Future Arctic Temperature Change resulting from a Range of Aerosol Emissions Scenarios

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Key Points

Reductions in anthropogenic black carbon emissions alone could slow Arctic warming by mid-century.

Arctic cooling from reduced BC is more than offset by warming from reduced SO_2 across all of the RCP mitigation scenarios.

Domestic and transport emissions from Asia hold the greatest potential for reducing Arctic warming from anthropogenic aerosols

Abstract

The Arctic temperature response to emissions of aerosols – specifically black carbon (BC), organic carbon (OC), and sulfate – depends on both the sector and the region where these emissions originate. Thus, the net Arctic temperature response to global aerosol emissions reductions will depend strongly on the blend of emissions sources being targeted. We use recently published equilibrium Arctic temperature response factors for BC, OC, and sulfate to estimate the range of present-day and future Arctic temperature changes from seven different aerosol emissions scenarios. Globally, Arctic temperature changes calculated from all of these emissions scenarios indicate that present-day emissions from the domestic and transportation sectors generate the majority of present-day Arctic warming from BC. However, in all of these scenarios, this warming is more than offset by cooling resulting from SO_2 emissions from the energy sector. Thus, long-term climate mitigation strategies that are focused on reducing carbon

dioxide (CO_2) emissions from the energy sector could generate short-term, aerosol-induced Arctic warming. A properly phased approach that targets BC-rich emissions from the transportation sector as well as the domestic sectors in key regions – while simultaneously working toward longer-term goals of CO_2 mitigation – could potentially avoid some amount of short-term Arctic warming.

Index Terms and Keywords

Short-lived climate forcers

Black carbon

Arctic climate

Climate policy

1. Introduction

Climate change in the Arctic has important regional implications due to its potential impacts to human health, ecosystems, economic interests, infrastructure, and traditional ways of life. Changes in the Arctic may also have global implications, whether due to thawing permafrost accelerating emissions of stored carbon from frozen ground [e.g., *Schuur* et al., 2015], reduced surface albedo adding to global warming [e.g., *Holland and Bitz*, 2003], or possible connections between Arctic temperature change and large-scale weather patterns [e.g., *Francis and Vavrus*, 2012]. Strategies focused on mitigating Arctic climate change – in particular, strategies that mitigate Arctic temperature increases – could therefore have both regional and global benefits.

Short-lived climate forcers (SLCFs) are a subset of greenhouse gases (GHGs) and aerosols that absorb or scatter radiation and remain in the atmosphere for relatively shorter time periods compared to other, long-lived GHGs (e.g., carbon dioxide, CO_2). This group of climate forcers includes carbonaceous aerosols such as black carbon (BC) and organic carbon (OC) (atmospheric lifetimes of 3–8 days), ozone (~ 22 days), and sulfate (~ 4 days), and also includes species with relatively longer lifetimes such as methane (~12 years) and some hydrofluorocarbons (typically 1-20 years). SLCFs contribute considerably to Arctic temperature change; emissions of BC, in particular, are estimated to generate approximately 0.5 K of present-day Arctic warming, which is approximately equivalent to the projected reduction in Arctic warming attainable by 2050 under the most aggressive GHG mitigation scenario [e.g., *Sand* et al., 2015]. Temperature responses in the Arctic are stronger relative to global responses for all forcing agents, including SLCFs, due to Arctic amplification [e.g., *Holland and Bitz,* 2003]. Moreover, BC in particular may amplify Arctic temperature change because deposition onto snow and ice surfaces reduces surface albedo, causing a forcing that results in local, surface warming [e.g., *Hansen and Nazarenko*, 2004; *Flanner* et al., 2007; *Jacobson*, 2010].

Because of the relatively short lifetimes of these atmospheric constituents, reducing emissions of SLCFs– in particular aerosols such as BC – has been identified as a potentially fruitful avenue for slowing Arctic warming in the short-term [e.g., *AMAP*, 2015; *Sand* et al., 2015]. However, such emissions reductions must be carefully planned to achieve the desired results. BC typically has a net warming effect on Arctic temperatures, whereas co-emitted aerosols such as OC and sulfur dioxide (SO_2) – the precursor to atmospheric sulfate – are typically net cooling [e.g., *Sand* et al., 2015; *Smith and Mizrahi*, 2013]. As one example, recent work suggests that declining SO_2 emissions from Europe may have resulted in as much as 0.5˚C of observed Arctic warming over the past 25 years [e.g., *Navarro et al.*, 2016]. Thus, reducing emissions from sources that have higher ratios of BC to OC and SO_2 will result in greater temperature reduction benefits [e.g., *Bond* et al., 2013]. Furthermore, the latitude of emissions sources has a strong impact on the Arctic temperature response. BC emissions from higher latitudes tend to reside lower in the Arctic atmosphere and are more likely to deposit to local snow surfaces than emissions from lower latitudes, and therefore typically generate a stronger Arctic temperature response per ton of emissions [e.g., *Sarofim* et al., 2013; *AMAP*, 2015]. Thus, the net Arctic impact of different emissions reduction strategies will depend on both the location and sources being targeted.

Using a multi-model ensemble, the Arctic Monitoring and Assessment Programme (AMAP) estimated the equilibrium Arctic temperature response per unit of sustained emissions of BC, OC, and SO_2 from six sectors and seven regions [*AMAP*, 2015]. Using these temperature response factors, *Sand et al*. [2015] estimated that an aggressive, aerosol and ozone precursor focused mitigation scenario could reduce Arctic warming by up to 0.2 K by 2050 compared to a "business as usual" strategy. Although this scenario represents a useful upper bound on potential Arctic temperature reductions from mitigation of these substances, it assumes very targeted mitigation measures and does not consider implementation costs or broader goals for long-term GHG stabilization [e.g., *van Vuuren* et al., 2011a; *Stohl* et al., 2015].

Because any future climate change strategy must meet a wide range of objectives – including mitigating both short- and long-term climate change, protecting air quality, and minimizing implementation costs – it is useful to consider the implications of a broader range of emissions reduction pathways in the context of short-term impacts on the Arctic. This study extends the results of *AMAP* [2015] and *Sand et al*. [2015] by using the equilibrium temperature response factors from those studies to estimate the Arctic temperature changes resulting from a wider range of current and future emissions scenarios. Specifically, we used present-day and future global emissions for BC, OC, and SO_2 from three sources: (1) two scenarios (CLE and MIT, representing a Current LEgislation and a MITigation scenario) developed for the Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants (ECLIPSE) project [*Stohl* et al., 2015]; (2) each of the four representative concentration pathways (RCP8.5, RCP6.0, RCP4.5, and RCP2.6) developed for the Intergovernmental Panel on Climate Change Fifth Assessment Report [e.g., *van Vuuren* et al., 2011a]; and (3) a reference scenario pathway from the Global Change Assessment Model (GCAM) version 4.2 [*Kim* et al., 2006; *Thomson* et al., 2011]. Two of the above datasets represent reference case projections of future pollution control (ECLIPSE-CLE and GCAM-Ref), although these do differ in that the CLE scenario assumes no additional policies, while the Ref scenario assumes that additional controls are implemented as incomes increase in the future. Although we also acknowledge the contributions of other SLCFs such as ozone and methane to Arctic temperature change (e.g., *Shindell* et al. [2012]), we do not explicitly consider those species in this analysis.

Three of the RCP scenarios (RCP6.0, RCP4.5, and RCP2.6) represent future emissions pathways that assume actions to reduce greenhouse gas emissions to reach the specified radiative forcing levels by 2100, while the fourth scenario (RCP8.5) leads to 8.5 W/m^2 of radiative forcing in 2100 with forcing continuing to increase. Each of these four scenarios was developed using a different integrated assessment model (IAM) – Message for RCP8.5 [*Riahi* et al., 2011], AIM for RCP6.0 [*Masui* et al., 2011], GCAM for RCP4.5 [*Thomson* et al., 2011], and IMAGE for RCP2.6 [*van Vuuren* et al., 2011b]. Emissions of BC, OC, and sulfate were harmonized in the year 2000 by these four groups, but diverge after that date partly due to model differences, and partly as a consequence of different policy and technology assumptions made in order to reduce radiative forcing in the stabilization scenarios. All four RCPs assume that rising incomes will lead to more stringent air pollution controls in the future. One dataset (ECLIPSE-MIT) illustrates strong action to limit global emissions of BC. While many of the details of these scenarios are idealized (such as assumptions of near-term global actions to reduce GHG emissions in three RCPs, and maximum feasible reductions of BC in the ECLIPSE scenario), their use provides a wide range of near-term results for use in this analysis. Although most of these emissions scenarios also include projections for species such as methane and nitrogen oxides, we focus our analysis on BC, OC and sulfate as these SLCFs have the shortest atmospheric lifetimes and therefore the most immediate effects on short-term Arctic warming.

For each of these scenarios, we estimate both present-day, aerosol-induced Arctic temperature change and a range of future Arctic temperature changes resulting from different assumed aerosol emissions pathways. Based on the total emissions from the different scenarios and the Arctic temperature change per unit of emissions, we also identify key combinations of regional and sectoral emissions where targeted emissions reductions could provide the largest short-term Arctic temperature mitigation benefits.

2. Methods

We used the equilibrium temperature response factors from *Sand* et al. [2015] to calculate the Arctic temperature change attributable to each sector-region pair for all of the current and future emissions projections. For each sector-region pair, these calculations included temperature response factors that account for direct and indirect forcing from OC and sulfate, in addition to direct BC forcing in the atmosphere and from BC deposition onto snow and ice. As detailed by *Sand* et al. [2015], these factors were derived from the global distributions of radiative forcing for each sector-region pair, simulated by four different aerosol models, combined with regional temperature potentials provided by *Shindell and Faluvegi* [2009], *Collins* et al. [2013], and *Flanner* [2013]. The emissions sectors as defined by AMAP [2015] and *Sand* et al. [2015] are energy+industry+waste (EIW), transport (TRA), domestic (DOM), agricultural burning (AGR), wildfires (i.e., burning of forests, savanna, woodland, and peat; FIR), and flaring (FLR). The regional groupings include the United States (USAM), Canada (CANA), Russia (RUSS), the Nordic (NORD) countries (Denmark, Finland, Iceland, Norway, and Sweden), the rest of Europe (OEUR), Asia (ASIA), and the rest of the world (ROW).

Uncertainty in future Arctic temperature change caused by aerosol emissions can be separated into contributions from uncertainty in (1) the spatial and temporal distributions of radiative forcing resulting from aerosol emissions changes, (2) Arctic temperature response to these patterns of radiative forcing, and (3) current and future aerosol emissions. *Sand* et al. [2015] explore the first contribution by incorporating radiative forcing estimates from four distinct global aerosol models, all driven with identical emissions from each region/sector combination. The spread in net forcing estimates across these models is small for many individual region/sector emissions pairs (20% of the mean or less), but is large for other pairs (see *Sand* et al. [2015], Figure 1). Moreover, *Eckhardt* et al [2015] evaluated the Arctic concentrations of BC and sulfate simulated by these models, and found that while the models miss some important details in the seasonality and spatial distribution of deposition, they simulate reasonable annual-mean surface concentrations compared with measurements from six Arctic monitoring stations.

Uncertainty in the regional temperature response to forcing (contribution 2) was not quantified by *Sand* et al. [2015], due to the very large computational cost and effort associated with conducting a sufficient number of equilibrium climate simulations. Most of the regional temperature response factors applied here and by *Sand* et al. [2015] were derived from a single climate model [*Shindell and Faluvegi*, 2009]. Future studies applying multiple models to derive these response factors will lead to a more thorough understanding of uncertainties associated with temperature response factors, but such quantification is beyond the scope of this study.

The purpose of this study is to explore the third contribution to uncertainty in Arctic temperature evolution (namely, current and future emission scenarios). Uncertainty in present-day emissions results from challenges in estimating both emission factors and activity levels for polluting sectors. Future emissions projections involve uncertainty in societal decision making, population growth, economic development, and technology development, which we believe to be among the largest sources of uncertainty in future Arctic temperature change.

We obtained gridded BC, OC, and SO_2 emissions data for the ECLIPSE version 5 dataset from the ECLIPSE project site (http://eclipse.nilu.no) and for the RCPs from the online RCP database (http://tntcat.iiasa.ac.at/RcpDb/). For these gridded emissions data, we subdivided total emissions using the same regional definitions as those used by *Sand* et al. [2015]. The GCAM was reconfigured here to produce a reference emissions scenario with regional and sectoral definitions to also match those used by *Sand* et al. [2015]. Note that this scenario is distinct from the RCP4.5 scenario, which is a stabilization scenario and was produced by an earlier version of the GCAM.

The ECLIPSE inventory does not include aerosol emissions from wildfires. Thus, we applied year 2007–2010 emissions from the Global Fire Emissions Database (GFED) version 3 [*van der Werf* et al., 2010] to the ECLIPSE scenarios, to allow comparisons with the RCP and GCAM scenarios. The sectors from GFED applied here are: peat, deforestation, savanna, forest, and woodland. The agricultural burning sector from GFED was omitted because it is included in the ECLIPSE inventory. Since changes in future wildfire emissions are largely outside of the control of emissions policy prescriptions, we assume that these emissions remain constant in both future ECLIPSE scenarios. Wildfire emissions are allowed to change, however, in the future RCP and GCAM scenarios. For the GCAM and the RCP scenarios, the sectoral definitions do not correspond directly to the emissions inventories from ECLIPSE/GFED; thus, we bundled these emissions data into categories that matched those used in ECLIPSE/GFED.

3. Results

3.1 Summary of Current and Future Emissions

Figure 1 illustrates the global distribution of BC and OC emissions in 2010, showing the key emissions sources and sectors based on the combined ECLIPSE/GFED dataset. As shown in Figure 1, aerosol emissions in the northern hemisphere are dominated by emissions from Asia, with the majority of these emissions coming from the domestic, transport, and EIW sectors.

Although total emissions from the highest latitudes are dominated by wildfire, anthropogenic emissions from these latitudes come primarily from the EIW sector. Wildfire emissions represent the single largest source of emissions in the southern hemisphere. Although other sectors such as international shipping are not considered here, aerosol emissions from these sources generally have much smaller contributions to Arctic warming relative to the sectors we evaluated here, despite potentially large growth in Arctic shipping activity as sea ice retreats, and a high per-ton impact of emissions emitted directly in the Arctic [*Browse* et al. 2013]**.**

Global present-day (2010) emissions estimates for BC, OC, and SO_2 are generally similar across all of the scenarios, with minor exceptions. In particular, OC emissions are approximately 20% lower for ECLIPSE/GFED than for the other scenarios, and SO_2 emissions are approximately 20% higher for GCAM than for the other scenarios. These differences in present-day emissions are generally small relative to differences in future emissions projections across the scenarios (Figure 2). In particular, SO_2 emissions from all of the RCP scenarios decrease substantially over the first half of the century, with several of these scenarios projecting SO_2 emissions decreasing to less than half of their 2010 value by 2050. BC emissions decrease only slightly across the different scenarios, with the exception of the ECLIPSE-MIT scenario, which is based on mitigation strategies that specifically target BC emissions [e.g., *Stohl* et al., 2015]. OC emissions also decrease only slightly across the majority of the scenarios, with the exception of the ECLIPSE-MIT scenario, which shows these emissions decreasing by approximately 30% by 2050, consistent with the reduction in co-emitted BC.

3.2 Arctic Temperature Change from Present-Day Emissions

With the exception of the ECLIPSE/GFED dataset, all of the emissions scenarios project approximately the same net global aerosol contribution to Arctic temperature change. The present-day (2010) contribution of BC to Arctic equilibrium temperature change ranges from approximately +0.7 to +0.8 K across all scenarios, and the total contribution of OC and sulfate to Arctic temperature change ranges from approximately -0.8 to -1.1 K (Figure 3). The net present-day global contribution of BC, OC, and sulfate to Arctic temperature change is therefore negative, and ranges from approximately -0.2 to -0.3 K across all scenarios except ECLIPSE/GFED. For ECLIPSE/GFED, the net aerosol contribution to Arctic temperature change is approximately -0.03 K. This smaller net cooling from the ECLIPSE/GFED scenario is due to a combination of slightly larger BC warming and slightly smaller OC and SO_2 cooling than the other scenarios.

Estimates of the sectoral contributions of aerosols to current Arctic temperature change are also broadly consistent across the different emissions scenarios. Emissions from the domestic and transportation sectors generate net Arctic warming of approximately +0.1 to +0.2 K and +0.05 to +0.1 K, respectively, whereas emissions from the EIW sector generate net cooling of approximately -0.3 to -0.5 K (Figure 4). Total emissions from wildfire are large globally, but because BC warming from wildfire is largely balanced by OC cooling, the net contribution of global wildfire to Arctic temperature change is close to zero. Arctic temperature changes due to agricultural emissions are also smaller than the other sectors.

Notably, the EIW sector represents the largest sectoral contribution to present-day Arctic cooling. This is because sulfate cooling from this sector is up to five times greater than BC warming. As will be discussed later, this implies that global GHG mitigation strategies could have unintended short-term consequences for the Arctic, since emissions reductions from the energy sector (e.g., targeting CO_2) figure prominently into all of the most aggressive GHG mitigation scenarios, and any such strategies would necessarily result in reduced sulfate [e.g., *van Vuuren* et al., 2011a]. However, it is important to note that the EIW sector has very heterogeneous sources: some, like industrial coal boilers, are likely to have higher sulfate and lower BC emissions than the average EIW sector source and contribute to global and Arctic cooling, and others, like certain brick kilns or construction machinery (included in the industry sector in the IAM models), are more BC-rich and can contribute to global and Arctic warming [*Bond* et al., 2013].

When emissions are evaluated by sector and region, domestic emissions from Asia represent the single-largest source of aerosol-generated Arctic warming, contributing a net Arctic warming of almost 0.1 K (Figure 5). Although there is significant variability across the different emissions scenarios, net warming from this sector is more than twice as large as the next largest anthropogenic warming source, the Asian transportation sector (~ 0.03 K). Domestic and transportation emissions from Arctic Council nations (USAM, CANA, NORD, and RUSS) are also net warming; however, despite the proximity of these high-latitude emissions sources to the Arctic, the net contribution of these sources to Arctic warming is small when compared to emissions from Asia. Aerosol emissions from the energy sector contribute to net Arctic cooling from all of the regions defined by AMAP, with the most significant cooling coming from the Asian EIW sector. Figure 5 also shows the net Arctic temperature change per capita based on 2010 aerosol emissions and population. For example, although the domestic sector in Asia is the largest single contributor to Arctic warming, the Arctic temperature change per capita from this sector is less than half of that for domestic emissions from Russia. Similarly, per capita temperature change from the Asian transportation sector is a small fraction of that from Russia, North America or Europe.

Although Arctic temperature change from global wildfire emissions is nearly net zero (Figure 4), the magnitude and sign of Arctic temperature change from wildfire emissions depends strongly on the source of these emissions. In particular, wildfire emissions from high-latitude forests have a net cooling effect in the Arctic, whereas wildfire emissions from Asia and the rest of the world have a net warming effect in the Arctic (Figure 5). This result is consistent with results from *Sand* et al. [2015], who also found that wildfire emissions from high latitudes are net cooling, whereas lower-latitude wildfires are net warming, but contrary to the intuition that wildfires closest to the Arctic would have the highest probability of being net-warming due to higher warming per ton of BC emissions. This difference between high latitude and lower-latitude wildfires in this analysis results from two factors: first, the OC:BC ratios from extratropical forest fire emissions are approximately twice as high as for low-latitude forest and grass fires [approximately 16:1 vs 8:1; e.g., *Andreae and Merlet,* 2001]; and second, wildfires at high latitudes typically occur in warmer months, when there is reduced potential for BC deposition onto Arctic snow and ice. The net result is that OC cooling outweighs BC warming by approximately a factor of two for high latitude wildfire sources, whereas the inverse is true for low latitude wildfire sources. This analysis does not consider the carbon-cycle impacts of boreal fires.

3.3 Scenarios of Future Arctic Temperature Change

Although the Arctic temperature impacts estimated using the seven different present-day aerosol emissions scenarios are similar, future Arctic temperature impacts vary considerably among scenarios and models. In this section we consider the impacts of 2030 or 2050 emissions on equilibrium temperature, relative to 2010 emissions. For example, the ECLIPSE-MIT scenario indicates up to 0.35 K of equilibrium Arctic *cooling* resulting from global aerosol emissions changes by 2030, or up to 0.45 K of equilibrium Arctic cooling associated with 2050 aerosol emissions, relative to 2010 emissions (Figure 6), indicating the potential climate benefits of targeting mitigation actions. These results are consistent with previous studies, although here we report equilibrium Arctic temperature reductions relative to 2010 emissions, rather than differences between emissions pathways from mitigation vs current legislation as reported by *Sand* et al. [2015] or mitigation relative to reference [*Smith and Mizrahi* 2013]. In contrast to ECLIPSE-MIT, the most aggressive GHG-focused mitigation strategy (RCP2.6) projects up to 0.2 K of additional Arctic *warming* from aerosol emissions reductions occurring between 2010 and 2050. The three other RCP scenarios (RCP4.5, RCP6.0, and RCP8.5) also project increases in Arctic temperature due to reductions in aerosols.

The projected aerosol-induced increases in Arctic temperature in the RCP scenarios are almost entirely due to reductions in sulfate cooling, and virtually all of this cooling comes from the EIW sector (Figure 7). This result – that GHG mitigation can lead to "unmasking" of warming by reducing SO_2 emissions – is consistent with a number of previous studies that have shown that mitigation of CO_2 from coal combustion can lead to short-term increases in global temperature due to reduced co-emissions, followed by longer-term decreases in global temperature due to the GHG reductions [e.g., *Charlson* et al., 1992]. Our analysis demonstrates that this effect is important for the Arctic as well. Thus, although the longer-term temperature benefits of aggressive GHG mitigation via CO_2 reductions would at some point offset this short-term Arctic warming via aerosols [e.g., *van Vuuren* et al., 2011a], the GHG mitigation strategies embodied by the RCP scenarios may come at a short-term cost in terms of Arctic temperature change. In contrast, the ECLIPSE-MIT scenario demonstrates that targeted BC reduction can achieve short-term cooling, and this suggests that combining BC-targeted policies with GHG mitigation policies could reduce the short-term unmasking effect. Further exploration of the transient effects of both aerosol and CO_2 mitigation strategies is warranted to evaluate how longer-term temperature change due to CO_2 reductions would interact with short-term effects due to "unmasking" of warming from aerosols [e.g., *Rogelj* et al., 2014].

3.4 Arctic-Focused Aerosol Mitigation Strategies

Each of the emissions scenarios included in our evaluation has specific assumptions embedded within it regarding future population, technological, and policy changes, or strategic objectives for climate stabilization. As a result, these emissions scenarios project significantly different outcomes for short-term Arctic climate change. An alternative way of looking at these data is to instead examine the major aerosol emissions sources generating present-day Arctic temperature increases, and to develop an estimate of Arctic temperature reduction potential from each region and sector. In this way, we can begin to develop customized emissions reduction strategies that would yield the most significant short-term Arctic temperature change benefits.

Figure 8 shows the net Arctic temperature change per unit of annual emissions summed across all of the major aerosol species (BC, OC, and SO_2) compared to the total emissions from each sector-region pair. Within each sector, the highest-latitude aerosol emissions sources (e.g., RUSS, CANA, and the NORD countries) tend to exert the most leverage on Arctic temperature change [e.g., *Sarofim* et al., 2013; *AMAP*, 2015]. For example, Russia exerts the highest Arctic warming per unit of emissions for the transport and domestic sectors, and the Nordic countries generate the highest cooling per unit of emissions from the energy sector. However, because total emissions from high-latitude sources tend to be orders of magnitude smaller than emissions from other regions, the total mitigation potential from high-latitude emissions reductions is relatively low. An Arctic-focused aerosol mitigation strategy must therefore rely heavily on aerosol emissions reductions from lower-latitude regions with more substantial total emissions contributions. The domestic and transportation sectors in Asia may be the clearest opportunities for these strategies (see Figure 5).

4. Summary

Because of the potential regional and global impacts of Arctic climate change, reducing Arctic temperature change in the short-term should be a priority [*AMAP*, 2015]. Previous work has indicated that very aggressive, targeted SLCF mitigation strategies have the potential to reduce Arctic warming in the short-term [e.g., *AMAP*, 2015; *Sand* et al., 2015; *Stohl* et al., 2015]. However, with an increased likelihood that long-term global GHG mitigation strategies could begin to be implemented following the Paris agreement, it is possible that strongly CO_2-focused mitigation strategies could also create short-term warming in the Arctic. In particular, as illustrated here, the most aggressive CO_2-focused mitigation strategies could generate up to 0.2 degrees of aerosol-generated Arctic warming in the short-term.

Over the long-term, future Arctic temperature benefits of global GHG mitigation under the most aggressive RCP scenarios will outweigh any short-term warming due to SO_2 emissions reductions from the energy sector. However, a properly phased approach that targets BC-rich emissions from the transportation sector as well as the domestic sectors in key regions – while simultaneously working toward longer-term goals of CO_2 mitigation – could potentially avoid some amount of short-term Arctic warming. Because of the clear co-benefits of emissions reductions from these sectors in terms of air quality and international health [e.g., *Shindell* et al., 2012], this blended approach could slow Arctic warming in both the short- and long-term, minimizing local impacts on the Arctic and potentially helping to avert some of the potential global-scale impacts of Arctic temperature change [e.g., *Schuur* et al., 2015 *Francis and Vavrus*, 2012]. While this study identifies the transport sector generally, and the domestic sector in Asia, Russia, and the rest of the world as sectors to target in order to reduce the rate of Arctic warming, it should be noted that sectors are not homogeneous. Within a given sector/region combination, mitigation of individual source types that have a higher ratio of BC to cooling aerosols can still lead to a reduction in the rate of Arctic warming even if the sector/region combination overall does not.

The net short-term impact of aerosol and GHG mitigation on Arctic temperatures will depend on the rate of emissions reductions, the timescales over which these reductions are implemented in different regions and sectors, and the timescale over which Arctic temperatures respond to changes in radiative forcings. Further exploration of the transient impacts of both aerosol and CO_2 mitigation strategies could shed further light on the magnitude and timing of Arctic temperature changes resulting from different blends of aerosol and CO_2 mitigation strategies.

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Figure Captions

Figure 1. Global distribution of BC and OC emissions in 2010, represented by the combined ECLIPSE/GFED dataset.

Figure 2. Total emissions of BC, OC, and SO_2 through time for all emissions scenarios. Major differences come from SO_2 reductions in the RCPs, drop in BC from ECLIPSE-MIT by 2025, and lower OC from ECLIPSE.

Figure 3. Equilibrium Arctic temperature change resulting from 2010 emissions across all of the emissions scenarios. Red triangles represent net aerosol contribution to Arctic temperature change from BC, OC, and SO_2 combined.

Figure 4. 2010 global contributions to Arctic temperature change, divided into individual sectoral contributions. Sectors are shown on the x-axis, and Arctic ” T is shown on the y-axis. Each sector has six bars for each of the scenarios evaluated (the two ECLIPSE emissions scenarios are identical in 2010). BC contributions are positive, whereas OC and SO_2 values are negative. SO_2 contribution is the horizontal hatched portion of the OC + SO_2 bar. Dots represent the net contribution of each sector for each inventory.

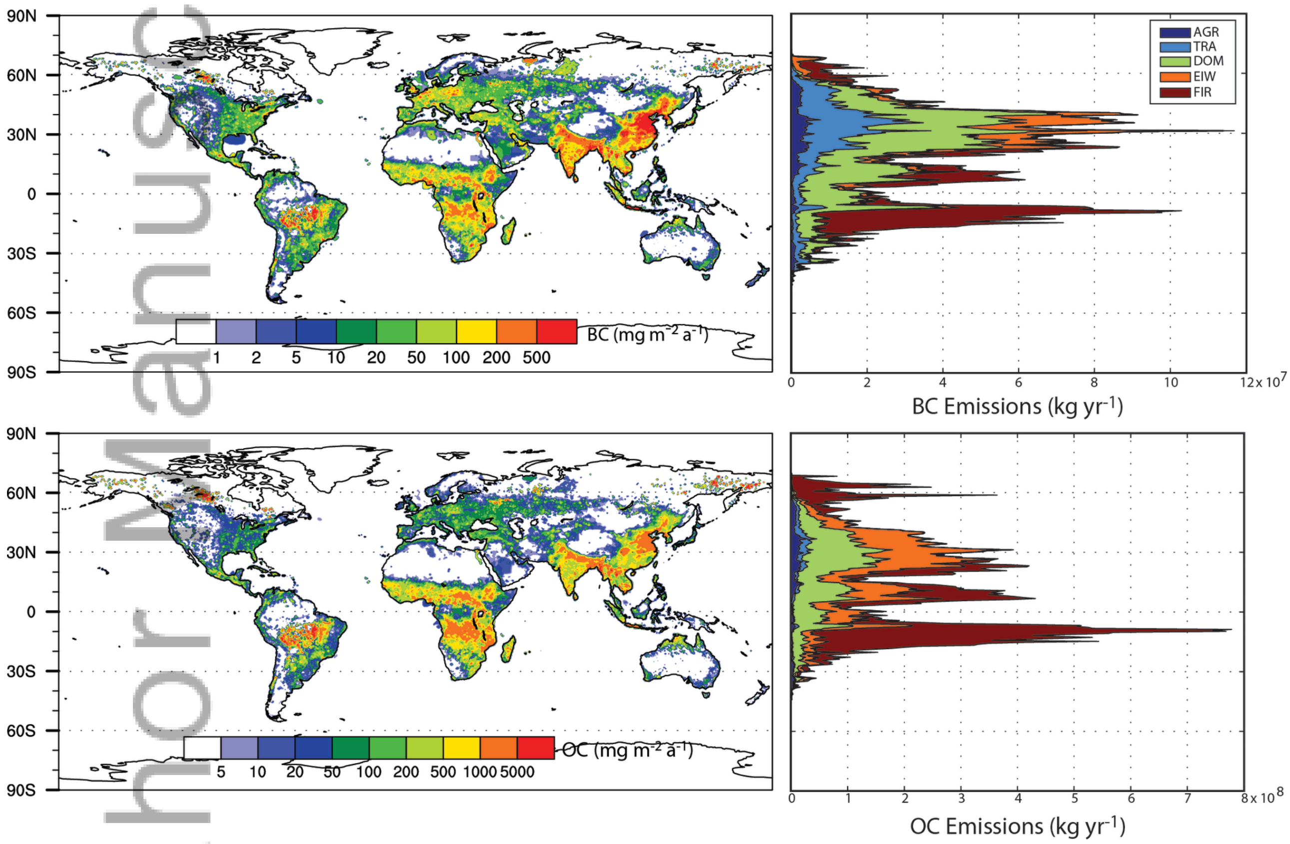
Figure 5. 2010 global contributions to Arctic temperature change, divided into individual region-sector pairs, from the GCAM model. BC contributions are positive, whereas OC and

SO_2 values are negative. SO_2 contribution is the horizontal hatched portion of the OC + SO_2 bar. Dots represent the net contribution of each sector for each region. Grey bars represent the range of net contributions from all scenarios evaluated. Lower panel shows the net Arctic temperature change per capita from the GCAM model, by sector and region.

Figure 6. Net change in Arctic equilibrium temperature for 2030 and 2050 emissions vs 2010 emissions. BC, OC, and SO_2 changes are shown by blue, green, and red bars, and net change from 2010 emissions is shown by red triangles.

Figure 7. Change in Arctic equilibrium temperature for 2030 emissions versus 2010 emissions, and 2050 emissions relative to 2010 emissions, partitioned into sectoral contributions from different scenarios. Scenarios are shown on the x-axis, Arctic ” T is shown on the y-axis, and colored bars represent individual sectors.

Figure 8. Total aerosol emissions by sector/region (x-axis) vs net ” T per unit emissions (y-axis) based on 2010 emissions. The highest Arctic temperature mitigation potential comes from region/sector pairs with high net emissions (right) and high ” T per unit emissions (top). Colored lines are contours of total Arctic temperature mitigation potential from different combinations of emissions and ” T per unit emissions.



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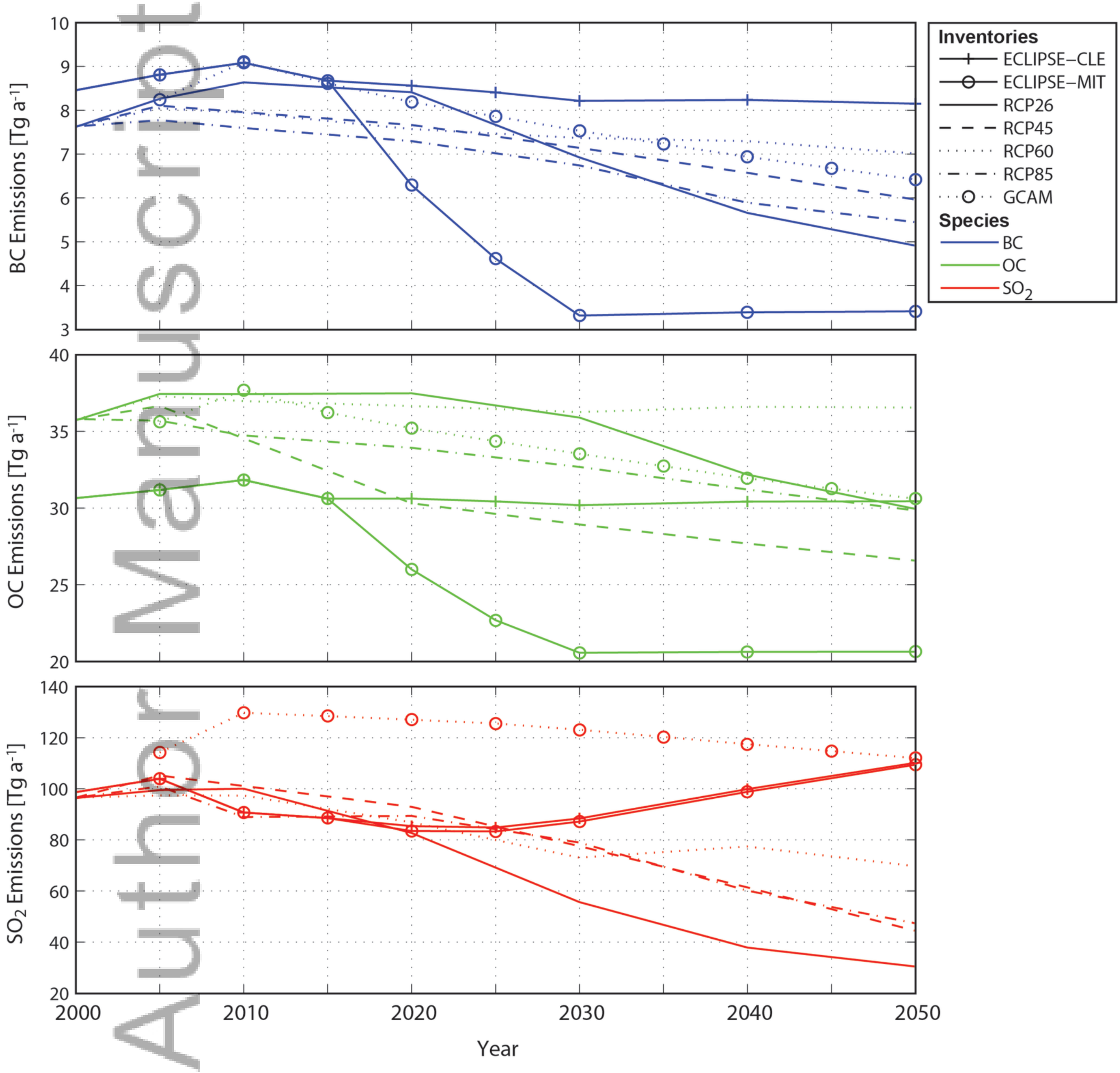

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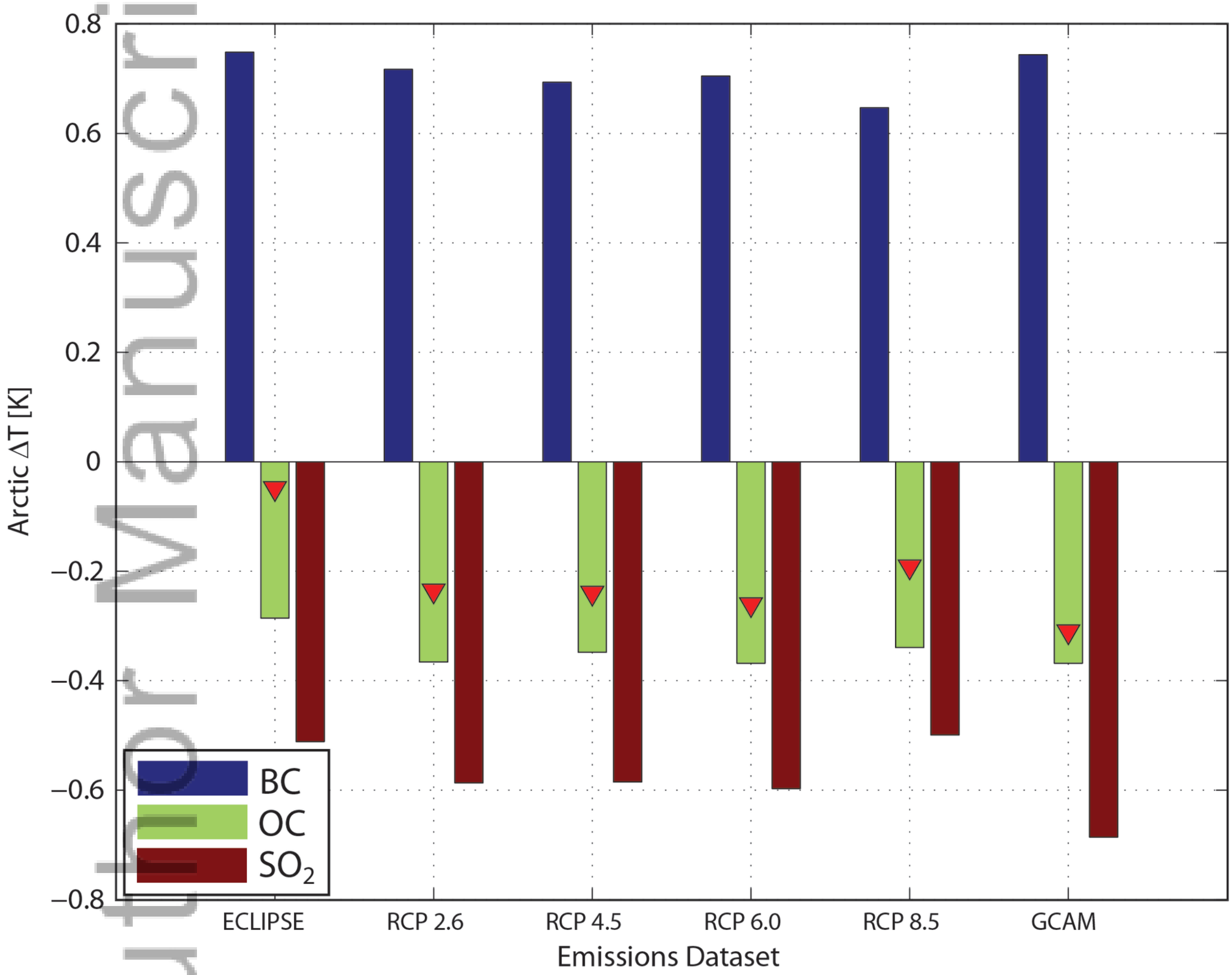

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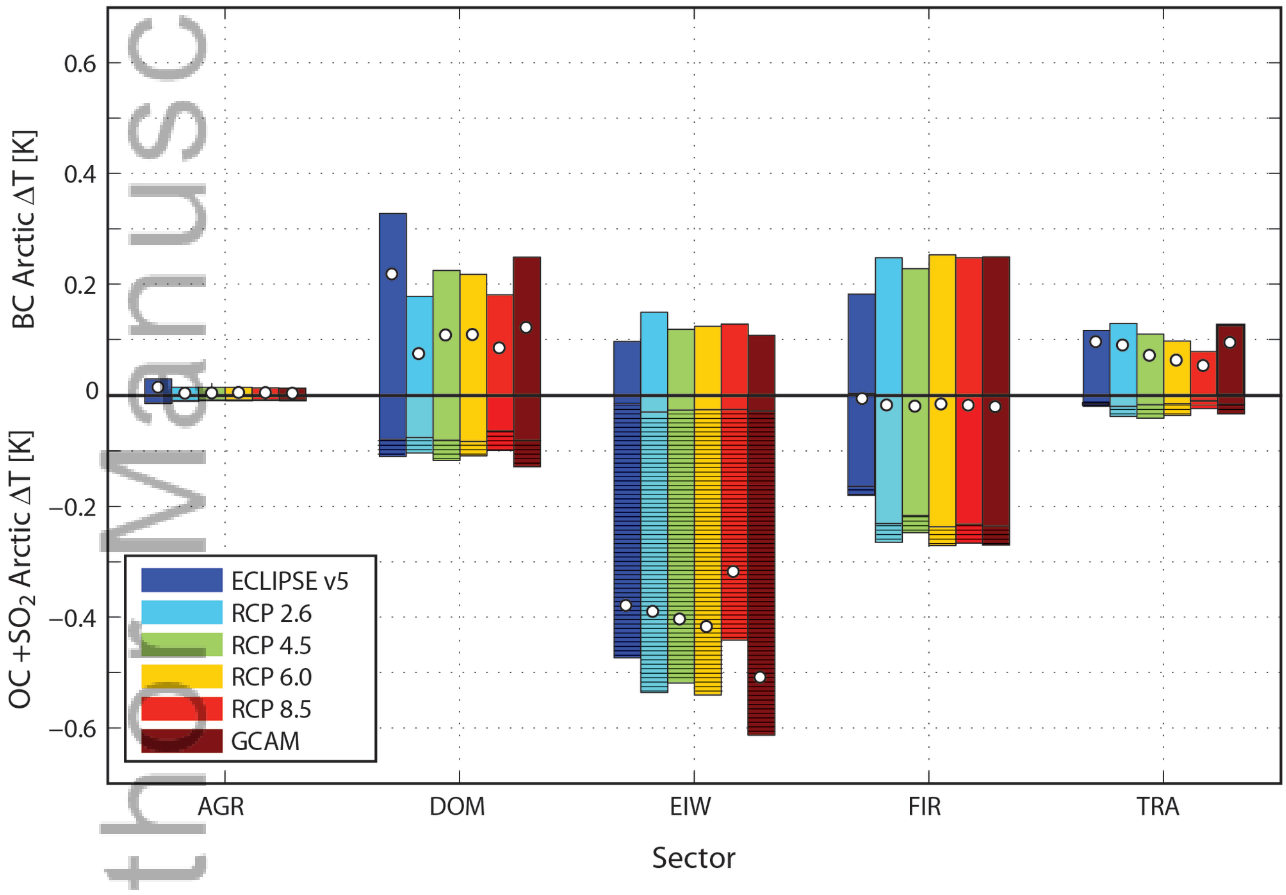

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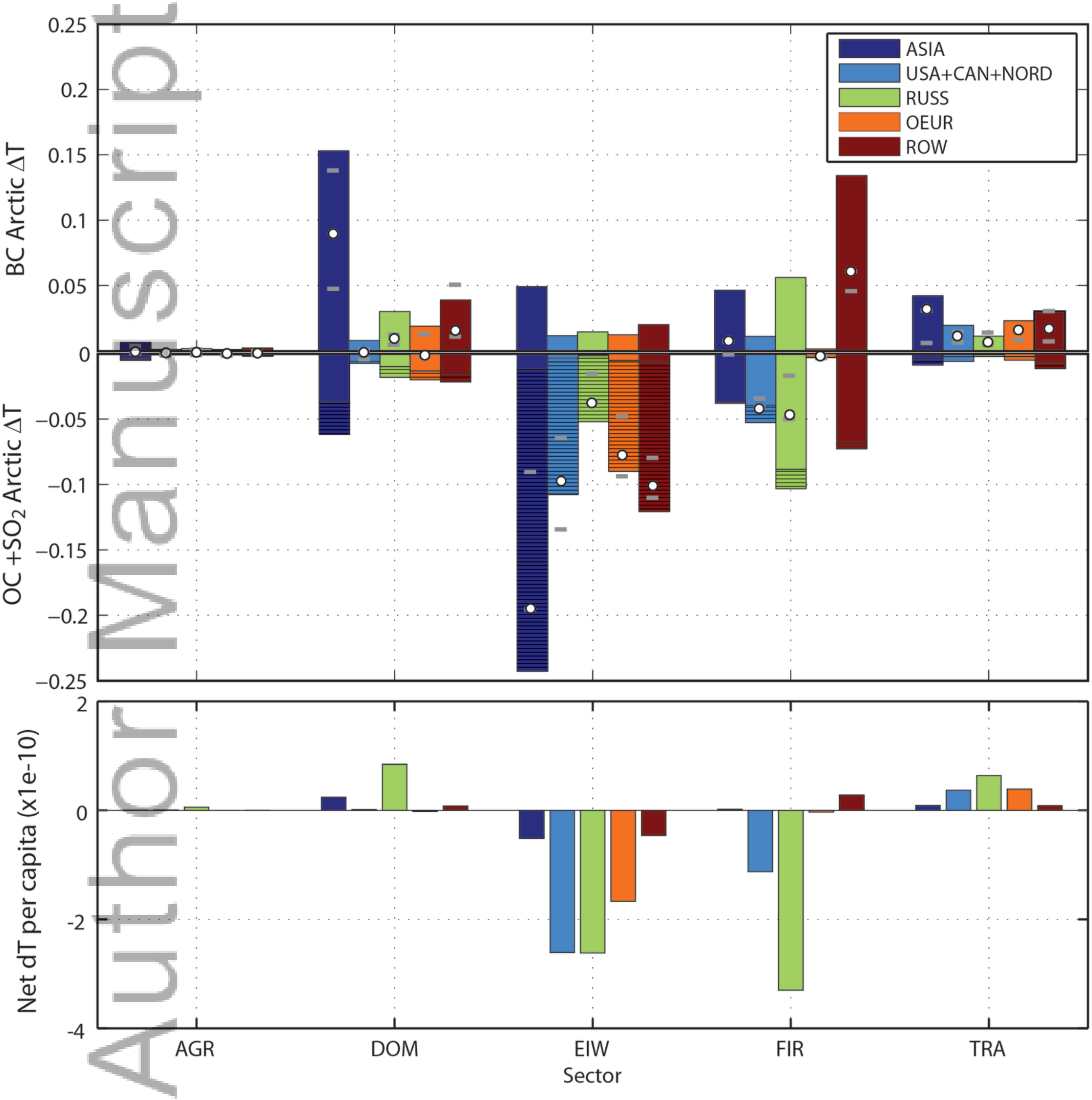

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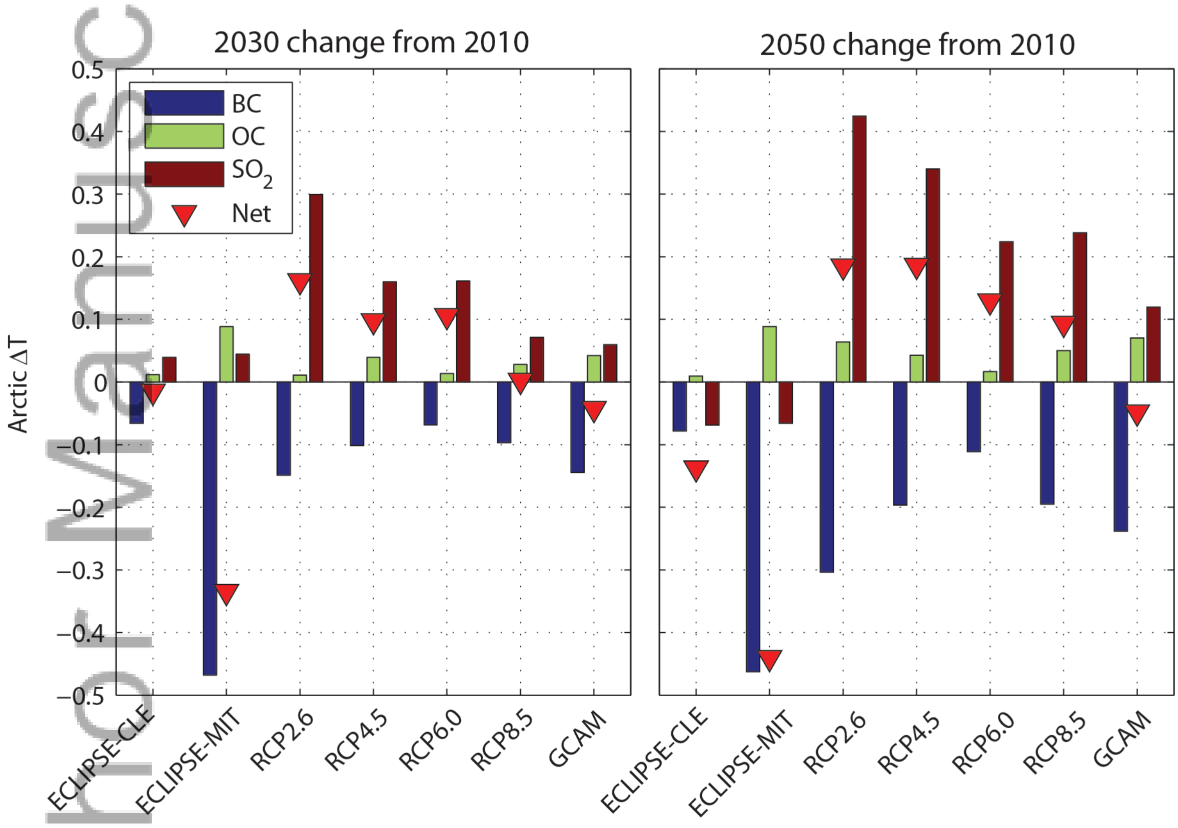

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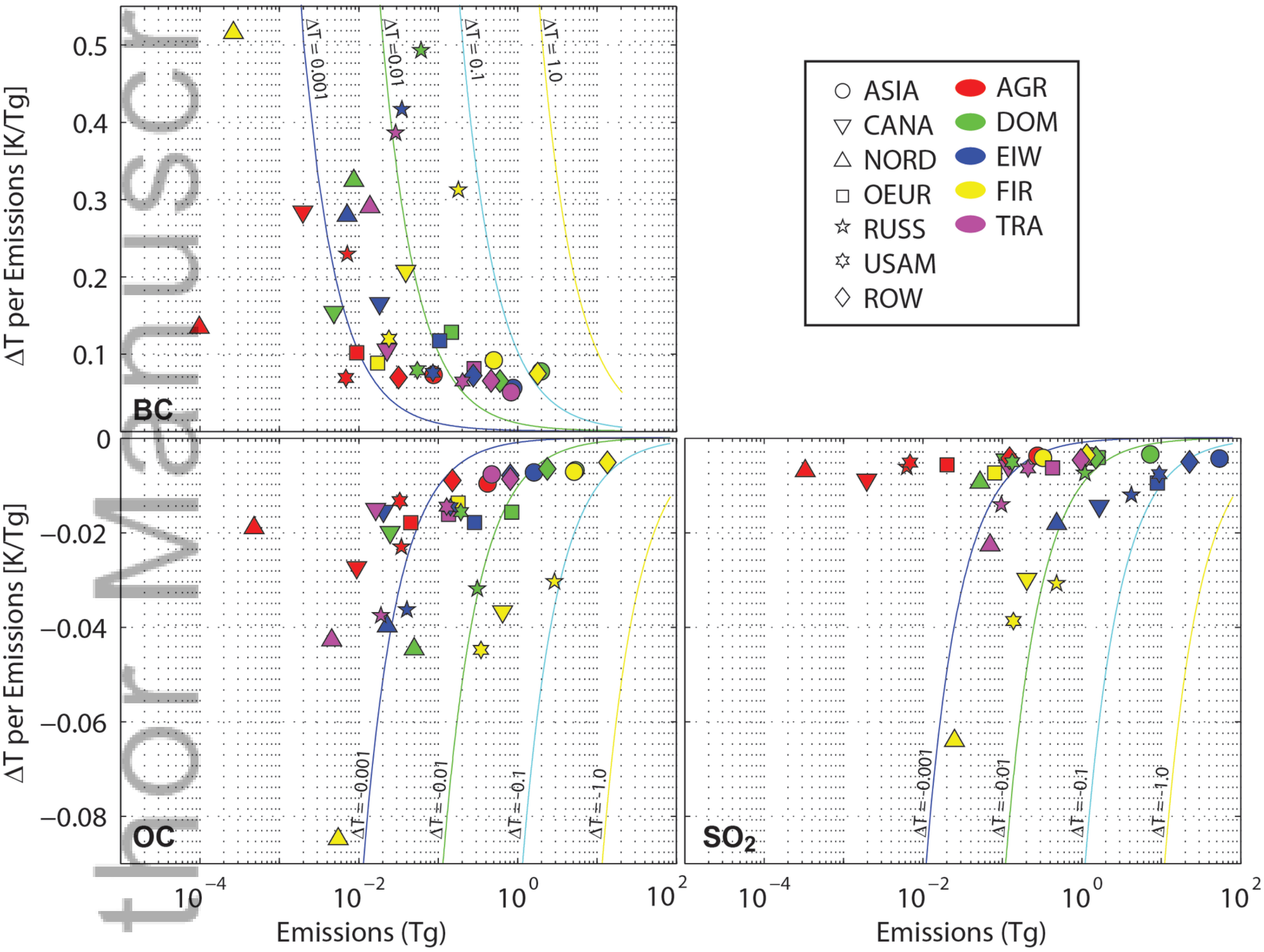

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