Findings, Issues, Opportunities, and Recommendations

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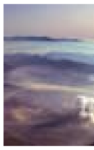
4.1 INTRODUCTION

This Chapter, which is intended for both technical and non-technical audiences, provides a summary of the key findings, presents a number of new questions that were revealed by our study, and identifies new opportunities for future research.

4.2 KEY FINDINGS

The key findings of Synthesis and Assessment Product 3.2 are summarized below:

1. Our results suggest that the projected changes in short-lived[1] radiatively active[2] gases and particles may significantly influence the climate, even out to year 2100. Their projected changes can account for up to 40 percent of the projected warming over the summertime continental United States by 2100.
2. We find that spatial patterns of radiative forcing[3] and climate response are quite distinct. Thus, both short-lived and long-lived[4] gases and particles cause enhanced climate responses in the same regions rather than short-lived gases and particles having an enhanced effect primarily in or near polluted areas. This means that regional pollution control strategies will have large-scale climate impacts.
3. Reductions of short-lived gas and particle emissions from the domestic fuel-burning sector in Asia appear to offer the greatest potential for substantial, simultaneous



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[1] Atmospheric lifetimes for the short-lived radiatively active gases and particles of interest in the lower atmosphere are about a day for nitrogen oxides, a day to a week for most particles, and a week to a month for ozone. As a result of their short lifetimes, their concentrations are highly variable in space and time and they are concentrated in the lowest part of the atmosphere, primarily near their sources.

[2] "Radiatively active" indicates the ability of a substance to absorb and re-emit radiation, thus changing the temperature of the lower atmosphere.

[3] Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate, such as atmospheric composition or surface reflectivity, are altered. When radiative forcing is positive, the energy of the Earth-atmosphere system will ultimately increase, leading to a warming of the system. In contrast, for a negative radiative forcing, the energy will ultimately decrease, leading to a cooling of the system. For technical details, see Box 3.2.

[4] Atmospheric lifetimes for the long-lived radiatively active gases of interest range from ten years for methane to more than 100 years for nitrous oxide. While carbon dioxide's lifetime is more complex, we can think of it as being more than 100 years in the climate system. As a result of their long atmospheric lifetimes, they are well-mixed and evenly distributed throughout the lower atmosphere. Global atmospheric lifetime is the mass of a gas or a particle in the atmosphere divided by the mass that is removed from the atmosphere each year.

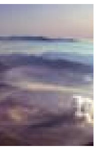
improvement in local air quality and reduction of global warming. Reduction in emissions from surface transportation would have a similar impact in North America.

4. The three comprehensive climate models[5], their associated chemical composition models[6] and the different projections of short-lived emissions all lead to a wide range of projected climate impacts by short-lived gases and particles. Each of the three studies represents a thoughtful, but incomplete, characterization of the driving forces and processes that are believed to be important to the climate or to the global distributions of the short-lived gases and particles. Much work remains to be done to characterize the sources of the differences and their range.

5. The two most important uncertainties in characterizing the potential climate impact of short-lived gases and particles are found to be the projection of their future emissions and the determination of the indirect effect of particles[7] on climate. See Section 4.3 for a discussion of the fundamental difference between uncertainties in future emissions and uncertainties in processes such as the indirect effect of particles on climate.

6. Natural particles such as dust and sea salt also play an important role and their emissions and interactions differ significantly among the models, with consequences to the role of short-lived pollutants. This inconsistency among models should be addressed in future studies.

7. The SAP 2.1a emissions scenarios (Clarke *et al.*, 2007) for long-lived gases produce climate projections that are within the IPCC range, although it should be noted that the lower-bound stabilization emissions scenario[8], which is equivalent to a carbon dioxide stabilization level of 450 parts per million, results in global surface temperatures below those calculated for the IPCC storyline emissions scenario with the most moderate carbon dioxide increases (B1), particularly beyond 2050.



4.3 ISSUES RAISED

It is important to recognize the difference between uncertainties in processes and uncertainties in future emissions. Uncertainties in chemical and physical processes, which are discussed in Sections 4.3.2 and 4.3.3, represent the state of our current knowledge. The fact that one modeling group chooses to include a process such as indirect forcing of climate by particles, while another group chooses not to, shows that our knowledge about short-lived gases and particles and their interactions with climate is still evolving. Eventually, with further research, uncertainties in chemical and physical processes can be significantly reduced. However, uncertainties in future emissions, which are discussed in Section 4.3.1, will always be with us. What we can do is develop a set of internally consistent emissions scenarios that include all of the important radiative gases and particles and bracket the full range of possible future outcomes.

4.3.1 Emissions Projections

The analysis presented in Chapter 3 showed that the main contributors to the divergence among model projections of future particle loading and climate forcing were the differences in the underlying emissions projections.

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[5] Comprehensive climate models are state-of-the-art numerical representations of the climate based on the physical, chemical, and biological properties of its components, their interactions and feedback processes that account for many of the climate's known properties. Coupled Atmosphere-Ocean (-sea ice) General Circulation Models (AOGCMs) provide a comprehensive representation of the physical climate system.

[6] Chemical composition models are state-of-the-art numerical models that use the emission of gases and particles as inputs and simulate their chemical interactions, global transport by the winds, and removal by rain, snow, and deposition to the earth's surface. The resulting outputs are global three-dimensional distributions of the initial gases and particles and their products.

[7] Particles may have an indirect effect on the climate system by modifying the optical properties and lifetime of clouds. A detailed technical discussion is given in Box 3.1.

[8] Stabilization emissions scenarios are a representation of the future emissions of a substance based on a coherent and internally consistent set of assumptions about the driving forces (such as population, socio-economic development, technological change) and their key relationships. These emissions are constrained so that the resulting atmospheric concentrations of the substance level off at a predetermined value in the future.

Those differences arose from two primary factors. First, different integrated assessment models[9] interpret a common socio-economic 'storyline' in different ways, as demonstrated in Chapter 2. Second, emissions scenarios were not produced for some short-lived gases and particles and had to be added in later by other emissions modeling groups or by the climate modeling groups themselves. These same issues were also encountered in Chapter 2 which focused on the SAP 2.1a stabilization emissions scenarios (Clarke *et al.*, 2007). While emissions scenarios for short-lived gases and particles were outside of SAP 2.1a's mandate, climate projections require them. Part of the reason for the different emission inventories used here and in the IPCC studies was that the integrated assessment models did not recognize that they were necessarily important when the scenarios were first constructed.

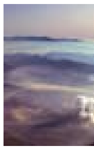
Just consider two of the integrated assessment models used to generate the sulfur dioxide and nitrogen oxide emissions for the A1B scenario used in Chapter 3. The two models project different rates of growth; total energy use is also different in the two models, with 3 percent greater use in one model by 2030, but 9 percent less usage at 2050. That same model is less optimistic about emissions controls.

None of the emissions models predict black and organic carbon particle emissions. The GFDL composition model followed the IPCC suggestion to scale future carbon particle emissions by the emissions for carbon monoxide, which are projected to increase throughout the twenty-first century. By 2050, the projected carbon monoxide emissions increase ranges from 8 percent to 119 percent across the collection of integrated assessment models used for the last IPCC report. In contrast, the GISS global chemical composition model used recent estimates by Streets *et al.* (2004) that project a substantial decrease in future emissions of carbon particle (Figure 3.1; Table 3.1). Ammonia emissions present a similar problem. They are sometimes scaled by default to follow nitrous oxide, which is projected to increase significantly. Given the number of ammonia sources that are disconnected from nitrous oxide production, this may be questionable. Moreover, newer projections for ammonia emissions have a much slower rate of increase.

Finally, the global chemical composition models all used their own natural emissions. Though these were held constant, they influence the response to anthropogenic emissions by determining the background abundance of short-lived gases and particles. The level of a natural particle, dust, can also directly affect the level of an anthropogenic particle, as it does in the GISS model by removing sulfate.

We face very significant problems in projecting the future emissions for short-lived gases and particles. Future climates are only weakly dependent on projected emissions for the next 20 years when, due to the inertia in major emitters, we may have credibility in forecasting emissions trends for short-lived gases and particles such as the nitrogen oxides and sulfur dioxide. However, we have shown that plausible emissions scenarios have the potential for significant impacts on climate through the rest of the twenty-first century.

Unlike the long-lived greenhouse gases, short-lived gases and particles do not accumulate, so their full impact at year 2100 depends on end of the century emissions. At this time, there is no credible quantitative skill in forecasting these emissions out to 2100. As Chapter 3 demonstrates, it is not even clear that we can currently predict the sign of the change for black carbon emissions over the next decade. This is a problem that requires not just enhanced scientific knowledge, but also the ability to predict social, economic and technological developments as far as 100 years into the future. One needs only to think back to 1907 to realize how difficult that is and will be.



4.3.2 Particles (Indirect Effect, Direct Effect, Mixing, Water Uptake)

We find that several aspects of particle modeling have large uncertainties (see Figure SPM.2 in IPCC Fourth Assessment Report [IPCC, 2007] for a qualitative estimate of these uncertainties), of which the particle indirect effect, which is

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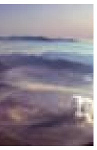
[9] Integrated assessment models are a framework of models, currently quite simplified, from the physical, biological, economic, and social sciences that interact among themselves in a consistent manner and can be used to evaluate the status and the consequences of environmental change and the policy responses to it.

very poorly known, is probably the most critical. Many aspects of the particle-cloud interaction are not well quantified, and hence the effect was left out entirely in the GFDL and CCSM simulations. The GISS model used a highly parameterized approach that is quite crude. The modeling community as a whole cannot yet produce a credible characterization of the climate response to particle/cloud interactions. Moreover, the measurements needed to guide this characterization do not yet exist. All mainstream climate models (including those participating in this study) are currently either ignoring it, or strongly constraining the model response. Attempts have been made using satellite and ground-based observations to improve the characterization of the indirect effect, but major limitations remain.



As discussed in Section 3.2.4, observations of aerosol optical depth[10] are best able to constrain the total extinction (absorption plus scattering) of sunlight by all particles under clear-sky conditions, but not to identify the effect of individual particles which may scatter (cool) or absorb (warm). Improved measurements of extinction and absorption may allow those two classes of particles to be separated, but will not solve the fundamental problem of determining their relative individual importance. As seen in this and other studies, models exhibit a wide range of relative contributions to total aerosol optical depth from the various natural and anthropogenic particles (Figure 3.2). Thus, the direct radiative effect of changes in a particular particle can be substantially different among models depending upon the relative importance of that particle.

Additionally, particles are not independent of one another. They mix together, a process that is only beginning to be incorporated in composition and climate models. In these studies, for example, the GISS model included the influence of sulfate particles sticking to dust, which can decrease the sulfate radiative forcing, by ~40 percent between 2000 and 2030 (Bauer *et al.*, 2007), but the sticking rates are quite uncertain. Mixing of other particle types is also highly uncertain, but is known to occur in the atmosphere and would also affect the magnitude of particle radiative forcings.

Another process that influences the effect of particles on climate is their uptake of water vapor, which alters their size and optical properties. This process is now included in all state-of-the-art comprehensive climate models. As the uptake varies exponentially with relative humidity, small differences in treatment of this process have the potential to cause large discrepancies. However, our analysis in Chapter 3 (*e.g.,* Table 3.7) suggests that the differences induced by this process may be small relative to the others we have just discussed.

4.3.3 Climate and Air Quality Policy Interdependence

Chapter 3 exposes major uncertainties in the climate impacts of short-lived gases and particles that will have to be addressed in future research. We raise important issues linking air quality control and global warming, but are unable to provide conclusive answers. We are able, however, to identify key questions that must be addressed by future research.

Most future sources of short-lived gases and particles result from the same combustion processes responsible for the increases in atmospheric carbon dioxide. However, while reductions in their emissions are currently driven by local and regional air pollution issues that can be addressed independently of any reductions in carbon dioxide emissions, in the future a unified approach could effectively address both climate and air quality issues. Furthermore, the climate responses to emissions changes in short-lived pollutants can be felt much more quickly because of shorter atmospheric lifetimes. The good news is that there is at least one clear win-win solution for climate (less warming) and

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[10] Aerosol optical depth is a measure of the fraction of the sun's radiation at a given wavelength absorbed or scattered by particles while that radiation passes through the atmosphere.

air quality (less pollution): methane reduction. Decreases in methane emissions lead to reduced levels of lower atmospheric ozone, thereby improving air quality; and both the direct methane and indirect ozone decreases lead to reduced global warming (Fiore *et al*., 2002; Shindell *et al*., 2005; West and Fiore, 2005; West *et al*., 2006). Reductions in emissions of carbon monoxide or volatile organic compounds (VOCs) have similar effects, namely leading to reduced abundances of both methane and ozone (Berntsen *et al*., 2005; Shindell *et al*., 2005; West *et al*., 2006; West *et al*., 2007), therefore providing additional win-win strategies for improvement of climate and air quality. Reductions in black carbon particles and nitrogen oxide are potentially win-win as well, but the climate impact of reductions in their emissions is uncertain. On the other hand, the reduction of sulfur and organic carbon particles results in a reduction of cooling and increased global warming.

The cases of black carbon (soot) and nitrogen oxide gases are illustrative of the complexities of this issue. A major source of soot is the burning of biofuel, the sources of which are primarily animal and human waste as well as crop residue, all of which are considered carbon dioxide neutral (*i.e.,* the cycle of production and combustion does not lead to a net increase in atmospheric carbon dioxide). Current suggested replacements result in the release of fossil carbon dioxide. Therefore this reduction in biofuel burning, while reducing the emission of soot, will increase the net emission of carbon dioxide. The actual net climate response from reduced use of biofuel is not clear. The case of nitrogen oxides appears to be approximately neutral for climate, though clearly a strong win for air quality. Reducing nitrogen oxides reduces ozone, which reduces warming. However, reductions in both lead to reduced hydroxyl radicals and therefore an increased level of methane, which increases warming.

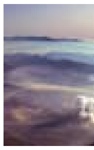
There clearly are win-win, win-uncertain, and win-lose situations regarding climate and actions taken to improve air quality. We are not making any policy recommendations in Synthesis and Assessment Product 3.2, but we do identify the policy relevant scientific issues. At this time we can not provide any quantitatively definitive scientific answers beyond the well known facts that the decrease of sulfur and organic carbon particles, both of which cool the climate, will increase global warming, while decreased methane, carbon monoxide, and volatile organics will decrease global mean warming. Decreases in the burning of biofuel, as well as decreased emissions of nitrogen oxides, are more complex and the net result is not clear at this time.

4.4 RESEARCH OPPORTUNITIES AND RECOMMENDATIONS

This last section of the report is a call for focused scientific research in emissions projections, radiative forcing, chemical composition modeling and regional downscaling. Particular emphasis needs to be paid to the future emissions scenarios for sulfur dioxide, black carbon particles and nitrogen oxides, to the indirect radiative forcing by particles, and to a number of ambiguities in current treatments of transport, deposition, and chemistry.

4.4.1 Emissions Scenario Development

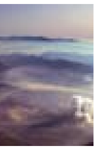
Future climate studies must seriously address the very difficult issue of producing realistic and consistent 100-year emissions scenarios for short-lived gases and particles that include a wide range of socio-economic and development pathways and are driven by local and regional air quality actions taken around the globe.



The current best projections used in this report and in the Fourth Assessment Report of the IPCC do not even agree on whether black carbon particle and nitrogen oxide emissions trends continue to increase or decrease. While all the current sulfur dioxide emissions projections used in this study assume that emissions in 2100 will be less than at present, how much less is quite uncertain, and all of these projected decreases by 2100 may well be wrong. Part of the reason for the different emission inventories used here and in the IPCC studies was that the integrated assessment models did not recognize that these gases and particles were necessarily important when the scenarios were first constructed. Clarification of the challenges associated with emissions projections (not a simple matter of improving quantitative skill, as these are a function of difficult-to-anticipate socio-economic choices) is also necessary.

As the greatest divergences in our study came from the carbon particles that were not projected for the A1B scenario, we strongly recommend that future emissions scenarios pay greater attention to them and provide consistent emissions projections for carbon particles and ammonia along with the other gases and particles. We are aware that many integrated assessment models are already capable of providing this information (*e.g.,* two of the three discussed in Chapter 2 provide carbon particle emissions).

We also recommend that climate models make greater efforts to study the effects of short-lived emissions projections in a manner that isolates their effect from that of the long-lived greenhouse gases. In particular, we believe there is merit in continuing to use a broad distribution of integrated assessment models to realistically characterize the range of potential futures for a given socio-economic storyline. In order to understand the contribution to uncertainty by the composition and climate models, it would also be worthwhile to perform a controlled experiment with identical emissions projections using multiple composition and climate models.



4.4.2 Particle Studies (Direct Effect, Indirect Effect, Mixing, Water Uptake)

Calculation of the indirect effect is potentially the single most important deficiency in this study that can be directly improved. None of the models in the IPCC Fourth Assessment Report study or in this Product realistically accounted for the full particle indirect radiative forcing.

Given that the inclusion of a crude treatment of the particle indirect effect played a substantial role in one model's response in this study, it is clear that better characterization of this effect is imperative. The development of a measurement program to characterize particle indirect effects is a critical need.

It is also clear that other potential particle processes need to be examined. An example is interactive dust loading, which can influence the composition of other short-lived gases and particles and can also be influenced by them (*e.g.,* via changes in solubility due to acid uptake [Fan *et al*., 2004; Bauer and Koch, 2005]). Dust emissions will also respond to vegetation changes as the climate warms. It has been speculated that arid regions may contract as a result of fertilization of plants by increased CO_2, reducing emissions (Mahowald and Luo, 2003), while source regions may expand as a result of global warming and reduced rainfall, and thus increase emissions (Woodward *et al*., 2005). Note that the actual trend will depend upon local changes in climate, especially rainfall, which is among the least robust aspect of current climate projections. Other processes of potential importance that were not included in these transient climate simulations are changes in atmospheric levels of sea-salt particles and changes in darkening of snow and ice surfaces by soot deposition.

Additional observations are clearly needed to better constrain the optical properties of aerosols. Measurement by devices such as the aerosol polarimeter on the NASA satellite, Glory, should provide some of the needed information. We recommend emphasis on long-term particle monitoring from ground and space, and on better characterization of particle interactions with clouds in the laboratory. We also recommend greater use of the distinction between scattering and absorbing particles to characterize their relative importance.

4.4.3 Improvements in Transport, Deposition, and Chemistry

The emissions issues become even more problematic when the future distributions employed in the comprehensive climate models are generated by multiple global composition models, all with differing treatments of mixing in the lowest layers of the atmosphere, different treatment of transport and mixing by turbulence and clouds, different treatments of the removal of gases and particles by rain, snow and contact with the earth's surface, and different approximate treatments of the very large collection of chemical reactions that we do not yet fully understand. There are research opportunities in the study of all phases of the physical and chemical processes that determine the global distribution of short-lived gases and particles from their emission through their removal from the atmosphere.

4.4.4 Recommendations for Regional Downscaling

Regional downscaling, where global climate models introduce climate forcing into regional climate models, is a relatively new development. Current regional downscaling results have relied on older comprehensive climate model simulations. Data from the newer comprehensive global models are needed and coordination and planning are critical since downscaling require input data every three or six hours. While this will lead to huge amounts of data to be stored and transferred and poses a non-trivial technical problem, it is essentially an infrastructure/practical restriction rather than a source of scientific challenges. A carefully coordinated set of region climate model predictions using various global and regional scale models and future scenarios is needed to reduce the uncertainty and identify methodological improvements.

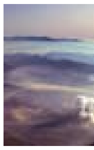
The North American Regional Climate Change Assessment Program (NARCCAP, <http://www.narccap.ucar.edu>) is an ongoing effort that is actively taking this approach of multiple regional climate model simulations and multiple future scenarios. Four different comprehensive global models and six different regional models are being used to intercompare and evaluate regional climate simulations for North America. This effort and others like it should greatly help to advance regional downscaling approaches and provide important model archives for environmental quality and resources applications.

It is important to also note that these studies do not currently include short-lived gases and particles in the global climate simulations. Further, many regional models do not include feedbacks between air quality, the radiation budget and climate. These feedbacks may be quite important. For example, The U.S. EPA Clean Air Interstate Rule requires almost a 30 percent reduction in sulfur dioxide emissions in the eastern United States during the next two decades. This could have a significant impact on the climate projections, as was shown in Chapter 3. We also need to separate the impacts on regional climate by the direct and indirect effects of particles in general from the impacts on regional climate by local emissions changes.

More research is clearly needed to determine if downscaled regional climate simulations actually provide more detailed and realistic results. The higher regional resolution is important for a wide range of environmental issues including water and air quality, agricultural productivity, and fresh water supplies. For example, highly resolved regional climate information is needed to accurately predict levels of ozone and small particles, which are strongly influenced by local changes in emissions and climate.

4.4.5 Expanded Analysis and Sensitivity Studies

Analyses of surface temperature response to changes in short-lived gases and particles need to be strengthened by additional sensitivity studies that should help to clarify causes and mechanisms. For example, in the GISS model, how much warming did the declining trend in the indirect effect contribute to its climate response and where? How would the GISS results differ if dust had not been permitted to take up sulfate particles? Determining the relative importance of these and other processes to the climate response would help prioritize the gaps in our knowledge. There are also a wide range of climate-chemistry feedbacks and controls that should be explored. Both the response of the climate system to controls on short-lived gases and particles and the possible feedbacks, and the possible impacts of climate changes on levels of short-lived gases and particles are all fertile areas for future research. While it was not possible, both due to time and resource restraints, for this study to explore these additional analyses, we recommend their future study.



The major unfinished analysis question in this study is the relative contribution of a model's regional climate response, as opposed to the contribution from the regional pattern of radiative forcing, to the observed regional change in seasonal surface temperature. (See Section 9.2.2.1 of Chapter 9 in the IPCC Fourth Assessment Report [Hegerl *et al*., 2007] and references therein for further discussion of this issue.) Specific modeling studies are needed to answer questions such as: Is there a model independent regional climate response? and What are the actual physical mechanisms driving the regional surface temperature patterns that we observe? These questions appear to identify a very important area of study, particularly given the apparently strong climate response in the summertime central United States.

4.5 CONCLUSION

After considering all of the issues discussed in this chapter, the net result is that we agree that short-lived species may have significant impact on future climate out to 2100. However, we could not find a consensus in this report on the duration, magnitude or even sign (warming or cooling) of the climate change due to future levels of the short-lived gases and particles. We have presented a plausible case for enhanced climate warming due to air quality policies that focus primarily on sulfate particle reduction and permit the emission of soot to continue to increase as realized in a version of the IPCC's A1B scenario. Alternative versions of this scenario that follow different pollution control storylines could have less impact. While we do not have definitive answers to the second goal of this report to "assess the sign, magnitude, and duration of future climate changes due to changing levels of short-lived gases and particles that are radiatively active and that may be subject to future mitigation actions to address air quality issues," we do provide plausible estimates that begin to characterize the range of possibilities and we identify key areas of uncertainty and provide motivation for addressing them.