Disentangling the effects of CO_2 and short-lived climate forcer mitigation

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Anthropogenic global warming is driven by emissions of a wide variety of radiative forcers ranging from very short-lived climate forcers (SLCFs), like black carbon, to very long-lived, like CO_2. These species are often released from common sources and are therefore intricately linked. However, for reasons of simplification, this CO_2–SLCF linkage was often disregarded in long-term projections of earlier studies. Here we explicitly account for CO_2–SLCF linkages and show that the short- and long-term climate effects of many SLCF measures consistently become smaller in scenarios that keep warming to below 2 °C relative to preindustrial levels. Although long-term mitigation of methane and hydrofluorocarbons are integral parts of 2 °C scenarios, early action on these species mainly influences near-term temperatures and brings small benefits for limiting maximum warming relative to comparable reductions taking place later. Furthermore, we find that maximum 21st-century warming in 2 °C-consistent scenarios is largely unaffected by additional black-carbon-related measures because key emission sources are already phased-out through CO_2 mitigation. Our study demonstrates the importance of coherently considering CO_2–SLCF coevolutions. Failing to do so leads to strongly and consistently overestimating the effect of SLCF measures in climate stabilization scenarios. Our results reinforce that SLCF measures are to be considered complementary rather than a substitute for early and stringent CO_2 mitigation. Near-term SLCF measures do not allow for more time for CO_2 mitigation. We disentangle and resolve the distinct benefits across different species and therewith facilitate an integrated strategy for mitigating both short and long-term climate change.

climate change mitigation | air pollution | short-lived climate forcers | carbon dioxide | black carbon

For about two decades, policy-makers have considered options to avoid dangerous anthropogenic interference with the climate system (1). So far, many countries support limiting warming to below a 2 °C temperature limit, but the required global mitigation action to achieve this has been limited (2–4). To inform policy-makers about options and challenges, the United Nations Environment Program (UNEP) published several reports over the past years on three interlinked aspects: climate stabilization and greenhouse gas (GHG) mitigation (3), short-lived climate forcers (SLCFs) and clean-air benefits (5, 6), and hydrofluorocarbons (7) (HFCs). We build here upon the insights of these reports (henceforth referred to as "Gap Report," "SLCF Reports," and "HFC Report," respectively) to disentangle the joint effects of CO_2 and SLCF mitigation for limiting global warming. We evaluate the potential for limiting global-mean warming until 2100 and the rate of near-term warming, with a focus on 2 °C-consistent scenarios (Fig. 1). Reductions in CO_2 and SLCFs also provide important cobenefits like energy security (8), and local health and agricultural benefits (9–12), which fall outside the scope of this paper.

The main challenge in this exercise is the interdependence of coemitted climate forcers and the differences between their net forcing effects (13). For example, energy-related black carbon (BC) aerosols have an overall warming effect (14), whereas sulfate aerosols and some biomass-related BC emissions together with their coemitted species are cooling (13, 14). Because CO_2 and BC-related emissions often have common combustion sources (14), CO_2 mitigation will also influence the abundance of SLCFs. This linkage has already been well studied for other air pollutants (15, 16). Due to data limitations, the first studies that analyzed the mitigation potential of SLCFs (5, 6, 9, 17–19) did not account for these linkages in the long term and kept post-2030 SLCF forcing constant across a wide range of CO_2 paths. Alternatively, simple relationships between species were used (20). Such approaches, however, cannot guarantee that the long-term SLCF and CO_2 evolutions remain internally consistent. To provide an integrated view, we here account for this linkage and apply relationships (21) derived from detailed energy–environment–economy scenarios that explore various levels of air pollution control and track technological linkages between SCLF and CO_2 sources (8). Each CO_2 scenario in our analysis is thus associated with a consistent evolution of SLCFs at a specific level of pollution control stringency (see below). In policy discussions, methane (CH_4) and BC are often subsumed under the single term "short-lived climate pollutants" (SLCP) but in light of their different influence on the

Significance

Climate change is one of the greatest challenges of our times. Human activities, like fossil-fuel burning, result in emissions of radiation-modifying substances that have a detectable, either warming or cooling, influence on our climate. Some, like soot (black carbon), are very short lived, whereas others, like carbon dioxide (CO_2), are very persistent and remain in the atmosphere for centuries to millennia. Importantly, these substances are often emitted by common sources. As climate policy is looking at options to limit emissions of all these substances, understanding their linkages becomes extremely important. Our study disentangles these linkages and therewith helps to avoid crucial misconceptions: Measures reducing short-lived climate forcers are complementary to CO_2 mitigation, but neglecting linkages leads to overestimating their climate benefits.

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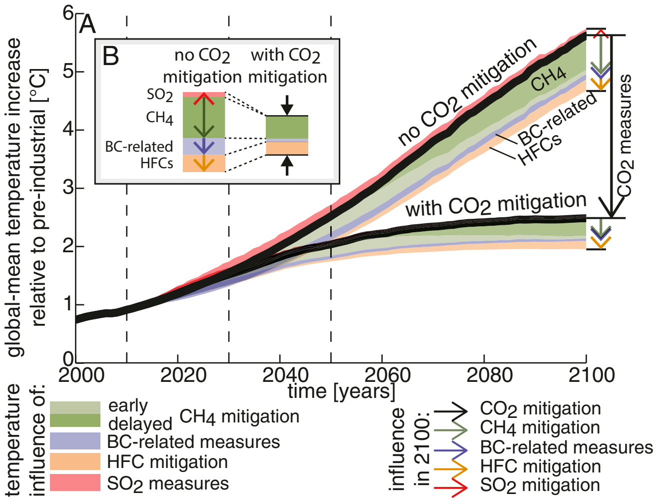

Fig. 1. Influence of SLCF-CO_2 linkages under varying CO_2 mitigation. (*A*) Global-mean surface temperature implications and interdependence of CO_2 (black), CH_4 (green), HFC (orange), BC-related (blue), and SO_2 mitigation (red). (*B*) The general effect of SLCF-CO_2 linkages. CO_2 paths show a world "with CO_2 mitigation" (32) and with "no CO_2 mitigation" (24). Early CH_4 mitigation is represented by the combined light and dark green area. HFC mitigation is shown for the lower end of the range assessed in this study. BC-related (and SO_2) measures show the difference between Case 6 and Case 2 (Case 4 and Case 2). Alternative cases are provided in *SI Appendix*, Fig. S1. Vertical dashed lines are time points relevant to Figs. 2 and 3.

climate, as well as differing technological and policy instruments for mitigation, they are explicitly distinguished here.

Our Analysis Framework

We approach our research question by modifying the emissions for BC-related SLCFs, HFCs, and CH_4 in the scenarios from ref. 22 in a structured and internally consistent way. For BC-related SLCFs, several cases are created (Table 1, *Methods*, and *SI Appendix*, *SI Text 1*) following the approach described in ref. 21. Our "reference" (Case 1) assumes air pollution controls (8, 23) at the level of current legislation by 2030, and a worldwide convergence, along with economic affluence, to current levels of industrialized countries thereafter (8, 23–25). We also assume gradual improvements over the next fifty years with respect to access to clean energy for the poor (26), long-term transitions to new energy technologies (25), and account for cocontrol in case of CO_2 mitigation, resulting in a large share of the mitigation assumed by the SLCF Reports to be achieved at some point in the second half of the century.

Our "early measures" (Case 2) mimic implementation of the full package of BC-related measures of the SLCF Reports by 2030, and maximum feasible reductions for BC afterward (*SI Appendix*, Table S5; "maximum feasible reductions" assume best practice technologies of today to be implemented globally, ref. 8). This case also assumes no further measures that would reduce polluting but cooling species, like sulfur-dioxide (SO_2) or nitrogen-oxides (NO_x), beyond what is already assumed in their "reference" projections (Case 1). Measures in this package were selected based on their potential to reduce warming (6, 9). Many other air pollution control measures are available (including BC-related measures), yet would result in a smaller decrease or possibly increase in warming (14). The package of BC-related measures assessed in this study thus represents a high-end estimate of the potential influence of BC-related measures.

The influence of alternative reference levels and timing of measures is explored in four sensitivity cases: a 20-y "delay" in implementation of Case 2 (Case 3); "stringent SO_2 controls" together with Case 2 (Case 4); a "frozen legislation" case with no air pollution control improvements beyond 2005 (Case 5); and a case without policies that promote access to clean energy for poor populations (no energy access policies; Case 6).

Because HFCs and CH_4 are part of the Kyoto-GHG basket, multigas approaches (27) take into account these species together with CO_2, but are often criticized from a long-term climate protection perspective (28–30). We here do not follow this basket approach, but disentangle the suitability of the respective species for reducing near and long-term warming.

CH_4 only has a few sources that are linked to, and thus possibly affected by, CO_2 mitigation (e.g., CH_4 release from fossil-fuel extraction). For each scenario in our set, we construct reference CH_4 emissions that take into account this weak linkage (*SI Appendix*, *SI Text 2*) and are consistent with recent estimates (25, 31). We then compare these to a strong mitigation path (32) (RCP2.6). RCP2.6 reduces CH_4 emissions from energy and waste, but also from agriculture (32), generally considered much harder (33), and represents the low end of CH_4 mitigation scenarios (31) (*SI Appendix*, Fig. S3).

HFC emissions (34–36) are projected to continue growing, especially in countries with emerging economies and increasing populations (34). They are part of the Kyoto-GHG basket, but discussions are under way to regulate them under the Montreal Protocol. Our HFC reference cases (34) reflect the high end of the literature (35), and the mitigation case reflects emissions in line with the SRES scenarios (37) (*SI Appendix*, *SI Text 3* and Fig. S12).

The combination of our BC-related cases captures the SLCF Reports' ranges (*SI Appendix*, Table S5) and for the same emission reductions, total radiative forcing simulated by our climate

Table 1. Description of BC-related SLCF cases analyzed in this study

Case label	Case description
1-Reference	Air pollution legislation is applied at the level of currently planned and legislated controls and converges globally over the 21st century, along with economic affluence, to the level of current legislation in the developed world (8, 24). Additional reductions in SLCF emissions occur because of cocontrol resulting from CO_2 mitigation, technological transitions, and a gradual access to clean energy technologies of the global poor.
2-Early measures	This case mimics the most ambitious BC-related SLCF reduction case from the SLCF Reports (*SI Appendix*, Table S5). Stringent air pollution control is enacted from now until 2030 and applied further throughout the 21st century, except on SO_2, NO_x, and NH_3, which remain as in Case 1.
3-Delay	As Case 2, but measures are delayed by 20 y.
4-Stringent SO_2 control	As Case 2, but also SO_2 is subjected to stringent control which assumes that current best practice technologies are effectively implemented worldwide in all regions by 2030.
5-Frozen legislation	Alternative reference case with air pollution controls frozen at their 2005 levels (i.e., no further legislation changes).
6-No energy access policies	As Case 1, but assuming no targeted policies to promote access to clean energy. Large fractions of poor populations continue to rely on traditional biomass for their residential energy use during the 21st century.

For further details see *SI Appendix*, Table S1 and *SI Text 1*.

model changes consistently with earlier studies (17) and the SLCF Reports (9). Present-day forcing of BC was updated based on recent estimates (14, 38) that are considerably higher than earlier ones (13) (*SI Appendix*, *SI Text 4*, Fig. S11, and Table S6).

Effect on Absolute Temperatures

Maximum temperature increase (peak warming) is to first order determined by the cumulative emissions of long-lived GHGs until the peak (39–41), and by the annual emissions of SLCFs at the time of the peak (42). We here assess the influence of measures on temperature increase until 2100, but note that temperatures will continue to rise in scenarios with positive nonzero CO_2 emissions (43) in 2100.

For HFCs, we find that if the assumed increase in baseline emissions in developing countries (34) is not abated, maximum warming until 2100 can increase an additional 0.1–0.3 °C (Fig. 2*B*). For CH_4, global-mean warming decreases by 0.3–0.7 °C by 2100 when moving from no to stringent CH_4 mitigation (32) (median estimates dependent on concurrent CO_2 mitigation, Fig. 2 *B* and *C*). CH_4 mitigation measures in the latter half of the century become important if CO_2 emissions have already been curbed, and warming thus peaks before 2100. Early action on CH_4 is less important for limiting warming to below 2 °C: also when delaying CH_4 reductions by three decades, a similar effect on maximum warming during the 21st century remains (Fig. 2*B*) (30, 41).

Looking at BC-related measures (i.e., measures that reduce BC and its coemitted species), the influence of early measures (Case 2) on maximum 21st-century warming is small compared with our reference (Case 1). Maximum 21st-century warming is reduced by less than 1% (<<0.02 °C, about an order of magnitude smaller than natural variability in the climate system; Fig. 2*B*). This small reduction is due to similar emission levels in the long term, which are much lower than the levels suggested by studies that did not yet account for long-term CO_2–SLCF linkages (9, 18). The influence of BC-related measures critically depends on how much concurrent CO_2 mitigation is assumed and the timeframe considered. For instance, the cooling influence of BC-related measures is larger in the near-term (0.05–0.11 °C by 2030; Fig. 2*A*) and is largest in scenarios with little to no CO_2 mitigation, which, even when taking into account this largest cooling due to BC measures, still have the highest medium and long-term warming. Delaying BC-related measures (Case 3) results in similarly small effects (Fig. 2*B*).

The effect of BC-related measures on maximum warming is thus limited, because scenarios that stabilize temperatures always require zero (or negligibly small) anthropogenic CO_2 emissions for temperatures to peak (40). As a large fraction (55–65%) of the energy-related BC emissions with the largest net warming effect (14) are linked to CO_2-emitting fossil-fuel sources, they also decline in low-carbon scenarios, also in the near term. The reference level of BC-related emissions is thus lowered as a cobenefit from CO_2 mitigation, and achieving BC-related mitigation in 2 °C-consistent scenarios hence requires less additional reductions in comparison with scenarios that do not curb temperatures.

The robustness of our findings is illustrated by two sensitivity cases. Our frozen legislation (Case 5) explores the effect of more pessimistic air pollution control assumptions in line with the SLCF Reports' reference. This case results in significantly higher BC emissions by 2030 (*SI Appendix*, Tables S4 and S5). However, the effect on maximum 21st-century warming remains small in 2 °C-consistent scenarios (<0.05 °C, Case 5 vs. 1; *SI Appendix*, Figs. S4 and S5) because also here BC reference levels are lowered due to the phase-out of common CO_2-emitting sources (21). Not accounting for CO_2–SLCF linkages would overestimate possible mitigation effects of BC-related measures in 2030 by about 50% (*SI Appendix*, Figs. S4–S8).

Not all SLCF emissions are cocontrolled by CO_2 mitigation. Although about 70% of global BC emissions in the industrial era are related to energy use, the remainder is related to open burning (14) (e.g., from grassland and woodland fires). Of the energy-related BC emissions, 35–45% result from the residential use of traditional biomass (14), which is often considered carbon-neutral in integrated assessment models. These sources are therefore not cocontrolled in CO_2 mitigation scenarios, but nevertheless decline in projections due to policies that promote access to clean energy.

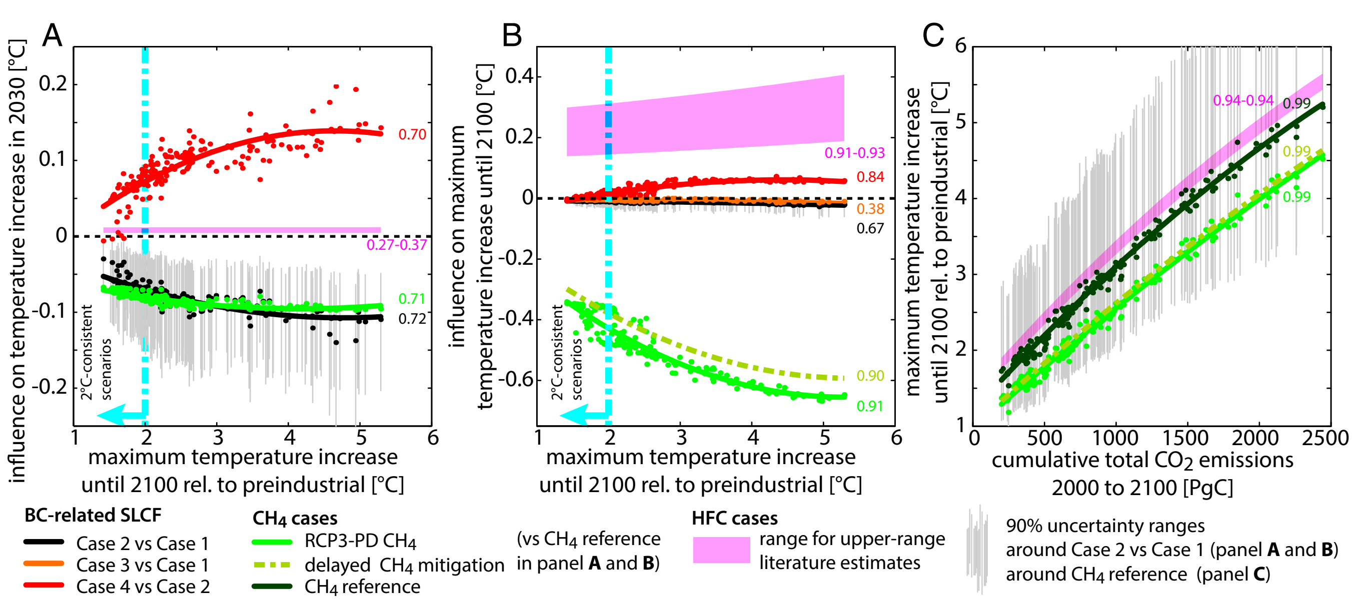

Fig. 2. Influence of various SLCF measures on global-mean warming by 2030 (*A*) and on maximum warming until 2100 (*B*), as a function of maximum warming until 2100 relative to preindustrial levels under the reference scenario (Case 1). (*C*) Maximum temperature increase until 2100 as a function of cumulative CO_2 emissions between 2000 and 2100. Scenarios at the left of the "2°C-consistent scenarios" line limit warming to below 2 °C with at least 50% probability. The effect of SLCF measures is smaller in stringent CO_2 mitigation scenarios. Variation along each colored line is entirely driven by CO_2 mitigation and technological SLCF linkages. Dots represent the median response per scenario (vertical gray lines: 90% range). Solid lines and numbers are quadratic fits and associated R^2 values for each case, respectively. Pink ranges are defined by the quadratic fits for the HFC estimates. Additional cases and metrics are shown in *SI Appendix*, Figs. S4-S6.

However, also when assuming no energy access policies (Case 6) over the 21st century, maximum warming by 2100 does not increase much (0.04–0.09 °C; *SI Appendix*, Figs. S4 and S5). Despite affecting a large share of BC-related emissions, the climate effect of energy access policies is assessed to be small (44) because the net forcing of BC and coemitted (reflecting) SLCFs from biomass burning is only slightly positive (14). Recent laboratory measurements (45) and modeling studies (46), however, suggest that this effect might be higher. Finally, policies that increase residential biomass use in industrialized countries (or the share of diesel in transport) can result in higher SLCF emissions, unless appropriate control measures are adopted.

Our cases show the importance of accounting for CO_2–SLCF linkages. In a "no CO_2 mitigation" world (Fig. 1) the maximum temperature influence in 2100 by CH_4, HFCs and BC measures is about 0.7 °C, 0.2 °C, and 0.1 °C, respectively, adding up to a combined effect of about 0.9 °C. This differs markedly from a world "with CO_2 mitigation," where the influence declines to 0.4 °C, 0.1 °C and <0.05 °C, respectively, adding up to about 0.5 °C in 2100. Our study thus reveals that not accounting for CO_2–SLCF linkages can lead to overestimating the temperature effect of the combined SLCF mitigation measures by almost 100% (with important differences across various SLCF species). For comparison, our combined "no CO_2 mitigation" estimate for 2100 is approximately consistent, given uncertainty bounds, with the effect estimated by earlier studies, like 1.1 °C in ref. 17. However, this changes once CO_2–SLCF linkages are accounted for. Assuming constant extrapolated values after 2030 for all BC-related emissions (5, 6, 9, 17–19) would suggest a near-constant lowering of long-term warming (0.2–0.25 °C) consistent with very high temperature scenarios (see *SI Appendix*, *SI Text 6* for a detailed comparison). By 2100, this effect is up to a factor two to four larger than the maximum found in 2 °C-consistent scenarios (i.e., for our two sensitivity cases that have the highest pollution loading combined, *SI Appendix*, Figs. S4 and S5), and this discrepancy exacerbates to an order of magnitude when using current legislation (Case 1) as the reference. As a consequence, our results invalidate suggestions that BC-related measures would allow higher near-term (2020) Kyoto-GHG emissions (5) in line with staying below 2 °C, or allow for more time for CO_2 reductions (47) (*SI Appendix*, Table S2). Our measures case (Case 2) assumes that no additional efforts are made to control cooling SO_2 emissions beyond cocontrol by CO_2 mitigation strategies. Because dominant sources of SO_2 (48) and BC (9, 14) are not the same, SO_2 emissions will not be significantly reduced by BC-related measures. However, as SO_2 contributes to the formation of acid rain and has adverse local health effects by forming secondary aerosols (49), public-health concerns drive additional near-term reductions. Such reductions then unmask warming induced by other species (50). If we assume stringent SO_2 controls (assuming current best practice technologies to be implemented globally by 2030), the unmasking of warming due to SO_2 removal is larger than the cooling effect of the our BC-related measures package, resulting in a net temperature increase (Fig. 2, red vs. black lines).

The main contributors to maximum 21st-century warming are long-lived GHGs, of which the most important is CO_2 (41, 43). When varying trajectories of CO_2 emissions up to 2050 from less to more stringent reduction measures over a range comparable with the SLCF measures (*SI Appendix*, *SI Text 5*), maximum 21st-century warming varies by more than 2.5 °C (*SI Appendix*, Fig. S6). For most scenarios in our set warming peaks after 2100 (*SI Appendix*, Fig. S7), making relative contributions of SLCF measures to peak warming increasingly smaller over time (41).

Rates of Temperature Change

We also assess implications for the change in average decadal rates of temperature change (ARTCs) between 2010–2030, 2030–2050, and 2010–2050. The ARTCs over our scenario set in all three periods are ∼0.23 °C per decade (Fig. 3 *D* and *E*).

The potential influence on ARTCs of the projected post-2020 HFC emissions becomes visible after 2030. ARTCs rise by about 10–20% and 5–10% between 2030–2050 and 2010–2050, respectively (Fig. 3, rounded to the nearest 5%). Our stringent CH_4 mitigation case reduces ARTCs by about 20% between 2010–2030, by about 25–40% between 2030–2050, and by about 20–30% between 2010–2050. For BC, we find that ARTCs are reduced at the time that the reductions of Case 2 take place (10–20% by 2030). However, they are increased by about 5% between 2030–2050, at the time when emissions would otherwise have declined in the reference case. This results in a small overall reduction between 2010–2050 (about 5–10%; *SI Appendix*, Fig. S8). When assuming frozen legislation as the reference, ARTCs between 2030–2050 can either increase or decrease depending on the concurrent CO_2 mitigation (*SI Appendix*, Figs. S8 and S9). This finding thus highlights the importance of accounting for CO_2–SLCF linkages.

Also, changes in CO_2 emissions influence rates of temperature change (43, 51). We here explore the effect of reducing CO_2 emissions while accounting for technologically linked SLCF-reductions. On shorter time scales (until 2030), the effect on temperature rates is virtually zero. However, limiting cumulative CO_2 emissions until 2050 to 2 °C-consistent levels (<350 PgC, *SI Appendix*, Fig. S6*B*) leads to ARTCs between 2030–2050 of about 0.15 °C/decade instead of about 0.35 °C/decade when emissions are on track for 4 °C (∼700 PgC), a shift of more than 50% (*SI Appendix*, Fig. S9*B*). Path dependency due to lock-in of carbon-intensive infrastructure constrains attainable emission reduction rates (52) and early measures to reduce CO_2 are thus required to significantly limit cumulative emission by 2050. For each 5 PgC/y that annual CO_2 emission targets are set lower for 2050, ARTCs between 2030–2050 (2010–2050) decline by about 15% (10%, Fig. 3*C*).

Discussion and Conclusions

For around a decade, scholars have been discussing SLCFs and CO_2 mitigation in relation to combating climate change (17, 53–55), with two seminal papers (17, 54) identifying SLCFs as a way to mitigate short-term warming. Our results provide an integrated view and quantitatively support earlier statements (9, 17) that mitigation of SLCFs can only be a complementary strategy on top of CO_2 mitigation, but also reveal distinct benefits across different SLCFs and highlight the importance of a coherent consideration of dependencies between SLCFs and CO_2.

Eventual CH_4 mitigation forms an integral part of long-term climate protection strategies, and also the potential increase of HFCs requires attention in the long run. Although early CH_4 and BC-related measures reduce the rate of temperature rise in the coming two decades, early action to limit SLCFs by 2030 brings only small benefits insofar as peak warming goes. Deep CH_4 reductions help hedging the risk of exceeding temperature thresholds (52, 56), yet only when CO_2 reductions are already put in place (19). The effects of CH_4 and HFC measures are robust across a wide range of CO_2 scenarios. However, when accounting for CO_2–SLCF linkages in scenarios that stabilize global warming, long-term effects of BC-related measures become virtually zero. Earlier studies also found reduced effects because of uncertainties in aerosol emissions and forcing (31), or found that forcing estimates lower than those applied here would be more consistent with observations (57). Other studies (45, 46), however, indicate that the forcing effect of biomass burning might have been underestimated in the past. Caution is therefore advised.

Delaying stringent action on CO_2 results in lock-in of carbon-emitting infrastructure (52) and higher cumulative CO_2 emissions that imply a higher committed warming. Because of this, and the persistence of CO_2 in the atmosphere, near-term initiation of CO_2 mitigation is required to control midcentury to long-term climate change. Replacing near-term CO_2 reductions

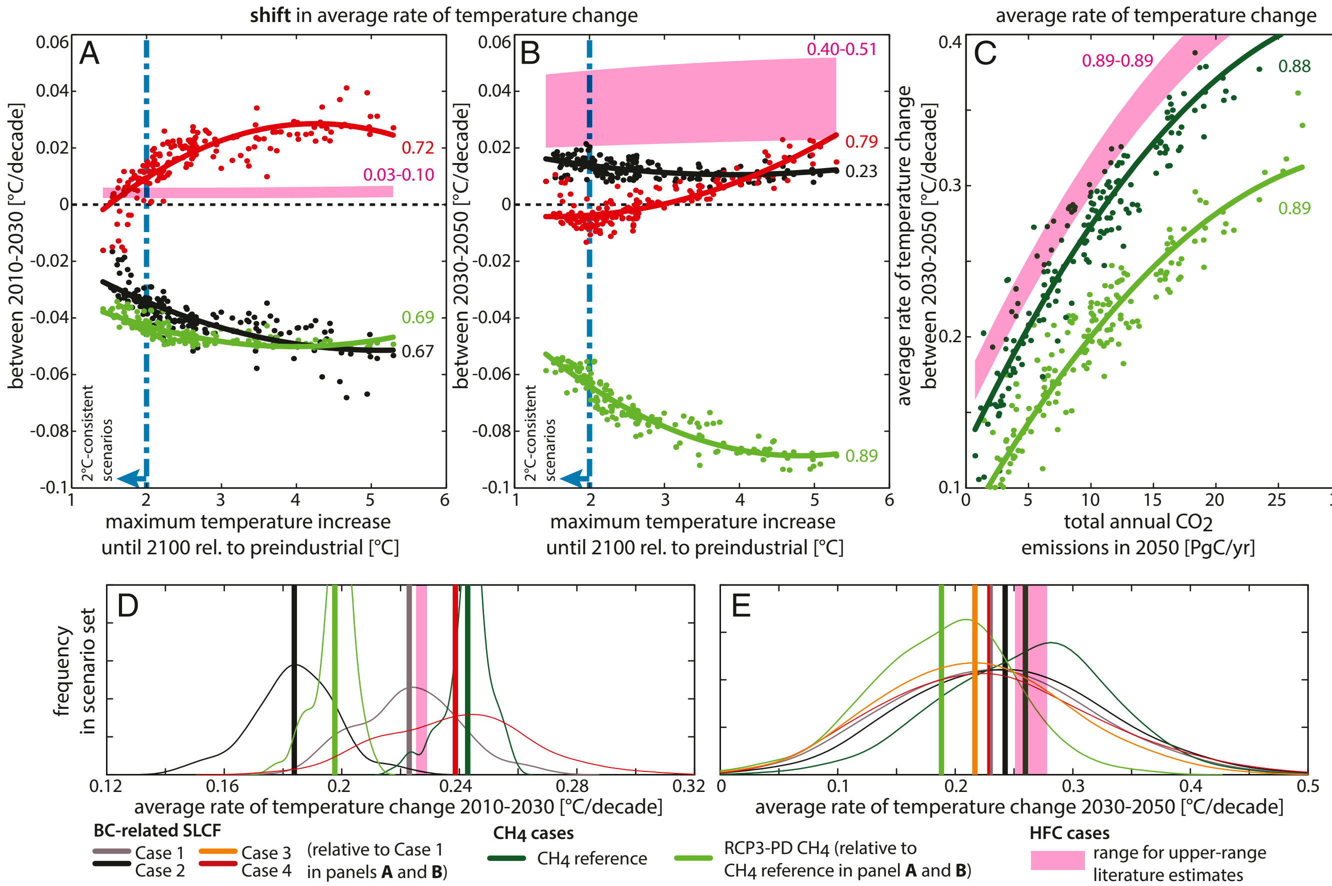

Fig. 3. Influence of SLCF and CO_2 mitigation on ARTCs between 2010–2030 (*A*) and 2030–2050 (*B*) as a function of maximum warming until 2100 relative to preindustrial levels under the reference scenario (Case 1). (*C*) ARTCs between 2030–2050 as a function of CO_2 emissions in 2050. (*D* and *E*) Frequency distributions of ARTCs between 2010–2030 and 2030–2050, respectively, together with mean estimates (vertical solid lines) over the entire ensemble. Each dot represents the median response per scenario. Solid lines and numbers in *A*–*C* are quadratic fits and associated R^2 values for each case, respectively. Pink ranges in *A*–*C* are defined by the quadratic fits for the range of HFC estimates. Additional cases are shown in *SI Appendix*, Figs. S8 and S9.

with SLCF mitigation leads to a higher risk that stabilization of concentration and warming is not achieved (28–30, 52, 56). Even when action on CO_2 continues to be delayed, the effect of our package of BC-related measures is smaller than previously estimated (*SI Appendix*, Fig. S10). These results imply that SLCF measures are not able to buy substantial time for CO_2 action, and our study therewith rectifies a misconception present in the policy literature (47), despite multiple studies already having warned against such interpretation (6, 9, 17, 19, 29, 41).

The package of BC-related emission reduction measures in this paper represents a high-end estimate of BC-related climate mitigation, in line with the SLCF Reports (5, 6, 9). This package is currently promoted to spur momentum for international climate collaboration (47), together with action on CH_4 and HFCs. Our analysis shows that lumping all SLCF measures in one category would obscure many of the important differences between the species. Moreover, imposing air pollution controls on cooling SO_2 emissions significantly reduce the overall temperature effect by 2030. Meanwhile, at current CO_2 emission rates of ~10 PgC/y (4), each decade of delayed CO_2 mitigation implies around 0.17 °C further warming over multiple centuries [Fig. 2*C*; the IPCC estimate (58) for similar CO_2-only emissions is 0.08–0.25 °C]. In none of our cases can BC-related measures compensate for the persistent impacts of unabated CO_2 emissions. Without early and stringent CO_2 mitigation, warming from 2050 onward will become increasingly larger than what SLCF measures can reduce.

Achievement of the BC-related emissions reductions assessed in this study has important benefits beyond near-term climate protection (e.g., for public health). These other benefits can provide a valid rationale for early implementation, and will require dedicated and sustained policy interventions, whether through accelerated implementation of air pollution controls, through cocontrol due to stringent CO_2 mitigation strategies, or by promoting access to clean energy for poor populations in developing countries. CH_4 and CO_2 mitigation provide also multiple other benefits.

The results presented here are consistent with the earlier UNEP Reports and underlying studies (9, 22, 34) but only in the near term (2030) and when assuming frozen legislation as the reference policy in scenarios with little to no CO_2 mitigation (*SI Appendix*, *SI Text 6*). In the long term (2050 and beyond) and for stringent CO_2 mitigation scenarios, we find only modest effects of SLCF reductions, even compared with our sensitivity cases with the highest loading of pollutant emissions. Our results robustly demonstrate that not accounting for cocontrol due to SLCF-CO_2 linkages in a low-carbon world leads to strongly overestimating the long-term effect of BC-related measures. By disentangling the distinct benefits across different species in time, our results provide a robust basis for an integrated strategy for mitigating both short and long-term climate change.

Methods

We use the reduced-complexity carbon-cycle and climate model MAGICC (59) in a probabilistic setup (39) updated such that the marginal climate sensitivity distribution is consistent with IPCC AR4 (60); for AR5 consistency, see ref. 61. Temperature increase relative to preindustrial (1850–1875) is computed from a 600-member ensemble (39). Our setup is closely in line with historical radiative forcing estimates of IPCC AR4 (13) and has been updated to reflect the most recent BC forcing estimates (14), included in IPCC AR5 (*SI Appendix*, *SI Text 4* and Table S6). Reported results are robust for a wide range of climate sensitivity estimates (*SI Appendix*, Fig. S13). Emissions in our scenarios have been harmonized (62) with recent inventories of historical emissions (63, 64).

BC-related cases are described in Table 1, *SI Appendix*, *SI Text 1* and Table S1. Sectors that are not affected by the measures (for example, forest and savannah burning) do not vary between scenarios. HFC cases are described in *SI Appendix*, *SI Text 3*.

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