Atmos. Chem. Phys. Discuss., 15, 14111–14139, 2015
www.atmos-chem-phys-discuss.net/15/14111/2015/
doi:10.5194/acpd-15-14111-2015

Atmospheric Chemistry and Physics Discussions
Open Access

Impacts of historical climate and land cover changes on tropospheric ozone air quality and public health in East Asia over 1980–2010

Y. Fu[1,*] and A. P. K. Tai[1]

[1]Earth System Science Programme and Graduate Division of Earth and Atmospheric Sciences, Faulty of Science, The Chinese University of Hong Kong, Hong Kong, China
[*]now at: Climate Change Research Center (CCRC), Chinese Academy of Sciences, Beijing 100029, China

Received: 29 March 2015 – Accepted: 29 April 2015 – Published: 19 May 2015

Correspondence to: A. P. K. Tai (amostai@cuhk.edu.hk)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Understanding how historical climate and land cover changes have affected tropospheric ozone in East Asia would help constrain the large uncertainties associated with future East Asian air quality projections. We perform a series of simulations using a global chemical transport model driven by assimilated meteorological data and a suite of land cover and land use data to examine the public health effects associated with changes in climate, land cover, land use, and anthropogenic emissions over the past 30 years (1980–2010) in East Asia. We find that over 1980–2010 land cover change alone could lead to a decrease in summertime surface ozone by up to 4 ppbv in East Asia and ~ 2000 fewer ozone-related premature deaths per year, driven mostly by enhanced dry deposition resulting from climate- and CO_2-induced increase in vegetation density, which more than offsets the effect of reduced isoprene emission arising from cropland expansion. Over the same period, climate change alone could lead to an increase in summertime ozone by 2–10 ppbv in most regions of East Asia and ~ 6000 more premature deaths annually, mostly attributable to warming. The combined impacts (−2 to +12 ppbv) show that while the effect of climate change is more pronounced, land cover change could offset part of the climate effect and lead to a previously unknown public health benefit. While the changes in anthropogenic emissions remain the largest contributor to deteriorating ozone air quality in East Asia over the past 30 years, we show that climate change and land cover changes could lead to a substantial modification of ozone levels, and thus should come into consideration when formulating future air quality management strategies. We also show that the sensitivity of surface ozone to land cover change is more dependent on dry deposition than isoprene emission in most of East Asia, leading to ozone responses that are quite distinct from that in North America, where most ozone-vegetation sensitivity studies to date have been conducted.

1 Introduction

Air pollution is one of the most pressing environmental and public health concerns facing us today especially in rapidly developing regions such as East Asia. Several projection studies have suggested the important roles of climate and land cover changes on future air quality in addition to changing anthropogenic emissions (Fiore et al., 2012; Wu et al., 2012; Tai et al., 2013), albeit great uncertainties not only in the projected emissions and land use, but also in the coupling between climate, atmospheric chemistry and the land cover. A better understanding of how all these factors have interacted in the past to shape air quality would be particularly useful to shed light on the likely course of atmospheric chemical evolution in the coming decades. The attribution of air quality trends and public health outcomes in East Asia, which has undergone enormous social and environmental changes over the past few decades, would also provide valuable insights for policy formulation.

One of the most important air pollutants is surface ozone (O_3) due to its detrimental effects on human health, and its significance in changing the Earth's climate as a greenhouse gas has also been recognized (IPCC, 2013). Tropospheric ozone is produced by photochemical oxidation of precursor gases such as carbon monoxide, methane, and non-methane volatile organic compounds (VOCs) in the presence of nitrogen oxides ($NO_x \equiv NO + NO_2$). Most of these precursor gases have large anthropogenic sources, but the natural biosphere also represents significant sources depending on the region. The single most important non-methane VOC is isoprene, emitted primarily by land vegetation. Isoprene acts as a precursor for ozone in polluted, high-NO_x regions, but reduces ozone by ozonolysis or by sequestering NO_x as isoprene nitrate in remote, low-NO_x regions. The major global sink for ozone is photolysis in the presence of water vapor, but dry deposition onto the leaf surfaces of vegetation also represents a dominant sink within the boundary layer. Surface ozone is thus dependent not only on anthropogenic emissions of precursors but also on vegetation characteristics and local chemical environments, all of which are influenced by meteorological conditions.

ACPD
15, 14111–14139, 2015

A strong positive correlation between temperature and ozone concentration has long been observed in many polluted regions, driven primarily by increased biogenic VOC emissions from vegetation and reduced lifetimes of peroxyacetyl nitrate (PAN) due to accelerated decomposition of PAN into NO_x at higher temperatures (Jacob and Winner, 2009). This is further complicated by the covariation of temperature with frontal and cyclone passages, which represent an important ventilating mechanism for all air pollutants including ozone (Leibensperger et al., 2008; Tai et al., 2012a, b). Coupled general circulation model (GCM) and chemical transport model (CTM) studies generally show that warming would lead to increased summertime surface ozone in major populated regions by 1–10 ppbv by 2050 based on IPCC future scenarios (Weaver et al., 2009; Jacob and Winner, 2009). Wang et al. (2013) reported that under the IPCC A1B scenario, climate change alone over 2000–2050 would lead to an ozone increase by up to 3.5 ppbv in eastern China but a decrease by 2 ppbv in western China, and 40 % of the so-called "climate change penalty" over eastern China is attributed to enhanced biogenic VOC emissions. These studies demonstrate the potential of future climate change to at least in part offset the benefits of emission regulation in East Asia, but also highlight the large uncertainty in ozone simulations in the region arising from, e.g., different treatments of isoprene chemistry and regional chemical regimes. Few studies have examined how ozone has historically changed in East Asia, which could provide constraints for the future projections of climate change penalty on ozone air quality.

As noted above, vegetation can significantly modulate ozone air quality via biogenic VOC emissions, dry deposition, and transpiration, which controls near-surface water vapor concentration and boundary layer meteorology. Historical and future changes in the land cover and land use driven by climate change, CO_2 fertilization and economic activities are shown to have important ramifications for atmospheric composition. Sanderson et al. (2003) and Lathière et al. (2010) showed using a combination of vegetation models and historical land cover data that natural and anthropogenic land cover change significantly alters isoprene emission over multidecadal timescale. Wu et al. (2012) and Tai et al. (2013) predicted that changes in natural vegetation and land

ACPD
15, 14111–14139, 2015

use over 2000–2050 could modify summertime surface ozone by up to ±5 ppbv in East Asia. Stavrakou et al. (2014) estimated that annual isoprene emission in Asia in 2005 is 21 % lower if cropland expansion is accounted for in the model inputs of vegetation distribution. There are only a limited number of studies quantifying how such historical changes might have affected ozone air quality in East Asia. Fu and Liao (2014) found that seasonal mean surface ozone changes within −4 to +6 ppbv in China between the late 1980s and mid-2000s due to changes in biogenic VOC emissions driven by climate and land cover changes. This study considered only historical changes in fractional coverage of plant functional type (PFT), but not in leaf area index (LAI), dry deposition, and soil NO_x emission, all of which could have large impacts on the local chemical environments and thus ozone air quality.

In this study, using historical meteorological and satellite-derived land cover data to drive a chemical transport model, we examine the individual and combined effects of changes in climate, land cover and land use on tropospheric ozone in East Asia from 1980 to 2010, accounting for a more comprehensive set of potentially interacting mechanisms and variables including LAI (representing vegetation density), biogenic and soil NO_x emissions, and dry deposition, in addition to PFT (representing vegetation distribution). We compare such effects with the contribution from anthropogenic emission changes over the same period. We further calculate the annual mortality attributable to respiratory diseases caused by ozone pollution by applying concentration-response functions from epidemiological cohort studies, as a means to explore the public health implications of historical climate change and land use trends in East Asia.

2 Model description and numerical experiments

2.1 GEOS-Chem model

We use the GEOS-Chem global 3-D chemical transport model version 9-02 (http://acmg.seas.harvard.edu/geos/), driven by assimilated meteorological data from Mod-

ACPD
15, 14111–14139, 2015

ern Era Retrospective-analysis for Research and Applications (MERRA) (http://gmao.gsfc.nasa.gov/merra/) with a horizontal resolution of 2.0° latitude by 2.5° longitude and reduced vertical resolution of 47 levels. MERRA, produced by the NASA Goddard Earth Observing System (GEOS), focuses on historical analysis of the hydrological cycle on a broad range of timescales and covers the modern satellite era from 1979 to present. In this work, we conduct 5 year simulations in the historical (1981–1985) and present-day (2007–2011) periods using various combinations of MERRA and land cover data. GEOS-Chem performs fully coupled simulations of ozone–NO_x–VOC–aerosol chemistry (Bey et al., 2001), and its ozone simulations over East Asia have been previously evaluated with measurements from surface sites (Wang et al., 2011; He et al., 2012) and satellites (Wang et al., 2013). These studies demonstrate the ability of GEOS-Chem to reasonably reproduce the magnitude and seasonal variation of surface ozone in the region.

Global anthropogenic emissions of CO, NO_x and SO_2 use the EDGAR3.2-FT-2000 global inventory for 2000 (Olivier et al., 2005), and that of non-methane VOCs use the RETRO monthly global inventory for 2000 (Schultz et al., 2008). Global ammonia emissions are from the GEIA inventory (Bouwman et al., 1997). These global inventories are then scaled to 2005 levels on the basis of economic data and energy statistics as described by van Donkelaar et al. (2008). In this study, anthropogenic emissions in Asia are from Streets et al. (2003, 2006) and are also scaled to 2005 levels. Biomass burning emissions are from the GFED-3 inventory (van der Werf et al., 2010).

Biogenic VOC emissions in GEOS–Chem are computed by the Model of Emissions of Gases and Aerosols from Nature (MEGAN) v2.1 (Guenther et al., 2006, 2012) but as implemented by Barkley et al. (2011). Emissions of VOC species, including isoprene, monoterpenes, methyl butenol, sesquiterpenes, acetone and various alkenes, are simulated as a function of PFT-specific emission factors modulated by environmental activity factors to account for changing temperature, light, leaf age and LAI. We use the empirical values of PFT-specific emission factors provided by Guenther et al. (2012) (Table S1 in the Supplement). Soil NO_x emission follows Yienger and Levy (1995),

ACPD
15, 14111–14139, 2015

with updates from Hudman et al. (2012). It considers biome-specific emission factors, temperature, soil moisture, the latest gridded inventory for fertilizer and manure emissions, and the timing and distribution of nitrogen fertilizer based on satellite-derived seasonality. Wet deposition of soluble gases and aerosols follows the scheme of Liu et al. (2001). Dry deposition follows the resistance-in-series scheme of Wesely (1989), which depends on species properties, land cover types and meteorological conditions, and uses the Olson land cover classes with 76 land types (Olson, 1992) reclassified into 11 land types. Although transpiration is a potential mechanism via which the land cover affects ozone, we do not address it in this study because water vapor concentration in GEOS-Chem is prescribed from assimilated relative humidity (i.e., not computed online from evapotranspiration).

2.2 Land cover and land use change

To examine the impacts of historical changes in land cover and land use (LCLU) on air quality, we derive model-specific land cover inputs for East Asia in the present-day and historical periods using as the baseline the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover product (MCD12Q1) for year 2010 that includes five land cover classification schemes. Here we choose the scheme of International Geosphere-Biosphere Program (IGBP) with 17 land cover types, including 13 vegetation classes and 4 non-vegetated land types, we further combine them with the Koppen main climate classes following Steinkamp and Lawrence (2011). The distribution of LCLU types are shown in Fig. S1 in the Supplement.

To derive the vegetation distribution in 1980, we integrate multiple sources of data and information including the National Land Cover Dataset (NLCD) for China for the late 1980s and 2005 produced by the Chinese Academy of Science (Liu and Buheaosier, 2000; Liu et al., 2005a, b), MODIS-IGBP land cover types for 2005, and RCP harmonized historical land use for 1980–2005 from Hurtt et al. (2011) (Supplement Sect. S1). In the model, 23 land cover types are used for simulating soil NO_x emission. For biogenic VOC emissions, we merge the 23 PFTs into the 5 PFTs used by MEGAN

ACPD
15, 14111–14139, 2015

(broadleaf trees, needleleaf trees, shrubs, crops and grasses) (Table S2). The 23 PFTs are mapped into Olson land types when calculating dry deposition velocities (Table S3). To examine the historical changes in vegetation density, an LAI dataset for East Asia for 1980–2010 are obtained from a consistent long-term global LAI product derived using a quantitative fusion of MODIS (2000–2011) and Advanced Very High Resolution Radiometer (AVHRR) (1981–2000) satellite data with a resolution of half month and 8 km (Liu et al., 2012). Monthly mean LAIs are then averaged over the fraction of land area covered by vegetation in the model grid cell following the approach of Guenther et al. (2006) and Müller et al. (2008).

2.3 Numerical experiments

In this study, we conduct two sets of GEOS-Chem simulations (Table 1). In the first set of simulations (Simulation I), we consider five cases: [CTRL], [SIM_LCLU], [SIM_CLIM], [SIM_COMB], and [SIM_ANTH]. For each case, a 5 year simulation is performed. In the control simulation [CTRL], present-day (2007–2011) climate, land cover types (i.e., PFT fractional coverage) and LAIs are used to drive the model. In the sensitivity simulation [SIM_LCLU], we use the same meteorological fields as [CTRL] but with the historical (1981–1985) PFTs and LAIs. In [SIM_CLIM], we use historical climate but present-day PFTs and LAIs. In [SIM_COMB], we use historical climate, PFTs and LAIs. In all the four simulations above, anthropogenic emissions of ozone precursors are set at present-day levels (2005). The [SIM_ANTH] simulation is the same as [CTRL] but with historical anthropogenic emissions of ozone precursors scaled to 1985 levels.

To determine the key factors that modulate summertime (JJA) ozone concentration, we further perform a series of sensitivity experiments for a chosen year representative of each of the present-day and historical periods (Simulation II): [CTRL_2010], which is simply year 2010 results from the control experiment [CTRL], and [SIM_PFT], [SIM_LAI], [SIM_TMP], and [SIM_RH], in which we keep every variable at the present-day level but with one of land cover types, LAIs, temperature, and relative humidity,

ACPD
15, 14111–14139, 2015

respectively, from the historical period. Results from these sensitivity simulations enable first-order estimates of the potential relative contribution from each of the variables considered.

3 Changes in land cover and land use over 1980–2010

The vegetation changes in terms of distribution and density over 1980–2010 in East Asia as a result of environmental and anthropogenic land use changes are shown in Fig. 1. We find that the cropland fraction in northeast and most of eastern China, Korea and various other places increases by up to 20 % from 1980 to 2010, often associated with deforestation. Significant cropland-to-grassland conversion and reforestation are observed in northern China (e.g., Inner Mongolia) and many parts of southwestern and southern China, likely due to the land use polices of the Chinese government such as the "Grain for Green" project (J. Liu et al., 2010). Forested areas have generally decreased where croplands have expanded, whereas reforestation in southwestern and southern China is associated with reduced coverage of all of croplands, grasslands and shrubs (Fig. 1a).

In summer (JJA), LAI values in most of East Asia have generally increased, except in some parts of Southeast Asia (Fig. 1b). The enhanced summertime LAI is likely a result of warming and CO_2 fertilization, which promotes plant growth as is shown by a number of vegetation modeling studies (Gonzales et al., 2008; Kaplan et al., 2012). The increase in summertime LAI despite significant cropland expansion in northeastern and eastern China suggests that increased foliage density of the remaining forests may have more than offset the impact of reduced forest coverage on the grid-cell scale. On the other hand, a decline in LAI is observed in most of East Asia in spring (MAM), encompassing northeastern and southern China, Korea, and Japan (Fig. 1b). Such a decline for 1981–2006 are also reported in S. Liu et al. (2010) and Sangram (2012), possibly due to the warming-induced drought stress, reduced springtime precipitation and/or changes in agricultural practices.

ACPD
15, 14111–14139, 2015

4 Impacts of land cover and land use change alone on ozone air quality

Figures 2a and 3a show the changes in surface ozone concentration arising from 1980–2010 LCLU change alone in summer and spring, respectively, expressed as seasonal mean of maximum daily 8 h average ozone concentration (MDA8 O_3). Summertime surface ozone changes by ±2 ppbv in many regions of East Asia, particularly in most of China (except in Tibet and southern China), Korea and Japan where ozone decreases locally by up to 4 ppbv (Fig. 2a). We find that such LCLU-driven decreases in ozone are primarily driven by increased summertime LAI that leads to enhanced ozone dry deposition (Fig. 2c). Much of China east of $\sim 100^{\circ}$ E is in a high-NO_x, VOC-limited regime, so the increased isoprene emission in much of central China and Japan (where ozone decreases) should play a relatively minor role in affecting ozone. Exceptions include northeastern China, where reduced isoprene emission following cropland expansion (despite increased LAI) contributes in part to the lower ozone; and southern China, where higher isoprene emission following increased forest coverage and LAI contributes significantly to the increased ozone there. In spring, an ozone increase in the range of 0.5–2 ppbv is found in most of China (except part of eastern China) and part of Southeast Asia (Fig. 3a). In much of China, Korea and Japan, the changes in springtime ozone are largely driven by dry deposition changes. Places where isoprene emission changes may be important include southwestern China and some parts of Southeast Asia, where a NO_x-limited regime prevails and the strong reduction in isoprene emission, together with increased soil NO_x and reduced dry deposition, leads to worse ozone air quality. See Supplement Sect. S2 for details of isoprene emission changes.

Compared with the results of Fu and Liao (2014), our simulated impacts of LCLU on surface ozone are generally larger over China. Fu and Liao (2014) primarily considered the roles of vegetation distribution in affecting biogenic VOC emissions only. Our results demonstrate that dry deposition and vegetation density are equally, and potentially more, important in shaping ozone air quality in East Asia depending on the region. We

ACPD
15, 14111–14139, 2015

investigate this further by considering the two important factors via which the land cover could influence ozone in the model – PFT fractional coverage (representing vegetation distribution) and LAI (representing vegetation density) – and comparing the results from [CTRL_2010] with those from [SIM_PFT] and [SIM_LAI] to better understand the relative importance of these two vegetation parameters. Without LAI changes, changes in PFT distribution alone reduce JJA surface ozone by up to 4 ppbv in Japan, Korea, northeastern, eastern and southwestern China, and parts of Southeast Asia, whereas in southern and western China it increases by 0.5–2 ppbv (Fig. S3a). This indicates that cropland expansion might benefit public health in VOC-limited regions due to reduced isoprene emission, but might worsen ozone air quality in low-NO_x regions due to reduced isoprene and increased soil NO_x emissions (Fig. S3a). Afforestation would have the opposite effects. On the other hand, as a result of LAI changes alone, JJA ozone exhibits reduction by as much as 2 ppbv in most of China (except in southern China), primarily driven by increased dry deposition following increased JJA LAI, though in part offset by increased isoprene emission in VOC-limited regions (Fig. S3b). Enhanced LAI leads to higher ozone in southern China, which is the most isoprene-abundant (but still high-NO_x) region of China. The LAI (density) effect generally dominates over the PFT (distribution) effect in East Asia.

5 Impacts of climate change alone on ozone air quality

Figure 4 shows the effects of 1980–2010 climate change alone on surface ozone ([CTRL]–[SIM_CLIM]). Simulated surface ozone changes in summer are within the range of −2 to +12 ppbv over East Asia due to climate change alone, with the largest over Mongolia, eastern and northeastern China, representing significant "climate penalty" on ozone regulatory effort over 1980–2010 (Fig. 4a). In contrast, surface ozone decreases in some parts of western China by up to 2 ppbv. Surface ozone increases in spring by as much as 8 ppbv in southern and eastern China, but decreases

ACPD
15, 14111–14139, 2015

Y. Fu and A. P. K. Tai

by up to 4 ppbv over mid-latitude regions of East Asia (~ 30–40° N) and in Myanmar (Fig. 4b).

From the sensitivity simulations we find that the 1980–2010 ozone changes in most of East Asia are primarily driven by changes in temperature in both summer and spring (Fig. 4c and d), reflecting enhanced (reduced) isoprene emission and PAN decomposition at higher (lower) temperatures in these mostly high-NO_x regions (Wang et al., 2013). The widespread summertime ozone increase east of ~ 110° E (Fig. 4a) are also driven in lesser part by reduced relatively humidity (Figs. S4 and S5), which inhibits ozone destruction in the presence of water vapor. The summertime ozone increase in the Shandong province of China despite a small drop in temperature and rise in relative humidity may reflect influence of westerly transport. The ozone decrease in west-central China in both seasons is also consistent with enhanced relative humidity and reduced mixing height (Fig. S4). This agrees with Dawson et al. (2007) who found that in the eastern US a shallower mixing height reduces ozone in polluted areas, because it increases NO_x concentration in the mixed layer and thus inhibits ozone production in regions with an overabundance of NO_x (Kleeman, 2008; Jacob and Winner, 2009).

6 Comparison between the impacts of changes in climate, land cover and anthropogenic emissions

Under the combined effects of climate and LCLU changes ([CTRL]–[SIM_COMB]), changes in summertime surface ozone range between −2 and +12 ppbv in most of East Asia, with an ozone enhancement of 2–8 ppbv in the most densely populated coastal regions (Fig. 5a). The spatial pattern of ozone changes under the combined effects is similar to that from climate change alone (Fig. 4a), reflecting the more dominant role of climatic factors in affecting ozone, although the LCLU effects often offset (and at some locations enhance) a sizable portion of the climate effects. In several places (e.g., Japan and Korea), the sign of change from the combined effects even becomes

ACPD
15, 14111–14139, 2015

Impacts of historical climate and land cover changes on ozone

Y. Fu and A. P. K. Tai

opposite to that from climate change alone, indicating the importance of LCLU change in offsetting the climate-driven ozone increases in some East Asian regions.

Figure 5b shows that the changes in anthropogenic emissions alone (with fixed, present-day climate and LCLU) over 1985–2005 enhance summertime ozone by 2–25 ppbv in East Asia ([CTRL]–[SIM_ANTH]), reflecting the unsurprisingly dominant role of anthropogenic emissions in controlling East Asian air quality over the past few decades. The largest ozone increase occurs in southern, eastern and central China. Against the backdrop of changing emissions, Fig. 5a demonstrates that in most of East Asia, emission-driven ozone increases could be substantially enhanced by multidecadal changes in climate but then partially offset by climate- and CO_2-driven changes in vegetation density.

7 Impacts on human health

Previous epidemiological studies have shown that ozone has a detrimental effect on human health, and the exposure to ozone could lead to premature respiratory mortality (e.g., Jerrett et al., 2009). We thus further assess the possible public health implications of historical ozone changes in East Asia as a result of changes in climate, land cover, and anthropogenic emissions over the past three decades (1980–2010). Our approach follows the methods of Anenberg et al. (2010) and Raquel et al. (2013), using concentration-response functions (CRFs) from the American Cancer Society (ACS) study (Supplement Sect. S6).

Figure 6 shows the estimates with uncertainties of the ozone-related respiratory mortality (concerning adults aged 30 and above) attributed to historical climate change ([CTRL]–[SIM_CLIM]), land cover and land use change ([CTRL]–[SIM_LCLU]), and anthropogenic emissions ([CTRL]–[SIM_ANTH]). The mortality attributed to past changes in anthropogenic emissions is the largest – about 61 600 more deaths in East Asia and 28 370 more deaths in China annually. The effect of past climate change on mortality is 5600 more deaths and 4409 more deaths annually in all of East Asia and

ACPD
15, 14111–14139, 2015

China, respectively. Historical LCLU change (mainly via climate- and CO_2-driven increase in vegetation density) causes ozone-related respiratory mortality to decrease by 2200 deaths yr^{-1} in East Asia and by 243 deaths yr^{-1} in China, reflecting the relatively small but not insignificant public health benefit of multidecadal LCLU change over the past 30 years due to the alleviation of ozone pollution that in part offsets the health damage of warming and increasing emissions.

8 Conclusions and discussion

In this study, we investigate the effects of historical (1980–2010) changes in climate, land cover and land use on surface ozone concentration in East Asia using the GEOS-Chem chemical transport model driven by assimilated meteorological fields, land use data from historical RCP harmonization, and several satellite-derived land cover products. We characterize the possible changes in vegetation distribution and density, as well as various climate variables, in East Asia over the past 30 years, and examine their influences on ozone air quality and public health along the backdrop of changing anthropogenic emissions, focusing on spring and summer when ozone pollution is usually the most serious. East Asian land cover change is generally characterized by a reduction in forest coverage (mostly due to cropland expansion) in most of southern, eastern and northeastern China and adjacent regions, but an increase in forest coverage in parts of northern, southwestern and western China. LAI has generally increased in summer likely due to warming and CO_2 fertilization, but decreased in spring.

From the simulations using different combinations of present-day (2007–2011) vs. historical (1981–1985) meteorological fields, land cover data and anthropogenic emissions of ozone precursors, we estimate that historical land cover and land use change alone over 1980–2010 could have led to reduced summertime surface ozone by up to 4 ppbv in most of East Asia, driven mainly by warming- and CO_2-induced enhancement in summertime LAI, but enhanced springtime ozone by 0.5–2 ppbv in most of East Asia. Historical climate change alone has increased summertime surface ozone by 2–10 ppbv in most places of East Asia except in some parts of western China. In spring, climate change alone has increased surface ozone by up to 8 ppbv in southern and eastern China, but decreased ozone by as much as 4 ppbv over much of the midlatitude regions of East Asia. Such climate effects are driven mainly by changes in seasonal mean temperature. Changes in anthropogenic emissions of ozone precursors mostly from industrial sources remain the largest contributor to worse ozone air quality (by as much as 25 ppbv) in most of East Asia, but climate change could substantially further enhance ozone, while land cover and land use change could partially offset the rising ozone levels in various regions over the past 30 years. We further examine the public health implications of these results by estimating the possible changes in annual mortality attributable to ozone-related respiratory diseases from 1980 to 2010. Rising anthropogenic emissions have increased respiratory mortality by tens of thousands more deaths per year in East Asia over the past three decades. The multidecadal land cover change (mostly via enhanced vegetation density), however, might have alleviated the emission-driven health impacts, while climate change (mostly warming) might have aggravated those impacts. Such results highlight the importance of considering the effects of future climate and land cover changes in formulating adequate emission control strategies to tackle public health issues related to air pollution.

We also find that, at least in ways represented in our model, the effects of land cover change on ozone air quality in East Asia differ substantially from those elsewhere due to different background chemical environments. Changes in vegetation density and dry deposition appear to be more important factors in East Asia than changes in plant type distribution and isoprene emission, whereas the opposite is true in most of the US, which contains one of the largest isoprene hotspots in the world (Millet et al., 2008; Tai et al., 2013), even though both regions are mostly high-NO_x. Future work should thus focus on a more systematic analysis on the global spatial variability of ozone sensitivity to vegetation changes (e.g., driven by climate and land use changes), which may yield opposite responses depending on the region. Another source of uncertainty is related to the use of several independent land cover datasets, which all contain

ACPD
15, 14111–14139, 2015

various degrees of errors and may not be consistent with one another. Though in part cross-validated with potential vegetation from dynamic vegetation models, the limited spatial and temporal information provided by existing datasets still poses a challenge for a complete characterization and physical interpretation of land cover change in many of the regions concerned. Moreover, there have been relatively few related long-term studies concerning air quality and health in East Asia, thus the health impact functions and parameters used in this study are only derived from a limited number of epidemiological cohort studies mainly in North America. More regionally specific information for the relationships between human health and long-term ozone exposure is required to constrain the estimates of the public health impacts of climate and land cover changes in future studies.

The Supplement related to this article is available online at doi:10.5194/acpd-15-14111-2015-supplement.

Acknowledgements. This work was supported by a faculty start-up allowance from the Croucher Foundation and The Chinese University of Hong Kong given to the principal investigator, Amos P. K. Tai. MERRA data used in this study were provided by the Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center through the NASA GES DISC online archive. We acknowledge the MODIS LAI product provided by Land Processes Distributed Active Archive Center (LP DAAC).

References

Anenberg, S. C., Horowitz, L. W., Tong, D. Q., and West, J. J.: An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling, Environ. Health Persp., 118, 1189–1195, doi:10.1289/ehp.0901220, 2010.

ACPD

15, 14111–14139, 2015

Barkley, M. P., Palmer, P. I., Ganzeveld, L., Arneth, A., Hagberg, D., Karl, T., Guenther, A., Paulot, F., Wennberg, P. O., Mao, J., Kurosu, T. P., Chance, K., Müller, J. F., De Smedt, I., Van Roozendael, M., Chen, D., Wang, Y., and Yantosca, R. M.: Can a "state of the art" chemistry transport model simulate Amazonian tropospheric chemistry?, J. Geophys. Res., 116, D16302, doi:10.1029/2011jd015893, 2011.

Bey, I., Jacob, D. J., Yantosca, R. M., Logan, J. A., Field, B. D., Fiore, A. M., Li, Q., Liu, H. Y., Mickley, L. J., and Schultz, M. G.: Global modeling of tropospheric chemistry with assimilated meteorology: model description and evaluation, J. Geophys. Res., 106, 23073–23095, doi:10.1029/2001jd000807, 2001.

Bouwman, A. F., Lee, D. S., Asman, W. A. H., Dentener, F. J., Van Der Hoek, K. W., and Olivier, J. G. J.: A global high-resolution emission inventory for ammonia, Global Biogeochem. Cy., 11, 561–587, doi:10.1029/97GB02266, 1997.

Dawson, J. P., Adams, P. J., and Pandis, S. N.: Sensitivity of ozone to summertime climate in the eastern USA: a modeling case study, Atmos. Environ., 41, 1494–1511, doi:10.1016/j.atmosenv.2006.10.033, 2007.

Fiore, A. M., Naik, V., Spracklen, D. V., Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-Smith, P. J., Cionni, I., Collins, W. J., Dalsoren, S., Eyring, V., Folberth, G. A., Ginoux, P., Horowitz, L. W., Josse, B., Lamarque, J.-F., MacKenzie, I. A., Nagashima, T., O'Connor, F. M., Righi, M., Rumbold, S. T., Shindell, D. T., Skeie, R. B., Sudo, K., Szopa, S., Takemura, T., and Zeng, G.: Global air quality and climate, Chem. Soc. Rev., 41, 6663–6683, 2012.

Fu, Y. and Liao, H.: Impacts of land use and land cover changes on biogenic emissions of volatile organic compounds in China from the late 1980s to the mid-2000s: implications for tropospheric ozone and secondary organic aerosol, Tellus B, 66, 24987, doi:10.3402/tellusb.v66.24987, 2014.

Gonzales, L. M., Williams, J. W., and Kaplan, J. O.: Variations in leaf area index in northern and eastern North America over the past 21,000 years: a data-model comparison, Quaternary Sci. Rev., 27, 1453–1466, doi:10.1016/j.quascirev.2008.04.003, 2008.

Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P. I., and Geron, C.: Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature), Atmos. Chem. Phys., 6, 3181–3210, doi:10.5194/acp-6-3181-2006, 2006.

Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions, Geosci. Model Dev., 5, 1471–1492, doi:10.5194/gmd-5-1471-2012, 2012.
He, J., Wang, Y., Hao, J., Shen, L., and Wang, L.: Variations of surface O_3 in August at a rural site near Shanghai: influences from the West Pacific subtropical high and anthropogenic emissions, Environ. Sci. Pollut. R., 19, 4016–4029, doi:10.1007/s11356-012-0970-5, 2012.
Hudman, R. C., Moore, N. E., Mebust, A. K., Martin, R. V., Russell, A. R., Valin, L. C., and Cohen, R. C.: Steps towards a mechanistic model of global soil nitric oxide emissions: implementation and space based-constraints, Atmos. Chem. Phys., 12, 7779–7795, doi:10.5194/acp-12-7779-2012, 2012.
Hurtt, G. C., Chini, L. P., Frolking, S., Betts, R. A., Feddema, J., Fischer, G., Fisk, J. P., Hibbard, K., Houghton, R. A., Janetos, A., Jones, C. D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., Vuuren, D. P., and Wang, Y. P.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, Climatic Change, 109, 117–161, doi:10.1007/s10584-011-0153-2, 2011.
IPCC: Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK, New York, NY, USA, 1535 pp., 2013.
Jacob, D. J. and Winner, D. A.: Effect of climate change on air quality, Atmos. Environ., 43, 51–63, doi:10.1016/j.atmosenv.2008.09.051, 2009.
Jerrett, M., Burnett, R. T., Pope, C. A., Ito, K., Thurston, G., Krewski, D., Shi, Y., Calle, E., and Thun, M.: Long-term ozone exposure and mortality, New Engl. J. Med., 360, 1085–1095, doi:10.1056/NEJMoa0803894, 2009.
Kaplan, J. O., Krumhardt, K. M., and Zimmermann, N. E.: The effects of land use and climate change on the carbon cycle of Europe over the past 500 years, Glob. Change Biol., 18, 902–914, doi:10.1111/j.1365-2486.2011.02580.x, 2012.
Kleeman, M.: A preliminary assessment of the sensitivity of air quality in California to global change, Climatic Change, 87, 273–292, doi:10.1007/s10584-007-9351-3, 2008.

Lathière, J., Hewitt, C. N., and Beerling, D. J.: Sensitivity of isoprene emissions from the terrestrial biosphere to 20th century changes in atmospheric CO_2 concentration, climate, and land use, Global Biogeochem. Cy., 24, GB1004, doi:10.1029/2009gb003548, 2010.
Leibensperger, E. M., Mickley, L. J., and Jacob, D. J.: Sensitivity of US air quality to mid-latitude cyclone frequency and implications of 1980–2006 climate change, Atmos. Chem. Phys., 8, 7075–7086, doi:10.5194/acp-8-7075-2008, 2008.
Liu, H., Jacob, D. J., Bey, I., and Yantosca, R. M.: Constraints from ^{210}Pb and ^{7}Be on wet deposition and transport in a global three-dimensional chemical tracer model driven by assimilated meteorological fields, J. Geophys. Res., 106, 12109–12128, doi:10.1029/2000jd900839, 2001.
Liu, J. and Buheaosier: Study on spatial–temporal feature of modern land-use change in China: using Remote Sensing techniques, Quaternary Sciences, 20, 229–239, 2000.
Liu, J., Zhang, Z., Xu, X., Kuang, W., Zhou, W., Zhang, S., Li, R., Yan, C., Yu, D., Wu, S., and Jiang, N.: Spatial patterns and driving forces of land use change in China during the early 21st century, J. Geogr. Sci., 20, 483–494, doi:10.1007/s11442-010-0483-4, 2010.
Liu, J. Y., Liu, M., Tian, H., Zhuang, D., Zhang, Z., Zhang, W., Tang, X., and Deng, X.: Spatial and temporal patterns of China's cropland during 1990–2000: An analysis based on Landsat TM data, Remote Sens. Environ., 98, 442–456, doi:10.1016/j.rse.2005.08.012, 2005a.
Liu, J. Y., Tian, H. Q., Liu, M. L., Zhuang, D. F., Melillo, J. M., and Zhang, Z. X.: China's changing landscape during the 1990s: large-scale land transformations estimated with satellite data, Geophys. Res. Lett., 32, L02405, doi:10.1029/2004gl021649, 2005b.
Liu, S., Liu, R., and Liu, Y.: Spatial and temporal variation of global LAI during 1981–2006, J. Geogr. Sci., 20, 323–332, doi:10.1007/s11442-010-0323-6, 2010.
Liu, Y., Liu, R., and Chen, J. M.: Retrospective retrieval of long-term consistent global leaf area index (1981–2011) from combined AVHRR and MODIS data, J. Geophys. Res.-Biogeo., 117, G04003, doi:10.1029/2012JG002084, 2012.
Millet, D. B., Jacob, D. J., Boersma, K. F., Fu, T. M., Kurosu, T. P., Chance, K., Heald, C. L., and Guenther, A.: Spatial distribution of isoprene emissions from North America derived from formaldehyde column measurements by the OMI satellite sensor, J. Geophys. Res.-Atmos., 113, 1–18, doi:10.1029/2007jd008950, 2008.
Müller, J.-F., Stavrakou, T., Wallens, S., De Smedt, I., Van Roozendael, M., Potosnak, M. J., Rinne, J., Munger, B., Goldstein, A., and Guenther, A. B.: Global isoprene emissions esti-

ACPD
15, 14111–14139, 2015

Impacts of historical climate and land cover changes on ozone

Y. Fu and A. P. K. Tai

mated using MEGAN, ECMWF analyses and a detailed canopy environment model, Atmos. Chem. Phys., 8, 1329–1341, doi:10.5194/acp-8-1329-2008, 2008.
Olivier, J. G. J., Aardenne, J. A. V., Dentener, F., Pagliari, V., Ganzeveld, L. N., and Peters, J. A. H. W.: Recent trends in global greenhouse gas emissions: regional trends 1970–2000 and spatial distribution of key sources in 2000, Environ. Sci., 2, 81–99, 2005.
Olson, J.: World Ecosystems (WE1.4). Digital raster data on a 10 min geographic 1080 × 2160 grid, in: Global Ecosystems Database, Version 1.0: Disc A., edited by: NOAA National Geophysical Data Center, Boulder, Colorado, 1992.
Raquel, A. S., West, J. J., Yuqiang, Z., Susan, C. A., Jean-François, L., Drew, T. S., William, J. C., Stig, D., Greg, F., Gerd, F., Larry, W. H., Tatsuya, N., Vaishali, N., Steven, R., Ragnhild, S., Kengo, S., Toshihiko, T., Daniel, B., Philip, C.-S., Irene, C., Ruth, M. D., Veronika, E., Beatrice, J., MacKenzie, I. A., David, P., Mattia, R., David, S. S., Sarah, S., Sophie, S., and Guang, Z.: Global premature mortality due to anthropogenic outdoor air pollution and the contribution of past climate change, Environ. Res. Lett., 8, 034005, doi:10.1088/1748-9326/8/3/034005, 2013.
Sanderson, M. G., Jones, C. D., Collins, W. J., Johnson, C. E., and Derwent, R. G.: Effect of climate change on isoprene emissions and surface ozone levels, Geophys. Res. Lett., 30, 1936, doi:10.1029/2003gl017642, 2003.
Sangram, G.: Long-term satellite data records for land-cover monitoring, in: Remote Sensing of Land Use and Land Cover, Remote Sensing Applications Series, CRC Press, 91–112, 2012.
Schultz, M. G., Backman, L., Balkanski, Y., Bjoerndalsaeter, S., Brand, R., Burrows, J. P., Dalsoeren, S., Vasconcelos, M. d., Grodtmann, B., Hauglustaine, D. A., Heil, A., Hoelzemann, J. J., Isaksen, I. S. A., Kaurola, J., Knorr, W., and Ladstaetter-Weißenmayer, A., Mota, B., Oom, D., Pacyna, J., Panasiuk, D., Pereira, J. M. C., Pulles, T., Pyle, J., Rast, S., Richter, A., Savage, N., Schnadt, C., Schulz, M., Spessa, A., Staehelin, J., Sundet, J. K., Szopa, S., Thonicke, K., Bolscher, M. v. h., Noije, T. v., Velthoven, P. v., Vik, A. F., and Wittrock, F: REanalysis of the TROpospheric chemical composition over the past 40 years (RETRO) – a long-term global modeling study of tropospheric chemistry funded under the 5th EU framework programme Project Number: EVK2-CT-2002-00170 (RETRO), Jülich/Hamburg, Germany, 2008.
Stavrakou, T., Müller, J.-F., Bauwens, M., De Smedt, I., Van Roozendael, M., Guenther, A., Wild, M., and Xia, X.: Isoprene emissions over Asia 1979–2012: impact of climate and land-use changes, Atmos. Chem. Phys., 14, 4587–4605, doi:10.5194/acp-14-4587-2014, 2014.

ACPD
15, 14111–14139, 2015

Steinkamp, J. and Lawrence, M. G.: Improvement and evaluation of simulated global biogenic soil NO emissions in an AC-GCM, Atmos. Chem. Phys., 11, 6063–6082, doi:10.5194/acp-11-6063-2011, 2011.
Streets, D. G., Bond, T. C., Carmichael, G. R., Fernandes, S. D., Fu, Q., He, D., Klimont, Z., Nelson, S. M., Tsai, N. Y., Wang, M. Q., Woo, J. H., and Yarber, K. F.: An inventory of gaseous and primary aerosol emissions in Asia in the year 2000, J. Geophys. Res.-Atmos., 108, 8809, doi:10.1029/2002JD003093, 2003.
Streets, D. G., Zhang, Q., Wang, L., He, K., Hao, J., Wu, Y., Tang, Y., and Carmichael, G. R.: Revisiting China's CO emissions after the Transport and Chemical Evolution over the Pacific (TRACE-P) mission: synthesis of inventories, atmospheric modeling, and observations, J. Geophys. Res., 111, D14306, doi:10.1029/2006jd007118, 2006.
Tai, A. P. K., Mickley, L. J., and Jacob, D. J.: Impact of 2000–2050 climate change on fine particulate matter ($PM_{2.5}$) air quality inferred from a multi-model analysis of meteorological modes, Atmos. Chem. Phys., 12, 11329–11337, doi:10.5194/acp-12-11329-2012, 2012a.
Tai, A. P. K., Mickley, L. J., Jacob, D. J., Leibensperger, E. M., Zhang, L., Fisher, J. A., and Pye, H. O. T.: Meteorological modes of variability for fine particulate matter ($PM_{2.5}$) air quality in the United States: implications for $PM_{2.5}$ sensitivity to climate change, Atmos. Chem. Phys., 12, 3131–3145, doi:10.5194/acp-12-3131-2012, 2012b.
Tai, A. P. K., Mickley, L. J., Heald, C. L., and Wu, S. L.: Effect of CO_2 inhibition on biogenic isoprene emission: implications for air quality under 2000 to 2050 changes in climate, vegetation, and land use, Geophys. Res. Lett., 40, 3479–3483, doi:10.1002/Grl.50650, 2013.
van Donkelaar, A., Martin, R. V., Leaitch, W. R., Macdonald, A. M., Walker, T. W., Streets, D. G., Zhang, Q., Dunlea, E. J., Jimenez, J. L., Dibb, J. E., Huey, L. G., Weber, R., and Andreae, M. O.: Analysis of aircraft and satellite measurements from the Intercontinental Chemical Transport Experiment (INTEX-B) to quantify long-range transport of East Asian sulfur to Canada, Atmos. Chem. Phys., 8, 2999–3014, doi:10.5194/acp-8-2999-2008, 2008.
van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.
Wang, Y., Zhang, Y., Hao, J., and Luo, M.: Seasonal and spatial variability of surface ozone over China: contributions from background and domestic pollution, Atmos. Chem. Phys., 11, 3511–3525, doi:10.5194/acp-11-3511-2011, 2011.

ACPD
15, 14111–14139, 2015

Impacts of historical climate and land cover changes on ozone

Y. Fu and A. P. K. Tai

Wang, Y., Shen, L., Wu, S., Mickley, L., He, J., and Hao, J.: Sensitivity of surface ozone over China to 2000–2050 global changes of climate and emissions, Atmos. Environ., 75, 374–382, doi:10.1016/j.atmosenv.2013.04.045, 2013.

Weaver, C. P., Cooter, E., Gilliam, R., Gilliland, A., Grambsch, A., Grano, D., Hemming, B., Hunt, S. W., Nolte, C., Winner, D. A., Liang, X. Z., Zhu, J., Caughey, M., Kunkel, K., Lin, J. T., Tao, Z., Williams, A., Wuebbles, D. J., Adams, P. J., Dawson, J. P., Amar, P., He, S., Avise, J., Chen, J., Cohen, R. C., Goldstein, A. H., Harley, R. A., Steiner, A. L., Tonse, S., Guenther, A., Lamarque, J. F., Wiedinmyer, C., Gustafson, W. I., Leung, L. R., Hogrefe, C., Huang, H. C., Jacob, D. J., Mickley, L. J., Wu, S., Kinney, P. L., Lamb, B., Larkin, N. K., McKenzie, D., Liao, K. J., Manomaiphiboon, K., Russell, A. G., Tagaris, E., Lynn, B. H., Mass, C., Salathé, E., O'Neill, S. M., Pandis, S. N., Racherla, P. N., Rosenzweig, C., and Woo, J. H.: A preliminary synthesis of modeled climate change impacts on U.S. regional ozone concentrations, B. Am. Meteorol. Soc., 90, 1843–1863, doi:10.1175/2009BAMS2568.1, 2009.

Wesely, M. L.: Parameterization of surface resistances to gaseous dry deposition in regional-scale numerical models, Atmos. Environ., 23, 1293–1304, doi:10.1016/0004-6981(89)90153-4, 1989.

Wu, S., Mickley, L. J., Kaplan, J. O., and Jacob, D. J.: Impacts of changes in land use and land cover on atmospheric chemistry and air quality over the 21st century, Atmos. Chem. Phys., 12, 1597–1609, doi:10.5194/acp-12-1597-2012, 2012.

Yienger, J. J. and Levy II, H.: Empirical model of global soil-biogenic NO_x emissions, J. Geophys. Res., 100, 11447–11464, doi:10.1029/95jd00370, 1995.

ACPD
15, 14111–14139, 2015

Y. Fu and A. P. K. Tai

Table 1. Summary of the simulations in this study.

Simulations	MERRA meteorology	Vegetation parameters PFT distribution*	LAI*	Anthropogenic emissions
Simulation I				
CTRL	2007–2011	2010	2010	2005
SIM_LCLU	2007–2011	1980	1982	2005
SIM_CLIM	1981–1985	2010	2010	2005
SIM_COMB	1981–1985	1980	1982	2005
SIM_ANTH	2007–2011	2010	2010	1985
Simulation II	Only for summer (JJA)			
CTRL_2010	2010 (T, RH, etc.)*	2010	2010	2005
SIM_PFT	2010 (T, RH, etc.)	1980	2010	2005
SIM_LAI	2010 (T, RH, etc.)	2010	1982	2005
SIM_TMP	1982 T; 2010 (RH, etc.)	2010	2010	2005
SIM_RH	1982 RH; 2010 (T, etc.)	2010	2010	2005

* T: temperature; RH: relative humidity; PFT: plant function type; LAI: leaf area index

ACPD
15, 14111–14139, 2015

Impacts of historical climate and land cover changes on ozone

Y. Fu and A. P. K. Tai

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

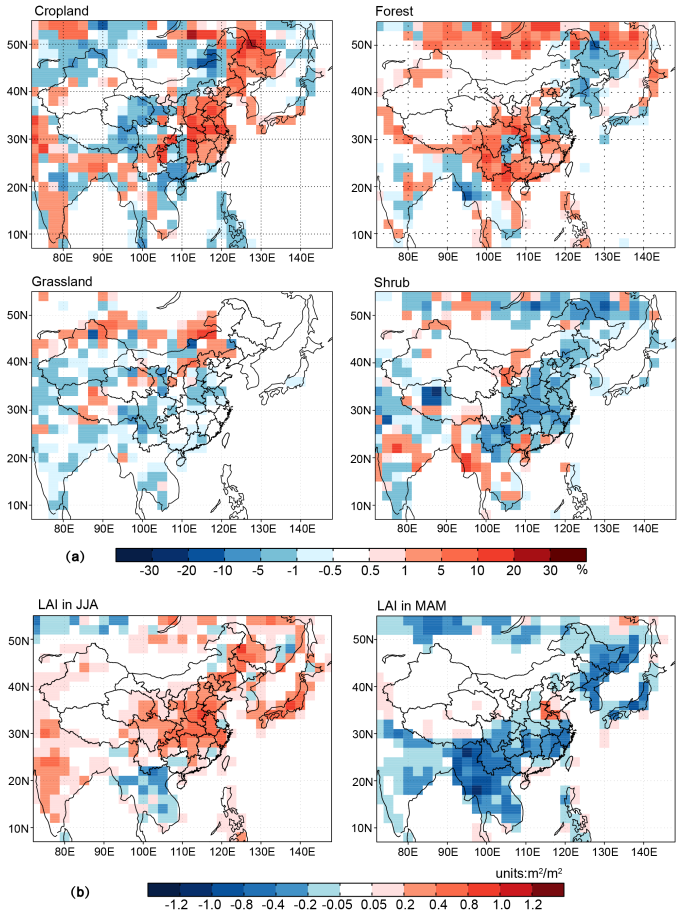

Figure 1. (a) 1980–2010 changes in fractional coverage of croplands, forests (needleleaf + broadleaf + mixed), grasslands and shrubs; **(b)** changes in summertime (JJA) and springtime (MAM) LAI over 1980–2010.

ACPD
15, 14111–14139, 2015

Impacts of historical climate and land cover changes on ozone

Y. Fu and A. P. K. Tai

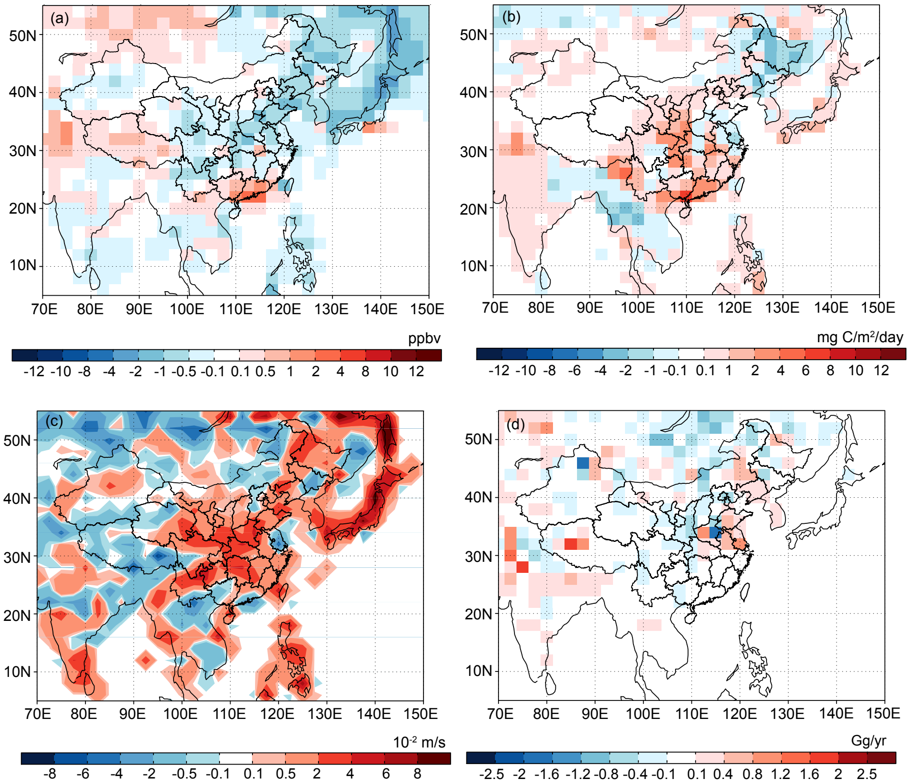

Figure 2. Changes in summertime (JJA) **(a)** surface maximum daily 8 h average ozone concentration (MDA8 O_3); **(b)** isoprene emission; **(c)** dry deposition velocity; and **(d)** soil NO_x emission, driven by 1980–2010 changes in land cover and land use alone ([CTRL]–[SIM_LCLU]). Values are differences between the five-year averages over the present-day and historical periods.

ACPD
15, 14111–14139, 2015

Impacts of historical climate and land cover changes on ozone

Y. Fu and A. P. K. Tai

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

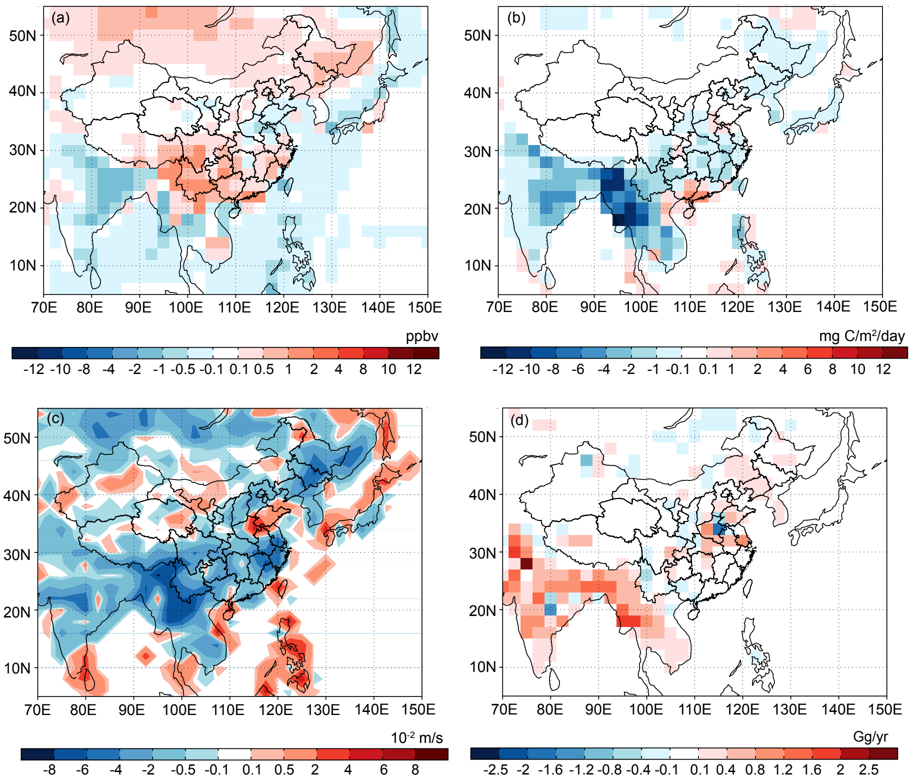

Figure 3. Changes in springtime (MAM) **(a)** surface maximum daily 8 h average ozone concentration (MDA8 O_3); **(b)** isoprene emission; **(c)** dry deposition velocity; and **(d)** soil NO_x emission driven by 1980–2010 changes in land cover and land use alone ([CTRL]–[SIM_LCLU]). Values are differences between the five-year averages over the present-day and historical periods.

ACPD
15, 14111–14139, 2015

Impacts of historical climate and land cover changes on ozone

Y. Fu and A. P. K. Tai

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

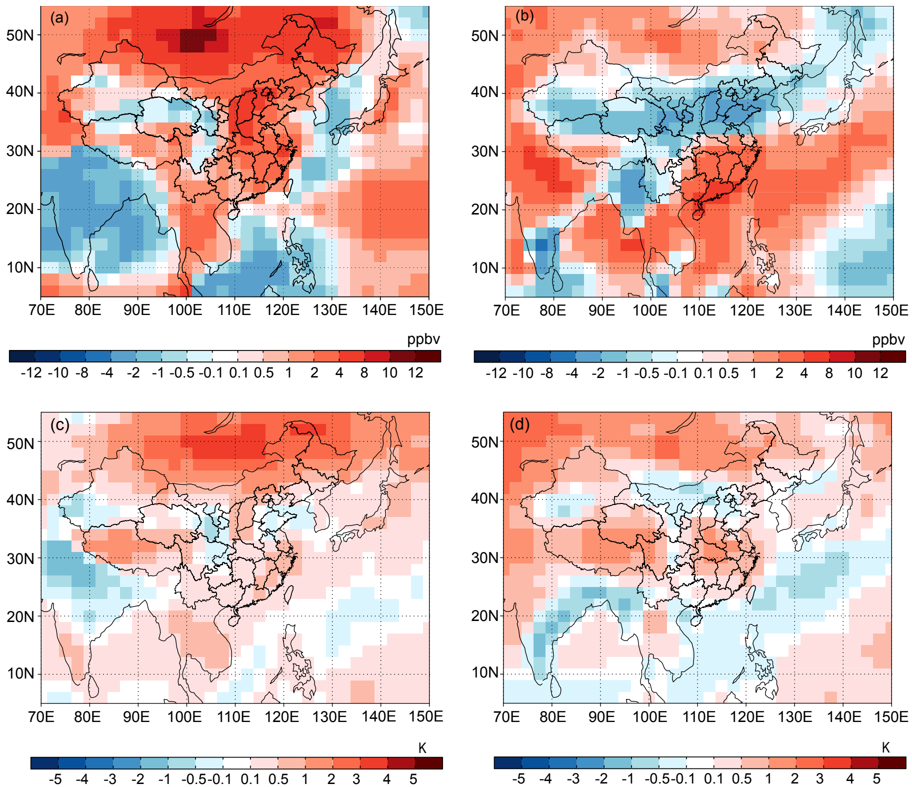

Figure 4. Changes in **(a)** surface maximum daily 8 h average ozone concentration (MDA8 O_3) in summer (JJA); **(b)** surface MDA8 O_3 in spring (MAM); **(c)** mean JJA temperature; and **(d)** mean MAM temperature driven by 1980–2010 changes in climate alone ([CTRL]–[SIM_CLIM]). Values are differences between the five-year averages over the present-day and historical periods.

ACPD
15, 14111–14139, 2015

Impacts of historical climate and land cover changes on ozone

Y. Fu and A. P. K. Tai

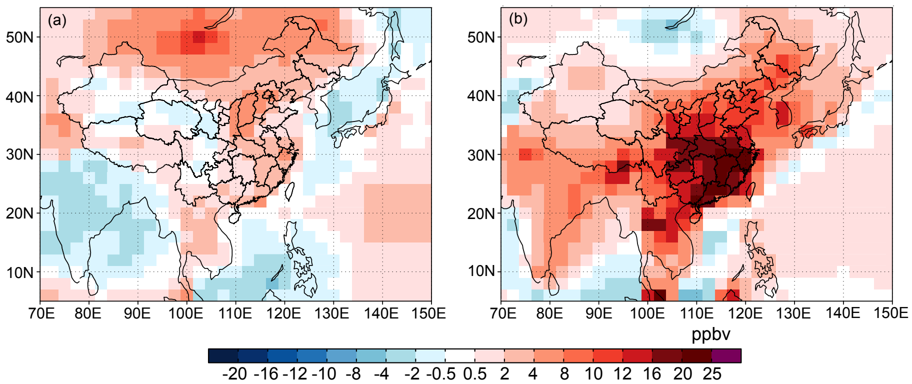

Figure 5. Changes in summertime (JJA) surface maximum daily 8 h average ozone concentration (MDA8 O_3) driven by changes in **(a)** climate, land cover and land use combined ([CTRL]–[SIM_COMB]); and **(b)** anthropogenic emissions alone ([CTRL]–[SIM_ANTH]).

ACPD
15, 14111–14139, 2015

Y. Fu and A. P. K. Tai

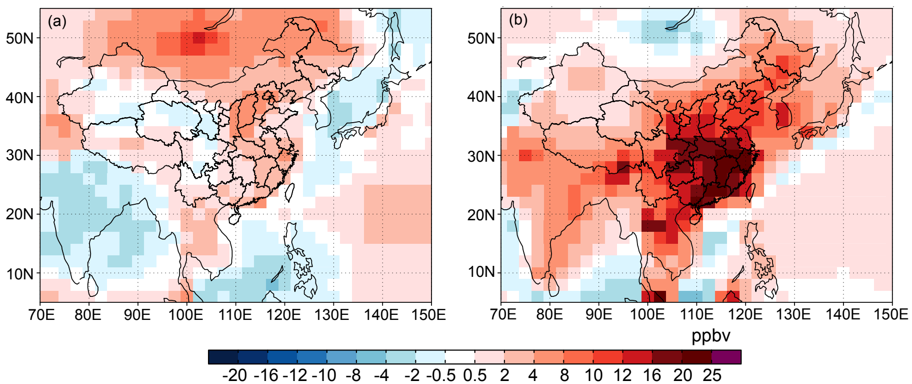

Figure 6. Estimates of ozone-related respiratory mortality (in 1000 deaths yr^{-1}) attributable to historical (1980–2010) changes in land cover and land use (LCLU), climate (CLIM), climate and LCLU combined (COMB), and anthropogenic emissions (ANTH) in all of East Asia and China. Uncertainty for each case represents the 95 % confidence interval of the concentration-response function.

ACPD
15, 14111–14139, 2015