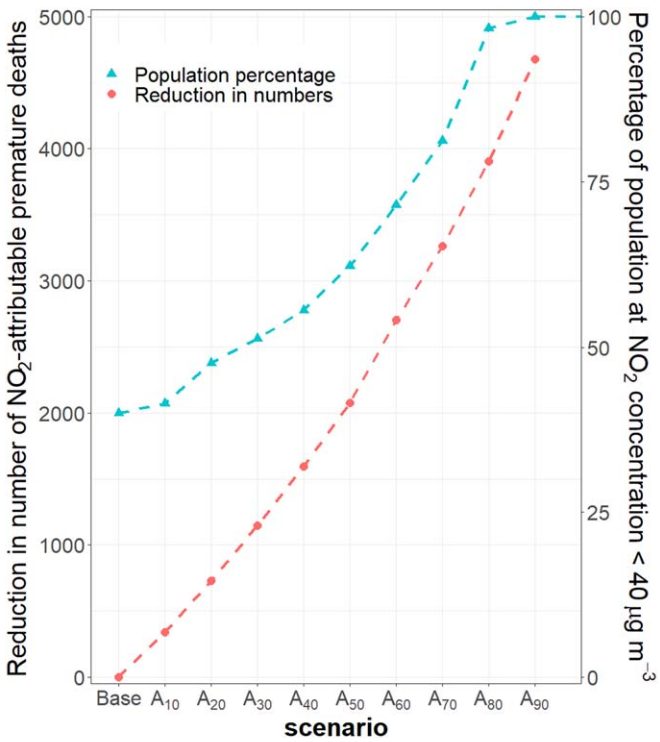

Figure 7. The percentage of population in locations where NO_2 is $\leqslant 40\ \mu g\ m^{-3}$ (blue triangles) and the reduction in the number of NO_2-attributable premature deaths compared with the base case (red dots) under the A_x set of scenarios.

controls within both the target area and surrounding areas are most effective for improving air quality holistically (Reis *et al* 2012, Xue *et al* 2014, Ou *et al* 2016, Yu *et al* 2019).

The benefits of emissions reductions in Guangzhou calculated as reductions in NO_2-attributable premature death presented in this paper also represent only part of the overall benefits. Emission reductions have important additional health and environmental benefits other than those directly experienced through NO_2 on health. For instance, NO_x emission reductions will also contribute to reducing the formation of secondary inorganic aerosols and hence $PM_{2.5}$ concentrations, and also reduce dry and wet deposition of reactive nitrogen on terrestrial ecosystems (Gao *et al* 2015, Guo *et al* 2018, Zhu *et al* 2018, Kanakidou 2019, Qiao *et al* 2019). Measures to reduce NO_x emissions will also often lead to reductions in co-emitted pollutants such as primary particulate matter and black carbon. Therefore, instead of focusing on attaining regulatory concentration targets only, a focus on rate of change and accounting for the integrated benefits from emission reduction might be more appropriate. This paper only focuses on NO_2, but benefits from emission reduction need to be assessed along with other pollutants including $PM_{2.5}$ and O_3.

5. Conclusions

To overcome limitations on availability of data for urban air quality modelling, we used a hybrid dispersion and land-use regression model to explore the impact of emission reductions within Guangzhou on annual-average NO_2 concentrations in relation to a policy target of $40\ \mu g\ m^{-3}$. We found that reductions from traffic emissions alone will not achieve the target everywhere but that substantial reductions in all-sector emissions will be required. On the other hand, we found that emissions reductions lead to faster gain in NO_2-attributable premature mortality avoided than in geographical area achieving the concentration target, and therefore recommend that a health-based metric of air quality be considered in parallel.

Whilst the results of the model simulations we present are for the specific situation in Guangzhou, the methodology we use and our discussion in relation to limitations of an NO_2 concentration target for assessing effectiveness of air pollutant emissions policies, are relevant to decision makers in other fast-growing megacities in China and elsewhere globally.

Acknowledgments

Baihuiqian He is grateful for studentship funding from the China Scholarship Council and the University of Edinburgh. The work of Stefan Reis was supported by the UK Natural Environment Research Council (NERC) National Capability award NE/R000131/1 (Sustainable Use of Natural Resources to Improve Human Health and Support Economic Development, SUNRISE) and award number NE/R016429/1 as part of the UK-SCAPE programme delivering National Capability. The assistance of Ed Carnell for making figures is acknowledged.

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