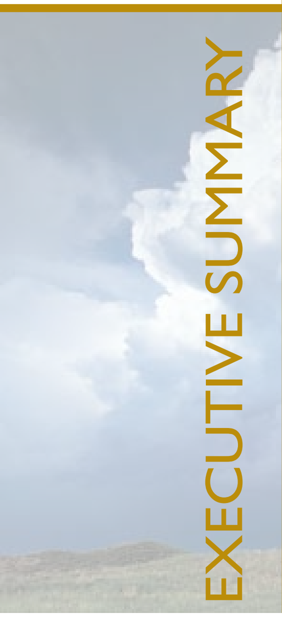


EXECUTIVE SUMMARY

Lead Authors: Hiram Levy II, NOAA/GFDL; Drew T. Shindell, NASA/GISS; Alice Gilliland, NOAA/ARL; M. Daniel Schwarzkopf, NOAA/GFDL; Larry W. Horowitz, NOAA/GFDL

Contributing Author: Anne Waple, STG Inc.

SYNOPSIS

The influence of greenhouse gases and particle pollution on our present and future climate has been widely examined and most recently reported in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. While both long-lived[1] (*e.g.*, carbon dioxide) and short-lived[2] (*e.g.*, soot) gases and particles affect the climate, previous projections of future climate, such as the IPCC reports, have focused largely on the long-lived gases. This U.S. Climate Change Science Program Synthesis and Assessment Product provides a different emphasis.

We first examine the effect of long-lived greenhouse gases on the global climate based on updated emissions scenarios produced by another CCSP Synthesis and Assessment Product (SAP 2.1a). In these scenarios, atmospheric concentrations of the long-lived greenhouse gases leveled off, or stabilized, at predetermined levels by the end of the twenty-first century (unlike in the IPCC scenarios). However, the projected future temperature changes, based on these stabilization emissions scenarios, fall within the same range as those projected for the latest IPCC report. We confirm the robust future warming signature and other associated changes in the climate.

We next explicitly assess the effects of short-lived gases and particles. Their influence is found to be global in nature, substantial when compared with long-lived greenhouse gases, and potentially extending to the end of this century. They can significantly change the regional surface temperature, and by the year 2100 short-lived gases and particles may account for as much as 40 percent of the warming over the summertime continental United States. It is noteworthy that the simulated climate response to these pollutants is not confined to the geographical area where they are released. This implies a strong linkage between regional air quality control strategies and global climate change. We identify specific emissions reductions that would lead to benefits for both air quality and climate change mitigation, including North American surface transportation and Asian domestic fuel burning. The results reveal the necessity for explicit and consistent inclusion of the short-lived pollutants in assessments of future climate.

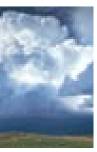
[1] Atmospheric lifetimes for the long-lived radiatively active gases of interest range from ten years for methane to more than 100 years for nitrous oxide. While carbon dioxide's lifetime is more complex, we can think of it as being more than 100 years in the climate system. As a result of their long 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.

[2] 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.

ES.1 KEY FINDINGS

These results constitute important improvements in our understanding of the influence of both long-lived gases and short-lived gases and particles. The Fourth Assessment Report of the IPCC recognized that most of the global-scale warming since the middle of last century was very likely due to the increase in greenhouse gas concentrations, and also that the warming has been partially damped by increasing levels of short-lived particle pollutants. However, while the IPCC models were coordinated in their use of greenhouse gas emissions scenarios, the short-lived pollutants were widely varying in the emissions scenarios used, and their future impacts were not isolated from those of the long-lived gases.

Changes in pollutant levels, primarily over Asia, may significantly increase surface temperature and reduce rainfall over the summertime continental United States.



This Synthesis and Assessment Product provides a more comprehensive and updated assessment of the relative future contributions of long and short-lived gases and particles, with special, explicit focus on the short-lived component. This study encompasses a realistic time frame over which available technological solutions can be employed, and this study, in particular, focuses on those gases and particles whose future atmospheric levels are also subject to reduction due to air pollution control.

1. Our results suggest that changes in short-lived gases and particles (pollutants) may significantly influence the climate, in the twenty-first century. By 2050, projected changes in short-lived pollutant concentrations in two of the three studies are responsible for approximately 20 percent of the simulated global-mean annual average warming (see Section 3.3.4 and Figure 3.5). As shown in Figure ES.1, projected changes in pollutant levels, primarily over Asia, may significantly increase surface temperature and reduce rainfall over the summertime continental United States throughout the second half of the twenty-first century (see Section 1.4 for details of the calculations).
2. The geographic patterns of factors that drive climate change due to short-lived gases and particles and the patterns of the resulting surface temperature responses are quite different. This is clearly seen in Figure ES.2, in which the largest fractional contribution to summertime radiative forcing from changes in short-lived pollutants in the last part of the twenty first century is primarily located over Asia, while the strongest warming response is located over the central United States. Regional emissions control strategies for short-lived pollutants will thus have global impacts on climate. The geographic disconnect between this driver of climate change and the surface temperature response is already apparent by 2050, as discussed in Section 3.3.4 and demonstrated in Figure 3.8.
3. Reductions of short-lived pollutants from the domestic fuel burning sector in Asia, whose climate impacts in this study (Section 3.4) are dominated by black carbon (soot), appear to offer the greatest potential for substantial, simultaneous

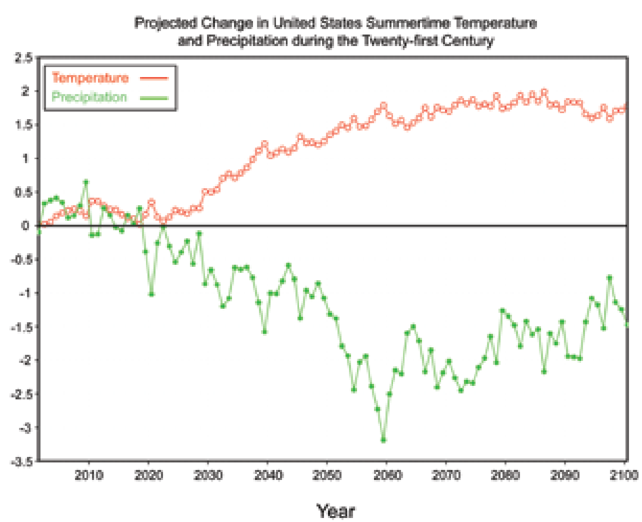


Figure ES.1 Calculation of twenty-first century temperature and precipitation change over the United States in summer (June through August) due to changes in short-lived gases and particles (see Section 1.4 for details). Temperature change in red is shown as the difference, in degrees Centigrade, from the 2001 value. Precipitation change in green is shown as the difference, in centimeters, from the 2001 value, and represents the sum of daily changes over the three months. The plotted data are 11 year moving averages.

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

4. The three comprehensive climate models[3], their associated chemical composition models[4] and their differing projections of short-lived emissions all lead to a wide range of projected changes in climate due to short-lived gases and particles. Each of the three studies in this report 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. The two most important uncertainties are found to be the projection of future emissions and the determination of the indirect effect[5] of particles on clouds. The fundamental difference between uncertainties in projecting future emissions and uncertainties in processes, such as the indirect effects of particles, is discussed in Section 4.3.

5. The range of plausible short-lived emissions projections is very large, even for a single well-defined global emission scenario (see Figures and discussion in Section 3.2 for details). Figure ES.3 clearly demonstrates this situation for the different emission projections of black carbon particles (soot) used by the three research groups. This currently limits our ability to provide definitive statements on their contribution to future climate change.

6. Natural particles such as dust and sea salt also play an important role in climate and their emissions and interactions differ significantly among the models, with consequences to the role of short-lived

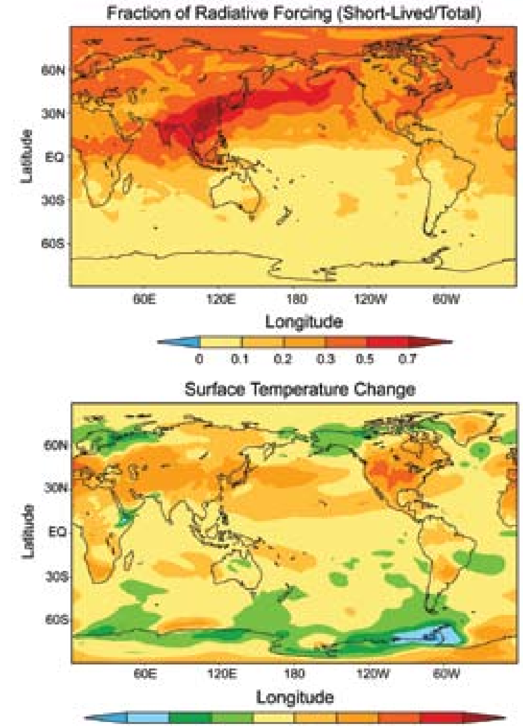


Figure ES.2 The fraction of summertime (June-August) radiative forcing* due to changing levels of short-lived gases and particles and the resulting summertime surface temperature change (degrees Centigrade) for year 2100.

*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.

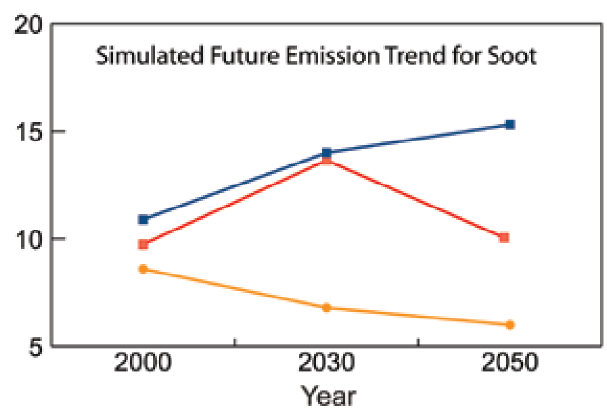


Figure ES.3 The three plausible but very different emissions trends projected for black carbon particles (soot). Each of the three groups in this study used a different trend. The units are million metric tons of carbon per year.

[3] A comprehensive climate model is a state-of-the-art numerical representation 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.

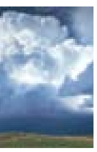
[4] Chemical composition models are state-of-the-art numerical models that use the emission of gases and particles as inputs and stimulate their chemical interactions, global transport by winds, and removal by rain, snow, and deposition to the earth's surface. The resulting outputs are global three-dimensional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

[5] Apart from the direct effects of particles absorbing and scattering radiation, particles produce an indirect forcing of the climate system through their aiding in the formation of cloud droplets or by modifying the optical properties and lifetime of clouds (see Box 3.1 for a more detailed discussion).

pollutants. This inconsistency among models should be addressed in future studies. This is discussed in Section 3.2.4 and demonstrated in Figure 3.2 and Table 3.5.

Regional emissions control strategies for short-lived pollutants will have large-scale impacts on climate.

7. Climate projections based on new emissions scenarios where atmospheric concentrations of the long-lived greenhouse gases level off, or stabilize[6], at pre-determined levels (from CCSP SAP 2.1a) generally fall within the range of IPCC climate projections for the standard scenarios considered in the Fourth Assessment Report. The lower bound stabilization emissions scenarios, which have a carbon dioxide stabilization level of approximately 450 parts per million (by volume), result in global surface temperatures below those calculated for the lower bound IPCC scenario used in the Fourth Assessment, particularly beyond 2050. Nonetheless, all of them unequivocally cause warming across the range of possible emissions scenarios (see Section 2.6 for details).



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

ES.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The five most critical areas for future research identified in this Report are:

1. The projection of future human-caused emissions for the short-lived gases and particles;
2. Indirect and direct effects of particles and mixing between particle types;
3. Transport, deposition, and chemistry of the short-lived gases and particles.
4. Regional climate forcing *vs*. regional climate response.
5. Sensitivity studies of climate responses to short-lived gases and particles.

1. Plausible emissions scenarios for the second half of the twenty-first century show significant climate impacts, yet the range of plausible scenarios is currently large and an increase in confidence in these scenarios is necessary. Short-lived gases and particles, unlike the well-mixed greenhouse gases, do not accumulate in the atmosphere. Therefore, combined with a large range of possible emissions scenarios, the climate impact of the short-lived gases and particles is currently extremely difficult to predict. Improvements in our ability to predict social, economic and technological developments affecting future emissions are needed. However, uncertainties in future emissions will always be with us. What we can do is develop a set of internally consistent emissions scenarios that include all of the important radiatively active gases and particles and bracket the full range of possible future outcomes.

2. The particle indirect effect (see Box 3.1 for a technical discussion), which is very poorly understood, is probably the process in most critical need of research. The climate modeling community as a whole cannot yet produce a credible characterization of the climate response to particle/cloud interactions. All 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 and additional observations are required.

3. The three global composition models in this study all employed different treatments of mixing in the lowest layers of the atmosphere, transport and mixing by turbulence and clouds, 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. Further coordinated model intercomparisons, evaluation of models against existing observations, and additional observations are all needed to achieve a better understanding of these processes.

4. 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 simulated regional change in seasonal climate. Specific modeling studies are needed to answer questions such as: Is there a model-independent regional climate response? What are the actual physical mechanisms driving the regional surface temperature patterns that we observe? This appears to be a very important area of study, particularly given the strong climate response projected for the summertime central United States.

5. 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. There are also a wide range of

Partly as a result of the large range of possible future emissions scenarios, the climate impact of the short-lived gases and particles is currently extremely difficult to predict.

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.

ES.3 GUIDE FOR READERS

For those readers who would like to learn more about the research behind the Key Results and Findings and the Recommendations for Future Research, we provide the following guide to reading the four chapters. Chapter 1 provides an introduction to this study and relevant findings from previous climate research, introduces the goals and methodology, and provides Box 1.1 and Box 1.2 with relatively non-technical descriptions of the modeling tools and definitions of terms. It is written in a non-technical manner and is intended to provide all audiences with a general overview. Chapters 2 and 3 provide detailed technical information about specific models, model runs and projected trends and are intended primarily for the scientific community, though the key findings and the introduction to each chapter are written in non-technical language and intended for all audiences. Chapter 4 is intended for all audiences. It provides a summary of the major findings and identifies new opportunities for future research.