LETTERS
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Response of Arctic temperature to changes in emissions of short-lived climate forcers

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There is growing scientific[1,2] and political[3,4] interest in the impacts of climate change and anthropogenic emissions on the Arctic. Over recent decades temperatures in the Arctic have increased at twice the global rate, largely as a result of ice–albedo and temperature feedbacks[5–8]. Although deep cuts in global CO_2 emissions are required to slow this warming, there is also growing interest in the potential for reducing short-lived climate forcers (SLCFs; refs 9,10). Politically, action on SLCFs may be particularly promising because the benefits of mitigation are seen more quickly than for mitigation of CO_2 and there are large co-benefits in terms of improved air quality[11]. This Letter is one of the first to systematically quantify the Arctic climate impact of regional SLCFs emissions, taking into account black carbon (BC), sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), organic carbon (OC) and tropospheric ozone (O_3), and their transport processes and transformations in the atmosphere. This study extends the scope of previous works[2,12] by including more detailed calculations of Arctic radiative forcing and quantifying the Arctic temperature response. We find that the largest Arctic warming source is from emissions within the Asian nations owing to the large absolute amount of emissions. However, the Arctic is most sensitive, per unit mass emitted, to SLCFs emissions from a small number of activities within the Arctic nations themselves. A stringent, but technically feasible mitigation scenario for SLCFs, phased in from 2015 to 2030, could cut warming by 0.2 (±0.17) K in 2050.

We focus on the Arctic impact of climate forcers with atmospheric lifetimes shorter than the typical hemispheric mixing times (about one month): BC and ozone precursors (CO and VOCs) that predominantly lead to warming, as well as co-emitted species that cause cooling (SO_2, OC, and NO_x). We omit methane and HFCs as their lifetimes are longer, although some other studies on SLCFs have included these species as well. In the Arctic, the effects of BC include both the warming from absorption of solar radiation in the atmosphere and absorption of radiation from deposition on snow/ice[13–15]. The Arctic warming from BC is highly variable with season of emission, physical transport into the Arctic, and the deposition to snow and ice[16]. In addition, processes that emit BC also co-emit other particles and gases that lead to sulphate and OC aerosols. Ozone precursors (CO, NO_x and VOCs) affect climate through the formation of ozone, a potent greenhouse gas, while also changing the oxidizing capacity of the atmosphere (and thus the lifetime and levels of, for example, methane)[17].

Using several chemical transport models we perform detailed radiative forcing calculations from emissions of these species. Geographically, we separate emissions into seven source regions that correspond with the national groupings of the Arctic Council, the leading body organizing international policy in the region (the United States, Canada, the Nordic countries, the rest of Europe, Russia, East and South Asia, and the rest of the world). We look at six main sectors known to account for nearly all of these emissions: households (domestic), energy/industry/waste, transport, agricultural fires, grass/forest fires, and gas flaring. The models have different treatments of SLCFs, and have simulated the years 2006–2010 with prescribed sea surface temperatures. To estimate the Arctic surface temperature we apply regional climate sensitivities (RCSs), the temperature response per unit of radiative forcing for each SLCF (refs 18–21). The RCSs are defined in four broad latitude bands (60°–90° N, 28°–60° N, 28° S–28° N, 90°–28° S) to account for contributions by local and remote forcing to surface temperature changes in each band. For example, BC at midlatitudes may increase the transport of heat into the Arctic by locally warming the atmosphere and increasing the north–south temperature gradient[18,22]. The RCS concept applied here accounts for this.

The simulations employ anthropogenic emissions of SLCFs from the ECLIPSE emission data set V4.0a (refs 23,24) for the year 2010. Using the RCS method we estimate the total equilibrium Arctic surface temperature response to all (natural and anthropogenic) global 2010 emissions of SLCFs to be −0.44 K, with a model range of −1.02 to −0.04 K. Of this 0.48 (0.33–0.66) K is due to BC in atmosphere and snow, −0.18 (−0.30–0.03) K is due to OC, −0.85 (−0.57 to −1.29) K is due to sulphate and 0.05 (0.04–0.05) K is due to ozone. We can compare the total impact to the CMIP5 multi-model ensemble historical simulations. A cooling of −1.8 K has been estimated in the Arctic between 1913 and 2012 due to all anthropogenic forcing agents other than greenhouse gases[25], whereas using the six best CMIP5 models (ranked based on the least square errors between the simulations and observations in the Arctic), a cooling trend of −0.1 K per decade from 1900 to 2005 has been reported[1]. These numbers are higher (negative) compared to ours, but they also include more climate forcers. Also note that our temperature response is an equilibrium result, whereas the CMIP5 calculations are from transient simulations.

Figure 1 shows the annual mean Arctic surface temperature response from current emissions separated into the different emission sectors, regions and components. The largest single contribution to warming in the Arctic originates from Asian domestic emissions, followed by Russian flaring emissions. Generally, the energy sector has a cooling effect due to the relatively large direct and indirect aerosol effects of SO_2 emissions. The doughnut chart in Fig. 1 reports the fractions of the Arctic warming/cooling

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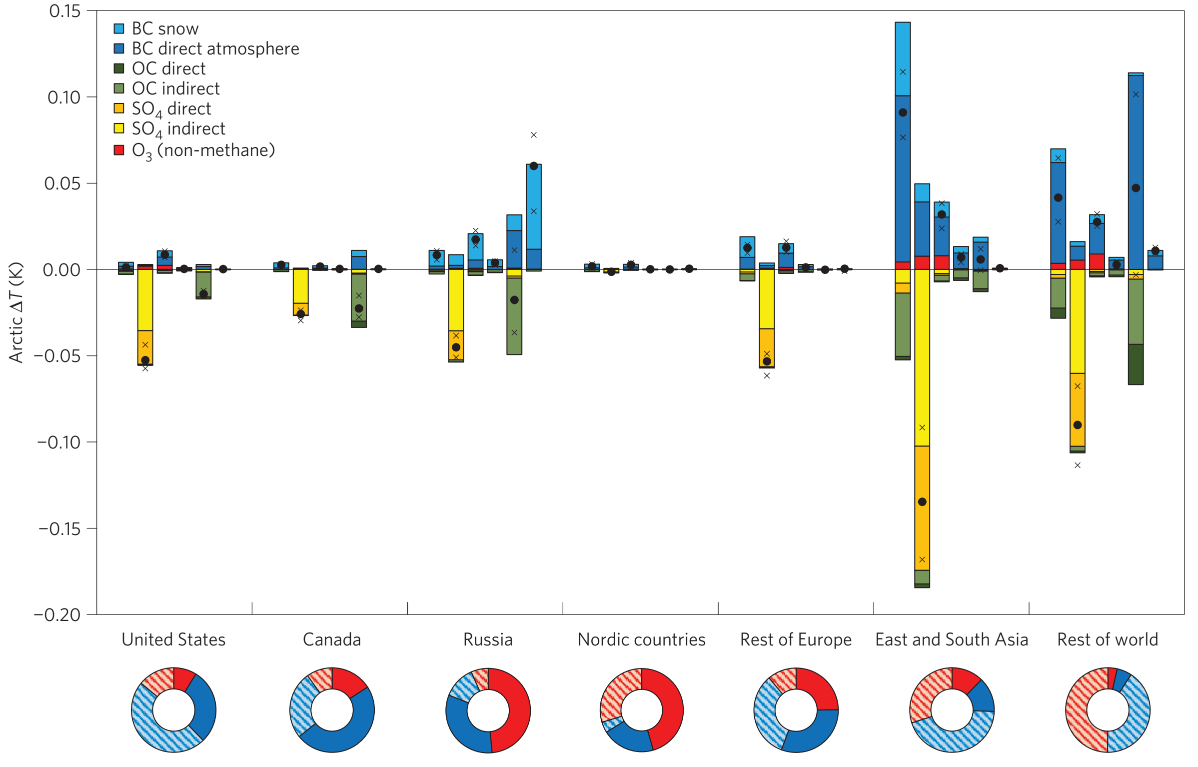

Figure 1 | Model-mean annual Arctic equilibrium surface temperature response. Each bar represents the different emission sectors for each source region specified on the *x* axis. The emission sectors are, in order from left to right: domestic, energy/industry/waste, transport, agricultural waste burning, grass/forest fires, and flaring. The black dots are the total temperature response and the crosses represent the model spread (of total response) as a root-mean-square error. The doughnuts illustrate how much of the Arctic warming (red) and cooling (blue) comes from forcing within the Arctic (solid fill) versus outside the Arctic (striped).

that are due to radiative forcing within the Arctic or outside the region—showing that most of the Arctic warming effects from Asian emissions are due to radiative forcing exerted outside the Arctic, whereas most emissions from Arctic nations such as Russia and the Nordic countries affect the Arctic more directly.

To facilitate an evaluation of the effectiveness of the emission mitigation options, Fig. 2 normalizes the temperature impacts in the Arctic from each of the regional and sectoral emissions (shown in temperature change per unit emissions; K $(\mathrm{Tg\,yr^{-1}})^{-1}$). It shows that Arctic surface temperature is most sensitive to flaring emissions from Russia, followed by forest fire and flaring emissions from the Nordic countries. This normalization of emissions also underscores earlier studies finding large warming impacts from BC via snow and ice relative to atmospheric warming. Looking at Figs 1 and 2 together reveals that although the absolute contribution from Asian emissions is large, the per unit emission impact on warming is only 13% compared to Russia and 25% compared to the Nordic countries.

We can estimate an upper bound on the potential for reducing warming in the Arctic with the recently reported global mitigation scenario (MIT) for SLCFs (ref. 24). By design, MIT includes all emission mitigation measures with both a beneficial air quality and short-term climate impact—that is, mitigation most likely to be politically feasible. Only the mitigation options that resulted in a global net cooling were included in the scenario (using the GTP_{20} metric). Because it excludes costs of mitigation, covers all measures that have even marginal impacts, and is implemented quickly over just 15 years from 2015 this should be seen as an extreme, but possible scenario if nations were to make a major push on SLCFs. Figure 3 shows the estimated difference in annual Arctic mean temperature between 2015 and 2050 between this MIT scenario and the standard current legislation scenario[26] for SLCFs. For all sectors and regions, mitigation of BC contributes most to reduced warming, with minor contributions from CO and VOCs. In terms of volume, the largest contribution to the reduction in Arctic warming comes from an improved domestic heating and cooking sector in Asia and in the rest of the world. Such measures see large cuts in warming from BC, although those benefits are offset 25–40% by reductions in the cooling effect of co-emitted OC. (For other sectors and regional sources the impact of co-emitted species is fairly minor.) This MIT scenario suggests that there is a relatively large potential net reduction in Arctic warming by 2050. However, the total reduction (0.2 K) is lower than the total current equilibrium warming by SLCFs (0.37 K), because the transient response in 2050 to these sustained emission changes is only about 65% of the equilibrium response, due to the long-term inertia of the climate system. In addition, the mitigation scenario does not reduce the emissions to zero.

Many uncertainties remain. Those include the accuracy with which the RCSs represent the climate response in the Arctic. The RCSs have been calculated with a single climate model (NASA GISS). The robustness of this approach has been evaluated against historical aerosol forcings in three other climate models, which found that nearly all RCS-based estimates fell within 20% of the explicitly simulated transient climate responses[19]. Other research[22], focused on BC within the Arctic and midlatitudes, has found these RCSs fell within 15% of the response from the NorESM model used in the present study. The inclusion of indirect effects—which we have done for aerosol cloud effects from sulphate and OC, but not BC—is another source of uncertainty. Earlier work suggests the indirect effects of BC can be both positive and negative[27], and in our simulations the forcing by indirect effects of BC was small compared to OC and sulphate.

To avoid large long-term warming of the Arctic, deep cuts in CO_2 emissions are needed. However, in the near term (up to 2050) even the large difference between CO_2 emissions in the RCP2.6 and

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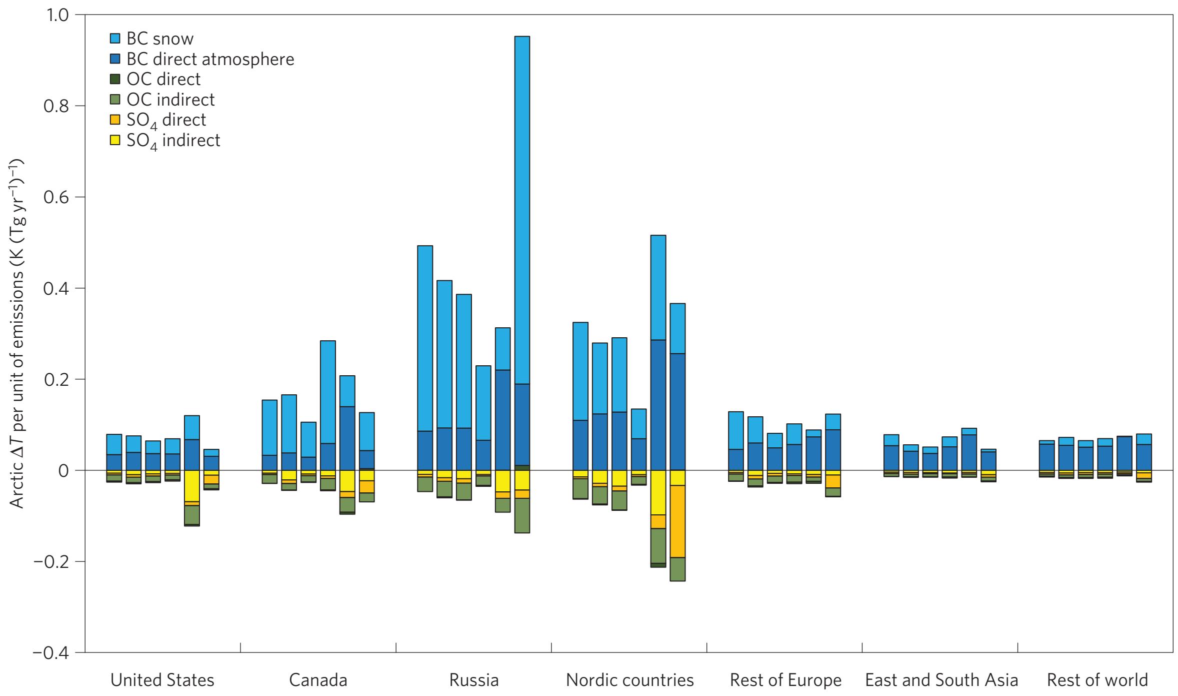

Figure 2 | Annual mean Arctic equilibrium surface temperature response per unit of emissions due to direct forcing of BC, BC in snow, and direct and indirect forcing from OC and sulphate averaged over the models. The sectors for each emission region are (in order from left to right): domestic, energy/industry/waste, transport, agricultural waste burning, grass/forest fires, and flaring. Ozone precursors are not shown as separate simulations for individual ozone precursors were not performed and would not be strictly comparable.

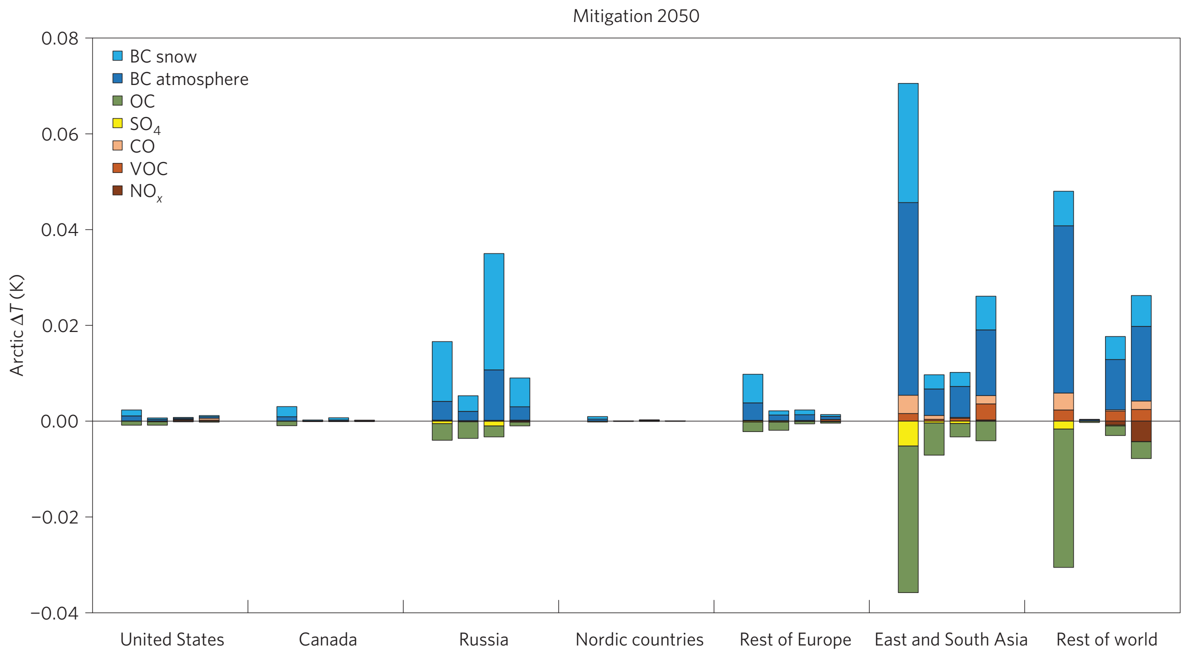

Figure 3 | Contribution to annual mean reductions of Arctic surface temperatures in 2050 due to mitigation of SLCFs according to the MIT mitigation scenario. The sectors for each emission region are (from left to right): domestic, agricultural waste burning, energy/industry/waste, and transport. Flaring is included in energy/industry/waste. Both direct and indirect aerosol effects are combined for OC and sulphate. CO, VOCs and NO_x are ozone precursors.

RCP8.5 scenarios[28,29] cause a reduction in Arctic warming (by CO_2 only) of only 0.5 K in 2050 (estimated using the same RCS-based method as for the SLCFs above). By 2100 this increases to 2.3 K due to the long lifetime of CO_2 and the growing difference in CO_2 emissions between the two RCP scenarios.

A wide range of SLCFs emissions—within the region and from afar—have large enough impacts on the Arctic to warrant further political consideration. The present study suggests three main policy findings. First, a small number of cooperating nations within the Arctic region itself could have a large impact on the problem of regional warming. This could be an advantage as earlier research has shown that international cooperation on climate change has been stuck in gridlock because diplomacy has tried to engage too many countries with diverse interests[30]. A smaller group of countries will find it easier to strike bargains, especially those Arctic countries that are the largest beneficiaries of action. The seeds of this 'club' of nations that can work to cut Arctic warming emissions have already been planted in the Climate and Clean Air Coalition (CCAC) and the Arctic Council. Second, a small number of activities offer the vast majority of the leverage on Arctic warming. This would allow policy makers to focus in a few areas. An urgent priority is for scientists and policy makers to link assessments such as those reported in this paper with information on costs and political feasibility of emission controls so that policy makers can rank the effectiveness of their efforts. New work programmes in the CCAC and Arctic Council might explicitly call for such applied research that could promptly lead to practical policy priorities. Third, although practical efforts can start with a few Arctic nations and a few sectors, they must expand if Arctic warming is to be avoided more fully—notably to include the large but diffuse emissions from Asia.

Methods

Methods and any associated references are available in the online version of the paper.

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References

1. Fyfe, J. C. *et al.* One hundred years of Arctic surface temperature variation due to anthropogenic influence. *Sci. Rep.* **3,** 2645 (2013).
2. Quinn, P. K. *et al. The Impact of Black Carbon on Arctic Climate* (Arctic Monitoring and Assessment Programme (AMAP), 2011).
3. *Time to Act to Reduce Short-lived Climate Pollutants* (Climate and Clean Air Coalition, UNEP, 2014); http://www.unep.org/ccac/Portals/50162/docs/publications/Time_To_Act/SLCP_TimeToAct_lores.pdf
4. *Summary for Policy-makers: Arctic Climate Issues 2015* (Monitoring and Assessment Programme (AMAP), 2015).
5. Hartmann, D. L. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) 159–254 (IPCC, Cambridge Univ. Press, 2013).
6. Screen, J. A. & Simmonds, I. The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature* **464,** 1334–1337 (2010).
7. Stroeve, J. C. *et al.* Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophys. Res. Lett.* **39,** L16502 (2012).
8. Pithan, F. & Mauritsen, T. Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geosci.* **7,** 181–184 (2014).
9. *Near-Term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers* (UNEP, 2011); http://www.unep.org/publications/ebooks/slcf
10. Shindell, D. T. *et al.* Simultaneously mitigating near-term climate change and improving human health and food security. *Science* **335,** 183–189 (2012).
11. Iyer, G. C. *et al.* Improved representation of investment decisions in assessments of CO_2 mitigation. *Nature Clim. Change* **5,** 436–440 (2015).
12. Quinn, P. K. *et al.* Short-lived pollutants in the Arctic: Their climate impact and possible mitigation strategies. *Atmos. Chem. Phys.* **8,** 1723–1735 (2008).
13. Hansen, J. & Nazarenko, L. Soot climate forcing via snow and ice albedos. *Proc. Natl Acad. Sci. USA* **101,** 423–428 (2004).
14. Jacobson, M. Z. Climate response of fossil fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity. *J. Geophys. Res.* **109,** D21201 (2004).
15. Flanner, M. G., Zender, C. S., Randerson, J. T. & Rasch, P. J. Present-day climate forcing and response from black carbon in snow. *J. Geophys. Res.* **112,** 2156–2202 (2007).
16. Bond, T. C. *et al.* Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res. Atmos.* **118,** 5380–5552 (2013).
17. Seinfeld, J. H. & Pandis, S. N. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change* 2nd edn (Wiley, 2006).
18. Shindell, D. T. & Faluvegi, G. Climate response to regional radiative forcing during the twentieth century. *Nature Geosci.* **2,** 294–300 (2009).
19. Shindell, D. T. Evaluation of the absolute regional temperature potential. *Atmos. Chem. Phys.* **12,** 7955–7960 (2012).
20. Collins, W. J. *et al.* Global and regional temperature-change potentials for near-term climate forcers. *Atmos. Chem. Phys.* **13,** 2471–2485 (2013).
21. Flanner, M. G. Arctic climate sensitivity to local black carbon. *J. Geophys. Res. Atmos.* **118,** 1840–1851 (2013).
22. Sand, M. *et al.* The Arctic response to remote and local forcing of black carbon. *Atmos. Chem. Phys.* **13,** 211–224 (2013).
23. Klimont, Z. *et al. ECLIPSE v4a: Global Emission Data Set Developed with the GAINS Model for the Period 2005 to 2050: Key Features and Principal Data Sources* (International Institute for Applied Systems Analysis (IIASA), 2013); http://eccad.sedoo.fr/eccad_extract_interface/JSF/page_login.jsf
24. Stohl, A. *et al.* Evaluating the climate and air quality impacts of short-lived pollutants. *Atmos. Chem. Phys.* **15,** 10529–10566 (2015).
25. Najafi, M. R., Zwiers, F. W. & Gillett, N. P. Attribution of Arctic temperature change to greenhouse-gas and aerosol influences. *Nature Clim. Change* **5,** 246–249 (2015).
26. Amman, M. (ed.) *Future Emissions of Air Pollutants in Europe–Current Legislation Baseline and the Scope for Further Reductions* TSAP Report No. 1, version 1.0 (DG-Environment of the European Commission, 2012).
27. Quaas, J. *et al.* Aerosol indirect effects—general circulation model intercomparison and evaluation with satellite data. *Atmos. Chem. Phys.* **9,** 8697–8717 (2009).
28. van Vuuren, D. *et al.* Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Climatic Change* **81,** 119–159 (2007).
29. Riahi, K., Gruebler, A. & Nakicenovic, N. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc.* **74,** 887–935 (2007).
30. Victor, D. G. *Global Warming Gridlock: Creating More Effective Strategies for Protecting the Planet* (Cambridge Univ. Press, 2011).

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Author contributions

M.G.F., K.v.S., J.L., T.K.B. and M.S. conceived, designed and performed the model simulations and analysed the data; M.S. made the figures and led the writing of the paper. All authors contributed to the writing of the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.S.

Competing financial interests

The authors declare no competing financial interests.

Methods

The five models used for forcing calculations are CAM5.2, CanAM4.2, NorESM, Oslo-CTM2 and SMHI-MATCH (see Supplementary Table 1 for details). All models are run with the same 2010 emissions (GAINS v4.0a ECLIPSE compiled by IIASA) for the years 2006–2010 with prescribed sea surface temperatures (2006 is used as spin-up). The domestic sector is monthly weighted based on spatially distributed global temperature data from the Climatic Research Unit at the University of East Anglia. The emissions data set is available from www.geiacenter.org. The emissions are separated into six sectors (domestic, industry/energy/waste, transport, flaring, forest fires, and agricultural waste burning) and seven source regions (United States, Canada, Russia, the Nordic countries, rest of Europe, East + South Asia, and the rest of the world). To calculate the burden change and radiative forcing in the Arctic to all the regions and sectors in this study, the models have been run with and without each region/sector combination. Tables of the forcing calculations and the emissions are provided in the Supplementary Information.

We have calculated the Arctic equilibrium surface temperature response by translating the independently diagnosed radiative forcings from each model through the use of sensitivity coefficients. These regional climate sensitivity coefficients (RCSs) were estimated with the NASA-GISS model[18] and extended further in following study[20]. The RCSs are defined in four latitude bands; the southern hemisphere (90°–28° S), the tropics (28° S–28° N), the midlatitudes (28°–60° N), and the Arctic (60°–90° N). Supplementary Table 3 shows the RCSs for the Arctic response region. The temperature calculations have been done separately for BC, ozone and scattering aerosols (OC and sulphate) and have units of $\mathrm{K\,W^{-1}m^2}$ averaged horizontally in each latitude band.

The Arctic equilibrium annual mean surface temperature change (ΔT) by emission of component (c_E), in region (r) and from source (s), is estimated from the modelled $\mathrm{RF}(j, c_\mathrm{F}, r, s)$, where j denotes the latitude band of the radiative forcing by:

$$\Delta T(c_\mathrm{E}, r, s) = \sum_F \sum_{j=1}^{4} \mathrm{RF}(j, c_\mathrm{F}, r, s) \times \mathrm{RCS}(j, c_\mathrm{F}) \quad (1)$$

Here c_E denotes the emitted component (for example, BC) and c_F denotes the forcing mechanisms caused by the emissions c_E. For BC the c_F includes both forcing by the direct absorption in the atmosphere and the albedo effect of BC deposition on snow. The RCSs (in units of $\mathrm{K\,W^{-1}\,m^2}$) give the Arctic equilibrium temperature response to a unit forcing by component/mechanism c_F, exerted in latitude band j. The analysis of temperature response in the three non-Arctic latitude bands is beyond the scope of this paper, but can readily be calculated by equation (1) using radiative forcings and RCSs for the non-Arctic bands.

In this study a more detailed treatment of the response to BC forcing in the Arctic is adopted. For forcing by absorption of short-wave radiation, in particular in a stably stratified atmosphere (that is, by BC in the Arctic atmosphere), the climate efficacy (that is, the RCS coefficients) depends strongly on the altitude of the absorption causing the radiative forcing[21,22]. For example, BC at higher altitudes in the Arctic probably cools the surface, despite exerting a positive TOA forcing, whereas BC at lower altitudes causes strong surface warming[18,21,22]. To take this into account we have derived vertically resolved radiative forcings in the Arctic (for each model) and applied these in combination with vertical climate sensitivity factors[21]. For the effect of the forcing by BC in the Arctic atmosphere the surface temperature change is given by

$$\Delta T(c_\mathrm{E}, r, s) = \sum_z \mathrm{RF}(z, c_\mathrm{F}, r, s) \cdot \mathrm{RCS}(z, c_\mathrm{F}) \quad (2)$$

The total temperature effect of BC forcing in the atmosphere is then given by the sum of (1) and (2), where in (1) the contribution by forcing in the Arctic is neglected and represented by (2). For all other components and forcing mechanisms the total effect is given by equation (1).

To derive the model mean estimate for the Arctic surface temperature response to the emissions from the different sources, regions and sectors, as given in Fig. 1, first the individual model estimates for all emissions from the sector and region (for example, from transportation in the US) are given by

$$\Delta T(r, s) = \sum_{c_\mathrm{E}} \Delta T(c_\mathrm{E}, r, s) \quad (3)$$

where the $\Delta T(c_\mathrm{E}, r, s)$ are estimated by Eqs (1) and (2). Finally, the model mean is calculated by averaging over the models.

For indirect cloud forcings from OC and sulphate we have used scattering aerosol RCSs. The sensitivity factors for BC in snow in the Arctic are from a study with idealized simulations with CESM1.0.3 (ref. 21), whereas for the other regions the effect of BC in snow was set to three times the atmospheric BC factor, based on efficacy factors found in other studies[15,31]. We have scaled the RCSs obtained by the CESM model (that is, BC in atmosphere and snow in the Arctic) to the global climate sensitivity of the GISS model. The equilibrium global climate sensitivity for the NASA-GISS model it is 2.9 K, whereas for CESM it is 4.0 K (ref. 32). We have therefore scaled the CESM obtained results by 0.725.

The mitigation scenario starts from 2015 and gives annual changes in emissions of all SLCFs (including co-emitted species). From the equilibrium temperature estimates described above we have calculated the regional climate response as given in Fig. 3. In equation (4) the $\mathrm{RCS_n}$ are the normalized regional climate sensitivity coefficients in units of $\mathrm{K\,W^{-1}\,m^{-2}\,(Tg\,yr^{-1})^{-1}}$. To estimate the transient response to the mitigation of the emissions we represent the inertia of the climate system by an impulse response function (IRF) for climate[33]. The full IRF includes both the global climate sensitivity and the temporal evolution of the response in the climate system to a forcing. To keep the estimate of the transient response consistent with the global climate sensitivity used for the equilibrium estimates using the RCSs in equation (1) we have normalized the IRF with their climate sensitivity ($1.06\,\mathrm{K\,W^{-1}\,m^2}$) to obtain IRF_N (units $\mathrm{yr^{-1}}$). The full Arctic response in year t is then given by

$$\Delta T_A(t) = \sum_{r,s,c_\mathrm{E}} \int_{t_e=2015}^{t} \Delta E(c_\mathrm{E}, r, s, t_e) \times \mathrm{RCS_n}(c_\mathrm{E}, r, s) \times \mathrm{IRF}_N(t - t_e)\,\mathrm{d}t_e \quad (4)$$

The original IRF is given by (in units of $\mathrm{K\,W^{-1}\,m^2\,yr}$):

$$\mathrm{IRF}(t) = \sum_{j=1}^{2} \frac{c_j}{\tau_j} \exp\left(-\frac{t_j}{\tau_j}\right) \quad (5)$$

where $c_1 = 0.631\,\mathrm{K\,W^{-1}\,m^2}$, $c_2 = 0.429\,\mathrm{K\,W^{-1}\,m^2}$, $\tau_1 = 8.4$ years and $\tau_2 = 409.5$ years. By normalizing with the global sensitivity we get

$$\mathrm{IRF}_N(t) = \sum_{j=1}^{2} \frac{c'_j}{\tau_j} \exp\left(-\frac{t_j}{\tau_j}\right) \quad (6)$$

where $c'_1 = 0.595$ and $c'_2 = 0.405$ (dimensionless).

Additional descriptions of the uncertainty estimates along with tables of the forcing calculations, emissions, the RCSs and the models used are given in the Supplementary Information.

References

31. Hansen, J. M. *et al.* Climate simulations for 1880–2003 with GISS modelE. *Clim. Dynam.* **29,** 661–696 (2007).
32. Gettelman, A., Kay, J. E. & Shell, K. M. The evolution of climate sensitivity and climate feedbacks in the Community Atmosphere Model. *J. Clim.* **25,** 1453–1469 (2012).
33. Boucher, O. & Reddy, M. S. Climate trade-off between black carbon and carbon dioxide emissions. *Energy Policy* **36,** 193–200 (2008).