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Contrasting regional versus global radiative forcing by megacity pollution emissions

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HIGHLIGHTS

- Apply a global chemistry-climate model to study impacts of megacity emissions.
- Quantify multi-pollutant climate effects of ten megacity regions.
- Calculate integrated radiative forcing metric on two time horizons.
- Combined pollution emissions from megacities contribute to net global warming.
- Ozone and aerosols from megacity regions have minor or no effects on global climate.

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ABSTRACT

We assess the regional and global integrated radiative forcing on 20- and 100-year time horizons caused by a one-year pulse of present day pollution emissions from 10 megacity areas: Los Angeles, Mexico City, New York City, Sao Paulo, Lagos, Cairo, New Delhi, Beijing, Shanghai and Manila. The assessment includes well-mixed greenhouse gases: carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4); and short-lived climate forcers: tropospheric ozone (O_3) and fine mode aerosol particles (sulfate, nitrate, black carbon, primary and secondary organic aerosol). All megacities contribute net global warming on both time horizons. Most of the 10 megacity areas exert a net negative effect on their own regional radiation budget that is 10–100 times larger in magnitude than their global radiative effects. Of the cities examined, Beijing, New Delhi, Shanghai and New York contribute most to global warming with values ranging from +0.03 to 0.05 $Wm^{-2}yr$ on short timescales and +0.07–0.10 $Wm^{-2}yr$ on long timescales. Regional net 20-year radiative effects are largest for Mexico City (−0.84 $Wm^{-2}yr$) and Beijing (−0.78 $Wm^{-2}yr$). Megacity reduction of non-CH_4 O_3 precursors to improve air quality offers zero co-benefits to global climate. Megacity reduction of aerosols to improve air quality offers co-benefits to the regional radiative budget but minimal or no co-benefits to global climate with the exception of black carbon reductions in a few cities, especially Beijing and New Delhi. Results suggest that air pollution and global climate change mitigation can be treated as separate environmental issues in policy at the megacity level with the exception of CH_4 action. Individual megacity reduction of CO_2 and CH_4 emissions can mitigate global warming and therefore offers climate safety improvements to the entire planet.

1. Introduction

Urbanization is a major driver of global change (Seto et al., 2014). More than half of the world's population now lives in urban areas (UNFPA, 2007). An urban area with more than 10 million inhabitants is termed a "megacity". The number of megacities has nearly tripled in the last 24 years, from 10 in 1990 to 28 in 2014 (United Nations, 2014). Megacities are planetary hotspots of atmospheric pollution emissions that contribute to air pollution and climate change across a wide range of spatiotemporal scales (Folberth et al., 2014).

Human energy use and agricultural activities in megacities and their surrounding areas emit the well-mixed greenhouse gases (WMGHGs): carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). These same fossil fuel, biofuel and biomass burning

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activities release short-lived emissions that are precursors for tropospheric ozone (O_3) and aerosol formation including nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2), ammonia (NH_3); and direct emissions of primary aerosols including black carbon and primary organic carbon. CH_4 is also an important O_3 precursor emission at large regional to global scales. O_3 and fine mode aerosols are toxic air pollutants that interact with the atmospheric radiation budget and therefore influence climate (Fiore et al., 2012). O_3 is a powerful greenhouse gas. Sulfate, nitrate and organic carbon aerosol particles scatter solar radiation back to space and lead to net global cooling. Black carbon absorbs solar radiation and warms the planet. Exposures to O_3 and fine mode aerosol have been linked in epidemiological studies to adverse health effects that include premature mortality, exacerbation of acute and chronic respiratory symptoms, and increased hospital admissions (Bell et al., 2004; Dockery et al., 1993; Pope et al., 2002; Schwartz, 1996). Thus, air quality and climate change are intrinsically linked through common emission sources and the short-lived climate forcers, O_3 and fine mode aerosols, but are usually allocated to separate policy domains with the result that actions for air pollution or WMGHG mitigation are not cross-evaluated against each other.

Concern about the environmental impacts of growing megacities led to the European Union Framework Programme 7 research projects in 2008–2011: MEGAPOLI (Megacities: Emissions, urban, regional and global atmospheric pollution and climate effects, and integrated tools for assessment and mitigation; http://megapoli.info) and CityZen (https://cityzen-project.eu). Similarly, an earlier international collaborative research project in 2006 focused on Mexico City, one of the world's largest megacities: The Megacity Initiative: Local and Global Research Observations (MILAGRO) campaign (Molina et al., 2010). Most research to date on the atmospheric impacts of megacities has focused on local air quality issues e.g. (Chan and Yao, 2008; Parrish et al., 2011). A few global chemistry-climate modeling studies begin to tackle the effects of megacity emissions on global-scale atmospheric chemistry and radiative forcing (Butler and Lawrence, 2009; Butler et al., 2012; Folberth et al., 2012; Stock et al., 2013). These studies calculated the impacts of megacity emissions on the global atmospheric composition by considering all of the world's megacities combined into a single entity perturbation using a 32-megacity global map (Butler et al., 2008). Remarkably, the studies concluded that pollution emissions from the world's 32 megacities combined make very small or negligible contributions to the O_3 global radiative forcing in the present and future world, and that the contribution is disproportionately smaller than the fractional contribution to global anthropogenic O_3 precursor emissions. The net global radiative forcing due to the direct effects of aerosols from megacity pollution emissions is also small and offsets the global O_3 radiative forcing (Folberth et al., 2012).

In this study, we apply a global chemistry-climate model to investigate the effects of pollution emissions from individual megacity regions on the global and regional atmospheric radiation budgets. We select a subset of 10 megacities for individual analyses from the 32 total that have been investigated collectively in previous studies (Butler et al., 2008). Our selection goal is to capture a range of geography, development level, and background chemistry and meteorology for the largest of the world's megacities (Fig. 1). The primary selection criterion is population size. New Delhi, Manila, Shanghai, Beijing and New York have populations over 20 million and are 5 of the world's top 10 megacities by population size. The secondary selection criterion is maximizing diversity of Köppen-Geiger climate zones. The final selection criterion is maximizing diversity of emission profiles. We target less well-studied tropical and subtropical megacities that are strongly influenced by household biofuel, biomass or agricultural burning (Lagos, Manila, Sao Paulo) or transportation emissions (Cairo). In addition, we pursue a well-studied megacity that has already experienced several decades of air pollution control (Los Angeles).

The previous studies were based on global emission inventories for ~2000 and ~2005, which is updated to a more recent time period here (2008/2010). The short-lived climate forcers are removed from the atmosphere in days to weeks such that their annual average radiative impacts are determined by the current year's emissions only. In contrast, the WMGHGs may persist in the atmosphere for decades to centuries such that assessment of annual average radiative effects from the current year's emissions must take into account the build up of WMGHG atmospheric concentrations over time. Therefore, our climate metric of choice is the integrated radiative forcing on the 20-year and 100-year time horizons due to a one-year pulse of present day emissions from each megacity region (Myhre et al., 2013a). This assessment includes emissions from all human-related activities that may occur in the megacity region: surface transportation, power plants, industry, residential, commercial, solvents, waste, agriculture, agricultural waste burning and biomass burning.

2. Methods

2.1. NASA GISS ModelE2 global chemistry-climate model

We apply the NASA GISS ModelE2 global chemistry-climate model to quantify the effects of megacity region emissions on the short-lived climate forcers (Schmidt et al., 2014). The model has $2^\circ \times 2.5^\circ$ latitude by longitude horizontal resolution with 40-vertical layers extending to 0.1 hPa. The NASA ModelE2 integration time step is 30 min. The tropospheric and stratospheric gas-phase chemistry and aerosol modules are fully integrated so that these components interact with each other and with the physics of the climate model (Shindell et al., 2013a; Unger et al., 2010). The standard tropospheric gas-phase chemistry scheme includes basic NO_x–HO_x–O_x–CO–CH_4 chemistry as well as peroxyacyl nitrates, alkyl nitrates, acetone and the hydrocarbons: terpenes, isoprene, aldehydes, alkenes, and paraffins. The lumped hydrocarbon family scheme was derived from the Carbon Bond Mechanism-4 (CBM-4) (Gery et al., 1989) and from the more extensive Regional Atmospheric Chemistry Model (RACM) (Houweling et al., 1998; Stockwell et al., 1997). Chemical calculations are performed seamlessly throughout the troposphere and stratosphere. The full scheme includes 156 chemical reactions among 56 species. The mass-based aerosol package includes simulation of sulfate, nitrate and sea salt (Koch et al., 2006), black carbon and primary organic carbon (Koch and Hansen, 2005) and secondary organic aerosol (Shindell et al., 2013a). Photolysis rates are calculated using the Fast-J2 scheme, which takes into account the model distribution of clouds, aerosols and O_3 (Bian, 2003). The NASA ModelE2 atmospheric composition has been well tested against observations and compared with other models e.g. (Koch et al., 2010; Myhre et al., 2013b; Shindell et al., 2013a, 2013b; Stevenson et al., 2013). The difference in radiative forcing calculated using modeled O_3 versus satellite-retrieved O_3 from the Tropospheric Emission Spectrometer is only $+0.016$ Wm^{-2} (Shindell et al., 2013a). The model reproduces monthly mean satellite and AeroNet observations for aerosol optical depth with a normalized mean bias not larger than 15% and a correlation coefficient of ~0.6 (Shindell et al., 2013a).

2.2. Emissions

Attributing emissions to individual cities is a complex task (Butler et al., 2008; Hillman and Ramaswami, 2010; Ramaswami