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REPORT

China's air pollution reduction efforts may result in an increase in surface ozone levels in highly polluted areas

Annela Anger, Olivier Dessens, Fengming Xi, Terry Barker, Rui Wu

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Abstract China, as a fast growing fossil-fuel-based economy, experiences increasing levels of air pollution. To tackle air pollution, China has taken the first steps by setting emission–reduction targets for nitrogen oxides (NO_x) and sulphur dioxide (SO_2) in the 11th and 12th Five Year Plans. This paper uses two models—the Energy–Environment–Economy Model at the Global level (E3MG) and the global Chemistry Transport Model pTOMCAT—to test the effects of these policies. If the policy targets are met, then the maximum values of 32 % and 45 % reductions below 'business as usual' in the monthly mean NO_x and SO_2 concentrations, respectively, will be achieved in 2015. However, a decrease in NO_x concentrations in some highly polluted areas of East, North-East and South-East China can lead to up to a 10% increase in the monthly mean concentrations in surface ozone in 2015. Our study demonstrates an urgent need for the more detailed analysis of the impacts and designs of air pollution reduction guidelines for China.

Keywords Surface ozone · China · Atmospheric pollution · Five Year Plan

INTRODUCTION

Over the last 20 years, China has experienced fast economic growth that has been accompanied by increasing concentrations of atmospheric pollutants such as SO_2, NO_x, particular matter (PM_x), CO, VOC and ozone (You and Xu 2010; Zhang et al. 2012). These changes in air pollution levels are not only impacting China but also affecting its neighbouring countries, such as Japan and the USA (Zhang et al. 2008).

The Chinese government sets targets for the performance of its economy in Five Year Plans (FYPs). The last two FYPs, the 11th (2006–2010) and the 12th (2011–2015) include energy- and pollution-related targets from the National Total Emissions Control (NTEC) Program. An 'energy-saving and emission reduction policy' was outlined in the 11th FYP, as an obligatory target for local governments, and a 20 % reduction in energy intensity and 14.29 % reduction in CO_2 emission intensity were achieved during the period from 2006 to 2010 (NPC and CPPCC 2005). China's latest Five Year Plan (12th FYP) foresees further reductions in energy intensity of GDP, sets targets for CO_2 intensity of GDP and for an increase in the deployment of renewable energy sources, while setting targets for continuing annual GDP growth of 7 % (NPC and CPPCC 2011).

The 11th FYP was the first FYP to include binding NTEC targets for reducing atmospheric pollution, and these were expanded in the 12th FYP. In the 11th FYP, the national SO_2 target was set to achieve 10 % emission reductions below the 2005 levels by 2010, and amended in the 12th FYP to be 8 % reductions below the 2010 levels by 2015. In addition to the SO_2 target, the 12th FYP has set a target to cut NO_x emissions by 10 % in 2015 compared to the 2010 level. The 12th FYP also obliges the Chinese economy to increase the share of non-fossil fuels in primary energy use (11.4 % in 2015), which can have co-benefits in terms of decreasing levels of air pollution in China (Xue et al. 2013). However, the nature and extent of these reductions will depend on the type of fuel used. For example, switching to burning biomass and biofuels can still lead to air pollution and therefore to negative health impacts (Tsao et al. 2012; Ashworth et al. 2013). On the other hand, the air pollution from wind turbines is only associated with the production of the turbines, and running them does not cause any additional annual emissions. The main countrywide targets of the two latest FYPs that are

Table 1 Main targets in the Chinese 11th and 12th FYP. *Source*: NPC and CPPCC (2005, 2011)

Five Year Plan (FYP)	11th	12th
Years	2006–2010	2011–2015
Base year	2005	2010
GDP growth p.a. (%)	7.5	7
Population, last FYP year (billions)	1.36	1.39
Non-fossil fuels in primary energy consumption, last FYP year (%)	n/a	11.4
Energy consumption reduction per unit of GDP below the base year (%)	20	16
CO_2 reduction per unit of GDP compared to the base year (%)	n/a	17
SO_2 emissions reduction compared to the base year, last FYP year (%)	10	8
NO_x emissions reduction compared to the base year, last FYP year (%)	n/a	10

used as inputs for the modelling exercises in this study are summarised in Table 1.

This paper examines the effects of SO_2 and NO_x control and energy policies in China on air pollution levels (SO_2, NO_x and surface ozone concentrations) throughout China. The Energy–Environment–Economy Model at the Global level (E3MG) is used to project the annual atmospheric emissions over the period from 2006 to 2015 using two scenarios: for the reference scenario (REF) in which there are no prescribed FYPs air-quality targets and no renewable energy targets (all other drivers, such as energy consumption or GDP growth, follow the FYP targets), and for the FYP scenario (FYP), all FYPs' targets listed in Table 1 are specified. The E3MG model (Barker et al. 2012) is fundamental in generating the REF scenario that forecasts annual air pollution levels at given growth targets for GDP, but without air pollution reductions in and without energy- and CO_2-intensity targets. Thereafter, the global Chemistry-Transport Model (CTM) pTOMCAT (O'Connor et al. 2005) is used to assess the effects of the FYP scenario (FYP), with reduced NO_x, SO_2 emissions in comparison to the REF scenario. This is done with the use of a one-way coupling of E3MG and pTOMCAT (the methodology is described in detail in Barker et al. 2010) where the regional distributions of NO_x, SO_2 emissions from E3MG 20 world regions are geographically distributed to produce emission fields for 2015. The results, given for emissions—representative for the year 2015, are the effects on ozone, NO_x and SO_2 concentrations at land and sea surface levels. Our analysis finds that, despite substantial reductions in NO_x and SO_2 concentrations, Chinese air pollution reduction policy may result in an increase (up to 10 %) of surface ozone in some highly polluted areas of East, North-East and South-East China. Surface ozone is a pollutant damaging for respiratory systems (WHO 2006) and reducing crop yields (Mauzerall and Wang 2001; Avnery et al. 2011). SO_2 and NO_x are damaging for respiratory systems as pollutants or as substances reacting with other compounds in the atmosphere forming PM_x (WHO 2006).

This paper is organised as follows: "Materials and methods" section gives an overview of the methodology and models employed for the analysis. Thereafter, the modelling results along with the relevant theory are presented in "Results" section. "Discussion and conclusions" section presents a discussion of the results and draws conclusions.

MATERIALS AND METHODS

To analyse impacts of the targets set in the Chinese FYPs (Table 1), a two-step analysis was deemed to be necessary. Firstly, the annual anthropogenic emissions of pollutants of interest needed to be calculated by using E3MG up to 2015, which is the last year of the 12th FYP for scenarios with and without reduction targets. Secondly, these emission flows need to be included in pTOMCAT to find the resulting changes in pollution concentrations. The following gives an overview of the two models and methodology employed for the analysis.

Energy–Environment–Economy Model at the Global level (E3MG)

The hybrid model, E3MG, is a 20-region, structural, annual, dynamic, and macroeconometric simulation model based on data covering the period of 1970–2006, and projected forward annually to 2050.[1] Each sector in each region is assumed to follow a different pattern of behaviour within an overall theoretical structure, implying that the commonly adopted representative agent assumption is invalid in this instance. The economic activity in the model leads to sector- and country-specific energy uses, which in turn are converted to atmospheric emissions by taking into account the fuel type and abatement technology. The

[1] For the description and manual of the latest version of the model (E3ME), please see www.e3me.com.

E3MG model covers emissions of 14 atmospheric pollutants (including six GHGs and seven non-GHGs) from 50 emission sources.

The model and the database are described in studies of global decarbonisation, e.g. Barker et al. (2012). E3MG has been previously used for assessing the co-benefits of low-carbon policies for Mexico (Barker et al. 2010).

Chemistry Transport Model pTOMCAT

The three-dimensional (3D) CTM pTOMCAT has been developed at the University of Cambridge (O'Connor et al. 2005). The model reproduces realistically the transport and chemistry of atmospheric tracers on a global scale. The wind and temperature needed to calculate these processes are extracted from the ECMWF operational analyses (pTOMCAT is an offline model). The model includes 48 species in the chemistry scheme, and 35 tracers advected only as some chemical species are regrouped in "family" groups (Chipperfield 2006). The advection of the 35 tracers is calculated using the highly conservative second-order moment as described in Prather (1986). The convection parameterisation follows the Tiedtke (1989) scheme. The chemistry consists of 112 gas-phase reactions; 27 photolysis rates; and 1 heterogeneous reaction, and represents the chemical processes relevant to the troposphere and the lower stratosphere. The pTOMCAT model has been used in international projects and has been subjected to validation and intercomparison with other atmospheric models (Brunner et al. 2003, 2005; Hoor et al. 2009; Russo et al. 2011).

The version of the model used in this study is the same version used in the QUANTIFY project as described in Hoor et al. (2009). All the simulations are calculated offline using the analysis (wind, temperature) from ECMWF for the year 2003 and the horizontal resolution of the model is 2.5° × 2.5°. NO_x and SO_2 emissions modify the chemistry of the troposphere (Hoor et al. 2009) mainly by changing its oxidising capacity (ozone and OH concentrations) or producing aerosols (sulphuric acid aerosol). The VOCs partitioning was performed according to von Kuhlmann et al. (2003), and a description of the method applied to pTOMCAT is given in Hoor et al. (2009). Due to the relatively short lifespan of these different constituents in the troposphere (from days up to a month), the new equilibrium in concentration due to the changes in emissions throughout China can be extracted from a 1-year simulation of pTOMCAT (preceded by 6-month spin-up).

Figure 1 presents a comparison of the monthly mean ozone concentrations simulated with the pTOMCAT model and the measured concentration data reported in Avnery et al. (2011) for validation. The observations are extracted from 12 measurement stations over China for the year 2000. The model has been integrated using its standard emission fields for the year 2000 in a specific simulation. The model data have been extracted from the grid-boxes that contain the geographical localisation (latitude and longitude) of the 12 stations used. Ozone values are within the variations of the reported measurements (except for March) and follow the seasonal cycle relatively closely with the exception to the spring maximum that seems slightly underestimated. This spring maximum can be

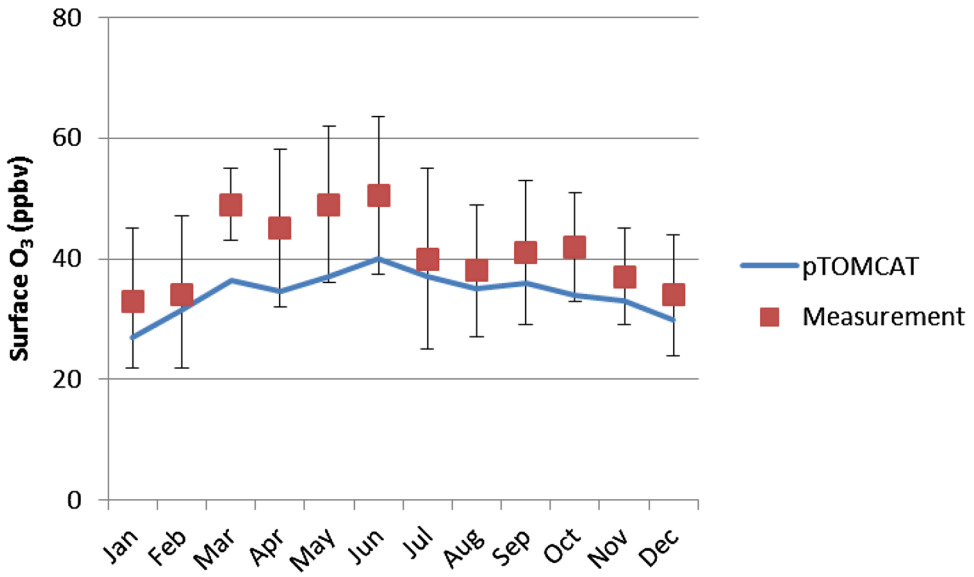

Fig. 1 Comparison of monthly mean surface ozone concentrations in the pTOMCAT model (*blue line*) and average monthly means (*red squares*) measured from 12 stations over China in 2000 (the *black bars* are the variability within the 12 stations monthly means). *Source* pTOMCAT modelling and Avnery et al. (2011)

explained as a combination of enhanced stratosphere–troposphere exchange, strong long-range transport of ozone from non-domestic precursors' emissions and a longer lifetime of surface ozone during this season (Wang et al. 2010). The lack of stratospheric representation in pTOMCAT explains this lower spring maximum in the model.

Globally over China, summer (July–September) ozone concentrations seem to be well represented; however, one seasonal pattern for surface ozone cannot fit all parts of China. In the North-East ozone, concentrations in July are lower in comparison to other publications; summer values reach 60–70 ppm over this area (Yamaji et al. 2008) with a peak production of ozone from local pollution representing 50 % of the surface concentration in August. Over Northern China, a weak or strong configuration of the East Asian summer monsoon can produce large differences in surface ozone (Yang et al. 2014). This specific synoptic situation can explain the weak values obtained with pTOMCAT.

One of the limitations of this study is the use of a large gridded area covering the global atmospheric chemistry model, at an average gridbox of 200 km × 200 km. Whilst this is a sufficient resolution for a country of the size of China, the strengths of emissions' hotspots over heavy industrialised regions of the north and eastern areas of China will be diluted in this large gridbox, modifying the effects of the surface concentrations. To assess the impacts on the human health, the changes derived from the CTM simulations would have to be converted into exposure metrics at an appropriately fine scale (Katragkou et al. 2010); this is out of the scope of this paper and forms the topic for the future work. Moreover, it has been reported by Pike et al. (2010) that differences between the simulated ozone concentrations in the pTOMCAT and local measurements are related to both the details of the emissions and the treatment of the physical processes. The emissions appear to control the overall ozone concentration when the parametrisation of the physical processes seemingly dominate the temporal variability. Finally, all the simulations for this study are calculated offline using the same analysis from ECMWF for the year 2003; the impact of climate variability on atmospheric concentrations is not included in the simulations. However, the focus of this paper is on the impact of anthropogenic emission on ozone changes, and it has been found by Zeng et al. (2008) that large anthropogenic emissions changes, not climate variability, cause the largest response in surface ozone concentrations.

One-way coupling of E3MG and pTOMCAT and the scenarios

E3MG and pTOMCAT were soft coupled in this study by using emission output data from E3MG as input data for pTOMCAT. E3MG is used to project economic activity and related energy use that is converted to annual amounts of atmospheric emissions for two policy scenarios:

1. *REF* is the reference scenario that is needed to initiate this study and obtain 'business as usual' (BAU) emissions. Air pollution emissions continue to rise with economic growth until China meets or exceeds its GDP growth target of 7.5 and 7 % in the 11th and 12th Five Year Period (FYP). We assume that there are no voluntary measures taken and there are no switches between fuel types in the REF scenario. In other words, everything continues in line with the observed trends before the 11th and 12th FYP. For example, the heavily coal-dominated electricity generation continues as standard. To allow for consistency with the official FYP documents, for 2005, China's NO_x and SO_2 emissions in E3MG are set equal to the atmospheric emission data published in the Statistical Yearbooks of China (MEP 2011). These emissions are lower (20 and 17 %, respectively) than the data for the year 2005 obtained from the Edgar Database (2012) that is otherwise used as the default historical emissions data within E3MG. Therefore, there are uncertainties related to the reported pollutant-emission levels. If the emission levels from the Edgar Database (2012), are used instead of calibrating the data to lower emissions from the Chinese Statistical Yearbooks (MEP 2011), then this is likely to result in higher SO_2 and NO_x concentrations and different levels of surface ozone. For the other 19 regions in E3MG, historic atmospheric emissions are based on the Edgar Database (2012) and future emissions are calculated based on projected fuel use and industrial activities. It is assumed that these regions will not adopt any new air pollution reduction measures. However, the current air pollution reduction measures will stay in place.
2. *FYP* is the same as the REF scenario but includes the air pollution reduction and the renewables' targets set by the 11th and 12th FYPs for China. It is assumed that the NO_x and SO_2 (mainly from the power sector and industrial combustion) targets are met linearly by using substance specific flue gas scrubbers over the 5 year time period and the targets are reached by the end of each policy period. For the renewable energy target, the share of non-fossil fuel energy in the REF scenario is 6.5 % in 2015, and this is increased to 11.4 % in the FYP scenario by assuming a switch to wind energy that does not emit any atmospheric pollutants. Coal use for electricity production was correspondingly reduced by the same amount. As there are no targets for VOC and CO emissions (mainly related to industrial processes and transport) in FYPs, it is assumed that no specific emissions control measures are

implemented for these pollutants. Comparing the annual NO_x, modelled and reported in Gu et al. (2014), of 22 thousand tonnes of NO_2 for 2011 with the FYP data (about 18 thousand tonnes of NO_2 for 2011) emphasises the further uncertainty related to estimating and calculating NO_x emissions.

The NO_x and SO_2 emissions from E3MG China region were geographically distributed to produce emission fields for REF and FYP scenarios for the year 2015 in pTOMCAT. The model is run twice for the year 2015 to represent REF and FYP scenarios. The spatial distribution of the emissions from E3MG is identical in the two pTOMCAT simulations; only the global amount emitted in each simulation over China is modified to accommodate the E3MG-scenario results. The modelling results obtained from pTOMCAT were NO_x, SO_2 and ozone concentrations over China and its surrounding areas for the year 2015 only.

RESULTS

Table 2 gives an overview of the main E3MG results for the 11th and 12th FYPs.

E3MG forecasts higher average annual GDP growth than that as was foreseen in the FYP targets. The real GDP data published by the World Bank (2013) for the period of the 11th FYP gives an average annual GDP growth of 11.2 % for China which is very similar to the one projected in E3MG for this study (Table 2). For the 12th FYP, the average annual GDP growth in E3MG is 0.7 % higher than the target. In other words, Chinese GDP growth in E3MG can be considered realistic.

Annual emissions from the REF and FYP scenarios are presented in Fig. 2 for the source gases NO_x, and SO_2 as calculated by the E3MG simulations. In the REF scenario, E3MG presents a decrease in NO_x and SO_2 in 2009, which is attributable to the 2008 economic recession resulting in reduced demand for goods and services, and subsequent air pollution reductions. In 2015 (after the two FYPs), the annual reductions for NO_x emissions, calculated and compared to the REF for the FYP simulation are 32 %. For SO_2, the reduction is greater at 49 %. This is because SO_2 targets are included in both the 11th and 12th FYPs, whilst for NO_x, the reduction started with the 12th FYP. These reductions in annual emissions are substantial especially given the 10-year time period, but are expected to deliver positive health impacts.

The REF and FYP emissions calculated in E3MG are geographically and temporally (monthly) distributed throughout China for the year 2015 to produce the database for the CTM simulations. Figure 3 represents NO_x and SO_2 emissions gridded geographically for the atmospheric model over South-East Asia for the REF scenario.

NO_x concentrations are generally high over the industrial areas of China (11–15 ppbv monthly mean in the REF simulation).

By comparing the REF scenario emissions with the FYP scenario results from the CTM simulations, there are reductions in NO_x and SO_2 concentrations at the surface level, maximal values being 32 and 45 %, respectively, throughout industrialised China (Fig. 4).

NO_x has a seasonal variation (the highest in winter and lowest in summer); this is because the chemical lifespan of NO_x in the planetary boundary layer is relatively short (hours to a day) (Tie et al. 2002), and the concentrations of NO_x are largely controlled by local emissions. In East, North-East and South-East China, where anthropogenic emissions dominate, the change in NO_x concentration in FYP compared to REF is typically higher in the winter. The change in the amount of sunlight is the principal driver of this variability in lifespan. Sunlight triggers OH production, causing NO_2 to be removed from the atmosphere. Since sunlight is reduced in winter, there will be less NO_2

Table 2 E3MG modelling results for 11th and 12th FYPs

Indicator	11th FYP	12th FYP
Base year	2005	2010
GDP average change p.a. (%)	11.1	7.7
NO_x emissions increase in REF (%, comparing the base and last FYP year)	24	24.1
NO_x emissions reductions below REF, last FYP year (%)	n/a	31.7
NO_x emissions reductions below base year, last FYP year (%)	n/a	10.0
SO_2 emissions increase in REF (%, comparing the base and last FYP year)	14.2	24.1
SO_2 emissions reductions below REF, last FYP year (%)	26.4	48.7
SO_2 emissions reductions below the base year, last FYP year (%)	14.2	8.0
Non-fossil fuels in primary energy consumption, last FYP year (%)	n/a	11.4
Reduction in VOC emissions below REF, last FYP year (%)	n/a	0.6
Reduction in CO emissions below REF, last FYP year (%)	n/a	2.2

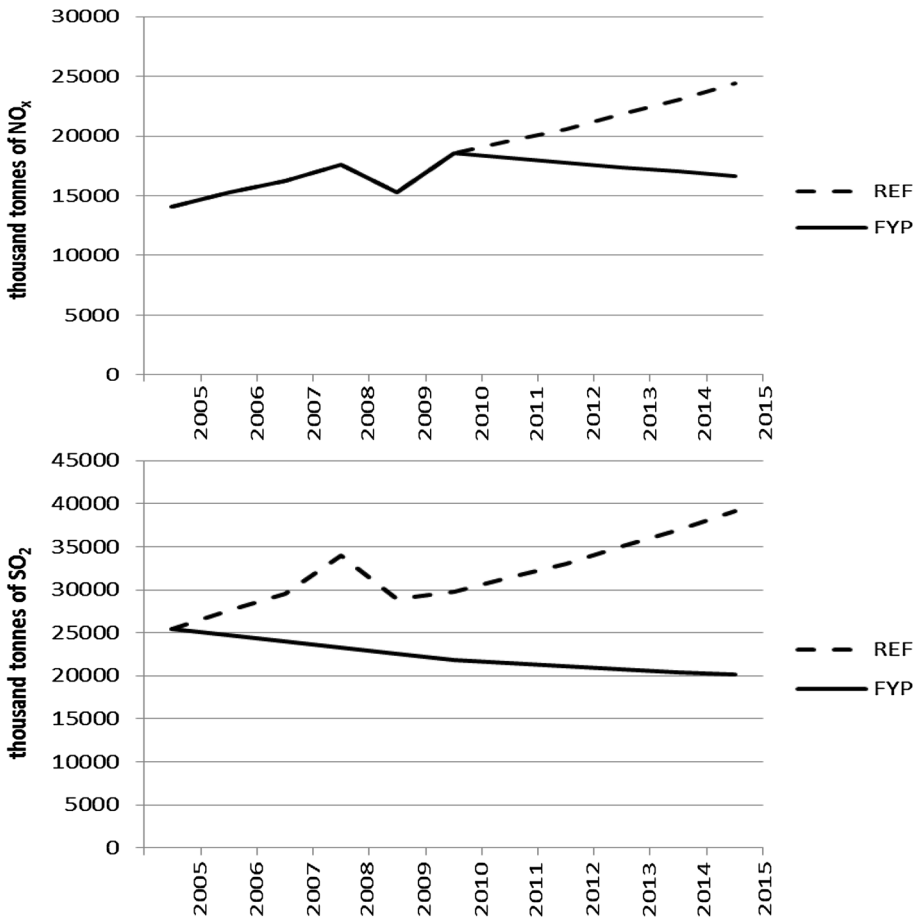

Fig. 2 E3MG results for NO_x (in thousands tonnes of NO_2—*top*) and SO_2 (*bottom*) annual emissions between 2005 and 2015 in the two scenarios: REF and FYP. *Source* E3MG modelling results

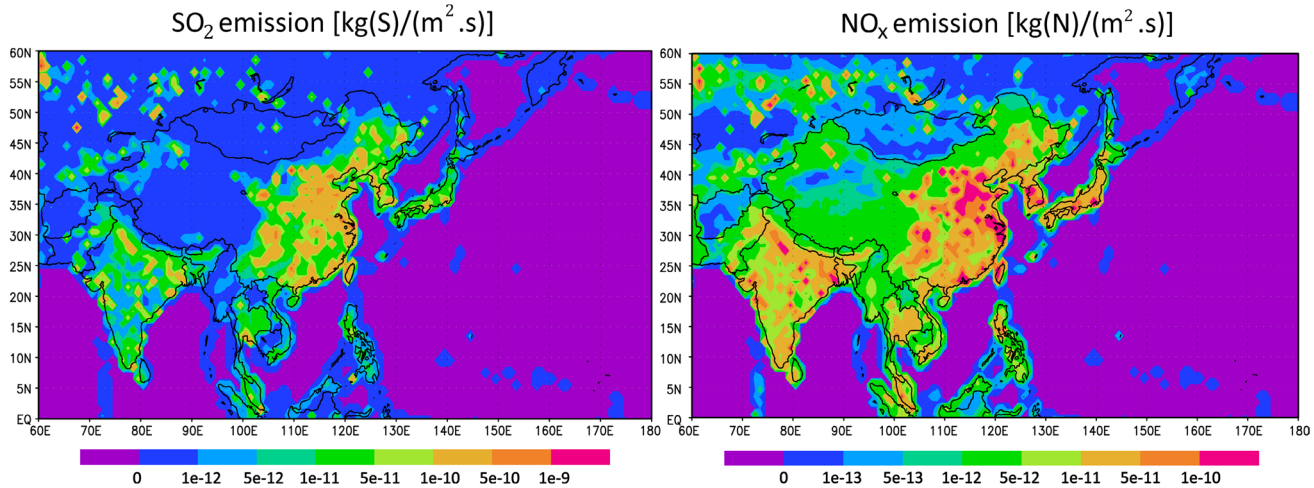

Fig. 3 Fluxes of anthropogenic emissions of SO_2 and NO_x over South-East Asia for the REF scenario in 2015. *Source* E3MG modelling results distributed to the grid in pTOMCAT

removal during that season, causing NO_2 concentrations to increase (as seen in the lower panels of Fig. 4). Lower NO_2 concentrations during July might also be exacerbated by the fact that during summer months, the rainy season prevails in south-east China. Finally, the external temperature plays a role—indoor space heating during winter

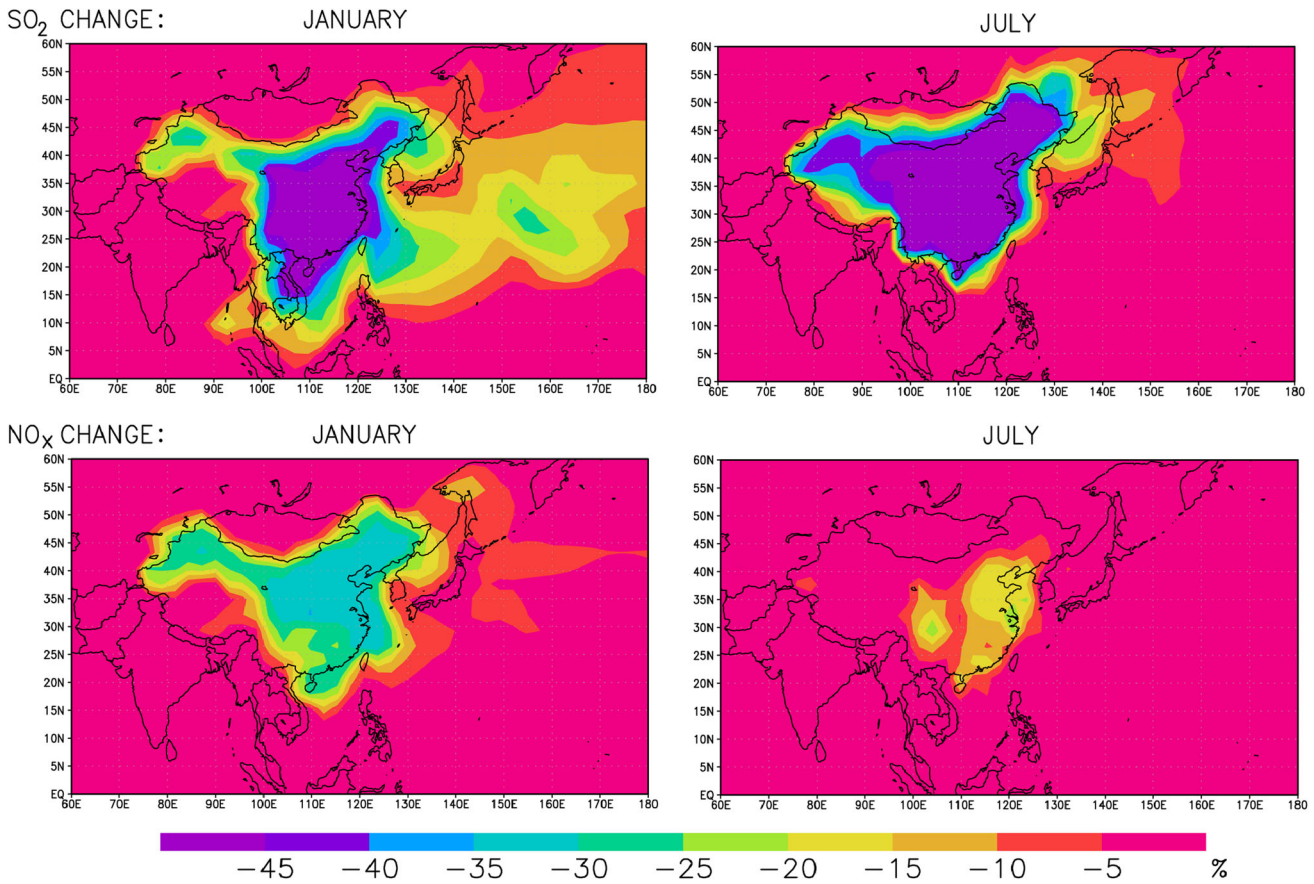

Fig. 4 January and July SO_2 and NO_x concentration changes at the surface due to FYP emissions implementation in pTOMCAT compared to the REF concentrations scenario. *Source* pTOMCAT modelling

increases NO_x anthropogenic emissions. In western China, however, natural NO_x emissions dominate other forms of emissions such as lightning and soil NO_x production; therefore, the FYP policy has less of an impact on the surface background concentration in this context.

The tropospheric sulphur chemistry cycle contains relatively few compounds and is decoupled from the cycling of other elements (as opposed to NO_x or hydrocarbon cycles). Emitted atmospheric SO_2 has a lifetime of 10 days in the troposphere. The oxidation of SO_2 occurs in both the gaseous phase with OH and, as it is soluble in water, occurs also in the liquid phase mechanism (atmospheric water). The result of these mechanisms is that predominantly sulphuric acid (H_2SO_4) is produced, which has a low saturated vapour pressure and consequently easily condenses into new particles or deposit on existing aerosols (depending on the background atmospheric conditions). The sulphate aerosols produced in the troposphere are believed to survive for about 5 days. The combined lifetime of SO_2 and the sulphate aerosols make their transport over long distances more efficient than, for example, the ozone produced by the other co-emitted anthropogenic species (NO_x) in the simulation, this explains the relatively larger coverage of changes observed with respect to these, in the case of the FYP policies. SO_2 and sulphate are carried towards Japan and the Pacific Ocean, and the annual mean concentrations there are reduced by up to 15 % compared with REF. In countries close to the Chinese southern border (Thailand, Cambodia, Laos and Vietnam), the monthly mean SO_2 concentrations are expected to be reduced locally by up to 45 % in 2015 due to the Chinese 11th and 12th FYP.

There are no specific targets to reduce CO and VOC emissions in the 11th and 12th FYP (NPC and CPPCC 2005, 2011), and these emissions increase by 22 and 70 %, respectively, from 2005 to 2015 in the REF scenario. Due to assumed increases in wind energy in primary energy consumption to meet the 12th FYP renewable energy target of 11.4 % by 2015, the annual emissions of CO and VOC for the entire country will be reduced by very meagre quantities, namely, 2.2 and 0.6 % below the REF scenario levels, respectively, in 2015. These small reductions have not been included in the design of the simulations of the FYP scenario, and produce only minimal changes to the ozone chemistry (Geng et al. 2008).

While the substantial reductions in annual means of SO_2 and NO_x concentrations no doubt have positive health

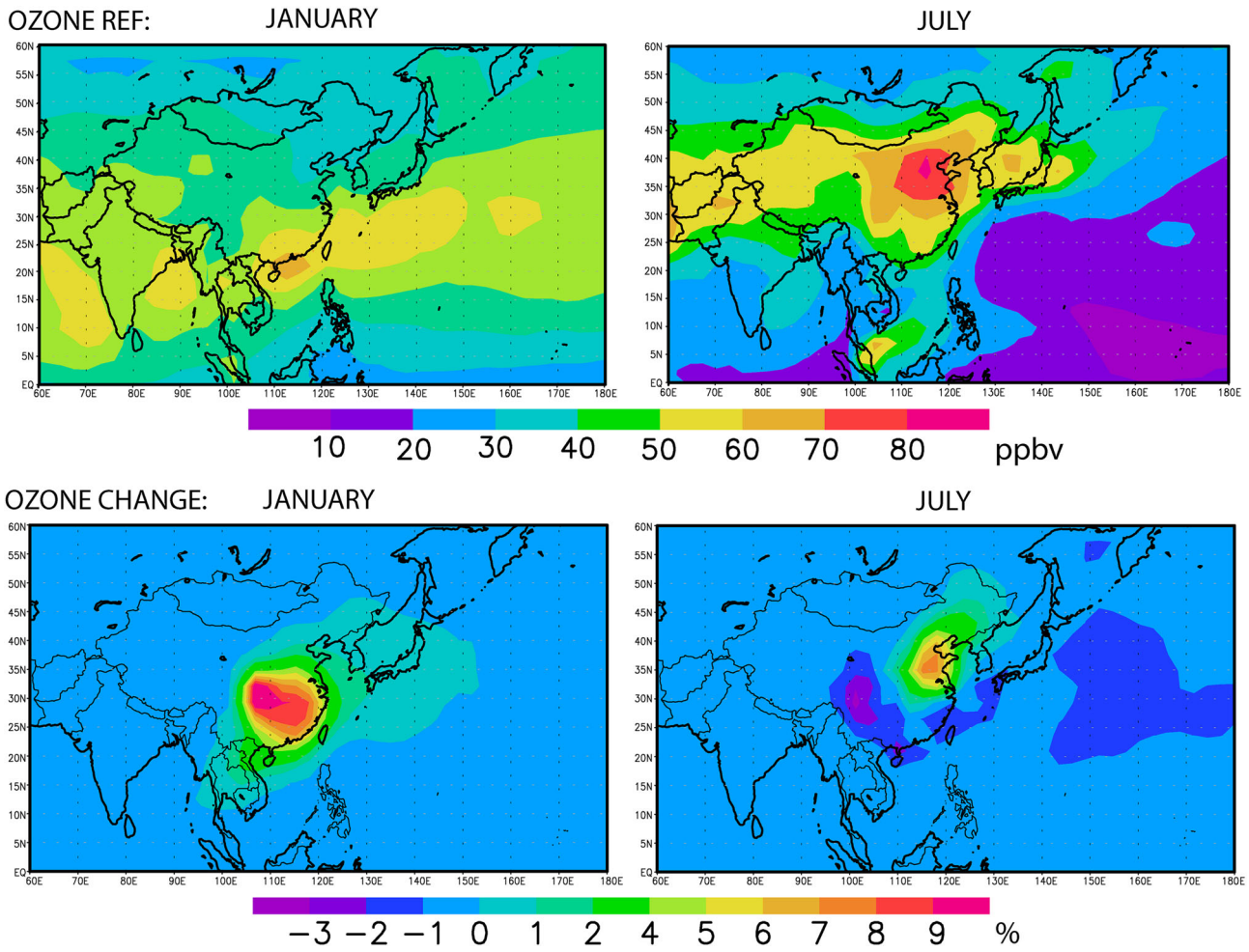

Fig. 5 pTOMCAT ozone concentration at the surface in January and July for the REF scenario (*upper panels*) and changes in comparison to REF due to FYP emissions implementation (*lower panels*). *Source* pTOMCAT modelling

impacts for residents in China and its neighbouring countries—for example, a reduction in aerosol formation, the outcome for changes in surface ozone levels is not so encouraging over some areas of China. Ozone in the lower troposphere is produced from NO_x and VOC in the presence of sunlight. Two key different states can define the atmospheric ozone chemistry in the lower troposphere: these are usually referred to as the low- and high-NO_x regimes. In the low-NO_x regime, the production of ozone is mainly governed by the amount of NO_x available, while in the high-NO_x regime, the amount of ozone which is produced is controlled by the VOC levels (Chameides et al. 1992). Reducing the emissions of the limiting precursor in one of the two regimes described (NO_x or VOC controlled) will reduce ozone production, whereas a reduction of the other precursor emissions will have little effect. Polluted regions, such as East, South-East and North-East China, are generally in the high-NO_x regime (VOC controlled). In addition to the preceding mechanism, NO_x emissions can have a supplementary effect on ozone concentration in areas which are already high in NO_x concentration. Additional NO_x emissions will increase the ozone reduction due to the fast reaction between ozone and NO (titration from NO). This is due to a limited production of hydroxyl radicals (OH) and occurs particularly in winter conditions at mid to high latitudes. This effect may prevail over a large geographical area, if the NO_x emissions from the area continue to be maintained at a high level. Therefore in regions of very high NO_x and low OH, reducing NO_x emissions actually increases the ozone concentrations as the titration of ozone by NO becomes less effective.

The peak ozone concentration season for surface ozone in the reference simulation differs by latitude and region, changing from autumn in the south to spring in central China and finally the beginning of summer in the north (Fig. 5 upper panels). In the FYP scenario that takes into account the 11th and 12th FYPs' reductions in NO_x, there are seasonal and spatial variations in surface ozone

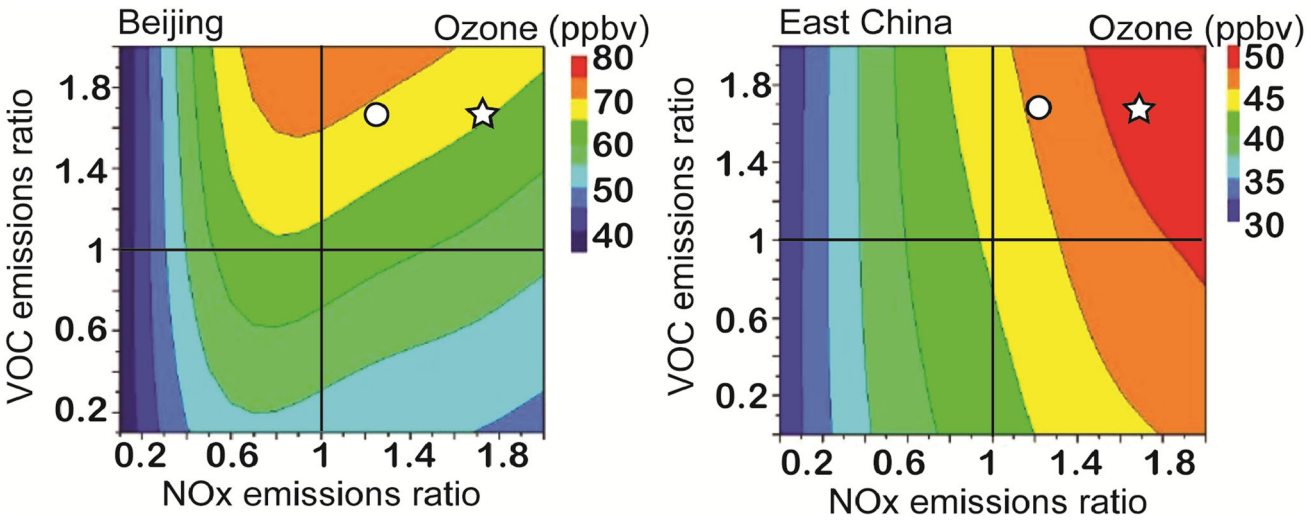

Fig. 6 REF and FYP NO_x and VOC emissions on 2-D ozone isopleths (ppbv) representative of July 2005 over Beijing and East China. *Source* E3MG results on Xing et al. (2011). *Star* and *circle* indicate the NO_x and VOC emissions ratios (compared to 2005) for 2015 REF and FYP, respectively. VOC emission ratios in REF and FYP remain almost the same

concentrations in China (Fig. 5 lower panels). During winter, the surface ozone concentrations increase in some industrialised and densely populated areas in East and South-East China with a regional maximum of 10 % or 5 ppbv compared to the reference concentration. In winter, this increase can result in a slight (up to 1 %) increase in the surface ozone levels in neighbouring countries such as Japan and during summer there could be some reduction (up to 2 %) over southern Japan.

During the summer of 2015 there is expected to be an increase of surface ozone up to 8 % (or 7 ppbv) in East and North-East China, while there is a small decrease up to 3 % (or 2 ppbv) over Central and South China. The reduction only represents 3 % of the background concentration as the background reference ozone concentrations are higher over Central and South China in summer.

Studies by Wang et al. (2005) and Xing et al. (2011) have shown that, though most areas in East China are in the NO_x-limited regime in summer when biogenic VOC emissions are high, some urban areas can still be in the NO_x-saturated regime in July. In the large coastal cities, in comparison to the rest of China, the ozone chemistry is responding under the high-NO_x regime. Figure 6 shows the 2-D isopleths of the ozone response to changes in NO_x and VOCs emissions in two different regions of China: Beijing and East China.

The emission ratio 1 corresponds to 2005 emissions. For illustration, the 2015 REF and FYP scenarios' ratios have been plotted over the figure as a star and a circle, respectively. Only NO_x ratios are varying as in our experiments the VOCs emissions are taken as a constant between REF and FYP. Reducing NO_x anthropogenic emissions by 32 % in FYP compared to BAU growth in REF has different effects on the ozone concentration depending upon the local situation. In July over Beijing (first panel Fig. 6), the reduction in emissions drives the ozone concentration towards higher levels as the region is under high-NO_x regime. The opposite effect is shown over East China (second panel Fig. 6), a region under low-NO_x regime, where the emission reductions under FYP decrease the ozone levels. Figure 6 also allows for intuitive assessment of the impacts related to uncertainties in 2015 NO_x emissions in the REF scenario. For example, if Edgar Database (2012) data were used, then it would have resulted in lower NO_x ratios for both REF and FYP scenarios for the same VOC emissions ratio.

DISCUSSION AND CONCLUSIONS

In 2015, the annual mean SO_2 concentrations in China and in countries close to its borders are expected to be reduced up to 45 % if the emission reduction targets outlined in the 11th and 12th FYPs are met. The reductions in SO_2 emissions are likely to result in reduced cases of respiratory and cardiac diseases and in less-frequent acid-rain events that damage vegetation and buildings (WHO 2006). Only the sulphate aerosol is taken into consideration in the model. This is a limitation of the study in terms of air-quality improvement as particulate matter concentration is a widespread concern over China. Analysis shows that sulphate in $PM_{2.5}$ aerosol composition is the highest abundant ion in mass; however, it represents only 20 % of the $PM_{2.5}$ composition over the central plain of China

(Zhang et al. 2011). Other inorganic ions, organic carbon and elemental carbon aerosols contribute toward a large portion in the composition of the East and South East Asian smog particulates, and their changes are not accounted for in this study.

Reductions in NO_x emissions are also likely to have a positive outcome of reduced cases of respiratory diseases, and may also bring about increases in crop yields due to reduced concentrations of toxic NO_2 and potentially decreased formation of ozone and particular matter (ibid.). However, as explained above, these reductions depend on the local NO_x regime. It has been claimed that, due to the high surface ozone levels experienced in China, the reductions in NO_x emissions alone are effective to solve China's problems in circumstances where low-NO_x regime persists (Wang and Hao 2012). Fiore et al. (2009) used average NO_x-emission quantities from 1996 to 2002 and find that a reduction of 20 % in NO_x emissions over South-East Asia produced a reduction in global surface ozone level by 2 ppbv in summer. However, increases in China's NO_x emissions during the years 2000–2010 were just below 10 % annually. Our study concentrates on the year 2015 when global NO_x emissions over China reach twice the annual amount of 2000 with even larger concentration increases observed over the densely populated and industrial East, North-East and South-East regions of the country. As a result, some areas in these regions of China are not within a low-NO_x regime but are more likely to be in a high-NO_x regime due to the 2015 NO_x emission quantities in the REF scenario. Therefore, reductions in NO_x emissions bring about a contrary outcome with a slight increase (up to 10 %) in annual surface ozone levels in 2015. In our study, we have used only a low spatial resolution combined with monthly and annual means; given this, in 2015, the surface ozone level increases in pollution hotspots, particularly over short periods of time, are going to be significantly higher than the levels presented here. Some of our findings are also supported by Wang et al. (2010) who present the surface ozone's impacts for a hypothetic NO_x reduction during the 11th FYP using a higher spatial resolution (36 km × 36 km cells). They found increases in ozone of 24–79 ppbv in maximum 1-h concentrations in the cities of Beijing, Tianjin and Shanghai for July 2010. Wang et al. (2010), however, do not consider monthly, seasonal or annual mean concentrations that would allow a fuller assessment of the overall impact of the policy and comparison of the results. In this modelling study, the direct positive impacts of the 11th and 12th FYP policies, if met, on the NO_x and SO_2 concentrations and on human health, are certain despite the uncertainties related to annual emission levels that differ between inventories and studies. However, the effects on ozone are more subtle and subject to some uncertainties. Despite this, supplementary measures should be taken to avoid possible damage from increasing ozone pollution. To become effective in terms of surface ozone reductions on a national level, China's air pollution control policies need to continue to bring about even tougher reductions in ozone-precursor emissions, and the policies need to be extended to include all precursors in the same framework, specifically the VOCs and CO (Xing et al. 2011; Tang et al. 2012). There is a need for more detailed studies on air pollution policy designs and related health impacts in this region. Other countries' and regions' experiences, for example, the European Union's example in its action in regulating surface ozone levels (Amann and Lutz 2000), could provide valuable insights for designing China's air pollution reduction policies.

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AUTHOR BIOGRAPHIES

Annela Anger (✉) is a Lecturer at the School of Environmental Sciences and the Tyndall Centre for Climate Change Research, University of East Anglia, UK. Her research interests include large-scale energy–environment–economy modelling of environmental policy impacts, co-benefits of climate change policies and applied macroeconomics. She is a College Research Associate in Economics at Emmanuel College, Cambridge and College Teaching Associate in Economics at Downing College, Cambridge.
Address: School of Environmental Sciences and the Tyndall Centre for Climate Change Research, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK.
Address: Emmanuel College, St Andrews Street, Cambridge CB2 3AP, UK.
Address: Downing College, Regent Street, Cambridge CB2 1DQ, UK.
e-mail: a.anger-kraavi@uea.ac.uk

Olivier Dessens is a Senior Research Associate at the Bartlett School of Environment, Energy & Resources, University College London. His research interests include atmospheric and climate modelling with strong skills in anthropogenic/biogenic emissions and their effects on the atmosphere.
Address: Energy Institute, University College London, 14 Upper Woburn Place, London WC1H 0NN, UK.
e-mail: o.dessens@ucl.ac.uk

Fengming Xi is an Associate Professor at the Institute of Applied Ecology, Chinese Academy of Sciences. His research interests include industrial ecology, carbon cycle and environmental policies for China.
Address: Institute of Applied Ecology, Chinese Academy of Sciences, P.O. Box 417, No. 72 Wenhua Road, Shenyang 110016, China.
e-mail: xifengming@iae.ac.cn

Terry Barker is a Honorary Professor at the School of Environmental Sciences and the Tyndall Centre for Climate Change Research, University of East Anglia and Senior Department Fellow at the Department of Land Economy, University of Cambridge. His research interests include developing large-scale models designed to address the issue of global decarbonisation and atmospheric pollution at the UK, European and global scales.
Address: School of Environmental Sciences and the Tyndall Centre for Climate Change Research, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ, UK.
Address: Department of Land Economy, University of Cambridge, 19 Silver Street, Cambridge CB3 9EP, UK.
e-mail: tsb1@cam.ac.uk

Rui Wu is a Master Student at the Institute of Applied Ecology, Chinese Academy of Sciences. His research interests include climate change and atmospheric pollution policies and carbon cycle.
Address: Institute of Applied Ecology, Chinese Academy of Sciences, P.O. Box 417, No. 72 Wenhua Road, Shenyang 110016, China.
e-mail: njwurui@126.com