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Novel policy tools to assess the environmental impacts of air pollutants

PETER STEIGLECHNER, DR APOSTOLOS VOULGARAKIS AND DR MATTHEW KASOAR

Headlines

- Anthropogenic emissions of short-lived pollutants – such as those that affect the levels of ozone and aerosol particles in the troposphere – have multiple effects on the environment and human living conditions.
- Short-lived pollutants have complex and diverse impacts on both air quality and climate. For example, sulphate aerosols, which cool the atmosphere and so offset some global warming, also increase air pollution levels and cause drought.
- The impacts of short-lived pollutant emissions on air quality and climate change vary greatly depending on both the region where emissions occur and the location of the affected region.
- The climate effects of air pollutants are best assessed on a region-by-region basis, and are not easily captured by global metrics.
- Reductions of emissions of short-lived pollutants to control air quality degradation can deliver co-benefits for mitigating regional climate change, and visa versa, as long as these reductions are not treated as a substitute for measures to reduce CO_2.
- Air quality and climate policy should be designed simultaneously to maximise beneficial outcomes.
- Novel multi-impact, multi-region emission metrics can help make such policy choices more informed.

Introduction

Short-lived pollutants such as sulphate particles, black carbon (BC), and tropospheric ozone are widely known to influence climate change indicators such as surface temperature and precipitation, and to degrade air quality.

Our ability to limit global temperature change within the 2°C target set by the Paris Agreement will be primarily determined by the cumulative emissions of long-lived greenhouse gases (GHGs), especially carbon dioxide (CO_2), after emissions have stopped. Short-lived climate pollutants (SLCPs), such as methane, ozone or BC have lifetimes of the order of days to a few decades and so impose only a short-term radiative forcing in the atmosphere. Therefore, reducing SLCPs that warm the atmosphere will have immediate benefits for climate impacts as well as air quality. A rapid reduction of CO_2 emissions can lead to lower future temperatures if warming SLCPs are simultaneously controlled[1,2].

Contents

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Box 1: Categories of air pollutants

Greenhouse gases (GHGs): Gases in the atmosphere that absorb and emit thermal radiation, and therefore warm the climate system. The most prominent greenhouse gases are carbon dioxide (CO_2), methane (CH_4), tropospheric ozone (O_3), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and hydrofluorocarbons (HFCs).

Atmospheric aerosols: Liquid or solid particles suspended in the atmosphere. Often also referred to as “particulate matter”. The most prominent aerosol constituents are sulphate, black carbon, organic carbon, dust, and sea-salt.

Short-lived pollutants: Pollutants with relatively short lifetimes in the atmosphere (i.e. from a few days to a few decades). This category includes all types of atmospheric aerosols, as well as gaseous constituents such as methane, tropospheric ozone and its precursors (nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOCs)), and HFCs.

Short-lived climate pollutants (SLCPs): A sub-category of short-lived pollutants that specifically have the characteristic of warming the climate system. The main SLCPs are methane, black carbon, tropospheric ozone, and HFCs, which are the most important contributors to the human enhancement of the global greenhouse effect after CO_2[3,4]. Most aerosol types are not SLCPs – for example sulphate aerosols, which are the aerosol type with the largest climate impact, cause cooling of the climate system, and therefore are not categorised as an SLCP. Black carbon is the main aerosol type that has important climate warming effects, and therefore is an SLCP.

What effects do short-lived pollutants have?

Short-lived pollutants do not always have warming effects on global climate (see Box 1). The primary effect of aerosol particles, for example, is to cool the climate system[5]. Short-lived pollutants also have indirect effects on temperature, such as affecting the carbon cycle (e.g. ozone causes damage to plants). Through these indirect routes, short-lived pollutants can make an impact on temperatures decades after emission. In addition to temperature impacts, short-lived pollutants can also change other parameters such as precipitation levels[6], extreme weather events[7], or air quality on local scales. These changes subsequently affect living conditions, agriculture, ecosystems, such as methane, ozone, hydrofluorocarbons and BC human health, and the economy[8].

Many short-lived pollutants have multiple effects which vary for different time-scales, some even changing from net warming to net cooling[i]. Due to their short lifetimes and the heterogeneity of the emission sources, the concentration of these pollutants – especially aerosols – is unevenly distributed in space, with the potential to significantly alter regional heating patterns. These heating patterns can affect local circulation more drastically than long-lived greenhouse gases, leading to local weather and climate effects even when the global effect of the emission is not particularly large[6,7].

Box 2: Air quality and human health

Human health is threatened by air pollution. The biggest threat comes from short-lived pollutants such as ozone, nitrogen oxides (NO_x) and particulate matter (PM, consisting of constituents such as sulphate and black carbon). PM, concentrations of particles smaller than 10μm or 2.5μm (PM10 or PM2.5), are used as a measure of air quality degradation. These fine particles can penetrate the lungs and cause respiratory diseases, cardiovascular diseases and lung cancer[8,9]. In addition to the direct effects of pollution, climate change caused by greenhouse gases and aerosols can lead to degradation of human health indirectly through affecting atmospheric chemistry processes that determine air pollutant levels.

This briefing note focuses on a group of short-lived pollutants – aerosols – but delivers messages that are also applicable for tropospheric ozone. Some of the conclusions drawn apply less so for methane (which is also short-lived from a GHG perspective) due to its more uniform distribution in the atmosphere resulting from its somewhat longer lifetime (~10 years) than other short-lived pollutants. However, it is important to consider impacts beyond global temperature when assessing impacts of any GHG.

Which metrics should be used?

Climate policy makers use metrics to evaluate and compare pollutants in terms of their impacts on global warming. For a metric that solely depends on temperature, a cooling agent could be perceived as beneficial. But if effects such as air quality or precipitation are included, these pollutants might end up being considered harmful. Most policies have focused on changes in surface temperature or radiative forcing on a global scale, as reflected by the Kyoto Protocol’s dominant use of GWP[12] (see Box 3), which has been an extremely valuable concept for climate policy design. However, as a result, the ways in which forcing and temperature changes vary in space are not accounted for. Furthermore, all metric values depend significantly on the time-horizon chosen, especially because of the different lifetimes of different pollutants, which means a varied sensitivity to short-lived pollutants (as compared to longer-lived pollutants).

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i. A NOx-emission pulse, for example, will usually have a warming effect for the first 10 years as it increases tropospheric ozone, but subsequently have a net cooling effect due to reducing methane. The crucial aspect here is the longer lifetime of methane (~10 years) compared to ozone (a few weeks).

Box 3: Emissions Metrics

Certain emission metrics have typically been used as tools to compare and evaluate pollutants' climate impacts and implement emission-control policies[2, 5, 12-16]. Traditional emission metrics with an emphasis on physical impacts include:

- **GWP (Global Warming Potential):** The average radiative forcing (a measure of heat input into the Earth system due to a specific influence, e.g. an emission) over a specified period (commonly 100 years) caused by a pulse emission of a specified GHG, divided by the average radiative forcing over the same period due to a pulse emission of the same mass of CO_2. The only metric used in the Kyoto Protocol.
- **GTP (Global Temperature-change Potential):** Similar to GWP but for global surface temperature change at a certain time horizon, relative to that caused by CO_2.

In recent years, the above metrics have also been defined for regional scales[17]:

- **RTP (Regional Temperature-change Potential):** Same as GTP, but for the impact of regional emissions on regional (and global) surface temperature.

Examples of more impacts-based emission metrics include[5]:

- **GDP (Global Damage Potential):** The ratio of the marginal damages from the emission of a gas (i.e. the damage costs to society resulting from an incremental increase in emissions), relative to the marginal damages of an emission of CO_2.
- **GCP (Global Cost Potential):** Also called price ratio. It refers to the ratios of marginal abatement costs for a range of pollutants to meet a global temperature target. Its focus is more on cost-effectiveness, whereas GDP is more suitable when policy is set within a cost–benefit framework.

We note that the more applied the metric, the higher the uncertainty (see Figure 1), and there is no ultimately right choice for all applications[5].

Emissions of short-lived pollutants are mostly controlled through air quality improvement strategies due to the immediate impact these pollutants have on human health[10,11]. However, only rarely does the design of air quality measures involve an evaluation of the climate response. An example of a trade-off between climate change and air quality is apparent in the de-sulfurisation of diesel by the EU's European emission standards. These standards improve air quality but at the same time lead to positive radiative forcing (i.e. warming) in the atmosphere, as fewer reflective aerosols are present. Conversely, the use of biofuels for energy production can reduce climate warming due to a decreased consumption of fossil fuels, but can also have adverse impacts on human health as a result of other emissions from biofuel production[9]. For climate and air quality policy makers, it is important to be aware of these trade-offs, unintended impacts, and co-benefits when designing emission control policies.

New metrics that combine multiple aspects of impacts and account for the diversity and regional nature of pollutants' effects should be designed in the future to support integrated policy-making. Such metrics would be physically-focused, but extend the traditional concepts to include the environmental impacts of pollutants beyond global temperature, and reflect impacts on a regional scale. Policy efforts could then be combined to balance benefits for climate change mitigation, human and ecosystem health, agriculture and the economy. Coordinated approaches have been shown to significantly increase the chance of reaching the 2°C or and 1.5°C threshold[2,12,18].

Here we provide an example to illustrate how current global scale metrics can be inadequate for representing the impacts of aerosol emissions, especially when it comes to including impacts on air quality and precipitation.

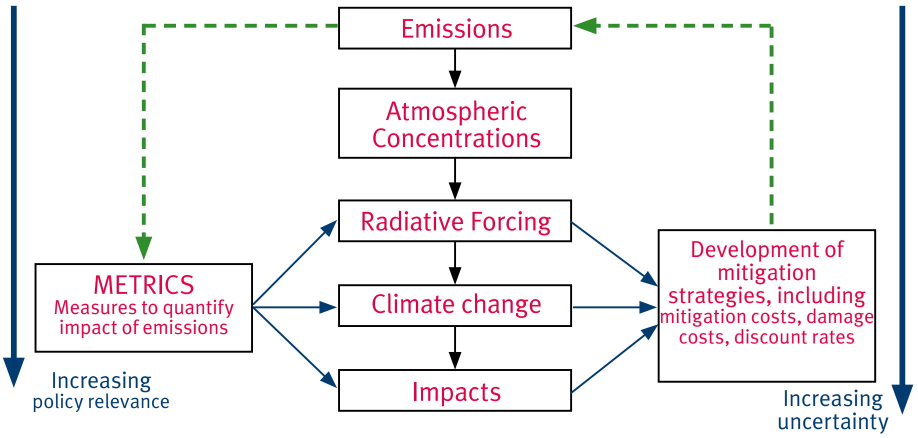


Figure 1: Diagram explaining the use of climate metrics for setting up emission control measures. The downward-structure emphasises the trade-off between accuracy and policy relevance. [Appears in IPCC AR5 WG1: Figure 8.27][1].

What conclusions can we reach from existing metrics?

Figures 2 and 3 have been constructed based on recent results from state-of-the-art global composition-climate modelling[19]. The metrics presented are derived from a single climate model. From the charts in Figure 2b, and Figure 3, the following main conclusions can be drawn:

- A pollutant can have desirable effects on temperature but undesirable effects on other important metrics such as precipitation and air quality. For example, SO_2 emissions lead to global cooling but also to global precipitation reductions (Figure 2b), especially over particularly vulnerable regions, such as the Sahel; and air quality degradation, especially in the areas of emission (Figure 3).
- The same amount of emissions (1 Tg yr^{-1} here) can have a very different impact on global and regional climate, depending on where the emissions are released. For example, here (Figure 2b), emissions from East Asia tend to have the smallest impact (per unit emission) on global temperatures and precipitation, while emissions from the US tend to have the largest impact[ii].
- The air quality effects of emissions are highly region-dependent. For example, European SO_2 emissions appear to have the largest effect on global surface PM2.5 concentrations, while emissions from India have the smallest effect (Figure 2b). However, the resulting health impacts per unit emission, considering factors like regionally-varying population densities or exposure levels, might be different again.
- The impacts are pollutant-dependent. BC has a larger impact than SO_2 on precipitation and air quality in most regions per unit emission (Figure 3; this refers to European emission impacts, and may not be true for other regions). However, BC absolute emissions are much lower than SO_2, meaning that overall SO_2 impacts are larger in reality.
- The global impacts of these short-lived pollutants are often small. Important regional impacts are often not captured and are more likely (than for long-lived pollutants) to be lost as the result of globally averaging opposing effects for different regions (e.g. compare values in Figure 2b with those in Figure 3, especially for precipitation and PM2.5).
- The regional metric values can vary substantially in magnitude and even have either positive or negative effects, depending on the region examined. There are cases (not shown) where metric values can vary even within the region, especially for precipitation. For example, 1 Tg yr^{-1} emission of BC significantly increases precipitation in Tibet but reduces it in nearby North East India in the climate model used. Meteorological and topographical effects play a major role in determining the sub-regional impacts of a pollutant, especially for precipitation.
- Emissions of short-lived pollutants can severely harm air quality on a local scale, but less so remotely (with the exception of BC impacts on Arctic air quality – see Figure 3), while their climate effects can be sizeable also remotely to the emissions.

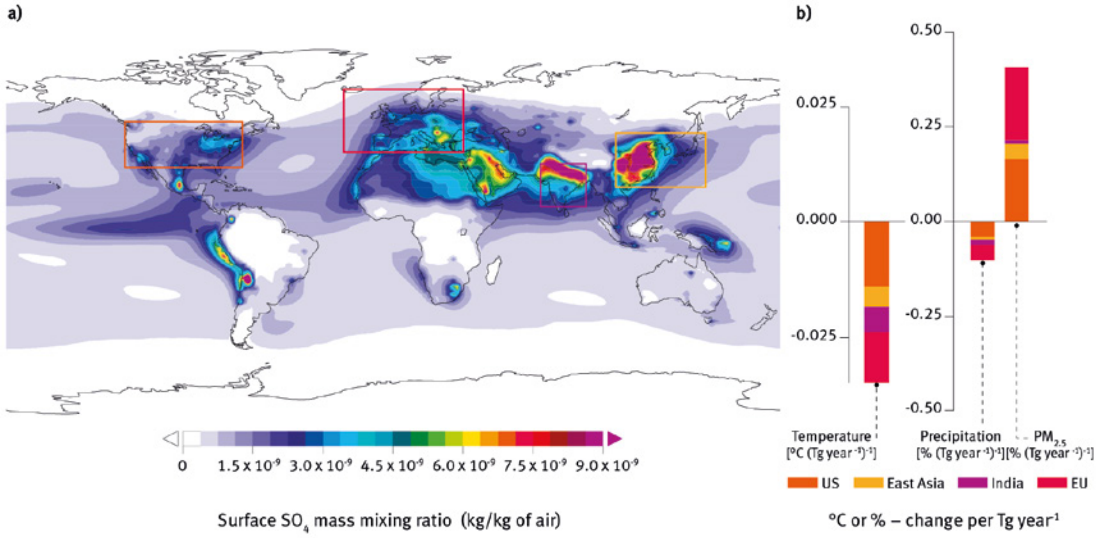
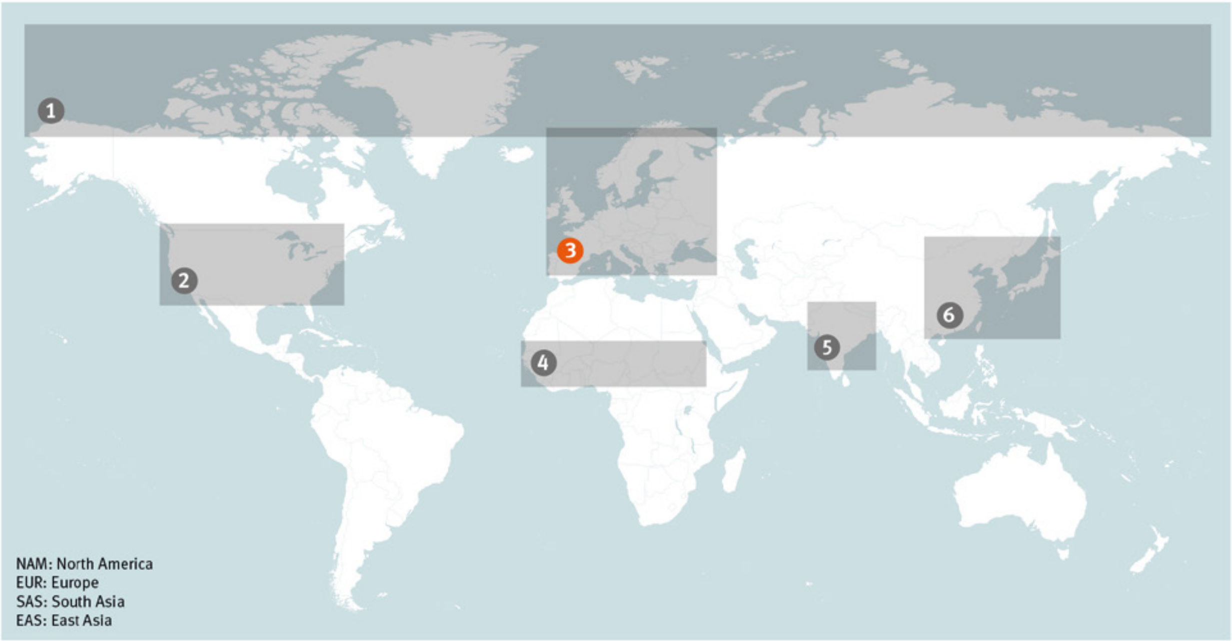
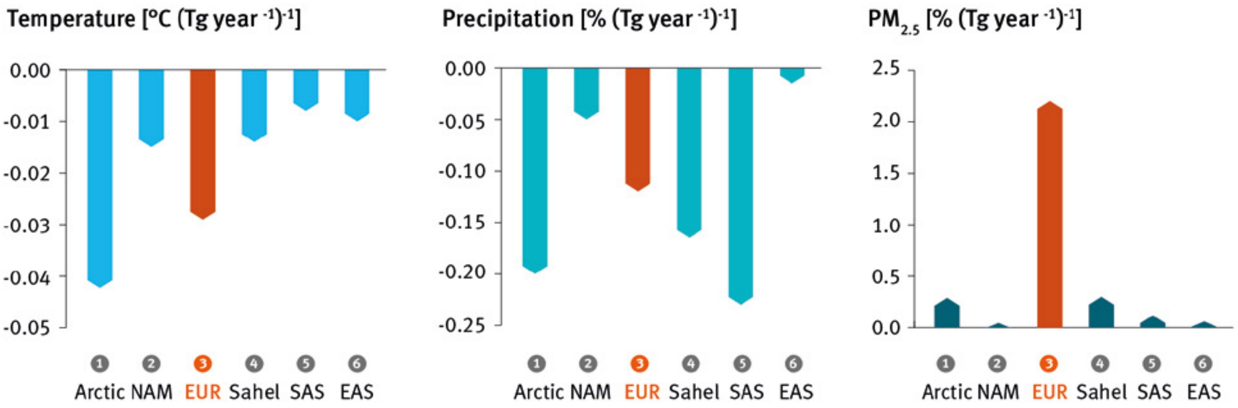


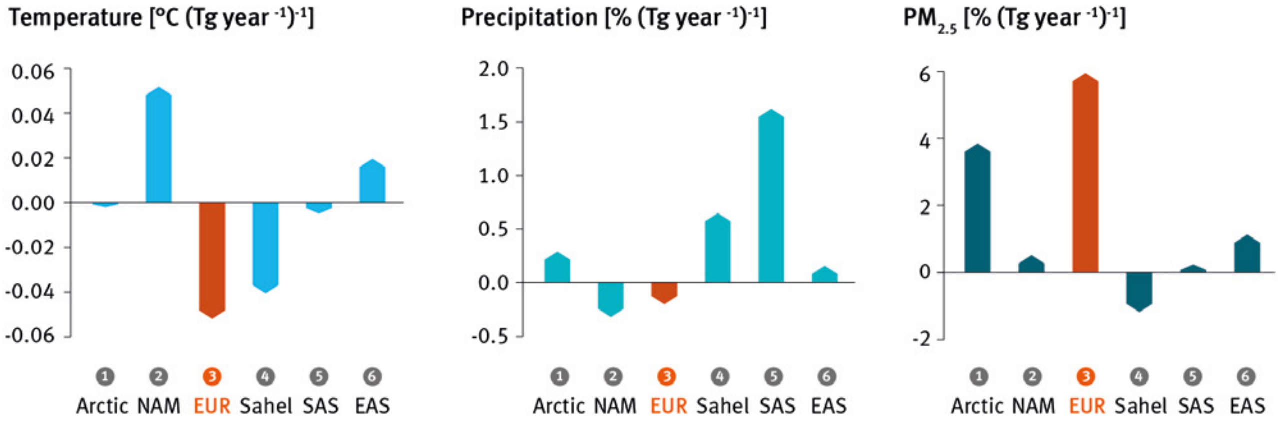
Figure 2: a) Map of year 2000 surface concentrations of sulphate, the most abundant anthropogenic aerosol constituent in the atmosphere and the most important cooling agent for climate. The distribution is highly heterogeneous, with much higher concentrations localised over industrialised areas (note: some presence of sulphate in remote areas is mainly contributed by volcanic and oceanic emissions). The rectangles indicate the areas where emissions have been examined, e.g. in panel (b); b) Global equilibrium temperature, precipitation, and PM2.5 response per unit emission of sulphur dioxide (SO_2) (which produces sulphate, and is emitted by fossil fuel burning, especially coal-fueled power plants) split into contributions from different (sustained) emission regions (rectangles on the map). Results are from novel simulations using the Met Office's climate model (HadGEM3).

[ii] However, since the total aerosol emissions from China are larger than from any other region, their overall global effect on climate ends up being larger.





Changes due to SO_2 emissions from Europe



Changes due to BC emissions from Europe

Figure 3: Impacts of European emissions (per Tg yr^{-1} emitted) of sulphur dioxide (which produces sulphate aerosols) and BC on equilibrium temperature (T), precipitation (P) and PM2.5 concentration on a variety of important regions (selected either because they are highly populated, or because they are highly vulnerable to climate change). We focus on effects of European emissions as an example, though similar maps for the impacts of emissions from all regions shown in Figure 2a are available. Note that the BC effects on temperature and precipitation are generally not significant in this model when averaged over such broad regions, which is in agreement with previous multi-model studies[20,21] stressing the weaker role of BC compared to sulphate on large-scale climate. Note that the axes scales used vary depending on the pollutant (SO2 or BC) examined. Note that some variation is expected when using other models.

Combined metrics and best practice

Emission metrics focused only on global effects and warming have limited applicability when it comes to investigating the wide-ranging effects of short-lived pollutants on climate and air quality variables. This evidence indicates a need for a) regionally focused and b) multi-impact metrics in global environmental policy discussions. By being aware of the relationship between climate change and air quality impacts for different pollutants, the policies and measures that control anthropogenic emissions should simultaneously aim to enhance benefits for air quality and climate change mitigation. Air quality controls could even act as a driver for strong climate change mitigation policies[22] as policies to control CO_2 can lead to (often unintentional) reductions of short-lived air pollutants. In addition, it should be recognised that GHGs (such as CO_2) are traditionally not thought of as pollutants, but can drive changes in pollution levels through effects on atmospheric chemistry via climate[9].

To refine suitable emission targets, new climate metrics should include regional effects as well as a multi-impact evaluation. Regional metrics have been the subject of some research focus in recent years[17], while approaches on multi-impact metrics have only just started[23]. The main challenge now is how to compare climate change and air quality impacts on a level footing. Options include studying the cause-effect chain from temperature or precipitation changes to damages to compare various climate change impacts to air quality degradation and subsequently provide a unified assessment. To do this the different weightings of impacts (e.g. by population, by area, by location type etc.) and their discount rates[5] must be considered. The damage estimates are currently uncertain as changes in air quality and climate have a wide range of impacts on human living conditions and the environment.

Future evaluation of emission metrics could include additional aspects such as the increasing number of extreme weather events or sea level rise. To make these multi-component metrics more policy relevant, they could be designed to focus on specific emission sectors, such as power generation, transport, agriculture etc.[24]. By being aware of the different impacts on climate and air quality when evaluating emission control measures, policy-makers can try to create win-win situations with emission control strategies. Some examples of such strategies, such as the promotion of healthy plant-based diets or improving diesel particle filters, have been proposed in recent studies[4,25].

An additional use of simple metrics, such as those presented here, is that they can provide rapid calculations of the large-scale impacts of emissions from individual countries such as the UK[iii]. For example, using the documented reductions in SO_2 emissions from fuel combustion activities in the UK since 1970[26], in conjunction with the model-derived values from Figure 2a, we can estimate that without the sulphur emissions reductions in the UK, there would have been 0.18°C of cooling (in equilibrium) over the European continent since 1970, and 0.07°C of cooling globally, mediating the continuous GHG-induced warming[iv]. However, there would have also been decreases in precipitation levels both in Europe (by 0.7%) and elsewhere (e.g. by 1.4% over India and by 1% over the Sahel), and an increase in surface air pollution levels (PM2.5) especially over Europe (13%). Additionally, European and UK policy making can utilise such metrics for rapid estimates of the impacts of emissions from other regions on Europe, and, with further appropriate downscaling, the UK.

As noted earlier, the results that we present here are derived from a single climate model, which has been shown to be particularly sensitive when it comes to its climate response to sulphate aerosols[21]. These metrics will, at least to some extent, depend on the model used. For increased confidence, there is a need for more modelling groups to estimate such metrics to arrive at a consensus for their values.

Short-lived pollutant abatement measures to improve air quality can offer significant co-benefits for tackling climate change, as long as the reduction of SLCPs is not treated as a substitute for CO_2 reduction. However, the impacts of short-lived pollutants are wide-ranging and complex, varying considerably depending on where the emissions come from and the region where impacts are examined. Multi-impact, multi-region emission metrics can help make such policy choices more informed.

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[iii] We assume that the values for European emissions are broadly representative of countries within Europe, such as the UK.

[iv] Note that this calculation is solely accounting for SO2, and ignores other co-emitted gases and aerosols that can cause either warming or cooling.

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About the authors

Peter Steiglechner is a Master's student in physics at FAU Erlangen-Nuremberg in Germany, who pursued a two-month internship at Imperial College London during his undergraduate studies to work on this paper.

Dr. Apostolos Voulgarakis is a Lecturer in Global Climate & Environmental Change in the Space and Atmospheric Physics Group at Imperial College London. Before that, he was a research scientist at the NASA Goddard Institute for Space Studies and Columbia University, after pursuing a PhD at the University of Cambridge. He leads a team focusing on studies of climate change interactions with other components of the Earth system such as atmospheric composition and fire, primarily using global modelling tools and satellite information.

Dr Matthew Kasoar is a Research Associate in Climate Modelling at the Grantham Institute at Imperial College London. Prior to this he also completed his PhD in the Department of Physics at Imperial College London. His research focuses on simulating the regional and global climate impacts of different non-uniform forcings, using both complex and idealised models of the atmosphere and ocean.

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