An Empirical Approach toward the SLCF reduction targets in Asia for the Mid-term Climate Change Mitigation

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Research article

Keywords: SLCF, Asian emission control, CH₄, NO_x, NMVOC

Posted Date: April 6th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-20669/v1>

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Abstract

Although importance of co-control of SLCFs together with the emission reduction of CO₂ has attracted much attention for the mid-term climate change mitigation, their contribution to radiative forcing (RF) are rather complex, and chemical-climate model analysis for the future scenario tends to give black box for the contribution of each species. In order to deliver a more straightforward message on the effect of the reduction of SLCFs to policymakers, we propose “top-down” reduction targets of CH₄ and tropospheric O₃ in reference to the historical levels of their RF. Although the RF increase due to the increasing CO₂ concentration is inevitable in mid-term future (ca. 0.80 W m⁻² in 2040), the RF of CH₄ and O₃ is expected to decrease from 0.48 to 0.41, 0.34, 0.27, and 0.22 W m⁻², and from 0.40 to 0.29, 0.23, 0.19, and 0.15 W m⁻², respectively, if their atmospheric concentrations decrease from the level of 2010 to those of 1980, 1970, 1960 and 1950, according to the IPCC 2013 database. Consequently, the sum of -ΔRF_x(CH₄) and -ΔRF_x(O₃) (the difference of RF between the target year of x and 2010 as the base year) are 0.18, 0.31, 0.42 and 0.51

W m⁻² in 1980, 1970, 1960 and 1950, respectively. This indicates that the increase of $\Delta RF_{2040}(CO_2)$ can be compensated by of 23 to 64%, and the policy target can be selected from the combination of different target years for CH₄ and O₃. With these global reduction ratio the necessary reductions in CH₄, NO_x, and NMVOC in Asia was estimated and compared with the GAINS model-based cost-beneficial reduction amount proposed by the Solution Report prepared under UN Environment Asia pacific Office. The comparison suggests that the reduction of O₃ to the 1970 level is promising if the emissions of NO_x and NMVOC from other parts of the world are reduced coherently, but further efforts would be necessary for the reduction of CH₄ emissions to realize the 1970 concentration level.

Keywords

SLCF, Asian emission control, CH₄, NO_x, NMVOC

Introduction

Although the importance of the co-control of short-lived climate forcers (SLCFs), also called short-lived climate pollutants (SLCPs), for the alleviation of mid- and long-term climate change is now recognized in an academic society (UNEP/WMO, 2011; UNEP, 2011a), the concept has not necessarily received serious consideration by the public in general. While it is

rather well understood that co-controlling the main climate forcer, carbon monoxide (CO₂) and air pollutants (PM_{2.5}, SO₂, NO_x, and NMVOC) simultaneously results in co-benefits of mitigating climate change and human health impacts with less costs as compared to controlling them separately (Sivertsen and Bartonova, 2010; Thambiran and Diab, 2011; Winiwarter and Klimont, 2011; Yang and Teng, 2018), the need for controlling selected air pollutants as climate forcers for climate change control has not been well-received by the public and policymakers, even though the importance of co-controlling SLCPs in climate mitigation policy has been asserted (Shindell et al., 2012; Shoemaker et al., 2013; Rogelj et al., 2014).

It is generally agreed that Black Carbon (BC), Methane (CH₄), Tropospheric Ozone (O₃), and Hydrofluorocarbons (HFCs) are major SLCFs to be targeted with respect to reduction of their mixing ratios in the atmosphere by the UNEP (United Nations Environment Protection) and the CCAC (Climate and Clean Air Coalition) (UNEP, 2011a, b; CCAC, 2014). However, the problem for policymakers arises from the ambiguity of which species should be controlled with higher priority and how much each SLCF should be controlled. One of the reasons for the complexity is ascribed to the interrelationship between SLCFs and their precursors. It has been well established that emission reduction of NO_x and NMVOC is necessary for the control of regional ozone (Finlayson-Pitts and Pitts, 2000; Akimoto, 2016), and that the reduction of CH₄ also contributes to the decrease of hemispheric and global ozone (e.g. Dentener et al., 2005).

Meanwhile, discussions have been made that the reduction of NO_x emissions causes a decrease in atmospheric OH and leads to an increase in the atmospheric lifetime and mixing ratio of CH₄, which has an adverse effect on climate change (Fuglestad et al., 1999; Karlsdóttir and Isaksen, 2000). This may be the reason for excluding the control of O₃ by reducing NO_x in the CCAC report (CCAC, 2017). However, our previous study (Akimoto et al., 2015) revealed that the co-control of NO_x together with NMVOC and CO does not decrease much of the OH and only gives a nearly neutral effect on the change in CH₄ concentrations.

The CCAC has emphasized the need for reduction of BC together with CH₄ and HFCs (CCAC, 2014). However, a recent paper by Takemura and Suzuki (2019) reported that chemistry-climate modeling results only showed weak global warming mitigation by reducing BC emissions, since the sensitivity of the TOA (top of the atmosphere)-RF (radiative forcing) of BC on the surface temperature is minimal. Also, BC is emitted together with other “white” aerosols and the total climate impact of the reduction of BC emissions is uncertain, particularly when “indirect effects” are included in the climate change evaluation (e.g. Aamaas et al., 2018).

Another reason for ambiguity for policymakers is that the quantitative contribution of the control of each SLCP for climate change mitigation has not been clear according to previous discussions. The effectiveness of SLCP co-control for climate change has been discussed and scenarios for preventing global surface temperature rise were proposed for the aggregated

change of RF of SLCFs by using chemistry-climate models (Shindell et al., 2012; Smith, and Mizrahi, 2013; Rogelj et al., 2014). While all of these model analyses are important as a scientific guideline to seek the best scenario for the co-control of SLCFs, they are not straightforward enough for policymakers to set effective control measures for individual SLCFs.

In order to give a more straightforward message to policymakers, it would be preferable to make the reduction target for each SLCF visible with an evaluation of the RF value. In this paper, we propose to show the reduction targets of CH₄ and O₃ by an “empirical top-down” approach based on historical data. CH₄ and O₃ were selected since linearity between RF and surface temperature change can be presumed for these gaseous SLCFs to allow an additive discussion of RF of CO₂. In the present study, we adopted an approach in which the historical atmospheric mixing ratios of CH₄ and O₃ are referred to as having been related to the lower anthropogenic emissions of CH₄, NO_x, and NMVOC in the past, and we envisioned the targeted emission reduction of these species in Asia . The results were compared with a recent proposal of 25 cost-effective measures for the emission control of anthropogenic air pollutants in Asia in 2030 by the WHO air quality guidelines and the sustainable development goals (SDGs) (UNE, 2018) using the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model of IIASA (International Institute of Applied Systems Analysis) (Amann et al., 2011).

Methods/Experimental

Increase of RF due to the increase of CO₂ in 2040 and possible compensation by the decrease of CH₄ and O₃

Four future scenarios of GHG emissions until 2150 have been evaluated in the Fifth Assessment Report (AR5) of the IPCC (2013). Each scenario, named RCP8.5, RCP6.0, RCP4.5, and RCP2.6, corresponds to an RF at 8.5, 6.0, 4.5, and 2.6 W m⁻² in 2100, respectively, with reference to the preindustrial era. Figure 1 shows the past and future atmospheric mixing ratios of CO₂ according to these four scenarios (Meinshausen et al, 2011; Myhre and Shindell, 2013). It is clearly shown in Fig. 1 that the atmospheric mixing ratios of CO₂ of the RCP6.0, 4.5, and 2.6 (called RCP3PD in the figure) scenarios will not differ significantly until 2040 when they reach 450 ± 10 ppm (Myhre and Shindell, 2013). Based on these projections, the RF due to CO₂ is estimated to reach ~ 2.6 W m⁻² in all of these three scenarios in 2040. Since the RF of CO₂ is 1.82 ± 0.2 W m⁻² in 2011 (Myhre and Shindell, 2013), the increase of RF due to the increase of CO₂ from 2011 to 2040 is expected to be ca. 0.8 W m⁻². In order to mitigate the enhanced near- and mid-term climate change due to the increase of CO₂, the increase of RF has to be compensated by a reduction in the RF of SLCFs.

Historical change of the RF of Methane and Ozone

The global mean atmospheric mixing ratio of CH₄ has been increasing from the preindustrial

129 value of ~750 ppb in 1750 to the present value of 1803 ± 2 ppb in 2011 (Myhre and Shindell,
130 2013). Figure 2 shows the historical increase of CH₄ mixing ratios in the Antarctic (orange line)
131 compiled by Ghosh et al. (2015) together with the RF of CH₄ given by the IPCC AR5 (blue
132 line) (Myhre and Shindell, 2013). The growth rate of the CH₄ concentration is moderate (5.1
133 ppb yr⁻¹) in 1910-1950, fast (13.6 ppb yr⁻¹) during 1950-1990, moderate (6.7 ppb yr⁻¹) during
134 the 1990s, and near steady to moderate after 2000 (Ghosh et al., 2015). The increase of RF is
135 not linear but nearly proportional to the global averaged concentration for a shorter period of
136 time. As shown in Fig. 2, the RF of CH₄ in 2010 referenced to the preindustrial era of 1750 is
137 0.48 ± 0.20 W m⁻².

138 Figure 3 depicts the historical increase of the model-calculated global mean tropospheric O₃
139 column (orange line) together with the RF given by Myhre and Shindell (2013) in the IPCC
140 AR5 (blue line). Since the RF of O₃ reflects the change in the mean tropospheric burden rather
141 than the mixing ratio in the surface layer, the global mean tropospheric O₃ column represented
142 in Dobson unit (DU) by Skeie et al. (2011) is quoted here. The global mean tropospheric column
143 has increased from 2.3 DU in 1910 to 11.4 DU in 2010. The continuous increase of RF is in
144 parallel with the increase of the global mean tropospheric O₃ column, and it accelerated in the
145 1960s and slowed down after the 1980s. The historical increase of the tropospheric burden of
146 O₃ can be ascribed to the increase of anthropogenic emissions of its precursors, NO_x, NMVOC,

CO, and CH₄ (Lamarque et al., 2005; Stevenson et al., 2013; Hoesly et al., 2018). According to the IPCC AR5 (Myhre and Shindell, 2013), the radiative forcing of tropospheric O₃ in 2010 referenced to the preindustrial era is $0.40 \pm 0.20 \text{ W m}^{-2}$ mainly based on the ACCMIP model intercomparison study (Stevenson et al., 2013). Compared to the RF of well-mixed GHGs such as CH₄, the RF of tropospheric O₃ has a large uncertainty up to $\pm 50\%$ (5 to 95% confidence), which reflects a large inter-model spread because of a large latitudinal, longitudinal, and altitudinal variability reflecting the spatial and temporal non-uniformity of emission sources of its precursors, NO_x, VOC, and CO. Another large uncertainty arises from the lack of knowledge about the pre-industrial level of tropospheric O₃ that provides the reference value of RF. The reported observed values of ground-level O₃ in the late 19th and early 20th century have been reevaluated and revised to be approximately 10 ppbv and at the most 15 ppbv (Volz and Kley, 1988; Marenco et al., 1994; Cooper et al., 2014) in the mid-latitude in the northern hemisphere where data is available from. However, the model-simulated mixing ratio of the pre-industrial level of O₃ is typically ~20 ppbv (Mickley and Jacob, 2001; Lamarque et al., 2005; Young et al., 2018), substantially higher than the reported observed values, which tend to give a smaller industrial RF of O₃.

It should be noted that the RFs of CH₄ and tropospheric O₃ in 2011 relative to 1750 are 0.48 ± 0.05 and $0.40 \pm 0.20 \text{ W m}^{-2}$, respectively, (total 0.88 W m^{-2}), which is comparable to the increase

of RF due to the increase of CO₂ from 2011 to 2040 (Myhre and Shindell, 2013).

Results

Target setting of the Reduction of Global CH₄ and O₃ to a Historical Year

Based on Figs. 2 and 3, Table 1 cites the RF_x and Δ RF_x of CH₄ and O₃ for a specified year, x (x= 2010, 1980, 1970, 1960 and 1950), where Δ RF_x = RF_x – RF₂₀₁₀ for the year x. As shown in Table 1, the radiative forcing of CH₄ decreases from 0.48 to 0.41, 0.34, 0.27, and 0.22 W m⁻², and that of O₃ from 0.40 to 0.29, 0.23, 0.19, and 0.15 W m⁻² if their mixing ratios decrease from the level of 2010 to the levels of 1980, 1970, 1960 and 1950, respectively. Accordingly, Δ RF_x(CH₄) and $-\Delta$ RF_x(O₃) increase to 0.07, 0.14, 0.21, and 0.26, and 0.11, 0.17, 0.21, and 0.25, for 1980, 1970, 1960, and 1950, respectively. Therefore, the sums of $-\Delta$ RF_x(CH₄) and Δ RF_x(O₃) are 0.18, 0.31, 0.42, and 0.51 W m⁻² in 1980, 1970, 1960 and 1950, respectively, which means that if the atmospheric burdens of CH₄ and O₃ are decreased to the levels of 1980, 1970, 1960, and 1950, the increase of Δ RF₂₀₄₀(CO₂) (0.80 W m⁻²) can be compensated by 23%, 39%, 53%, and 64%, respectively.

To set the target year to which the level of CH₄ and O₃ should be reduced is rather arbitrary at this stage, but one can get a clear idea of how much of the total RF can be reduced by setting the target of emission reduction of CH₄ and NO_x/NMVOC as O₃ precursors. For example, if

both CH₄ and O₃ can be reduced to the levels of 1970 and 1960, 39% and 53% of the increase in RF by CO₂ can be suppressed by in 2040. If the target of CH₄ reduction is the 1970 level and that of O₃ is 1960 considering more difficulty of anthropogenic CH₄ emissions as will be discussed later, $-\Delta RF_x(\text{CH}_4) - \Delta RF_x(\text{O}_3)$ becomes 0.35 W m⁻², or the compensation rate becomes 44%. In the present study, the targeted year has been set rather arbitrarily to 1970 to see how feasible the compensation of ca. 40% of the RF increase by CO₂ is in 2040.

Targeted Reduction of Global and Asian Emissions of CH₄, NO_x, and NMVOC

Global total and Asia/Pacific historical anthropogenic sectoral emissions of CH₄, NO_x, and NMVOC were obtained from the Community Emissions Data System (CEDS) by Hoesly et al. (2018). Here, Asia/Pacific is grouped to cover East, Southeast, South and West Asia, and Oceania and the Pacific Islands. In this database, sectoral emission data are available every ten years. Table 2 shows the anthropogenic emissions of CH₄, NO_x, and NMVOC globally and in the Asia/Pacific region in 1970 (E₁₉₇₀) and 2010 (E₂₀₁₀). Also shown are the reduction ratios (1 - E₁₉₇₀/E₂₀₁₀) of each species, which are the necessary fractions of the emissions when we aim to reduce their emissions from the 2010 to the 1970 level.

The data in Table 2 show that the share of anthropogenic emissions of CH₄, NO_x, and NMVOCs in the Asia/Pacific region is 32%, 18%, and 27%, respectively, of the global total in 1970, and they increased to 47%, 48% and 53%, respectively, nearly 50% of the global

emissions in 2010.

It has been pointed out that the Asian emissions of NO_x and CO_2 are nearly half of the global emissions in 2008 (EANET/SAC/TFRC, 2015). The rapid growth of Asian emissions since 1970 was most clearly seen for NO_x compared with the emissions in Europe and North America (Akimoto, 2003). Thus, the contribution of the Asian emissions of air pollutants and climate forcers was minor in the global emissions in 1970, but Asia was the major emitter in the world in 2010 and emissions have been increasing further until recently.

This situation strongly suggests that controlling SLCFs and CO_2 emissions in Asia is particularly important for climate change mitigation, and setting a clear reduction target for SLCFs is urgent. However, if we set 1970 as the target year to which level the anthropogenic global emissions of CH_4 , NO_x , and NMVOC should be reduced, it would not be feasible for Asian emissions in 2040 to the level of 1970 of its own. Instead,, we take the global reduction ratio as a guideline for the emission controlled level of CH_4 , NO_x , and NMVOC in 2040, applying also to Asia. Although the statistical emission data of “Asia/Pacific” in Table 2 by Hoesly et al. (2018) includes the Pacific area, this group’s emissions are largely dominated by the emissions from Asia in the base year of 2010, therefore, we use the term “Asia” for the reduction estimates in the discussion hereafter.

In order to reduce the global anthropogenic emissions of CH_4 from the level of 2010 (357

Tg CH₄ yr⁻¹) to that of 1970 (233 Tg CH₄ yr⁻¹), total emissions in 2010 have to be reduced by 35%, as shown in Table 2. If this reduction ratio is applied to Asia, the target reduction of Asian emissions in 2040 becomes 110 Tg CH₄ with a decrease of 59 Tg CH₄.

Similarly, in order to reduce the global anthropogenic emissions of NO_x from the emission level of 141 Tg NO₂ yr⁻¹ in 2010 to 79 Tg NO₂ yr⁻¹ in 1970, emissions have to be reduced by 44% by 2040. When the global reduction ratio, 0.44, is applied to the Asian emissions, the target reduction in 2040 becomes 38 Tg NO₂ yr⁻¹ rather than the actual NO_x emission of 14 Tg NO₂ yr⁻¹ in the Asia/Pacific in 1970.

Anthropogenic emissions of NMVOC should be reduced by the global reduction ratio of 22%, and the Asian emissions in 2040 should be 60 Tg NMVOC yr⁻¹ with a decrease of 19 Tg NMVOC yr⁻¹. The increase of global and Asian anthropogenic NMVOC emissions from 1970 to 2010 is by a factor of 1.3 and 2.5, respectively, as compared to the ratios of 1.8 and 4.9 for NO_x. Thus, the anthropogenic emissions of NO_x have increased much more rapidly than NMVOC emissions in Asia. It should be noted that the emissions from biomass burning are not included in these emission data and are not discussed in the present study.

Comparison with the Reduction Scenario in the Cost-Benefit Measures Based on the GAINS Model

“Air Pollution in the Asia Pacific: Science-Based Solutions (Solution Report)” prepared by

237 the CCAC and APCAP (Asia Pacific Clean Air Partnership)/Science Panel has recently been
238 published by the UN Environment, Asia Pacific Office (UNE, 2018). In this report, 25 measures
239 to reduce emissions of air pollutants and CH₄ in Asia in 2030 in a cost-effective way have been
240 proposed based on the GAINS model (Amann et al., 2011) as actionable options for
241 policymakers. They aim at tackling air pollution to achieve the WHO guideline values for PM_{2.5}
242 and O₃ concentrations, and near-term climate change by a third of a degree Celsius by 2050.
243 Although the publication did not report any reduced amount of RF for climate forcers CH₄ and
244 O₃, it would be interesting to compare the cost-benefit reduction of CH₄, NO_x, and NMVOC in
245 Asia proposed in this publication with the top-down approach to reduce the RF of CH₄ and O₃
246 to the level of 1970 deduced in the present study.

247 Table 3 compares the Asian emissions of CH₄, NO_x, and NMVOC in 2010 and 2040 (after
248 subtracting the targeted reduction) so far discussed, to those in the baseline scenario in 2010
249 and 2030 with proposed measures deduced in the Solution Report (UNE, 2018). Since the
250 absolute amount of emissions of each species in the reference year of 2010 are substantially
251 different between the studies due to either different coverage of sources and/or uncertainties in
252 the emission factors, here we discuss the reduction ratios between the projected year and the
253 reference year. It is interesting to note that the proposed reduction of NO_x and NMVOC in the
254 Solution Report is more stringent than the targeted top-down RF reduction based on global

average reduction ratios and even closer to the reduction ratio based on Asian emissions in 1970. These results imply that the emission control to fulfill the targeted reduction is most feasible for NO_x and NMVOC, and the RF of O₃ could be reduced to 50% of the present value if the emissions of NO_x and NMVOC from other parts of the world could be reduced coherently. In contrast, the reduction ratio of CH₄ proposed in the Solution Report (0.26) is substantially smaller than the targeted reduction ratio (0.35) in this study, and the reduction of CH₄ would need further effort.

Feasibility of Reduction of Anthropogenic Emissions of CH₄, NO_x, and NMVOC in Asia by Sectors

In order to get an insight into the feasibility of the targeted emission reduction of CH₄, NO_x, and NMVOC in Asia, a comparison of targeted reduction with a single global reduction factor and the Solution Report proposal has been made by sector. Livestock farming (enteric fermentation from cattle and sheep), coal production (discharge from coal mining), gas and oil production (leaks from oil and natural gas production, transmission and use), followed by waste treatment and rice paddies are the predominant sources of anthropogenic CH₄ in Asia as of 2010. As for NO_x, power plants and industries are the dominant sources followed by transport in Asia. Major sources of anthropogenic emissions of NMVOC are distributed to coal, gas and oil production, transport, residential sector, and solvent use.

273 Table 4 compares the reduction of anthropogenic emissions of CH₄, NO_x, and NMVOC in Asia
274 by source sector between the top-down targeted approach and the cost-effective model approach.
275 Table 4 gives some insight into the feasibility of the reduction of SLCFs by sector proposed in
276 the Solution Report (UNE, 2018). For example, as for the reduction of anthropogenic CH₄
277 emissions, the emission reductions of coal production and gas and oil production are well
278 regulated according to the Solution Report. The much higher emission reduction of waste
279 treatment in the proposed measures implies that the control of this sector is expected to be cost-
280 effectively promising. In contrast, emission control of CH₄ from livestock farming is much less
281 feasible even though this source contributes significantly to the CH₄ emissions in Asia.

282 As for NO_x, The relative importance of the potential reduction of fixed sources (power
283 plant/industries and waste treatment) (17 Tg NO_x yr⁻¹) is about two times higher than those of
284 the mobile sources (transport) (9 Tg NO_x yr⁻¹) in Asia. The contribution of power plants in Asia
285 in 2010 is much higher and that of transport is much lower than the contribution of these sectors
286 to the global emissions. As for the reduction of anthropogenic sources of NO_x in Asia, road
287 transport emissions are the most feasible to reduce by measures according to the Solution
288 Report (UNE, 2018) as shown in Table 4. Also, it is suggested that the NO_x emissions from
289 waste treatment can also be controlled cost-efficiently.

290 In Asia, coal, oil and gas production, transport, and residential are the top three contributors of

the NMVOC emissions, followed by solvent use. It can be noted that the emissions from transport increased drastically from 9% in 1970 to 22% in 2010 in contrast to a slightly decreasing global trend from 23% to 20% during these years. Furthermore, a substantial reduction of NMVOC emissions from transport, solvent use, residential and waste treatment is feasible. The overall reduction of NMVOC more than targeted by the top-down approach is promising.

Discussion

Since the UNEP/WMO (2011) and UNEP (2011a) raised the importance of the co-control of SLCFs together with the emission reduction of CO₂ for the alleviation of mid- and long-term climate change and air pollution mitigation simultaneously, many studies have been conducted using chemistry-climate models for the evaluation of the reduction effect of CH₄, O₃, and HFC and BC as SLCFs (Shindell et al., 2012; Smith and Mizrahi, 2013; Rogelj et al., 2014; Akimoto et al., 2015). Among these, CH₄, O₃, and HFC are gaseous climate forcers and their RFs are thought to be used as a measure of global heating of near-surface temperature additively to that of CO₂ to evaluate their contribution to climate change. In addition, it has recently been reported that the reduction of BC, a particulate climate forcer, is less effective as global warming mitigation, since the sensitivity of the RF of BC on surface temperature is minimal, which is

309 attributed to the positive radiative budget of BC being largely compensated for by rapid
310 atmospheric adjustment (Takemura and Suzuki, 2019). Although a reduction in the emission of
311 BC is definitely advantageous from the point of human health and it also helps climate change
312 mitigation by reducing the absorption of solar radiation by BC-deposited snow/ice, its effect on
313 global warming is not additive to other gaseous SLCFs. For this reason, we give priority to the
314 gaseous SLCFs, CH₄ and O₃, to be reduced, and have discussed in this paper.

315 Particularly in Asia, the incentives for controlling climate change and air pollution vary
316 significantly by country (Akimoto et al, 2015), so that it is more appropriate to evaluate the
317 effect of emission reduction on RF by each species, since the reduction of each SLCF has
318 different implication from an air pollution control point of view. In reality, however, there are
319 complicated interactions among gaseous SLCFs and their precursors, e.g. the reduction of NO_x
320 emissions for the reduction of tropospheric O₃ causes a decrease in atmospheric OH
321 concentrations and leads to an increase in CH₄ concentrations, while a decrease in CH₄ will
322 reduce O₃, etc. (Fuglestad et al., 1999; Karlsdóttir and Isaksen, 2000). For these reasons, most
323 of the discussion for asserting the importance of SLCF co-control for the alleviation of surface
324 temperature rise have demonstrated the overall effect of co-control of typically BC and CH₄
325 excluding the discussion of the reduction of O₃ by NO_x and NMVOC based on chemical-climate
326 models (Shindell et al., 2012; Shoemaker et al., 2013; Rogelj et al., 2014).

In the present paper, we discussed the effects of the reduction of O₃ and CH₄ together, since the RF of tropospheric O₃ is the second highest next to that of CH₄ and it has more relevance to air quality and human health, which would give more incentive to policymakers to focus on reducing it. This paper proposed a top-down view of RF reduction of the empirical approach based on the assumption that if the emissions can be reduced to some historical level, it would ensure the reduction of concentrations to the same historical level, provided other conditions do not change much. The advantage of this approach is that it gives a relative importance of the targeted reduction of each SLCF which is thought to be useful for policymakers. On the other hand, the disadvantage of the empirical approach may include that atmospheric interactions between different species during the course of emission reduction before the targeted goal is attained cannot be considered, emission reduction is evaluated only by the total amount ignoring the change in spatial distribution, and climate conditions in 2040 will be different from those in the past, etc. On the other hand, the uncertainties in the modeling approach have also been pointed out and the fact that the results vary by model, and the effect of SLCF reduction has a large uncertainty when climate change due to aerosols is taken into account (Smith and Mizrahi, 2013). Thus, both the empirical and the model approach have advantages and disadvantages and they should be considered complementary.

Among the gaseous SLCFs, the RF of HCFC is ca. 0.1 W m⁻² as of 2010 (Shoemaker et al.,

2013). The complete phase-out of HCFCs will add another $\square\square\text{RF}_x(\text{HCFC}) = 0.1 \text{ W m}^{-2}$ to the total of $\square\square\text{RF}_x(\text{CH}_4) \square\square\text{RF}_x(\text{O}_3)$, i.e., to 0.31 and 0.42 W m^{-2} (Table 1) resulting in 0.41 and 0.52 W m^{-2} at the 1970 and 1960 level, respectively. Then, the compensation ratios for the 0.8 W m^{-2} increase of $\text{RF}_x(\text{CO}_2)$ in 2040 will be 51% and 65%, which is more promising for alleviating climate change than by reducing CH_4 and O_3 alone.

As shown in Table 3, the reduction ratio of CH_4 by the GAINS model, 0.26, is substantially lower than the 0.35 reduction required by the top-down approach using the global reduction factor. Table 4 shows that the reduction of CH_4 emissions is most feasible for waste treatment and coal, gas and oil production, and least feasible for livestock farming. Since the contribution of the emissions from livestock is the largest at both the global and Asian scale, the mitigation of climate change by reducing CH_4 emissions from this source will be more feasible if a new technology for the reduction of livestock CH_4 is developed in the future.

The reduction ratio of NO_x and NMVOC in Asia in 2030 compared to 2010 reported in the Solution Report is more than 50% (Table 3) which is much larger than what is required by the top-down approach with the global reduction ratios. This means that if the reduction presumed by the GAINS model together with the coordinated reductions in other parts of the world is realized, the RF of O_3 would be expected to decrease to be much lower than 0.17 W m^{-2} for the level of 1970. As for the NO_x control, the reduction in the power plant and industry sector is

less feasible than that in the transport sector, as shown in Table 4 according to the GAINS model. This suggests that the enhancement of energy transformation from fossil fuel to renewable energy is highly advantageous from the point of climate change mitigation by O₃ reduction in addition to the CO₂ reduction measures.

The emissions of CO have been known to contribute to the production of tropospheric O₃ (Lamarque et al., 2005). The global emission of CO has already decreased since 2000, and the increase in Asian emissions has also almost stopped (Dentener et al., 2005), which would lead to a decrease in regional and global O₃ together with a reduction of NO_x and NMVOC.

Conclusions

A guideline of the SLCP co-control in Asia for climate change mitigation in the mid-term future has been proposed by a “top-down” empirical approach based on historical concentrations and RF of CH₄ and tropospheric O₃. As an example, if the global concentrations of CH₄ and tropospheric O₃ can be decreased from the level of 2010 to the historical levels of 1970 and 1960, their RFs will decrease from 0.48 to 0.34 and 0.27 W m⁻², and from 0.40 to 0.23 and 0.19 W m⁻², respectively. The sum of $\Delta\Delta\text{RF}_x(\text{CH}_4)$ and $\Delta\Delta\text{RF}_x(\text{O}_3)$ are 0.31 and 0.42 W m⁻² for the reduction to the 1970 and 1960 levels, respectively, which can compensate for 39% and 53% of the increase of RF by the increase of CO₂ in 2040.

The necessary reductions of anthropogenic emissions of CH₄, NO_x, and NMVOC in Asia from the 2010 to the 1970 level have been deduced based on the Community Emission Data System (CEDS) (Hoesly et al., 2018). The estimated reductions have been compared with the cost-beneficial reduction amount in 2030 proposed in the Solution Report prepared under the UN Environment Asia Pacific Office based on the GAINS model (UNE, 2018). The comparison suggested that the reduction of O₃ to the 1970 level is promising, while further efforts would be necessary for the reduction of anthropogenic CH₄ emissions to reach the 1970 concentration level.

Abbreviations

CCAC: Climate and Clean Air Coalition; GAINS: Greenhouse gas and air pollution interactions and synergies; HFC: Hydrofluorocarbon; IIASA: International Institute of Applied System Analysis; IPCC: International Panel on Climate Change; NMVOC: Non-methane volatile organic compounds; RCP: Representative Concentration Pathways; RF: Radiative forcing; SDGs: Sustainable development goals; SLCF: Short-lived climate forcer; SLCP: Short-lived climate pollutant; TOA; Top of the atmosphere; UNE: United Nations Environment; UNEP: United Nations Environment Program; WHO: World Health Organization; WMO: World Meteorological Organization

399

400 **Declarations**

401 **Availability of data and material**

402 All the datasets except those of “solution report” in Table 4 are available in each of the cited
403 references. The numerical data for the “solution report” in Table 4 is available from ZK at
404 IIASA.

405

406 **Competing interests**

407 The authors declare no conflict of interest.

408

409 **Funding**

410 This research was funded by the Environmental Research and Technology Development Fund
411 (S-12 and 2-1803) of the Ministry of the Environment, Japan.

412

413 **Authors' contributions**

414 HA analyzed the data and wrote the first draft of the paper. TN worked out the preparation of
415 numerical data of emissions and conducted discussions for the paper. HT proposed the
416 interpretation of the data and contributed to the overall discussion of the paper. ZK and MA

provided the numerical data of the GAINS model output and ZK discussed the detailed interpretation of the data.

Authors' information

HA, TN and HT are atmospheric chemists who have been studying on reactive gases and aerosols relevant to air quality. They have recently been concerned in science and policy related to the co-control of air pollution and climate change. ZK and MA have developed the GAINS model for evaluating air pollutants and greenhouse gasses synergistically, and have been playing a key role on the establishment of the atmospheric management policy in Europe. Recently, they are interested in the mitigation of air pollution and climate change in Asia.

Acknowledgements

We thank Eric Zusman at IGES for his comments on the draft. We also thank Nagy [Tanaka Edit](#) for the English language review.

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Figure legends

Figure 1. Atmospheric concentration of CO₂ in the past and future according to the IPCC emission scenarios RCP8.5, 6.0, 4.5, and 3PD (Peak and Decline to 3 W m⁻² by 2100) (based on Meinshausen et al., 2011).

Figure 2. Historical trend of CH₄ concentrations at Antarctica (orange line) and radiative forcing of CH₄ (blue line) (adapted from Ghosh et al., 2015, and Myhre and Shindell, 2013, respectively).

Figure 3. Historical trend of Tropospheric O₃ column (blue line) and radiative forcing (orange line) (adapted from Skeie et al., 2011 and Myhre and Shindell, 2013, respectively).

Figures

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Figure 2

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