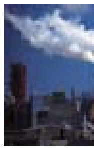
Introduction

Lead Authors: Hiram Levy II, NOAA/GFDL; Drew T. Shindell, NASA/GISS; Alice Gilliland, NOAA/ARL

Contributing Authors: Tom Wigley, NCAR; Ronald J. Stouffer, NOAA/GFDL

PROLOGUE



Comprehensive climate models[1] have become the essential tool for understanding past climates and making projections of future climate resulting from both natural and human causes. Projections of future climate require estimates (*e.g.,* scenarios) of future emissions of long-lived[2] greenhouse gases and short-lived[3] radiatively active[4] gases and particles. A number of standard emissions scenarios[5] have been developed for the Intergovernmental Panel on Climate Change (IPCC) assessment process, and the future impacts of these have been discussed extensively in the Fourth Assessment Report (IPCC, 2007).

As part of the Climate Change Science Program (CCSP) process, scenarios of long-lived greenhouse gas emissions, with the added requirement that their resulting atmospheric concentrations level off at specified values sometime after 2100 (*e.g.,* stabilization), were developed by the Synthesis and Assessment Product 2.1a team (Clarke *et al.*, 2007) and served as the basis for Synthesis and Assessment Product 3.2, for which the National Oceanic and Atmospheric Administration (NOAA) is the lead agency. NOAA's stated purpose for Synthesis and Assessment Product 3.2 is to provide information to those who use climate model outputs to assess the potential effects of human activities on climate, air quality, and ecosystem behavior. This report comprises two components that first assess the climate projections resulting from Synthesis and Assessment Product 2.1a scenarios in the context of existing IPCC climate projections, and then isolate and assess the future impacts on climate resulting from future emissions of short-lived gases and particles.

This second component explores the impact of short-lived radiatively active gases and particles on future climate, a critical issue that has recently become an active area of research in the reviewed literature (*e.g.,*

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[1] Comprehensive climate models are a numerical representation of the climate based on the physical properties of its components, their interactions, and feedback processes. Coupled Atmosphere-Ocean (-sea ice) General Circulation Models (AOGCMs) represent our current state-of-the-art. However, they contain assumptions that may constrain or affect the accuracy and uncertainty of model output or results.

[2] Long-lived gases of interest have atmospheric lifetimes that range from ten years for methane to more than 100 years for nitrous oxide and carbon dioxide. Due to 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 particle in the atmosphere divided by the mass that is removed from the atmosphere each year.

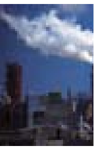
[3] Short-lived radiatively active gases and particles of interest in the lower atmosphere have lifetimes of about a day for nitrogen oxides, a day to a week for most particles, and a week to a month for ozone. Their concentrations are highly variable and concentrated in the lowest part of the atmosphere, primarily near their sources.

[4] Radiatively active gases and particles absorb, scatter, and re-emit energy, thus changing the temperature of the atmosphere. They are commonly called greenhouse gases and particles.

[5] Emissions scenarios represent future emissions based on a coherent and internally consistent set of assumptions about the driving forces (*e.g.,* population change, socioeconomic development, technological change) and their key relationships.

Hansen *et al.*, 2000; Brasseur and Roekner, 2005; Delworth *et al.*, 2005). The existing state-of-the-art models used in this study represent incomplete characterizations of the driving forces and processes that are believed to be important to the climate responses and global distributions of the short-lived gases and particles. Moreover, these incomplete treatments are not consistent across the models. However, despite these challenges, this Report shows that short-lived gases and particles have a significant impact on climate, potentially throughout the twenty-first century.

1.1 HISTORICAL OVERVIEW



Climate models used for projections of the future have evolved substantially during the past several decades.

The climate models and the representation of the agents driving climate change used for projections of the future have both evolved substantially during the past several decades. In 1967, Manabe and Wetherald published the first model-based projection of future climate change. Using a simple model representing the global atmosphere as a single column, they projected a 2ºC global surface air temperature change for a doubling of the atmospheric concentration of carbon dioxide. Model development continued on a wide range of numerical models, especially in the increasing sophistication of the ocean model.

In 1979, Manabe and Stouffer developed a global model at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) useful for estimating the climate sensitivity. They called this model an atmosphere-mixed layer ocean model, which is sometimes called a slab model. A slab model consists of global atmospheric, land, and sea ice component models, coupled to a static 50-meter deep layer of seawater. By construction, this type of model assumes no changes in the oceanic heat transports as the climate changes. It is used to estimate only equilibrium climate changes. In 1984, Hansen *et al.* used the NASA Goddard Institute of Space Studies (GISS) model in the first climate studies in which ocean heat transports were included in the climate calculation, although these were prescribed (fixed).

The two models discussed above, as well as one developed in part at the National Center for Atmospheric Research (NCAR), all played an important part in the first Intergovernmental Panel on Climate Change (IPCC) Assessment Report[6] (IPCC, 1990).

In the late 1980s, Washington and Meehl (1989) at NCAR and Stouffer *et al.* (1989) at GFDL developed the first comprehensive climate models (Atmosphere-Ocean General Circulation Models [AOGCMs]) useful for investigating climate change over multi-decadal and longer time periods. These models consisted of global atmosphere, ocean, land surface, and sea ice components. Both groups used an idealized radiative forcing to drive their models. Stouffer *et al.* used a one percent per year increase in the carbon dioxide concentration (compounded), where its atmospheric concentration doubles in 70 years.

By the time of the IPCC Second Assessment Report (IPCC, 1996), all three United States modeling centers were running comprehensive

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[6] It should be noted that the IPCC does not directly perform any research. Rather, its reports are intended to be reviews of current research. However, it must also be noted that the IPCC is, in fact, a powerful driver of research and setter of research agendas in climate science. Moreover, only the latest report (Fourth Assessment Report) strictly enforced the requirement that all results discussed in it be previously published in the reviewed literature.

climate models. In addition, representation of the climate forcing was improving. Mitchell *et al.* (1995) in the United Kingdom (U.K.) developed a scheme for crudely incorporating the impact of sulfate particles on climate. Similarly, actual concentrations of long-lived greenhouse gases were used for the past, allowing more realistic climate simulations of the historical time period (1860 to present day). Using emissions scenarios developed by the IPCC in 1992 (IPCC, 1992), the U.K. group also made future projections of climate change through the year 2100. Their results were very important in the Second Assessment Report of the IPCC.

By the time of the Third IPCC Assessment Report in 2001 (IPCC, 2001), 12 comprehensive climate models were used to project climate out to the year 2100. They used the emissions scenarios produced by the Special Report on Emission Scenarios (Nakićenović and Swart, 2000), with most groups using a high (A2) and low (B2) emissions scenario. Some of the models included components to predict atmospheric particle concentrations, but most of the 12 models used variants of the Mitchell *et al.* (1995) method to include their impact on climate. While particle changes were included in the historical simulations, most of the future projections did not include any changes in them or tropospheric ozone.

In the most recent IPCC report, the Fourth Assessment Report of Working Group I (IPCC, 2007), 24 comprehensive climate models participated. The component models continued to become more sophisticated and included more physical processes. The new components allowed the inclusion of more radiatively active agents such as dust, black carbon and organic carbon particles, and land use in the scenarios. Again, most models included all or nearly all these climate forcing agents in their historical simulations, but many did not do so for the future. Most groups used the three standard scenarios developed for the IPCC by the Special Report on Emission Scenarios (Nakićenović and Swart, 2000) (B1, A1B and A2)[7] to make their future climate projections. These are the same three scenarios represented in Figures 2.1 through 2.4 in Chapter 2.

1.2 GOALS AND RATIONALE

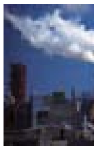
As described in the Prospectus outlining the purpose of this report, Synthesis and Assessment Product 3.2 has two primary goals:

1. Produce climate projections for research and assessment based on the stabilization emission scenarios of long-lived greenhouse gas emissions developed by Synthesis and Assessment Product 2.1a.
2. 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.

The eight key questions which address the above goals, and which were also listed in the Prospectus for this report, are:

Q1. Do SAP 2.1a emissions scenarios differ significantly from IPCC emissions scenarios?

Q2. If the SAP 2.1a emissions scenarios do fall within the envelope of emissions scenarios previously considered by the IPCC, can the existing IPCC climate simulations be used to estimate 50-to 100-year climate responses for the SAP 2.1a carbon dioxide (CO_2) emissions scenarios?



In the most recent IPCC report, the Fourth Assessment Report of Working Group I, used 24 comprehensive climate models.

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[7] B1: emissions increase very slowly for a few more decades, then level off and decline; A2: emissions continue to increase rapidly and steadily throughout the twenty-first century; A1B: emissions increase very rapidly until 2030, continue to increase until 2050, and then decline.

Q3. What would be the changes to the climate system under the scenarios being put forward by SAP 2.1a?

Q4. For the next 50 to 100 years, can the time-varying behavior of the climate projections using the emissions scenarios from SAP 2.1a be distinguished from one another or from the scenarios currently being studied by the IPCC?

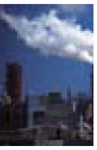
Q5. What are the impacts of the radiatively active short-lived species (gases and particles) not being reported in SAP 2.1a?

Q6. How do the impacts of short-lived species (gases and particles) compare with those of the well-mixed greenhouse gases as a function of the time horizon examined?

Q7. How do the regional impacts of short-lived species (gases and particles) compare with those of long-lived gases in or near polluted areas?

Q8. What might be the climate impacts of mitigation actions taken to reduce the atmospheric levels of short-lived species (gases and particles) to address air quality issues?

The answers to these questions are discussed in detail in Chapters 2 and 3.



This Report focuses on the direct effect of short-lived pollutants on climate.

Synthesis and Assessment Product 3.2 is intended to provide information to those who use climate model outputs to assess the potential effects of human activities on climate, air quality, and ecosystem behavior. Since neither the IPCC nor SAP 2.1a explicitly addressed the direct influence of changing emissions of short-lived pollutants (carbon and sulfate particles and lower atmospheric ozone) on climate change, their role became a major focus of this report. This study encompasses a realistic time frame over which available technological solutions can be employed, and focuses on those gases and particles whose future atmospheric levels are also subject to mitigation via air pollution control. Thus Synthesis and Assessment Product 3.2 can be very beneficial to all stakeholders of climate change science. The intended audiences include those engaged in scientific research, the media, policy makers, and members of the public. Policy and decision makers in the public sector (*e.g.*, congressional staff) need to understand the implications of these scenarios and the climates that they force, in contrast to the research science community, who may be more interested in the physical basis for the behavior.

1.3 LIMITATIONS

The first goal, assessing the climate projections for the SAP 2.1a stabilization emissions scenarios for long-lived greenhouse gases, is relatively narrowly defined and so treated. While the second goal, assessing the impact on climate of changing emissions of short-lived radiatively active gases and particles, could be viewed much more broadly, we do not. Our focus is primarily on the direct effect[8] of these short-lived pollutants on climate. Only in the case of methane do we explore any of the potential interactions of chemical sources, reactions, and removal resulting from a changing climate.

We do not examine any of the indirect effects[9] of pollutant particles on climate, nor do we address other potentially important impacts such as land use change, reactive nitrogen deposition and ecosystem responses, changing natural hydrocarbon emissions, changing oxidant levels and changing particle formation, or a wide range of other processes that can interact with climate, such as changes in ice clouds and vegetation burning. The resources were also not available for extensive sensitivity studies that might help explore more deeply the causes and mechanisms behind the potentially significant

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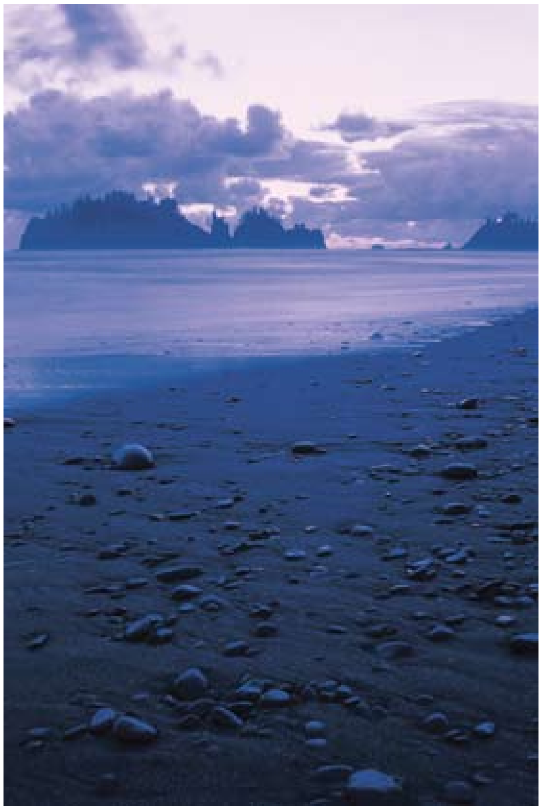
[8] The direct effect refers to the influence of gases and particles on climate through scattering and absorbing radiation.

[9] Particles may lead to an indirect radiative forcing of the climate system by acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds.

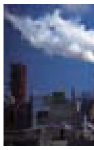


impact of short-lived pollutant levels on future climate. The above issues and many others are potential topics for future research, but were beyond the scope of this study. We will only address the impact on climate of direct radiative forcing by long- and short-lived greenhouse gases and particles.

1.4 METHODOLOGY

In addressing the questions posed above, we rely on several different types of computer models to project the climate changes that would result from the scenarios of emissions of greenhouse gases and particles. Projections of future climate first require estimates (*e.g.,* scenarios) of future emissions of long-lived greenhouse gases and radiatively active short-lived gases and particles. Next, global composition models (computer models of atmospheric transport and chemistry) employ the emissions scenarios to generate global distributions of the concentrations of short-lived radiatively active gases and particles. Then comprehensive climate models (computer models of the coupled atmosphere, land-surface, ocean, sea-ice system) employ global distributions of both the long-lived and short-lived radiatively active gases and particles to simulate past climates and make projections of future climates resulting from natural and anthropogenic changes affecting the climate system. This whole modeling process is discussed in more detail in Box 1.1.

A number of standard scenarios have been developed for the IPCC assessment process, and the future impacts of these have been explored. As part of the Climate Change Science Program (CCSP) process, updated scenarios of long-lived greenhouse gases and their atmospheric concentrations were developed by the Synthesis and Assessment Product 2.1a team (Clarke *et al.*, 2007), and served as a basis for this Product. In addressing the first four questions, we examine the 12 scenarios for long-lived greenhouse gases developed by SAP 2.1a. We simulate the global surface temperature increases and sea-level rise (due only to thermal expansion of water, not melting ice caps) resulting from these scenarios using a simplified global climate computer model, MAGICC.



In addressing the latter four questions listed in section 1.2, we focus on the effects of short-lived radiatively active gases and particles, and use three different state-of-the-art comprehensive climate models. Intercomparison studies, including the latest IPCC assessment, have shown that the performance of these models is comparable to other state-of-the-art comprehensive climate models (AOGCMs). Each of the three models was used to simulate future climate under two different scenarios: one in which human-caused short-lived gases and particles were allowed to change in the future, and one in which these gases and particles were held constant at present-day concentrations. The differences between the simulated climates for the two scenarios is attributed to the projected changes in the emissions of short-lived gases and particles.

Each of the three models was used to simulate future climate under two different scenarios: one in which human-caused short-lived gases and particles were allowed to change in the future, and one in which these gases and particles were held constant at present-day concentrations.

1.5 TERMS AND DEFINITIONS

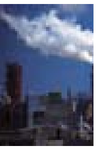
A number of technical terms are defined and briefly discussed for the benefit of those nontechnical readers who wish to proceed to Chapters 2 and 3. The definitions are collected in Box 1.2.

BOX 1.1: Model Descriptions *(modified from IPCC Fourth Assessment Report)*

Integrated assessment models combine key elements of physical, chemical, biological, and economic systems into a decision-making framework with various levels of detail for the different components. These models differ in their use of monetary values, their integration of uncertainty, and their formulation of policy with regard to optimization, evaluation, and projections. For our study, their product was a set of stabilization emissions scenarios.

Chemical composition models are used to estimate the concentrations and distributions of trace gases and particles in the atmosphere that result from a given emissions scenario. These models, known technically as chemical transport models, are driven by winds, temperatures, and other meteorological properties that are either compiled from observations or supplied by climate models. Once the gas and particle emissions from human-induced and natural sources are supplied to the chemical composition model, they can be transported through the atmosphere, converted by chemical reactions, and removed from the atmosphere by rain, snow, and contact with the surface. These models provide concentrations of radiatively active gases and particles that vary in space and time for use in climate models.

A **climate model** is a numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and their feedback processes. The climate system can be represented by models of varying complexity. For any one component or combination of components, a hierarchy of models can be identified that differ in the number of spatial dimensions represented, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterizations are involved.



Simple climate models estimate the change in global mean temperature and sea-level rise due to thermal expansion. They represent the ocean-atmosphere system as a set of global or hemispheric boxes, and predict global surface temperature using an energy balance equation, a prescribed value of climate sensitivity, and a basic representation of ocean heat uptake. Such models can also be coupled with simplified models of biogeochemical cycles, and allow rapid estimation of the climate response to a wide range of emissions scenarios. MAGICC (for details, see Appendix B) is such a coupled model.

State-of-the-art **comprehensive climate models** (generally referred to as AOGCMs, for Atmospere-Ocean General Circulation Models) include interacting components describing atmospheric, oceanic, and land surface processes, as well as sea ice. Although the large-scale dynamics of these models are treated exactly, approximations are still used to represent smaller, but still critical, processes such as the formation of clouds and precipitation, ocean mixing due to waves, and the mixing of air, heat, and moisture near the earth’s surface. Uncertainties in these approximations are the primary reason for climate projections differing among different comprehensive climate models. Furthermore, the global models are generally unable to capture the small-scale features of climate in many regions. In such cases, the output from the global models can be used to drive regional climate models that have the same comprehensive treatment of interacting components, but, as they are only applied to part of the globe, are able to represent a region’s climate in much greater detail.

“Storyline emissions scenario,” and “stabilization emissions scenario,” are two different approaches to estimating future emissions. The standard emissions scenarios used to provide the climate projections for the last two IPCC Assessment Reports (Third and Fourth) were storyline emissions scenarios. A set of economic development paths and rates of technological innovation, population growth, and social-political development were specified and Integrated Assessment Models (Box 1.1) were asked to solve for the greenhouse gas and particle emissions that were consistent with the specified conditions.

BOX 1.2: Useful Definitions

Storyline emissions scenarios are plausible representations of future emissions based on a coherent and internally consistent set of assumptions about the driving forces (*e.g.*, population change, socioeconomic development, technological change) and their key relationships.

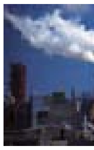
Stabilization emissions scenarios represent future emissions based on a coherent and internally consistent set of assumptions where, additionally, these emissions are constrained so that the resulting atmospheric concentration levels off at a predetermined value in the future.

Radiative forcing is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered. The word radiative arises because these factors change the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere. This radiative balance controls the Earth's surface temperature. The term "forcing" is used to indicate that Earth's radiative balance is being pushed away from its normal state. When radiative forcing from a factor or group of factors is evaluated as 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.

Global atmospheric lifetime is the mass of a gas or particle in the atmosphere divided by the mass that is removed from the atmosphere each year.

Long-lived gases of interest have atmospheric lifetimes that 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, long-lived gases are well mixed and evenly distributed throughout the lower atmosphere. Their concentrations also change slowly with time.

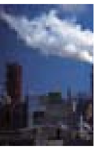
Short-lived gases and particles of interest to climate studies have lifetimes of about a day for nitrogen oxides, a day to a week for most particles, and a week to a month for ozone. As a result of their short lifetimes, their concentrations are highly variable in space and time and are concentrated in the lowest part of the atmosphere, primarily near their sources.



Synthesis and Assessment Product 2.1a (Clarke *et al.*, 2007) took quite a different approach. They effectively established a set of targets for long-lived greenhouse gas concentrations, and then had their three integrated assessment models determine emissions pathways to those targets by applying economic principles to the relationships existing among economic development paths and rates of technological innovation, population growth, and social-political development. Each group used somewhat different approaches to determine the economic pathway to stabilization. Technically, only one of the models used the "least cost" approach in its strictest economic sense. However, as we show in Chapter 2, the resulting emissions and concentrations of the long-lived greenhouse gases over the twenty-first century are similar among models for a given target. Furthermore, all of the stabilization scenarios, with the exception of those for the lower bound target (only 18 percent increase in carbon dioxide over the next 100 years), fall within the range of the principal storyline scenarios used for the last two IPCC assessments. While the two approaches to constructing the emissions scenarios are different, the resulting concentrations of greenhouse gases, and their impacts on climate, are quite similar.

Radiative forcing is an important quantity that is frequently used when discussing the impact of radiatively active gases and particles. A technical definition is provided in Chapter 3, Box 3.2. We provide a relatively non-technical explanation in Box 1.2 of this chapter. It will be useful in the following discussion of long- and short-lived gases and particles.

The long-lived greenhouse gases have atmospheric lifetimes ranging from a decade to more than a century. As a result, they are uniformly mixed and their radiative forcing is also relatively uniformly distributed, both in space and time, throughout the lower atmosphere. On the other hand, the short-lived gases and particles have atmospheric lifetimes ranging from a day to weeks. Their concentrations are highly variable in space and time, and they are concentrated in the lowest part of the atmosphere, primarily near their sources. As a result their radiative forcing is also highly localized and can vary significantly in time. However, one of our Key Findings is that, while radiative forcing patterns for long- and short-term gases and particles are quite different, the regional patterns of climate change due to long- and short-lived radiatively active gases and particles are similar.



The regional patterns of climate change due to long- and short-lived gases and particles are similar, despite their different concentrations and lifetimes.

For those wishing to read further, we provide a brief reader's guide. Chapters 2 and 3 provide detailed technical information about specific models, model runs, and trends, and are intended primarily for the scientific community, though the Questions and Answers and the Introduction sections of each chapter are written in nontechnical language and are 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.