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Global and regional climate impacts of black carbon and co-emitted species from the on-road diesel sector

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HIGHLIGHTS

- Climate impacts of BC and SLFCs from current and future on-road diesel emissions.
- Significant geographical differences in the responses to regional emissions.
- Vertical sensitivities of the BC forcing/response relation important.
- Current legislation reduces impacts of on-road diesel emissions in OECD countries.
- Accelerated policy implementation outside OECD required for further mitigation.

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ABSTRACT

Diesel vehicles are a significant source of black carbon (BC) and ozone precursors, which are important contributors to climate warming, degrade air quality and harm human health. Reducing diesel emissions could mitigate near-term climate change with significant co-benefits. This study quantifies the global and regional climate impacts of BC and co-emitted short-lived climate forcers (SLCFs) from present-day on-road diesel vehicles, as well as future impacts following a current legislation emission scenario. Atmospheric concentrations are calculated by the chemical transport model OsloCTM2. The following radiative forcing (RF) and equilibrium surface temperature responses are estimated. For year 2010 on-road diesel emissions we estimate a global-mean direct RF from BC of 44 m W/m^2 and an equilibrium surface temperature response of 59 mK, including the impact of BC deposition on snow. Accounting for cooling and warming impacts of co-emitted SLCFs results in a net global-mean RF and warming of 28 mW/m^2 and 48 mK, respectively. Using the concept of Regional Temperature change Potential (RTP), we find significant geographical differences in the responses to regional emissions. Accounting for the vertical sensitivities of the forcing/response relation amplifies these differences. In terms of individual source regions, emissions in Europe give the largest regional contribution to equilibrium warming caused by year 2010 on-road diesel BC, while Russia is most important for Arctic warming per unit emission. The largest contribution to warming caused by the year 2050 on-road diesel sector is from emissions in South Asia, followed by East Asia and the Middle East. Hence, in regions where current legislation is not sufficient to outweigh the expected growth in activity, accelerated policy implementation is important for further future mitigation.

1. Introduction

Black carbon (BC) aerosols have received significant attention over recent years due to their important impact on the climate system through several mechanisms; absorption of solar radiation (direct effect), influence on clouds and deposition on snow and ice, e.g., (Warren and Wiscombe, 1980; Hansen and

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Nazarenko, 2003; Flanner et al., 2007; Quinn et al., 2008; Ramanathan and Carmichael, 2008; Koch and Del Genio, 2010; Bond et al., 2013). Current best estimates give a direct radiative forcing (RF) over 1750–2010 of +0.4 (+0.05,+0.8) W/m^2 for fossil fuel and biofuel BC and +0.2 (+0.03,+0.4) for biomass burning BC (Myhre et al., 2013), while Bond et al. (2013) estimate an industrial-era forcing of BC through all mechanisms of +1.1 (+0.17,+2.1) W/m^2.

BC has a short atmospheric residence time and concentrations hence respond quickly to reductions in emissions. This, combined with the potentially strong climate warming, has directed attention to BC reductions as a potential measure for mitigating near-term warming (Bond and Sun, 2005; Quinn et al., 2008; Grieshop et al., 2009; Kopp and Mauzerall, 2010; UNEP/WMO, 2011; Bowerman et al., 2013). There are large regional and temporal variations in effects of BC emissions, which are important to understand in order to formulate effective mitigation strategies. In particular there has been significant policy focus on BC impacts on Arctic climate. The Arctic Monitoring and Assessment Program evaluated the role of BC on Arctic climate (AMAP, 2011) and the Arctic Council advocates increased reductions in Arctic BC (ACTF, 2013; MM08, 2013). In Norway the Climate and Pollution Agency is developing a National Action Plan for reducing emissions of short-lived climate forcers (SLCFs) and similar work is underway in other Nordic countries. Furthermore, the amendments to the Gothenburg Protocol to The Convention on Long-range Transboundary Air Pollution include, for the first time, particulate matter in the emission reduction commitments for 2020 and beyond (LRTAP, 2012). Reducing BC emissions will provide additional air quality and health co-benefits (Shindell et al., 2011; Chambliss et al., 2013). When considering measures for BC reduction, diesel engines offer among the best mitigation potential based on a set of criteria for net climate impact, mitigation technologies and cost effectiveness (Bond et al., 2013).

The current road transportation sector is a significant source of BC, providing 10–20% of global BC emissions (Uherek et al. (2010); Bond et al. (2013); this study). Of this, diesel engines are responsible for more than 90%. In some countries diesel vehicles account for up to 70% of total BC emissions (Kupiainen and Klimont, 2007; Amann et al., 2013). Stringent vehicle emissions standards and fuel sulfur limits motivated by air quality and health considerations are already in place in OECD (Organization for Economic Co-operation and Development) countries (e.g., Delphi_Inc. (2013)). Such regulations have contributed to stabilization and recent decrease in road transport BC emissions in these regions (Kupiainen and Klimont, 2007; UNEP/WMO, 2011; Bond et al., 2013). The progressively stringent standards in the developed world serve as a roadmap for implementation of emission standards in other countries as well, but currently the standards in the developing world are less stringent and often face delays owing to poor harmonization of legislation on fuel quality (CAI-Asia, 2011; Delphi_Inc., 2013). The global vehicle fleet is set to more than double by 2050 under business-as-usual assumptions (IEA, 2008) and vehicle activity is expected to grow in all regions (Chambliss et al., 2013). With no further action to reduce future vehicle emissions, an increase in emissions is expected in many regions once the full effect of current regulations is reached (Yan et al., 2011; Chambliss et al., 2013). Hence, both the current diesel emissions and the projected change in emissions over time have significant regional variations. Furthermore, the global and regional climate impact of specific species can vary depending on the emission source region (Berntsen et al., 2006; Collins et al., 2013). The location and timing of emissions changes can thus be important for the impact on global and regional climate, which is an important consideration for design and evaluation of mitigation strategies.

The objective of our study is to quantify the climate impact of emissions of BC and co-emitted SLCFs from the current and future on-road diesel sector. In addition to providing updated estimates of the global-mean impact of the global on-road diesel sector, we focus on quantifying and understanding the causes for relative differences between emission and response regions, and the contribution from different SLCFs. The global and regional climate impacts, in terms of RF and equilibrium temperature response, due to on-road diesel emissions globally and in six emission source regions are estimated using chemistry-transport modeling, normalized RF distributions and radiative transfer calculations, and the concept of Regional Temperature change Potential (RTP) (Shindell and Faluvegi, 2010; Shindell, 2012). Due to the recent policy focus on Arctic climate impacts of BC we pay special attention to the impact of on-road diesel emissions on this region. Calculations are performed for year 2010 emissions and for emissions in 2050 following a current legislation level (CLE) scenario, providing policy-relevant knowledge about the climate impacts of emission changes following the regulations in place today and how the future impacts vary regionally.

Section 2 outlines the approach, while Sections 3 and 4 present results and discussion, followed by conclusions in Section 5.

2. Method

The methodology is presented briefly below, with a detailed description given in Section SI1 of the Supporting information (SI).

The contributions from current and future (i.e., year 2010 and 2050) on-road diesel emissions to atmospheric concentrations of BC and other SLCFs are simulated with the chemistry transport model OsloCTM2 (Søvde et al., 2008), using the gridded anthropogenic emissions data set developed with the GAINS model (http://gains.iiasa.ac.at; Amann et al., 2011) as part of the EU project ECLIPSE (http://eclipse.nilu.no) and biomass burning emissions from the Global Fire Emission Database version 3 (van der Werf et al., 2010). Section SI2 describes the current and future on-road diesel emissions. Emissions of on-road diesel BC, OC, SO_2 and ozone precursors (NO_x + CO + VOCs) are reduced by 20% globally and in six emission source regions (Europe (EUR), North America (NAM), South Asia (SAS), East Asia (EAS), Russia/Ukraine/Belarus (RBU) and Middle East (MDE)), and the impact of on-road diesel is taken as the difference between the response to a reference run with all emissions and the response to the perturbed runs. To assess the impact of the activity of the sector as a whole, we scale the response to the 20% perturbation by a factor 5. Potential non-linearities arising from scaling a small perturbation are discussed in Section SI1. The direct RF (DRF) of BC, OC, SO_4 and nitrate is calculated using 3-dimensional normalized forcing distributions with the simulated concentrations and the RF of BC in snow (snwRF) is quantified by radiative transfer calculations. The RF of NO_x/CO/VOC-induced changes in O_3 and CH_4 is calculated as described in Section SI1. To obtain a measure of temperature response we use the RTP concept, which allows for an approximation of the equilibrium surface temperature response across four broad latitude bands (60°–90°N, 28°–60°N, 28°S–28°N and 90°–28°S) to a given pattern of forcing using a set of forcing-response coefficients for each band (Shindell and Faluvegi, 2010; Shindell, 2012; Collins et al., 2013). A separate treatment of the Arctic surface temperature response to Arctic BC forcing which accounts for the vertical sensitivity in the forcing-response relationship following Flanner (2013) is used. We note that the equilibrium temperature responses are the responses to constant emissions at the 2010 or 2050 level.