Recommendations on SLCP reduction measures

A shift from fossil fuel consumption to renewable energy to combat global warming can serve as an air pollution countermeasure. However, this countermeasure may increase global warming depending on the air pollutants being reduced. Therefore, effective mitigation scenarios are needed to simultaneously mitigate global warming and air pollution. The strategic research project S-12 of the Environment Research and Technology Development Fund, Ministry of the Environment (ERTDF)/Environmental Regeneration and Conservation Organization of Japan (ERCA), presents recommendations on short-lived climate pollutant (SLCP) reduction measures resulting from research on the evaluation of SLCP environmental impacts and the promotion of climate change countermeasures by seeking the optimal pathway (FYJ 2014-2018; Nakajima et al., 2020). The solution to this problem requires extensive cooperation from citizens and policy makers.

What is the problem?

The 21st Conference of Parties to the Framework Convention on Climate Change (COP21, Paris, France, Nov. 30- Dec. 11, 2015) adopted the Paris Agreement to maintain the global average surface air temperature (hereinafter referred to as "the surface air temperature") sufficiently lower than 2°C and to use 1.5°C as the goal. On the other hand, according to the IPCC Fifth Assessment Report, the temperature has increased approximately 0.9°C from 1880 to 2012, and a substantial effort is required to achieve the terms of the agreement.

The most important issue for this goal is the reduction of long-lived greenhouse gases (LLGHGs) such as carbon dioxide (CO_2). The effect of the reduction will not appear, however, until the middle of the 21st century, even if an immediate drastic reduction occurs, because their atmospheric residence time is as long as several decades. Therefore, in recent years, there has been increasing attention on SLCPs, such as black carbon (BC), tropospheric ozone, and methane (CH_4), which have a large global warming effect. Because SLCPs have a short residence time in the atmosphere, temperature changes due to their reduction appear relatively quickly. For example, according to a report by the United Nations Environment Programme (UNEP) and the World Meteorological organization (WMO) (2011) (Figure 1), SLCP reduction measures, in addition to LLGHG reduction measures, will produce a 0.5°C temperature reduction. For this reason, the Climate and Clean Air Coalition (CCAC) for the reduction of SLCPs has been launched with the aim of SLCP mitigation. The S-12 project conducted extensive studies on this problem and found that the climate impacts of SLCPs are complex and that their reduction measures require a careful strategy that is not considered in the UNEP scenario.

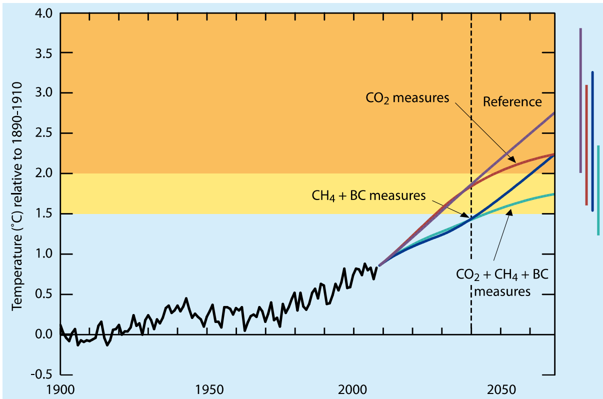

Figure 1: Changes in the surface air temperature and various countermeasure scenarios cited from the UNEP and WMO (2011). A line from 1900 to 2009 for the observed values and lines for various future scenarios after 2009 are shown. According to the report, simultaneous reductions in CO_2, CH_4 and BC (CO_2+CH_4+BC measures) and CH_4+BC measures can maintain the temperature at a rise to 2°C or less in 2040, as shown by the broken line.

A specific combination of SLCP reductions is needed for the simultaneous mitigation of both global warming and air pollution

The decline in the surface air temperature with reduced BC emissions is weaker than expected, which has been shown in a few recent studies. The S-12 study indicated that the sensitivity of surface air temperature to the instantaneous radiative forcing (the energy budget perturbation) at the top of the atmosphere due to scattering and absorbing solar radiation is weaker for BC than for sulfate aerosols (Figure 2). This is because the "rapid adjustment" due to changes in clouds and precipitation counteracts the instability due to weaker absorption of solar radiation with reduced BC emissions (Takemura and Suzuki, 2019; Suzuki and Takemura, 2019).

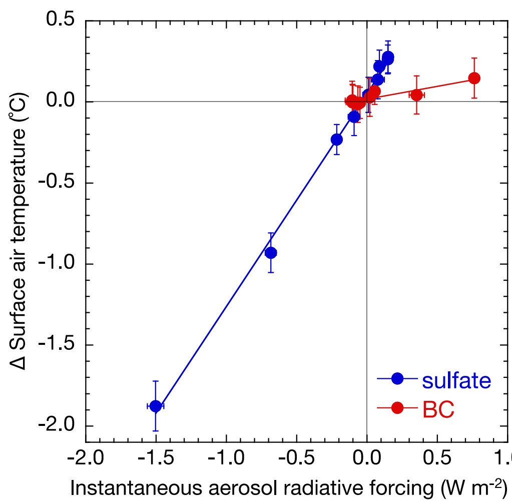

Figure 2: Relationship between global mean instantaneous radiative forcing and change in surface air temperature for sulfate aerosols (blue) and BC (red) simulated by the coupled atmosphere-ocean general circulation model MIROC-SPRINTARS. Cited from Takemura and Suzuki (2019).

Similarly, for BC, reducing emissions of nitrogen dioxides (NO_x) can also cause a counter effect to warming. NO_x emission reduction may lead to lower concentrations of ozone (O_3) in the troposphere but can also result in an increase in CH_4, which is one of the important LLGHGs due to the prolonged atmospheric lifetime of CH_4. In addition, reduced NOx levels decrease nitrate aerosols, which results in surface warming due to reduced scattering of sunlight. These two-sided effects of NO_x reduction can induce additional increases in surface air temperatures.

Figure 3 illustrates that positive and negative feedback processes exist among SLCPs, affecting the Earth's climate and environment. Therefore, a search for an optimum scenario must be developed using full knowledge of these complex interactions. For example, as illustrated in Figure 4, suitable combinations of BC and sulfur dioxide (SO_2) reduction, which can mitigate both negative impacts to health and global warming, are considered to exist in a narrow range due to the weak cooling effect of BC reduction. A similar situation exists for NO_x reduction.

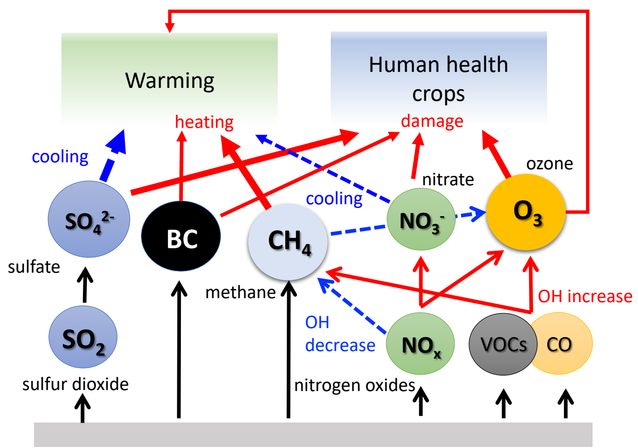

Figure 3: The SLCP impacts on climate change (global warming) and the surface environment (human health and agriculture) and mutual interactions of the individual SLCPs. Red solid and blue dashed arrows indicate positive and negative impacts, respectively, whose magnitudes are expressed with the thickness of the lines. Reducing the red arrows and enhancing (or unchanging) the blue arrows are the keys to effective mitigation of warming and environmental problems.

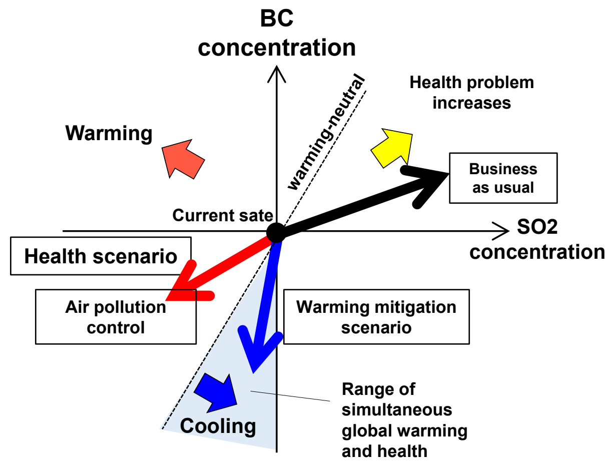

Figure 4: Impacts produced by changes in BC and SO_2 concentrations. Both reductions reduce negative impacts to health; however, BC reductions lead to weak cooling, and SO_2 reductions lead to large warming. As a result, the range of combinations that can mitigate both negative impacts to health and global warming is considered to be narrow.

Recommendation-1

Optimum SLCP reduction scenarios and mitigation measures should be developed taking into account the complex interactions of SLCPs, climate, and the atmospheric environment.

Reduction scenarios of LLGHGs and SLCP are proposed in the shared socioeconomic pathway (SSP) scenarios based on internationally considered future socioeconomic development (Figure 5). However, the relationships between BC and SO_2 emissions in India and China are similar for all the SSP scenarios, as indicated by Figure 6. Therefore, it is necessary to use a

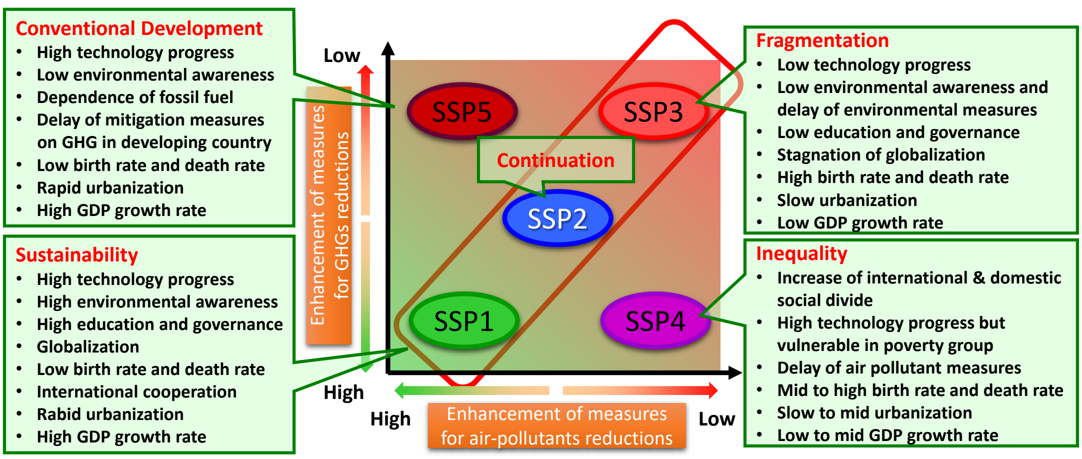

Figure 5: SSP (shared socioeconomic pathways) scenarios. Originally, this scenario framework involved future socioeconomic scenarios without any climate policies using a matrix with mitigation challenge on the vertical axis and adaptation challenge on the horizontal axis. In the S-12 study, the two axes are replaced by the vertical axis of challenge for climate mitigation and the horizontal axis of challenge for air pollution management. The concept is shown in Hanaoka and Masui (2018). All SSP data can be downloaded from the website of IIASA (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about#v2).

relatively wide range of reduction scenarios. The S-12 project proposes SLCP reduction scenarios that are based on the SSP2 middle of the road scenario, which is one of five SSP scenarios, and on a wide search of the combined reductions of BC, CH_4, and O_3 precursors (NO_x, CO, VOCs) taking into account their mutual interactions, as shown in Figure 3. Taking into account both achievements of the 2 degree (2D) target and SLCP reductions, the S-12 project developed SLCP reduction scenarios by using the AIM/Enduse model, which is a bottom-up model, to estimate the LLGHG and SLCP emission scenarios in the world and Asia, as shown in Table 1 and Figures 7 and 8.

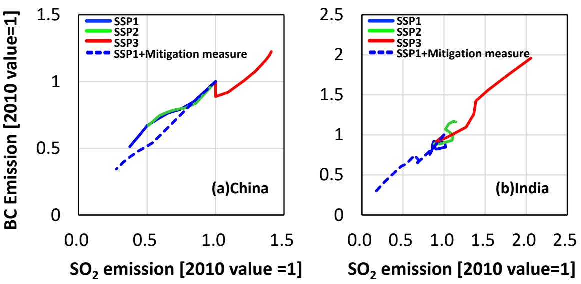

Figure 6: Relationships between emission changes in BC and SO_2 in China and India as evaluated by the SSP-based scenarios of S-12. All of the SSP-based scenarios have similar emission trends between BC and SO_2, indicating that the reduction scenarios of SLCP based on the SSP scenarios are limited. As a result, a broader assessment of SLCP reduction will be needed. The methodology is shown in Hanaoka and Masui (2018).

Table 1: Future scenarios developed by the S-12 project. Cited from Hanaoka and Masui (2020).

Scenario Group	Scenario code	Scenario name	line	Key measures for mitigating GHGs, SLCPs and air pollutants					
				Enhancement of end-of-pipe technology	2 degree Target measures	Enhancement of carbon capture and storage	Enhancement of renewable energy	Intensive electrification in building	Intensive electrification in transport
Reference	Ref	Reference							
End-of-pipe only	A1	EoPmid		Mid					
	A2	EoPmax		Max					
2 degree target and End-of-pipe	B1a	2D-EoPmid-CCSBLD		Mid	✔	✔		✔	
	B2a	2D-EoPmax-CCSBLD		Max	✔	✔		✔	
	B1b	2D-EoPmid-RESTRT		Mid	✔		✔		✔
	B2b	2D-EoPmax-RESTRT		Max	✔		✔		✔
	B1c	2D-EoPmid-RESBLDTRT		Mid	✔		✔	✔	✔
	B2c	2D-EoPmax-RESBLDTRT		Max	✔		✔	✔	✔

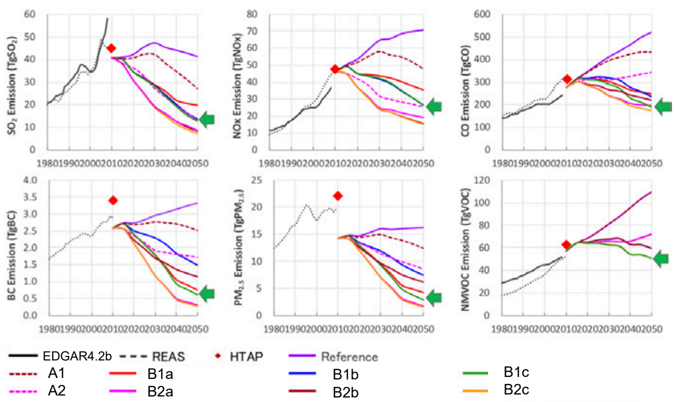

Figure 7: Emission pathways for gaseous composition in Asia. Among the emission pathways proposed by the S-12 project, the B1c (2D-EoPmid-RESBLDTRT) scenario is the best scenario for mitigating the global surface air temperature. Cited from Hanaoka and Masui (2020).

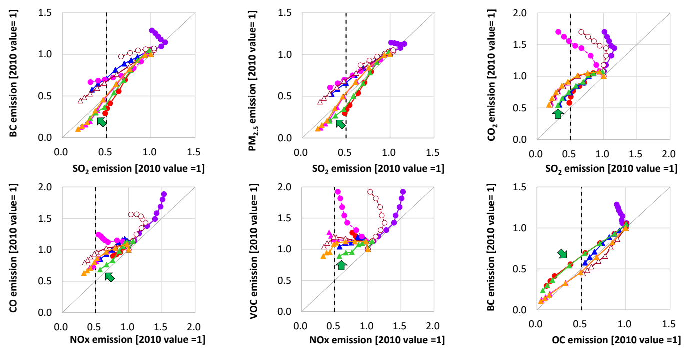

Figure 8: Emission pathways for gaseous composition in Asia (evaluating pathways to 2050 based on the 2010 value). Cited from Hanaoka and Masui (2020).

Figure 9 shows the time series of the surface air temperature simulated with the S-12 scenarios by using the MIROC climate model coupled with the SPRINTARS aerosol model and CHASER atmospheric chemistry model. The figure indicates that the main driver of global warming mitigation is the reduction in LLGHGs, which is included in the mitigation measures of the B1 and B2 scenarios in the figure. On the other hand, simple end-of-pipe (EoP) measures (A1 and A2 scenarios) to reduce air pollution will increase global warming. Therefore, the introduction of the SLCP mitigation technologies carbon capture and storage (CCS), renewable energy (RES), intensive electrification in building (BLD) and transport (TRT) can simultaneously reduce global warming and air pollution. Among the S-12 scenarios, the B1c scenario, i.e., the 2D scenario with enhanced renewable energy, electrification in residential and transportation sectors, and continuation of EoP technology treatment, can contribute to an effective reduction in the surface air temperature. This scenario cannot occur with measures implemented by only one country but needs all countries to contribute. On the other hand, the solution will become more complex if the condition in each country is largely different from that in other countries. Such an "ill structured problem", such as this case, makes it impossible to find the optimal solution, so that it is important for stakeholders to share their problems, analyze them and determine the solution through various challenges. This means that we will have to continue to assess new scenarios to address this issue.

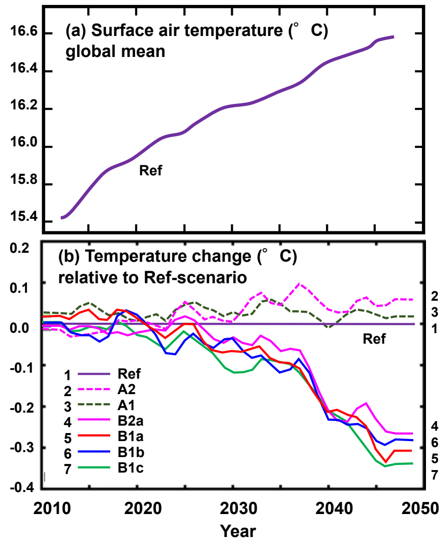

Figure 9: Time series of (a) global mean surface air temperature simulated with the S-12 Ref-scenario and (b) temperature changes simulated with the six S-12 scenarios relative to the Ref-scenario. The numbers to the right ordinate are scenario numbers in order of magnitude in 2050. Cited from Nakajima et al. (2020).

Recommendation-2

The impacts of SLCPs on health, agriculture and the hydrological cycle are also significant and need to be evaluated in the SLCP reduction assessment.

Concentrations of SLCPs are higher in Asia than in other regions of the world, and the number of deaths from respiratory and cardiovascular diseases and of the decreased life spans are remarkable (Figure 10). Future simulations indicate that the global excess mortalities due to $PM_{2.5}$ and high temperatures depend on the scenarios (Figure 11). The yield of rice significantly decreases with high ozone concentrations and changes depending on changes in temperature, precipitation, and radiation, as shown by future simulations (Figure 12). Based on these impact simulations, recommended S-12 scenarios are identified as B1c, B2a, and B1b according to their mitigation performances in terms of global mean surface air temperature reduction (Figure 9), reduction in mortality due to $PM_{2.5}$ and ozone (Figure 11), and rice yield decreases due to ozone and climate (Figure 12).

In addition, the population that could be exposed to large floods would increase in either case of an increase or decrease in the emissions of BC and SO_2, which are precursor gases of sulfate (Figure 13). This is because the amount of precipitation changes significantly due to the change in BC, despite the lower sensitivity to the surface air temperature. Very few studies have evaluated the impact of SLCP on extreme phenomena such as floods and heat waves, which have been increasing significantly in recent years. Given the amount of influence that the SLCP exerts on the energy balance of the Earth's atmosphere and surface and the fact that aerosols are essential substances for the formation of clouds and precipitation, it is necessary to carry out a quantitative assessment of the comprehensive environmental impacts of SLCPs in the future.

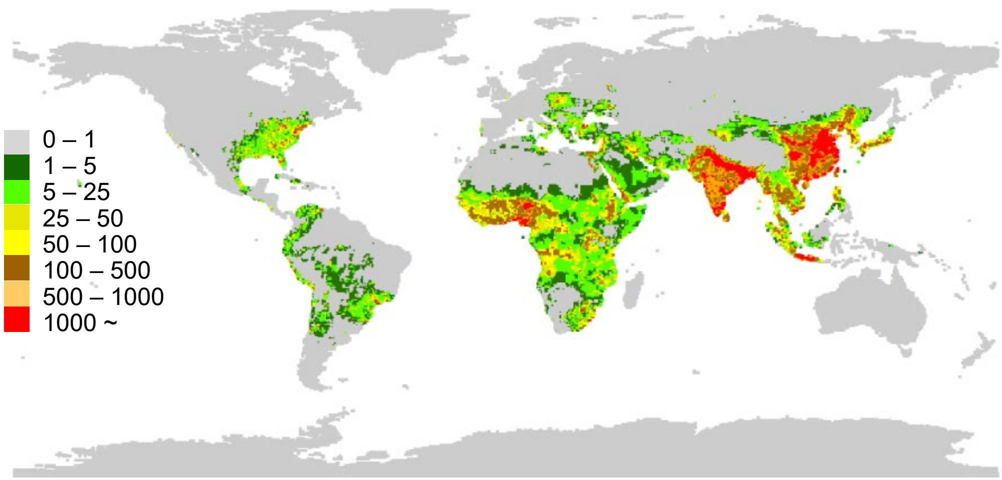

Figure 10: Spatial distribution of mortality attributable to $PM_{2.5}$ (person/250 km^2). The methodology is shown in Seposo et al. (2019).

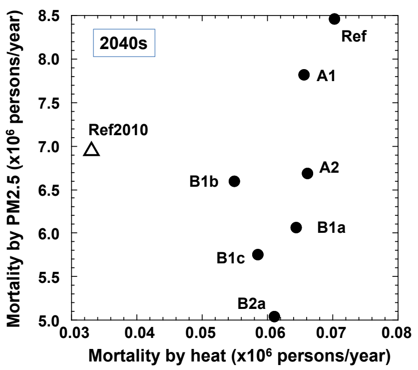

Figure 11: Global excess mortalities due to $PM_{2.5}$ and high temperatures in the 2010s (Ref2010) and the seven S-12 scenarios in the 2040s. Cited from Nakajima et al. (2020).

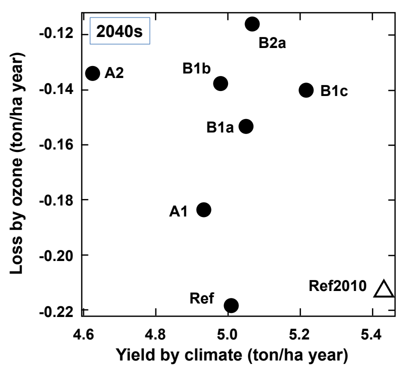

Figure 12: Global loss in rice yield from the ozone effect (ordinate) and from the climate, which exclude the ozone effect (abscissa) for the Ref-scenario in 2010-2019 denoted as Ref (2010) and the seven scenarios in 2040-2049. Cited from Nakajima et al. (2020).

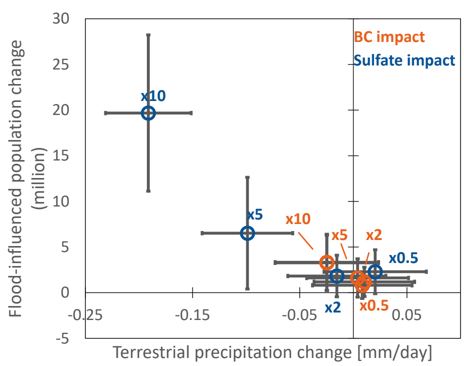

Figure 13: Relationship between the change in world population exposed to flood risks and the change in terrestrial precipitation due to BC (orange) or sulfate (blue) emission (from 0.5 to 10 times for both cases) differences. Error bars represent the standard deviation of interannual variation in the 20-year simulations. Cited from Nakajima et al. (2020).

Recommendation-3

Scenario-based analyses should be continued for the formulation of international and domestic SLCP reduction policies.

In the S-12 project, the emission process of SLCPs in the AIM/Enduse has been refined to accurately assess SLCP reduction measures, which are consistent with the latest SLCP emission inventory in Asia REAS. By combining the REAS and AIM/Enduse, we can estimate the SLCP emissions consistent with the inventory and the necessary reduction technology options.

Our study of emission scenarios suggested that various environmental and climate impacts will occur depending on the adopted scenarios. Determining the best scenario among various scenarios is a complex and difficult task because it will depend on the value judgment of the various stakeholders in the future. Therefore, it is useful to use the scenario development system of the S-12 project to help decide on the SLCP countermeasures that are consistent with future socioeconomic conditions and LLGHG emissions. The AIM/Enduse model, refined by S-12, can determine the optimum technology selection to minimize the total cost under the energy service demand and to estimate future emissions of SLCPs in addition to LLGHG emissions such as CO_2. Different parameter setups of the newly developed AIM/Enduse model can assess various future scenarios.

However, various skills related to database development and programming skill are needed to conduct AIM/Enduse model simulations, and the simulations require a long calculation period to drive the model. As a result, timely model simulations are not feasible for stakeholders to conduct during related discussions. To address this problem, AIM/SLCP, a web-based tool, has been developed to provide approximate yet timely simulation results to stakeholders to discuss decision making on pollution reduction activities. This tool is implemented with simplified equations reflecting the large database of mitigation measures calculated by the full AIM/Enduse model. It can also perform the quick calculations for environmental impacts based on simplified equations reflecting the database that includes complete climate and environmental models, such as precipitation change and population levels under water stress change rates, which are displayed based on global emissions.

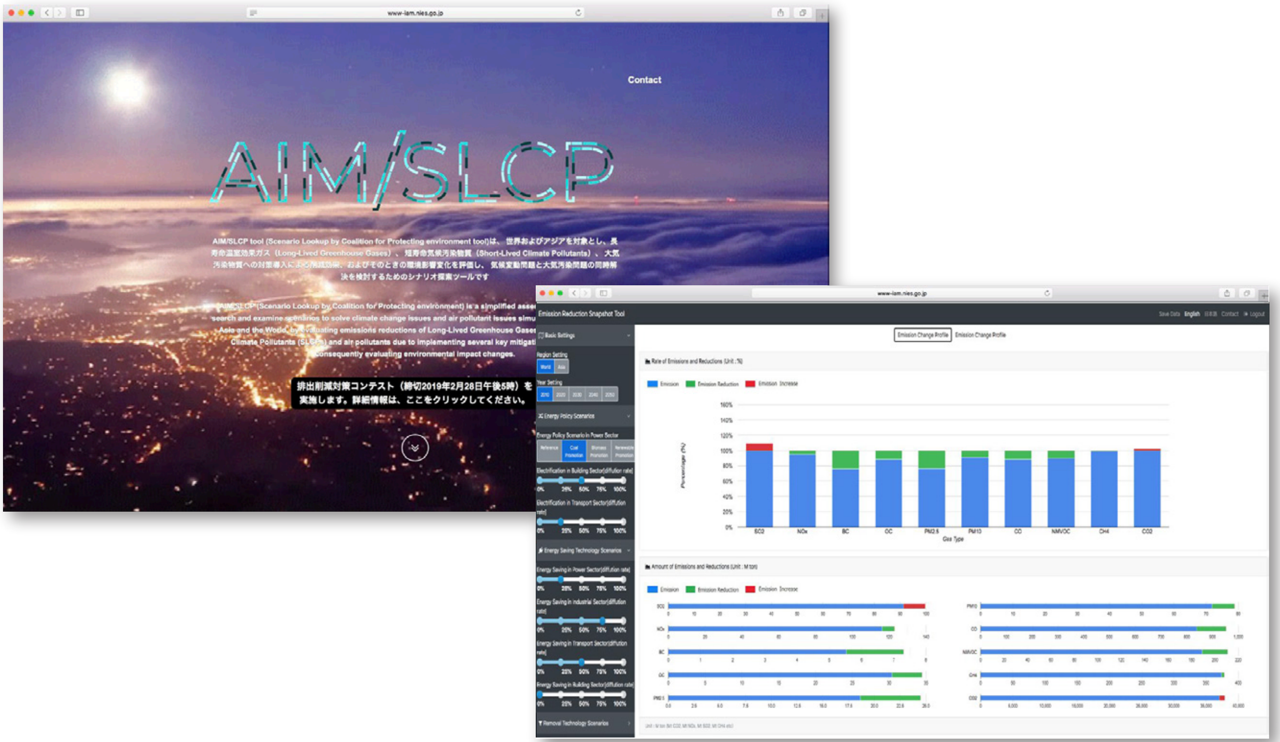

Figure 14: Website of AIM/SLCP: Simple tool to estimate future SLCP and LLGHG emissions in the world and Asia based on the results of AIM/Enduse (http://www-iam.nies.go.jp/aim/data_tools/S12/).

Recommendation-4

The scenario development system constructed by the S-12 project for evaluating SLCP impacts is useful for determining mitigation paths of SLCPs.

The S-12 project developed a system that identifies emission sources, extends the relevant adaptation models to determine future emission scenarios, and evaluates the climatic impacts, thereby connecting emission controls to the eventual environmental impact in an end-to-end fashion (Figure 15). Furthermore, the NICAM-Chem model has been developed and refined to enable seamless simulations across wide ranges of spatial scales from regional to global (Figure 16), including global simulations with unprecedentedly high resolutions (Figure 17). These innovative systems should be exploited in future efforts to explore emission scenarios that best address the multifaceted impacts of SLCP.

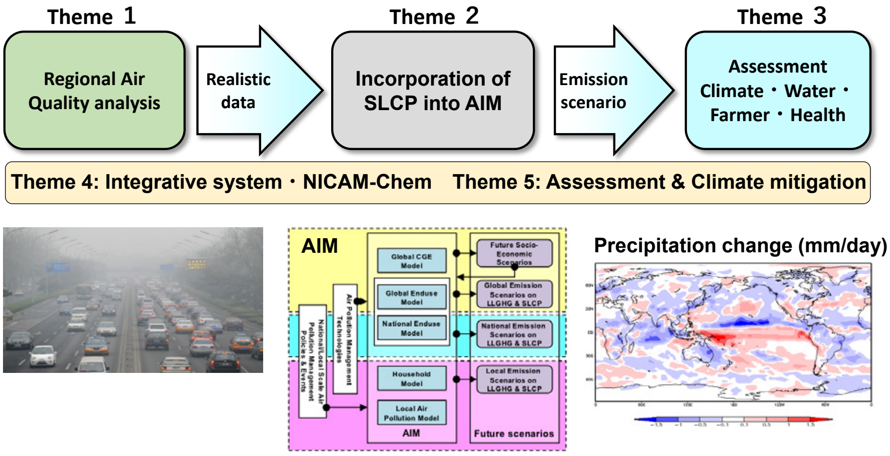

Figure 15: Schematic illustrations of the scenario development system for determining SLCP emission mitigation paths capable of evaluating the climatic impacts of emission controls depending on adaptation measures.

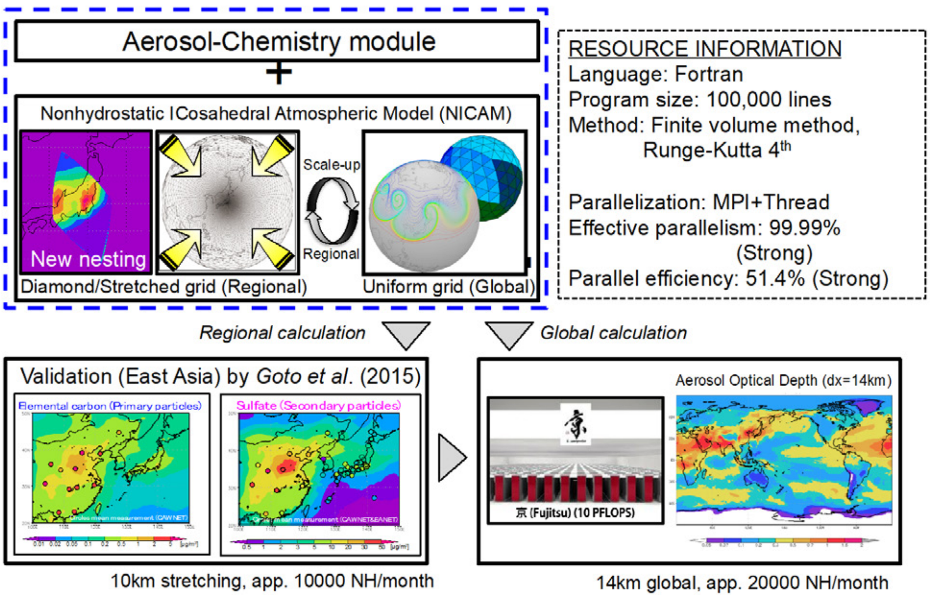

Figure 16: Overview of the NICAM-Chem modeling system that enables seamless simulations of SLCP impacts on weather and climate at regional to global scales.

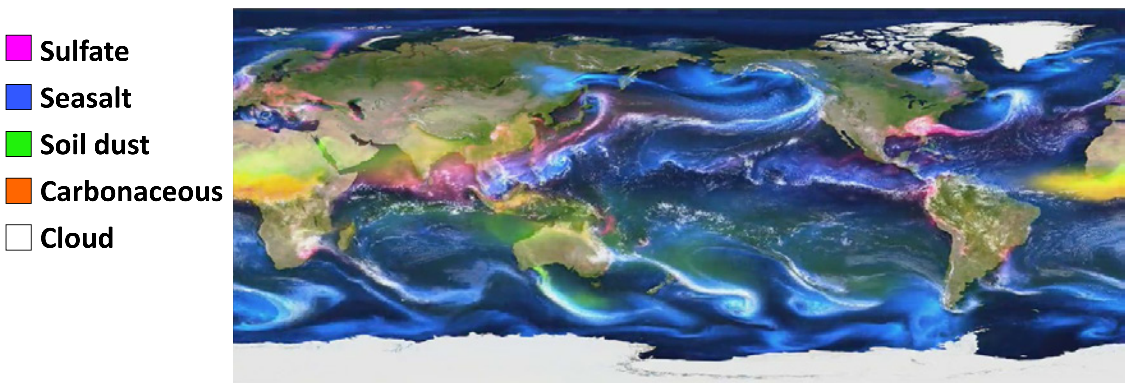

Figure 17: Visualization by NICAM-Chem of global simulations of various types of aerosols and their interactions with clouds with unprecedentedly high resolutions.

Recommendation-5

We should continue monitoring emission changes in air pollutants and updating the SLCP emission inventory in Asia, where intense changes in social economic activities and environmental measures occur. Hence, emission inventories should be developed routinely by using satellite data analysis.

The S-12 project has established a new method for SLCP emission inventory development by combining the conventional method (REAS emission inventory) with the inverse method (estimation based on satellite observations). Thus, updating the emission inventory in semireal time may be possible at the regional scale, including in developing countries where socioeconomic statistics data are difficult to obtain. In addition, by applying the method to the recent SLCP emission situation in China, the difference between this method and the conventional method was found, and REAS was improved based on a comparison and evaluation of both methods. Continuous monitoring of emission changes in air pollutants, including SLCPs, as well as differences in the emission scenarios and rapid updating of emission inventories are needed in Asia because of intense changes in socioeconomic activities and environmental measures. Hence, emission inventories should be developed routinely by using satellite data analysis.

The S-12 project conducted for the first time a quantitative evaluation of the effects of emission reductions and air quality improvements due to atmospheric environmental measures carried out in the past in Japan. A clear demonstration of the policy effects will be important for society to support atmospheric environment measures (EBPM: Evidence-Based Policy Making). In addition, the development of an integrated system consisting of an emission inventory, a chemical transport model, and an inverse estimate should be strengthened to quantitatively evaluate the effects of regional air pollution measures in Japan in reference to the system at the Asia scale developed in this project.

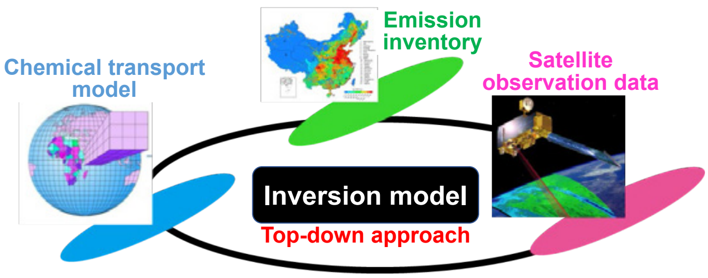

Figure 18: Schematic diagram of inverse estimates of emissions based on satellite observations.

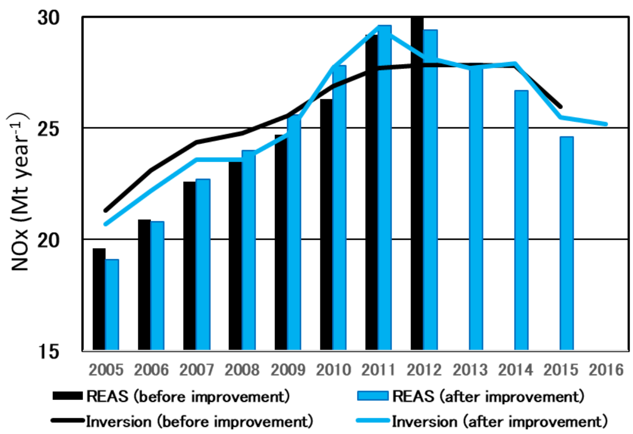

Figure 19: Comparison of NO_x emissions in China between the emission inventory and inverse estimates. Two estimates from the different methodologies become consistent after improvements (The methodology is shown in Itahashi et al., 2019).

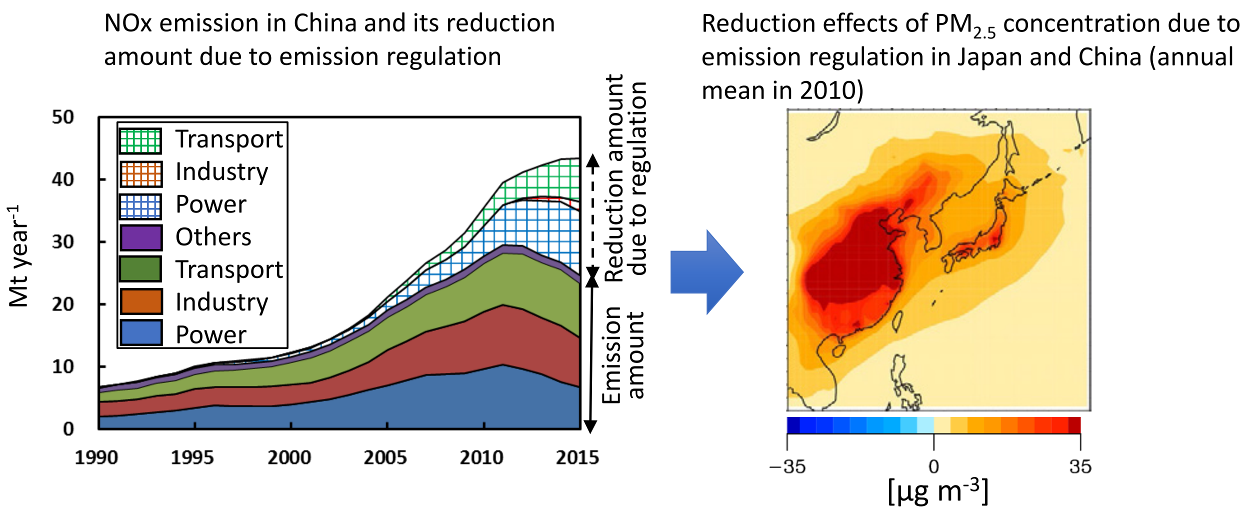

Figure 20: NO_x emissions in China and the amount of their reduction due to emission regulation (left) and the effects of the reduction in $PM_{2.5}$ concentrations due to emission regulation in Japan and China (right).

The S-12 project promoted SLCP research and its dissemination through the following activities:

- Discussion with the experts and the secretariat of The Climate and Clean Air Coalition (CCAC)
- Presentation of the S-12 research outcomes at a symposium for environmental institutes in Japan held at National Institute for Environmental Studies (NIES), Japan, on February 14-15, 2019
- Series of annual open symposia for dialogue with public to obtain feedback through presentations, discussions, and questionnaires
- Presentation and dialogue with public at a science cafe at 'EcoPro 2018' on December 6, 2018
- An open contest to determine the best scenario of SLCP reduction
- Compilation of the S-12 research results in governmental documents, promotion of the simplified tool AIM/SLCP for use by the government and public, and promotion of the S-12 scenario development system for governmental use

These activities and studies should be continued for a deeper understanding of the complex SLCP issues.

The S-12 project 'Evaluation of SLCP environmental impacts and promotion of climate change countermeasures through seeking the optimal pathway' (FY 2014-2018) is one of the strategic research projects of the Environment Research and Technology Development Fund, Ministry of the Environment (ERTDF)/Environmental Regeneration and Conservation Organization of Japan (ERCA). The project also cooperated with several SDGs.

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SUSTAINABLE DEVELOPMENT GOALS
13 CLIMATE ACTION
7 AFFORDABLE AND CLEAN ENERGY
3 GOOD HEALTH AND WELL-BEING
15 LIFE ON LAND
6 CLEAN WATER AND SANITATION

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