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An empirical approach toward the SLCP reduction targets in Asia for the mid-term climate change mitigation

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Abstract

Although importance of co-control of SLCPs together with the emission reduction of CO_2 has attracted much attention for the mid-term climate change mitigation, the contribution to radiative forcing (RF) is rather complex, and chemistry-climate model analysis for the future scenario tends to give a "black box" for the contribution of each species. In order to deliver a more straightforward message on the effect of the reduction of SLCPs to policymakers, we propose "top-down" reduction targets of CH_4 and tropospheric O_3 in reference to the historical levels of their RF. Although the RF increase due to the increasing CO_2 concentration is inevitable in mid-term future (ca. 0.80 W m^{-2} in 2040), the RF of CH_4 and O_3 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 $\Delta RF_x(CH_4)$ and $\Delta RF_x(O_3)$ (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, indicating that the increase of $\Delta RF_{2040}(CO_2)$ can be compensated by 23, 39, 53, and 64%, respectively. The policy target can be selected from the combination of different target years each for CH_4 and O_3. With this global reduction ratio, the necessary reductions in CH_4, NO_x, and NMVOC in Asia were estimated and compared with the GAINS model-based cost-beneficial reduction amount proposed by the Solution Report prepared under UN Environment Asia and the Pacific Office. In order to attain the targeted reduced emission level of CH_4 and NO_x, new technology/practice for the reduction of livestock emission of CH_4 and energy transformation from fossil fuel to renewable energy is highly advantageous for NO_x reduction from industrial/power plant sources.

Keywords: SLCP, Asian emission control, CH_4, NO_x, NMVOC

1 Introduction

The importance of co-control of short-lived climate pollutants (SLCPs) for the alleviation of mid- and long-term climate change has been well recognized in environmental academic society (UNEP/WMO 2011; UNEP 2011a), and by policy makers in for example some of Asian developing countries (ACP 2018). The terminology of Short-lived Climate Forcers (SLCFs) is also used in a similar context, but SLCFs include the cooling substances and their precursors such as sulfur dioxide and sulfate aerosols. Hence, SLCPs can be defined as "warming SLCFs". As for the mitigation of SLCPs, it is in general well understood that co-controlling the main climate forcer, carbon dioxide (CO_2) and air pollutants ($PM_{2.5}$, SO_2, 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). On the other hand, the

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target of SLCP mitigation for climate change control has not necessarily been well-recognized by policymakers or NGOs, 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 (CH_4), tropospheric ozone (O_3), and hydrofluorocarbons (HFCs) are major SLCPs to be targeted with respect to reduction of their mixing ratios in the atmosphere by the UNEP (United Nations Environment Protection) (UNEP 2011a, b) and the CCAC (Climate and Clean Air Coalition) (CCAC 2014). Based on these early international initiatives providing scientific basis, the importance of taking action on the SLCP reduction has been broadly recognized, in particular, in Asia. In some Asian countries, the governments have adopted an SLCP action plan. These include, for example, an intervention introducing soot-free buses in Indonesia and energy-efficient brick kilns in Nepal (ACP 2018). However, the "real" actions on the SLCP reductions are somewhat limited to the conceptual scope and initiatives within CCAC and the actions at the broader international level are rather slow. For this circumstance, there would be several reasons from the aspects of politics to science, and we will focus on the scientific aspects here.

When discussing how to implement SLCP into the policymaking process, the question often arises from the complexity ascribed to the interrelationship between SLCPs and their precursors. For example, 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 Jr 2000; Akimoto 2016) and that the reduction of CH_4 also contributes to the decrease in the hemispheric and global ozone levels (e.g., Dentener et al. 2005). However, 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 CH_4, which has an adverse effect on climate change (Fuglestvedt et al. 1999; Karlsdóttir and Isaksen 2000). This may be the reason for excluding the control of O_3 by reducing NO_x in the CCAC report (CCAC 2017). Meanwhile, Akimoto et al. (2015) showed 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 CH_4 concentrations.

The CCAC emphasized the need for reduction of BC together with CH_4 and HFCs (CCAC 2014). However, it has been revealed that response of removing BC emissions to lower the surface temperature is much smaller than expected from its RF (radiative forcing) at TOF (the top of the atmosphere) by the model intercomparison study by Stohl et al. (2015), and the effects have been analyzed more clearly in a recent paper by Takemura and Suzuki (2019). 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 possible reason of unclarity for the SLCP mitigation is that the quantitative contribution of the control of each SLCP for climate change alleviation has not been clearly shown according to previous studies. The effectiveness of SLCP co-control for climate change has in general been discussed by using chemistry-climate models (Shindell et al. 2012; Smith and Mizrahi 2013; Rogelj et al. 2014). While these model analyses are important as a scientific guideline to seek for the best scenario for the co-control of SLCPs, they are not straightforward enough for policymakers to set an effective control target for individual SLCPs.

In order to deliver more straightforward message to policymakers, we propose in this paper to show the reduction targets of CH_4 and O_3 by an "empirical top-down" approach based on historical data. CH_4 and O_3 were selected since linearity between RF and surface temperature change can be presumed for these gaseous species allowing the discussion of RF comparing with that of CO_2 additively. Under the situation that the alleviation of near surface temperature rise by the mitigation of BC is not expected than was thought before (Takemura and Suzuki 2019), pursuing the decrease of RF of O_3 in conjugation with that of CH_4 becomes of much importance.

In the present study, we adopted an approach in which the historical atmospheric mixing ratios of CH_4 and O_3 are referred to as having been related to the lower anthropogenic emissions of CH_4, NO_x, and NMVOC in the past, and we envisioned the targeted emission reduction of these species in Asia. The results were compared with the recent proposal of 25 cost-effective measures for the emission control of anthropogenic air pollutants in Asia in 2030 (so called Solution Report) targeting to attain the WHO air quality guidelines and the sustainable development goals (SDGs) (UNE 2018) by using the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model of IIASA (International Institute of Applied Systems Analysis) (Amann et al. 2011). Sectoral reduction has been discussed based on the Solution Report comparing with the historical increase of anthropogenic emissions of CH_4 and NO_x by sector.

2 Methods

2.1 Increase of RF due to the increase of CO_2 in 2040 and possible compensation by the decrease of CH_4 and O_3

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 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 CO_2 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 CO_2 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 CO_2 is estimated to reach ~2.6 W m^{-2} in all of these three scenarios in 2040. Since the RF of CO_2 is 1.82 ± 0.2 W m^{-2} in 2011 (Myhre and Shindell 2013), the increase of RF due to the increase of CO_2 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 CO_2, the increase of RF has to be compensated by a reduction in the RF of SLCPs.

2.2 Historical change of the RF of methane and ozone

The global mean atmospheric mixing ratio of CH_4 has been increasing from the preindustrial value of ~750 ppb in 1750 to the present value of 1803 ± 2 ppb in 2011 (Myhre and Shindell 2013). Figure 2 shows the historical increase of CH_4 mixing ratios in the Antarctic (orange line) compiled by Ghosh et al. (2015) together with the RF of CH_4 given by the IPCC AR5 (blue line) (Myhre and Shindell 2013). The growth rate of the CH_4 concentration is moderate (5.1 ppb $year^{-1}$) in 1910–1950, fast (13.6 ppb $year^{-1}$) during 1950–1990, moderate (6.7 ppb $year^{-1}$) during the 1990s, and near steady to moderate after 2000 (Ghosh et al. 2015). The reason of the changes in growth rate has not been cleared yet. The increase of RF is not linear but nearly proportional to the global averaged concentration for a shorter period of time. As shown in Fig. 2, the RF of CH_4 in 2010 referenced to the preindustrial era of 1750 is 0.48 ± 0.20 W m^{-2}.

Figure 3 depicts the historical increase of the model-calculated global mean tropospheric O_3 burden (orange line) together with the RF given by Myhre and Shindell (2013) in the IPCC AR5 (blue line). Since the RF of O_3 reflects the change in the mean tropospheric burden rather than the mixing ratio near the surface layer, the increase in modeled global mean burden of tropospheric O_3 since preindustrial times represented in Dobson unit (DU) by Skeie et al. (2011) is quoted here. The increment of global mean tropospheric burden has increased from 2.3 DU in 1910 to 11.4 DU in 2010. The continuous increase of RF is in parallel with the increase of the global mean tropospheric O_3 burden, and it accelerated in the 1960s and slowed down after the 1980s. The historical increase of the tropospheric burden of O_3 can be ascribed to the increase of anthropogenic emissions of its precursors, NO_x, NMVOC, CO, and CH_4 (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 O_3 in 2010 referenced to the preindustrial era is 0.40 ± 0.20 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 CH_4, the RF of tropospheric O_3 has a large uncertainty up to ± 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-

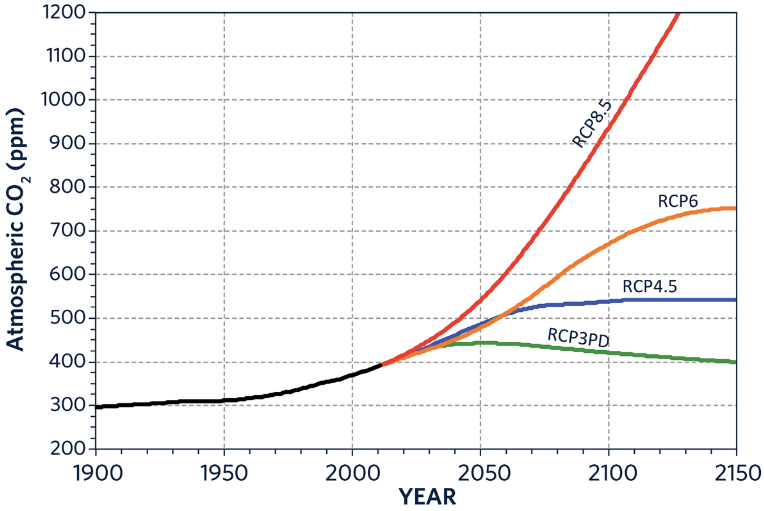

Fig. 1 Atmospheric concentration of CO_2 in the past and future according to the IPCC emission scenarios RCP8.5, 6.0, 4.5, and 3PD (peak and decline to 3 W m^{-2} by 2100) (based on Meinshausen et al. 2011)

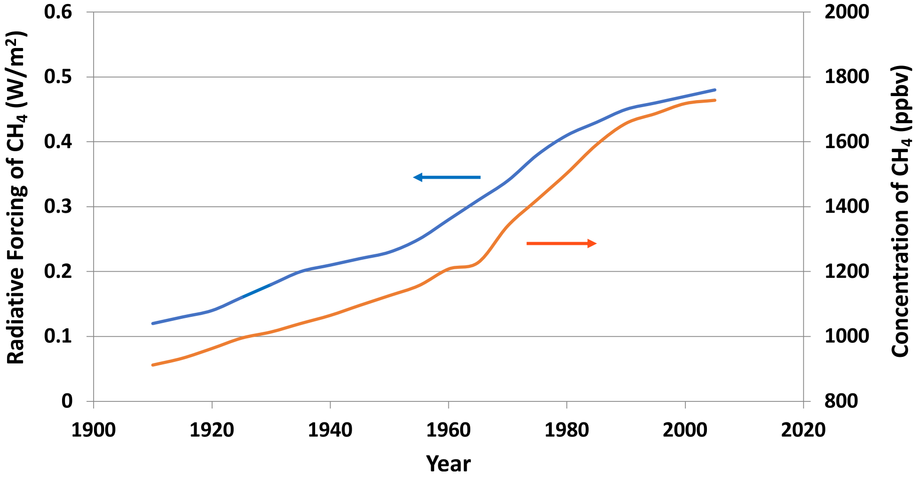

Fig. 2 Historical trend of CH_4 concentrations at Antarctica (orange line) and radiative forcing of CH_4 (blue line) (adapted from Ghosh et al. 2015, and Myhre and Shindell 2013, respectively)

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 O_3 that provides the reference value of RF. The reported observed values of ground-level O_3 in the late nineteenth and early twentieth centuries 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 O_3 is typically ~ 20 ppbv (Mickley and Jacob 2001; Lamarque et al. 2005; Young et al. 2018), substantially higher than the reported observed values. According to the recent analysis of oxygen isotopes in polar cores, it has been shown that tropospheric O_3 increased by less than 40% between 1850 and 2005, indicating that O_3 RF may be lower than 0.40 W m^{-2} (Yeung et al. 2019).

It should be noted that the RFs of CH_4 and tropospheric O_3 in 2011 relative to 1750 are 0.48 ± 0.05 and 0.40 ± 0.20 W m^{-2}, respectively, (total 0.88 W m^{-2}), and the total is comparable to the increase of RF due to the increase of CO_2 from 2011 to 2040 according to the IPCC AR5 (Myhre and Shindell 2013).

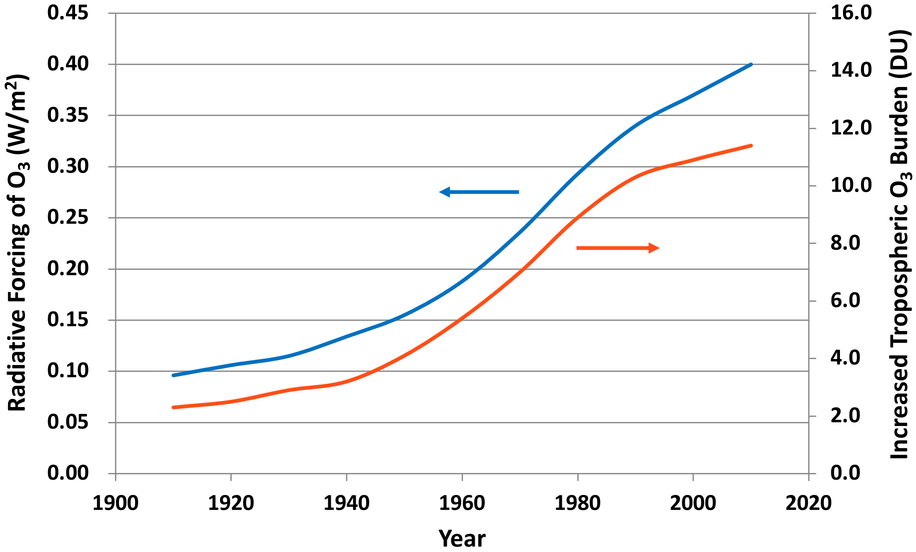

Fig. 3 Historical trend of Increased tropospheric O_3 burden (orange line) and radiative forcing (blue line) (data taken from Skeie et al. 2011 and adapted from Myhre and Shindell 2013, respectively)

3 Results

3.1 Target setting of the reduction of global CH_4 and O_3 to a historical year

Based on Figs. 2 and 3, Table 1 cites the RF_x and ΔRF_x of CH_4 and O_3 for a specified year, x (x = 2010, 1980, 1970, 1960, and 1950), where $\Delta RF_x = RF_{2010} - RF_x$ based on IPCC AR5 (Myhre and Shindell 2013). As shown in Table 1, the radiative forcing of CH_4 decreases from 0.48 to 0.41, 0.34, 0.27, and 0.22 W m^{-2}, and that of O_3 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, $\Delta RF_x(CH_4)$ and $\Delta RF_x(O_3)$ 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 $\Delta RF_x(CH_4)$ and $\Delta RF_x(O_3)$ 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 CH_4 and O_3 are decreased to the levels of 1980, 1970, 1960, and 1950, the increase of $\Delta RF_{2040}(CO_2)$ (0.80 W m^{-2}) can be compensated by 23%, 39%, 53%, and 64%, respectively.

To set the target year to which level CH_4 and O_3 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 CH_4 and NO_x/NMVOC as O_3 precursors. For example, if both CH_4 and O_3 can be reduced to the levels of 1970 and 1960, 39% and 53% of the increase in RF by CO_2 can be suppressed in 2040. If the target of CH_4 reduction is the 1970 level and that of O_3 is 1960 considering more difficulty of anthropogenic CH_4 emissions as will be discussed later, ΔRF_{1970} (CH_4) + $\Delta RF_{1960}(O_3)$ 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 will be the compensation of ca. 40% of the RF increase by CO_2 in 2040.

3.2 Targeted reduction of global and Asian emissions of CH_4, NO_x, and NMVOC

Global total and Asia/Pacific historical anthropogenic sectoral emissions of CH_4, 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 10 years. Table 2 shows the anthropogenic emissions of CH_4, NO_x, and NMVOC globally and in the Asia/Pacific region in 1970 (E_{1970}) and 2010 (E_{2010}) by the CEDS inventory. Also shown are the reduction ratios ($1 - E_{1970}/E_{2010}$) of each species, which are the fractions of the emissions to be reduced necessarily when we aim to decrease their emissions from the 2010 to the 1970 level. Global and Asian emissions and emission ratios (E_x/E_{2010}) for CH_4, NO_x, and NMVOC in every 10 years during 2010 and 1960 are given in Supplemental Tables, S1 and S2, respectively.

It should be noted here that although atmospheric O_3 concentrations will be adjusted to the equilibrium levels within a year after the change of the precursors, CH_4 concentration level will adjust slowly due to its longer lifetime of ca. 10 years. Therefore, the mixing ratio of CH_4 at a certain year must have been determined by integrated amount of emissions in the precedent ca. 10 years. This means that in order to attain to the mixing ratio, e.g., in 1970, the emissions should be reduced not to the level of 1970 but to the average level of precedent 10 years. Tables S1 and S2 list the global and Asian anthropogenic emission of CH_4 and the 10-year averaged emissions preceding every 10 years, together with emission ratios for each year and the year range referenced to 2010 and 2001–2010, respectively. As can be seen from Table S1 and S2, although the absolute amount of emission gives substantial difference between the target year and the precedent 10-year average, difference in emission ratio is not substantial. For this reason, discussion will be made only for the specified target year in this study.

The data in Table 2 imply that the share of anthropogenic emissions of CH_4, 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 pollutants was rather minor in the global total in 1970, but Asia is the major emitter in the world in 2010.

This situation strongly suggests that controlling SLCPs and CO_2 emissions in Asia is crucially important for climate change mitigation, and setting a clear reduction target for SLCPs is urgent. However, if we set 1970 as

Table 1 Radiative forcing (RF_X) and $\Delta RF_x = RF_{2010} - RF_x$ for CH_4 an O_3 for the years 2010, 1980, 1970, 1960, and 1950. The unit of RF_x and ΔRF_x is W m^{-2}

Year	CH_4		O_3		$\Delta RF_x(CH_4)$ + $\Delta RF_x(O_3)$
	$RF_x(CH_4)$	$\Delta RF_x(CH_4)$	$RF_x(O_3)$	$\Delta RF_x(O_3)$	
2010	0.48	0.00	0.40	0.00	0.00
1980	0.41	0.07	0.29	0.11	0.18
1970	0.34	0.14	0.23	0.17	0.31
1960	0.27	0.21	0.19	0.21	0.42
1950	0.22	0.26	0.15	0.25	0.51

Table 2 Global and Asia/Pacific emissions of CH_4, NO_x, and NMVOC in 1970 and 2010, and the reduction ratio (%) necessary to reduce the emissions in 2010 to the 1970 level. The units are Tg CH_4 year^{-1}, Tg NO_x year^{-1}, and Tg NMVOC year^{-1}, respectively (based on Hoesly et al. 2018)

Species	Global			Asia/Pacific		
	1970	2010	Reduction ratio	1970	2010	Reduction ratio
CH_4	233	357	0.35	72	169	0.57
NO_x	79	141	0.44	14	68	0.79
NMVOC	126	161	0.22	34	86	0.60

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 to reduce the Asian emissions in 2040 to the level of 1970 of its own. Instead, we presume the “global reduction ratios” should also be applied to Asia. Here, the “global reduction ratios” is defined as the reduction ratios of global emissions of CH_4, NO_x, and NMVOC needed to realize the atmospheric levels of CH_4 and O_3 in 1970. Although the emission data of “Asia/Pacific” in Table 2 by Hoesly et al. (2018) includes the Pacific area, the emissions are dominated by those from Asia in the base year of 2010, 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 CH_4 year^{-1}) to that of 1970 (233 Tg CH_4 year^{-1}), total emissions in 2010 have to be reduced by 35%, as shown in Table 3. If this reduction ratio is applied to the Asian emission of 169 Tg CH_4 year^{-1} in 2010, the required reduction of Asian emissions in 2040 is 61 Tg CH_4.

In order to reduce the global anthropogenic emissions of NO_x from the emission level of 141 Tg NO_2 year^{-1} in 2010 to 79 Tg NO_2 year^{-1} in 1970, emissions have to be reduced by 44% by 2040. When the global reduction ratio, 0.44, is applied to the Asian emission of 68 Tg NO_2 year^{-1} in 2010, the required reduction in 2040 is 31 Tg NO_2 year^{-1}. Similarly, anthropogenic emissions of NMVOC in Asia, 86 Tg NMVOC year^{-1} in 2010 should be reduced by 19 Tg NMVOC year^{-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 nearly twice more rapidly than NMVOC in Asia. It should be noted that the emissions from biomass burning are not included in these emission data.

Our discussion that the target level of the emission rates from Asia is not as low as that in Asia in 1970 assuming a milder global average target presumes that the rest of the world other than Asia must cut the CH_4 emission deeper than the levels in 1970. Considering that the rest of the world contributing to major emissions are Europe and North America during this period of time (see for example Akimoto (2003) for NO_x), and their effort of the emission control after 2000 has been successful, the achievement of this stringent reduction could be feasible although detailed analysis has not been made in this study.

3.3 Comparison with the reduction scenario in the cost-benefit measures based on the GAINS model

“Air Pollution in the Asia Pacific: Science-Based Solutions (so called Solution Report)” prepared by the CCAC and APCAP (Asia Pacific Clean Air Partnership)/Science Panel has recently been published by the UN Environment, Asia Pacific Office (UNE 2018). In this report, 25 measures to reduce emissions of air pollutants and CH_4 in Asia in 2030 in a cost-effective way have been proposed based on the GAINS model (Amann et al. 2011) as actionable options for policymakers. They aim at tackling air pollution to achieve the WHO guideline values for $PM_{2.5}$ and O_3 concentrations, and near-term climate change by a third of a degree Celsius by 2050. Although the publication did not report any reduced amount of RF for climate pollutants (CH_4 and O_3), it would be interesting to compare the cost-benefit reduction of CH_4, NO_x, and NMVOC in Asia proposed in this

Table 3 Baseline and targeted emissions of CH_4, NO_x, and NMVOC in Asia in the Solution Report (UNE 2018) (excluding biomass burning and international shipping) and comparison of reduction ratios from Table 2. The units of emissions are Tg CH_4 year^{-1}, Tg NO_x year^{-1}, and Tg NMVOC year^{-1} for CH_4, NO_x, and NMVOC, respectively

Species	Solution report			Top-down approach
	Baseline 2010 (E_{2010})	With measures 2030 (E_{2030})	Reduction ratio ($1 - E_{2030}/E_{2010}$)	Global reduction ratio ($1 - E_{2040}/E_{2010}$)
CH_4	118	87	0.26	0.35
NO_x	53	23	0.57	0.44
NMVOC	49	23	0.53	0.22

publication with the top-down approach to reduce the RF of CH_4 and O_3 to the level of 1970.

Table 3 compares the reduction ratios (E_{2030}/E_{2010}) of Asian emissions of CH_4, NO_x, and NMVOC in the baseline scenario in 2010 and 2030 with proposed measures deduced in the Solution Report (UNE 2018) to those in the present scenario for global reduction ratios given in Table 2. Since the absolute amount of emissions of each species in the reference year of 2010 are substantially different between the GAINS model in the Solution Report and the CEDS inventory due to either different coverage of sources and/or uncertainties in the emission factors, here we discuss only the emission ratios between the projected year and the reference year. It is interesting to note that the proposed reduction of NO_x and NMVOC in the Solution Report is more stringent than the targeted top-down RF reduction based on global average reduction ratios. Referring to the historical emissions in the CEDS inventory (Hoesly et al. 2018) (see Supplemental table, Table S2), the reduction ratios 26, 57, and 53% for CH_4, NO_x, and NMVOC by the Solution Report correspond to the actual emission levels in Asia in around 1995, 1985, and 1975 in Asia, respectively. These results imply that the emission control to fulfill the targeted reduction of the top-down scenario is most feasible for NMVOC followed by NO_x. In contrast, the reduction ratio of CH_4 proposed in the Solution Report (0.26) is substantially smaller than the targeted reduction ratio (0.35) in this study, and the reduction of CH_4 would need further effort.

3.4 Feasibility of reduction of anthropogenic emissions of CH_4, NO_x, and NMVOC in Asia by sectors

In order to get an insight into the feasibility of the targeted emission reduction of CH_4, 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. Coal, gas, and oil production (discharge from coal mining, leaks from oil and natural gas production, transmission and use); livestock farming (enteric fermentation from cattle and sheep); and followed by waste treatment and rice cultivation are the predominant sources of anthropogenic CH_4 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.

Table 4 compares the reduction shares of anthropogenic emissions of CH_4, NO_x, and NMVOC in Asia by source sectors between the top-down approach and the Solution Report scenario. For the top-down approach, the reduction amount for individual sectors are calculated by multiplying the reduction factor obtained from the sectoral global emissions in 2010 and 1970 to the sectoral Asian emissions in 2010 given in CEDS (Hoesly et al. 2018). The reduction share indicates the fraction of reduced emissions allocated to the specific sector. For the Solution Report scenario, the reduction shares are calculated as a fraction of reduction of each sector against total reduction under the intensive mitigation measures in 2030.

Table 4 gives some insight into the feasibility of the top-down reduction approach of SLCPs by sector comparing with the cost-effective model scenario of the Solution Report (UNE 2018). For example, as for CH_4, the emission from coal, gas, and oil production sector is the most important contributor in Asia in 2010, and the required reduction of this sector shares 47% of the total reduction according to the top-down scenario. In the Solution Report, the reduction of this sector shares 38% of the total reduction with measures, which is substantial but ca. 10% lower than the top-down request. The much higher reduction shares for waste treatment in the Solution Report than the top-down share implies that the control of this sector is expected to be cost-effectively promising. In contrast, emission control of CH_4 from livestock farming is much less feasible even though this source contributes significantly to the CH_4 emissions in Asia.

As for NO_x, the relative importance of the reduction shares of fixed sources (power plant/industries and waste treatment) is more than twice higher than those of the mobile sources (transport) in Asia. According to the Solution Report, road transport sector is the most feasible emission to be reduced by measures rather than fixed sources. In order to enhance the reduction of NO from power plant and industries, further promotion of energy transformation from fossil fuel to renewable energy would be required although the mitigation measures of renewables for power generation has been taken into consideration to some extent.

As seen in Table 4, the reduction shares for transport, waste treatment, solvent use, and residential sectors of NMVOC emissions by the Solution Report are higher than the top-down approach, supports the view that the future NMVOC control is very feasible as seen by the much higher reduction ratio of the Solution Report than the top-down reduction ratio in Table 3. Much higher and lower reduction shares for coal, gas, and oil production sector in the top-down approach and the Solution Report would be due to the fact that emission of NMVOC is counted substantially in this sector only in the former emission inventory.

4 Discussion

Since the UNEP/WMO (2011) and UNEP (2011a) raised the importance of the co-control of SLCPs together with

Table 4 Comparison of the reduction share of anthropogenic emissions of CH_4, NO_x, and NMVOC in Asia by sector. The reduction share of the top-down approach (2010–2040) and Solution Report Scenario with measures (2010–2030) are compared

Anthropogenic sources	**Reduction share in Asia by sector**					
	CH_4		**NO_x**		**NMVOC**	
	Top-down approach	**Solution report**	**Top-down approach**	**Solution report**	**Top-down approach**	**Solution report**
Coal, gas, and oil production	0.47	0.38	---	---	0.16	0.01
Power plant and industries	---	---	0.53	0.36	---	---
Transport	---	---	0.22	0.47	0.10	0.12
Rice cultivation	0.07	0.14	---	---	---	---
Livestock farming	0.17	0.03	---	---	---	---
Waste treatment	0.24	0.38	0.08	0.08	0.06	0.11
Solvent use	---	---	---	---	0.32	0.39
Residential	0.02	0.07	0.02	0.09	0.30	0.37
Others	0.03	0.00	0.15	0.00	0.06	0.00
Total sum	1.00	1.00	1.00	1.00	1.00	1.00

---, not applicable or not available

the emission reduction of CO_2 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 CH_4, O_3, and HFC and BC as SLCPs (Shindell et al. 2012; Smith and Mizrahi 2013; Rogelj et al. 2014; Akimoto et al. 2015). Among these, CH_4, O_3, 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 CO_2 to evaluate their contribution to climate change. Meanwhile, it has been reported that the reduction of BC, a particulate climate forcer, is less effective as global warming mitigation (Stohl et al. 2015). The effect is attributed to the positive radiative budget of BC being largely compensated for by rapid atmospheric adjustment (Takemura and Suzuki 2019). The multi-model mean of the effective RF including atmospheric adjustment is slightly positive (Thornhill et al. 2020) and the surface temperature change is slightly negative (Stohl et al. 2015), but their positive and negative responses differ from model to model. Although a reduction in the emission of BC is definitely advantageous from the point of human health and it also helps climate change mitigation by reducing the absorption of solar radiation by BC-deposited snow/ice, the effect of RF change of BC on near surface temperature rise is not additive to other gaseous SLCPs.

Particularly in Asia, the incentives for controlling climate change and air pollution vary significantly by country (Akimoto et al. 2015), so that it is more desirable to evaluate the effect of emission reduction on RF by each species, since the reduction of each SLCP has different implication from an air pollution control point of view. In reality, however, there are complicated interactions among gaseous SLCPs and their precursors, e.g., the reduction of NO_x emissions for the reduction of tropospheric O_3 causes a decrease in atmospheric OH concentrations and leads to an increase in CH_4 concentrations, while a decrease in CH_4 will reduce O_3, etc. (Fuglestvedt et al. 1999; Karlsdóttir and Isaksen 2000). Actually, most of the discussion for asserting the importance of SLCP co-control for the alleviation of surface temperature rise have estimated the overall effect of co-control of typically BC and CH_4 excluding the discussion of the reduction of O_3 by NO_x and NMVOC based on chemical-climate 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 O_3 and CH_4 together, since the RF of tropospheric O_3 is the second highest next to that of CH_4 and it has more relevance to air quality and human health, which would give more incentive to policymakers in Asia for mitigation. 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 SLCP. Instead, 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 the climate conditions in 2040 which will be different from those in the past, etc.

For example, the average temperature in 2040 will be higher than in 1970, which would form more O_3 even though the precursor emissions are the same as 1970. On the other hand, the uncertainties in the modeling approach have also been pointed out, e.g., the results vary substantially by model, and the effect of SLCP 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 complementarily.

Among the gaseous SLCPs, the RF of HFC is ca. 0.1 $W\,m^{-2}$ as of 2010 (UNEP 2011b; Shoemaker et al. 2013). The complete phase-out of HFCs will add another $\Delta RF_x(HFC) = 0.1\,W\,m^{-2}$ to the total of $\Delta RF_x(CH_4)$, $RF_x(O_3)$, 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 $RF_x(CO_2)$ 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, 26%, is substantially lower than the 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 effective if a new technology/practice 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 Solution Report 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 according to the Solution Report as shown in Table 4. This implies that the enhancement of energy transformation from fossil fuel to renewable energy is highly advantageous not only from the point of CO_2 reduction measures but also from the point of climate change mitigation by O_3 reduction.

The emissions of CO have been known to contribute to the production of tropospheric O_3 (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 help to decrease the regional and global O_3 together with a reduction of NO_x and NMVOC.

5 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 CH_4 and tropospheric O_3. As an example, if the global concentrations of CH_4 and tropospheric O_3 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 $\Delta RF_x(CH_4)$ and $\Delta RF_x(O_3)$ 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 CO_2 in 2040.

The necessary reductions of anthropogenic emissions of CH_4, 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 O_3 to the 1970 level is promising, while further efforts would be necessary for the reduction of anthropogenic CH_4 emissions to reach the 1970 concentration level.

Sectoral analysis of anthropogenic emission suggests that CH_4 emission reduction will be more effective if a new technology/practice for the reduction of livestock CH_4 is developed in the future. As for NO_x, enhancement of energy transformation from fossil fuel to renewable energy will reduce the emissions from power plant and industrial sector, which would be advantageous not only from the point of CO_2 reduction but also from the point of O_3 mitigation.

The results of this paper are hopefully communicated to policy makers to strengthen the science-policy interface through the Asia Pacific Partnership and other fora.

6 Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40645-020-00385-5.

Additional file 1: Table S1. Historical global emissions of CH_4, NO_x and NMVC in 1960-2010, and emission ratio to 2010 by the CEDS inventory. Averaged emission of CH_4 for the previous ten years, and the emission ratio to 2001-2010 are given in parenthesis. na: not available. **Table S2**. Historical emissions of CH_4, NO_x and NMVC in 1960-2010 in Asia, and emission ratio to 2010 by the CEDS inventory. Averaged emission of CH_4 for the previous ten years, and the emission ratio to 2001-2010 are given in parenthesis. na: not available.

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

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Authors' contributions

HA analyzed the data and wrote the first draft of the paper. TN worked out the preparation of numerical data of emissions and conducted discussions for the paper. HT proposed the 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. The authors read and approved the final manuscript.

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.

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Availability of data and materials

All the datasets except those of "Solution Report" in Table 4 are available in each of the cited references. The numerical data for the "Solution Report" in Table 4 is available from ZK at IIASA.

Competing interests

The authors declare no conflict of interest.

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