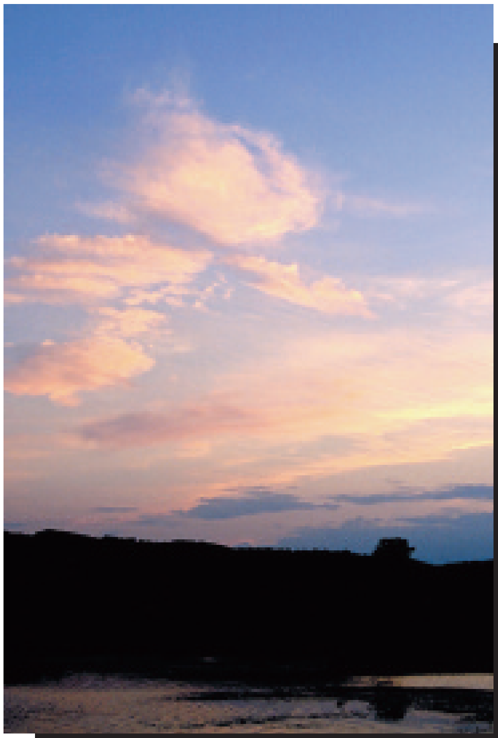
CHAPTER 3

Atmospheric Composition



CHAPTER CONTENTS

The composition of the atmosphere—its gases and particles—plays a critical role in connecting human welfare with global and regional changes because the atmosphere links all of the principal components of the Earth system. The atmosphere interacts with the oceans, land, terrestrial and marine plants and animals, and the frozen regions (see Figure 3-1). Because of these linkages, the atmosphere is a conduit of change. Emissions from natural sources and human activities enter the atmosphere at the surface and are transported to other geographical locations and often higher altitudes. Some emissions undergo chemical transformation or removal while in the atmosphere or interact with cloud formation and precipitation. Some natural events and human activities that change atmospheric composition also change the Earth's radiative (energy) balance. Subsequent responses to changes in atmospheric composition by the stratospheric ozone layer, the climate system, and regional chemical composition (air quality) create multiple environmental effects that can influence human health and natural systems.

Atmospheric composition changes are indicators of many potential environmental issues. Observations of trends in atmospheric composition are among the earliest harbingers of global changes. For example, the decline of the concentrations of ozone-depleting substances, such as the chlorofluorocarbons (CFCs), has been the first measure of the effectiveness of international agreements to end production and use of these compounds.

A principal feature of the atmosphere is that it acts as a long-term "reservoir" for certain trace gases that can cause global changes. The long removal times of some gases, such as carbon dioxide (CO_2, >100 years) and perfluorocarbons (PFCs, >1,000 years), imply that any associated global changes could persist over decades, centuries, and millennia—affecting all countries and populations.

An effective program of scientific inquiry relating to changes in atmospheric composition must include two major foci. The first is a focus on Earth system interactions: How do changes in atmospheric composition alter and respond to the energy balance of the climate system? What are the interactions between the climate system and

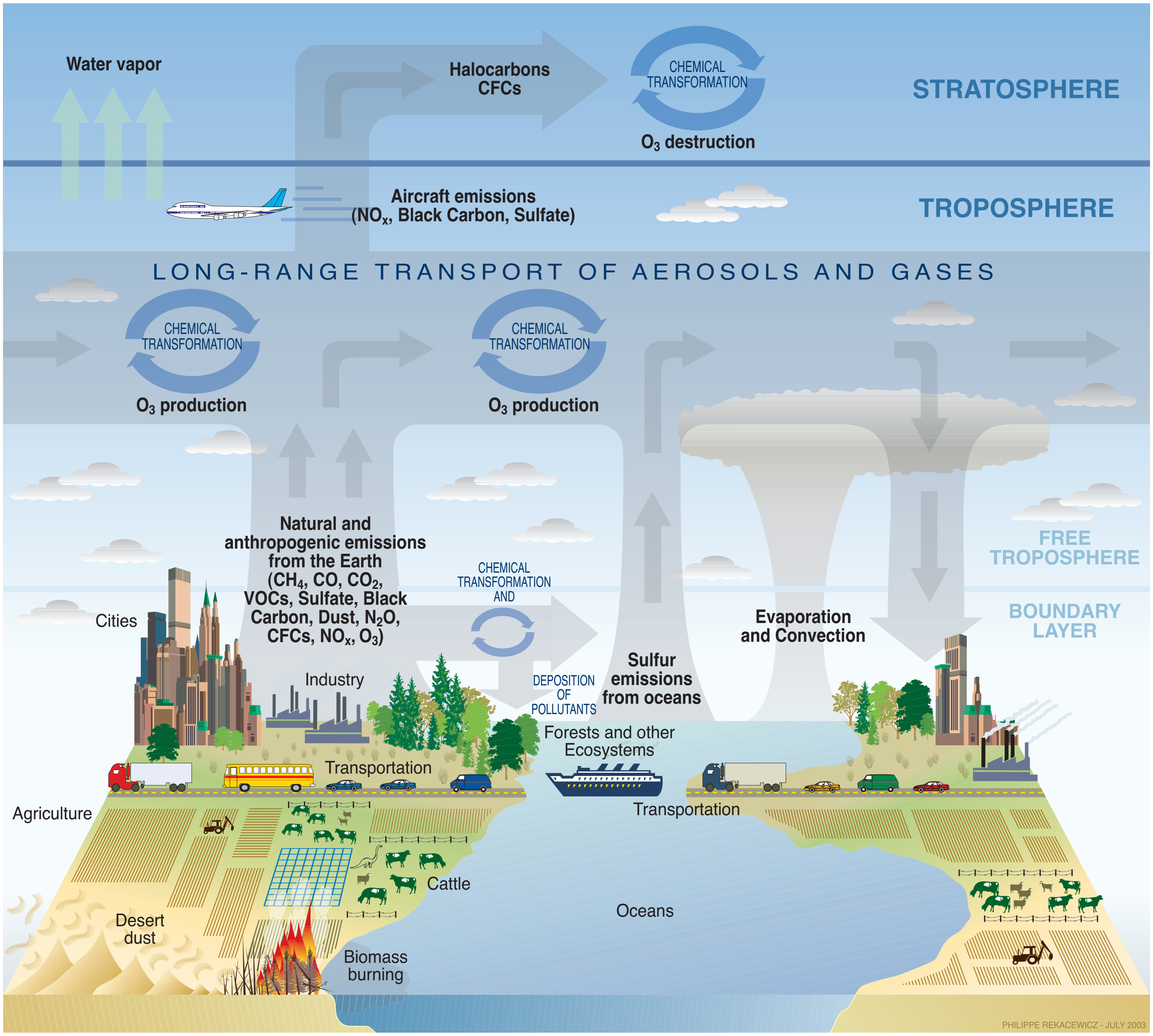


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Figure 3-1: Schematic of chemical and transport processes related to atmospheric composition. These processes link the atmosphere with other components of the Earth system, including the oceans, land, and terrestrial and marine plants and animals.

stratospheric ozone? What are the effects of regional pollution on the global atmosphere and the effects of global climate and chemical change on regional air quality? The second is a focus on Earth system and human system linkages: How is the composition of the global atmosphere, as it relates to climate, ozone depletion, ultraviolet radiation, and pollutant exposure, altered by human activities and natural phenomena? How quantitative is the knowledge of the major sources of emissions to the atmosphere? What are the atmospheric composition changes that could affect human health and natural ecosystems?

The *overall research approach* for understanding the role of atmospheric composition is an integrated application of long-term systematic observations, laboratory and field studies, and modeling, with periodic assessments of understanding and significance to decisionmaking.

Most of the activities related to atmospheric composition research are part of *national and international* partnerships, some of which are noted at the end of this chapter. Such partnerships are necessitated by the breadth and complexity of current issues and because the atmosphere links all nations. The overall research approach is based on the substantial body of knowledge and understanding available from the work of many international scientists. The status of understanding is reported as part of cooperative international assessment activities (e.g., IPCC, 2001a,b,d; WMO, 1999,2003).

In looking ahead at what the specific policy-relevant information needs associated with atmospheric composition will be, five broad challenges are apparent, with goals and examples of key research objectives outlined below.

Question 3.1: What are the climate-relevant chemical, microphysical, and optical properties, and spatial and temporal distributions, of human-caused and naturally occurring aerosols?

State of Knowledge

Research has demonstrated that atmospheric particles (aerosols) can cause a net cooling or warming tendency within the climate system, depending upon their physical and chemical characteristics. Sulfate-based aerosols, for example, tend to cool, whereas black carbon (soot) tends to warm the system (see Figure 3-2). In addition to these direct effects, aerosols can also have indirect effects on radiative forcing (e.g., changes in cloud properties). When climate models include the effects of sulfate aerosol, the simulation of global mean surface temperatures is improved. One of the largest uncertainties about the net impact of aerosols on climate is the diverse warming and cooling influences of the very complex mixture of aerosol types and their spatial distributions. Further, the poorly understood impact of aerosols on the formation of both water droplets and ice crystals in clouds also results in large uncertainties in the ability to project climate changes (see Figure 3-2). More detail is needed globally to describe the scattering and absorbing optical properties of aerosols from regional sources and how these aerosols impact other regions of the globe.

Illustrative Research Questions

The relationship of aerosols to climate change is complex because of the diverse formation and transformation processes involving aerosols (see Figure 3-3). This complexity underlies many of the important research questions related to aerosols.

- What are the global sources (e.g., oceanic, land, atmospheric) of particle emissions (e.g., black carbon/soot, dust, and organic compounds), and their spatial and temporal variability?
- What are the regional and global sources of emissions of aerosol precursor gases [e.g., sulfur dioxide (SO_2), dimethyl sulfide (CH_3SCH_3), ammonia (NH_3), and volatile organic carbon (VOC)]?
- What are the global distributions and optical characteristics of the different aerosol components, and how do they directly and

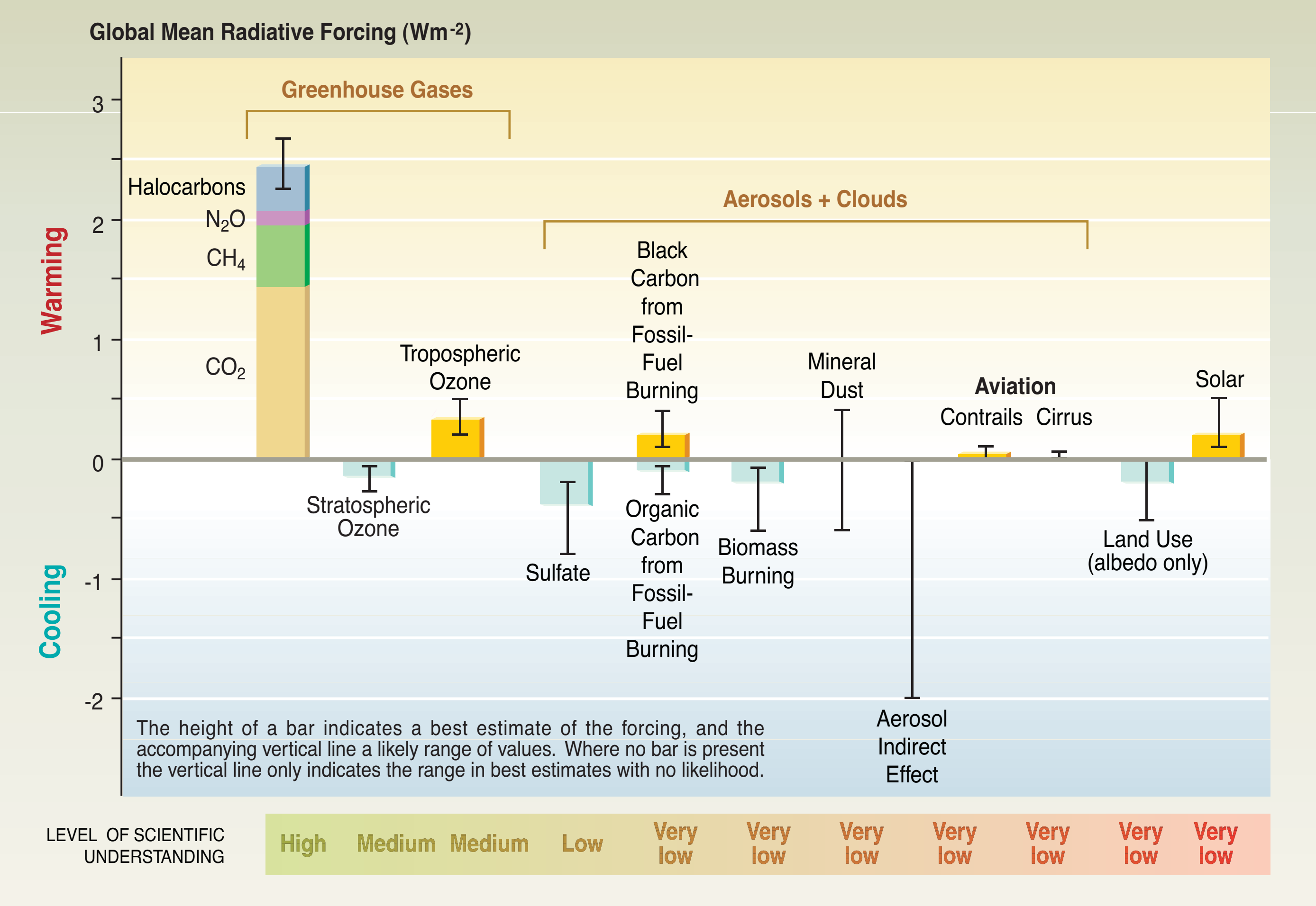

Figure 3-2: Schematic comparing several factors that influence Earth's climate on the basis of their contribution to radiative forcing between 1750 and 2000. Two principal categories of radiative forcing factors are the greenhouse gases and the combination of aerosols and clouds. The rectangular bars represent a best estimate of the contributions of these forcings, some of which yield warming and some cooling, while the vertical line about the rectangular bars indicates the range of estimates. A vertical line without a rectangular bar denotes a forcing for which no best estimate can be given owing to large uncertainties. Scientific understanding of aerosol effects is very low, as shown on the horizontal axis. Source: IPCC (2001d). For more information, see Annex C.

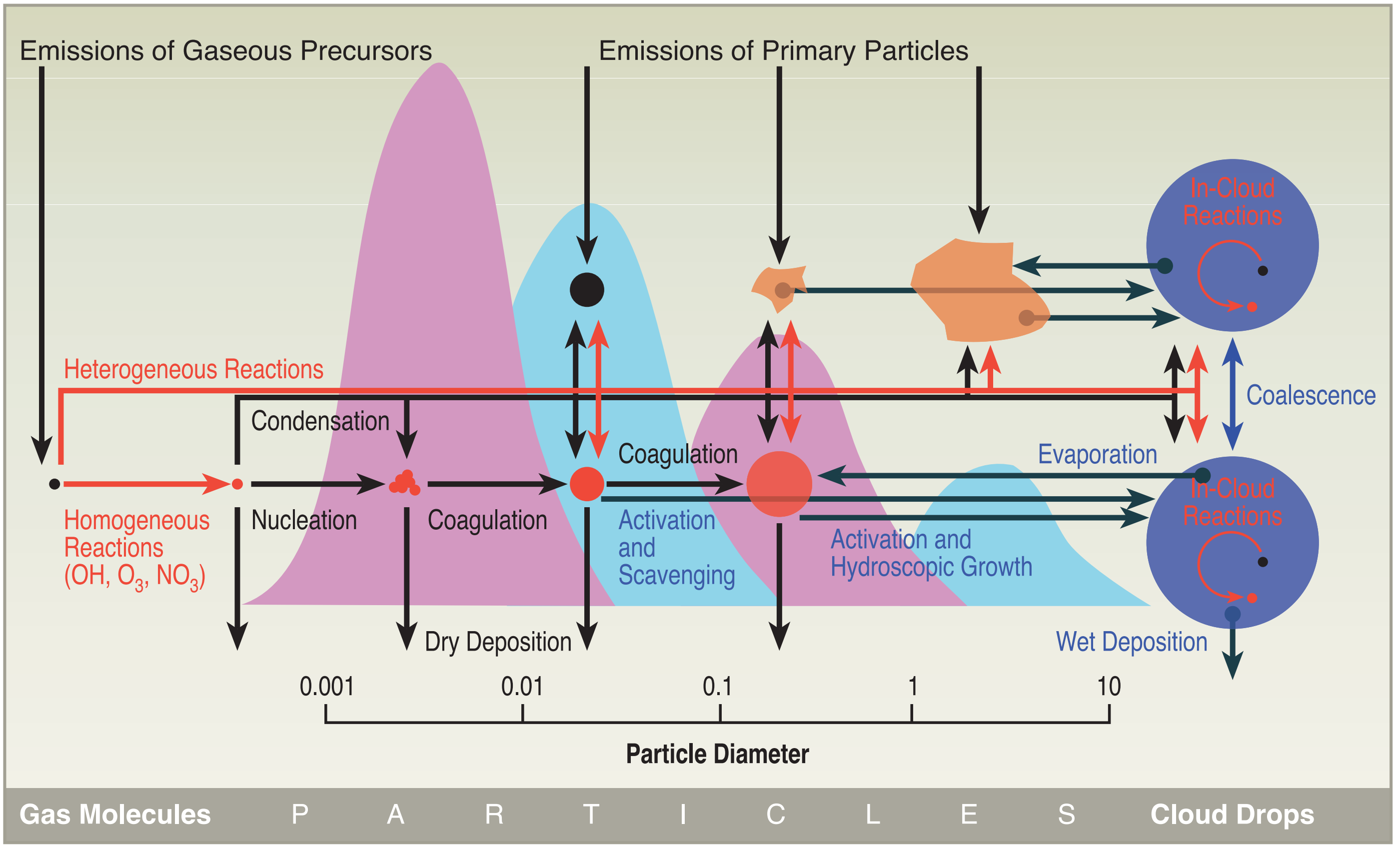

Figure 3-3: Schematic of the processes that cause the formation and transformation of aerosol particles in the atmosphere. Aerosols may be emitted directly into the atmosphere or be formed there from the emissions of gaseous precursors. Particles grow by condensation of gases and by coagulation with other particles, and their number and composition can influence the formation and radiative characteristics of clouds. For more information, see Annex C.

indirectly (e.g., cloudiness changes) affect the radiative balance of Earth's atmosphere?

- What are the processes that control the spatial and temporal distributions and variability of aerosols and that modify aerosol physical, chemical and optical properties during transport (see Figures 3-1 and 3-3), and how well do models simulate these processes and resulting spatial distributions?
- What are the effects of changes in aerosol abundance and composition on cloud formation and persistence, precipitation amounts, and cloud radiative properties (see Chapter 5)?
- How do aerosols and aerosol precursors emitted by aviation affect cloudiness in the upper troposphere?
- How do aerosols affect the chemical composition of the global troposphere?
- What are the abundances and sources of aerosols that affect human health and natural ecosystems (see Chapters 8 and 9)?

Research Needs

Significant research is required to complete our understanding of aerosols and their role in climate change processes. The representation of aerosol properties and their distribution in the atmosphere is highly complex. The needs outlined below describe important future steps to improve our understanding:

- Expand the use of space-based, airborne, and ground-based instruments and laboratory studies to provide better data for aerosols containing sulfate, black carbon/soot, dust, or organic compounds in the following areas:
  - Distributions (primarily from space-based instruments) of aerosols and precursor gases over land and oceans and their temporal variabilities
  - The physical, chemical, and optical properties of anthropogenic and natural aerosols
  - The contributions of aerosols to Earth's radiative balance.
- Enhance field and laboratory studies of the processes that influence aerosol distributions and characteristics, including those involved in indirect (e.g., cloud) effects.
- Improve comprehensive climate model simulations to estimate aerosol-induced temperature changes and associated uncertainties, and the direct and indirect effects of aerosols with an emphasis on establishing bounds on the magnitude of the indirect effects.
- Intensify efforts to determine the composition of organic aerosols and develop simpler instruments for the characterization and measurement of carbon-containing aerosols.
- Establish realistic aerosol and precursor source-strength estimates for specific aerosol compositions for the industrial era.
- Improve aerosol chemistry and transport models and carry out simulations for aerosol source-strength scenarios.
- Make comprehensive comparisons of the geographic and height dependence of simulated aerosol distributions and their radiative characteristics with results from field and satellite data (e.g., with multi-wavelength polarimetric measurements), with an emphasis on regions that can best test the reliability of current model simulations (e.g., using the extensive North American emissions database).
- Assess aerosol abundances and variability in the paleoaerosol record (e.g., ice, bog, and lake core data).

These research needs are strongly linked to those of the Climate Variability and Change (Chapter 4), Water Cycle (Chapter 5), Land-Use/Land-Cover Change (Chapter 6), and Carbon Cycle (Chapter 7) elements.

Milestones, Products, and Payoffs

- Improved description of the global distributions of aerosols and their properties [2-4 years].
- Empirically tested evaluation of the capabilities of current models to link emissions to (i) global aerosol distributions and (ii) the chemical and radiative properties (and their uncertainties) of aerosols [2-4 years]. Specific products and payoffs include:
  - Better estimates of the radiative forcing of climate change for different aerosol types and the uncertainties associated with those estimates. Aspects of these capabilities will be addressed in collaboration with the Climate Variability and Change research element (Chapter 4). These results will contribute to the preparation of Climate Change Science Program (CCSP) climate projections as decision support resources.
  - Better defined potential options for changing radiative forcing within a short time, in contrast to the longer response times associated with CO_2 and other greenhouse gases. The relatively short atmospheric residence times of aerosols form the basis of these options.
- An estimate of the indirect climate effects of aerosols (e.g., on clouds) that is improved beyond the estimate in the last Intergovernmental Panel on Climate Change report (IPCC, 2001a) [2-4 years].
- Characterization of the impact of human activities and natural sources on global and regional aerosol distributions [beyond 4 years].
- Better understanding and description of the physical and chemical processes (and their uncertainties) that form, transform, and remove aerosols during long-range atmospheric transport [beyond 4 years].

Question 3.2: What are the atmospheric sources and sinks of the greenhouse gases other than CO_2 and the implications for the Earth's energy balance?

State of Knowledge

The increasing concentrations of chemically active greenhouse gases, such as methane (CH_4), tropospheric ozone (O_3), nitrous oxide (N_2O), and halocarbons [e.g., CFCs, PFCs, hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF6)], represent primary contributions to the radiative forcing of the climate system (see Figure 3-2). Anthropogenic emissions of CO_2 are addressed in Chapter 7. Water vapor, considered the most dominant greenhouse gas (albeit as a feedback), is discussed as part of the hydrological cycle (see Chapter 5).

The natural and anthropogenic emissions sources leading to the observed growth rates of CH_4 (the second-most influential anthropogenic greenhouse gas) and N_2O abundances are qualitatively understood but poorly quantified (e.g., the amount of CH_4 emitted by rice agriculture). Trends in tropospheric ozone (the third-most influential anthropogenic greenhouse gas) are not well determined because they are driven by a mix of natural and anthropogenic emissions, including CH_4 and regional pollutants such as the reactive nitrogen oxides (NO_x). The atmospheric concentrations and sources of the CFCs and HCFCs have been well studied because of their role in stratospheric ozone depletion. Some important greenhouse gases are removed from the troposphere and stratosphere in reaction with the hydroxyl radical (OH) (e.g., CH_4, HFCs, HCFCs) or by photolysis (e.g., N_2O). Reactions that remove a greenhouse gas control its lifetime in the atmosphere and, hence, its contribution to radiative forcing of climate.

BOX 3-1

ATMOSPHERIC COMPOSITION

FY04 CCRI Priority - Aerosols

The Climate Change Research Initiative (CCRI) will leverage existing U.S. Global Change Research Program (USGCRP) research to address major gaps in understanding climate change. Uncertainties related to the effects of aerosols on climate are large, with both warming and cooling effects possible depending on the nature and distribution of the aerosol.

The CCRI will advance the understanding of the distribution of all major types of aerosols and their variability through time, the different contributions of aerosols from human activities, and the processes by which the different contributions are linked to global distributions of aerosols. The CCRI will support research to improve understanding of the processes by which trace gases and aerosols are transformed and transported in the atmosphere. Studies of how atmospheric chemistry, composition, and climate are linked will be emphasized, including those processes that control the abundance of constituents that affect the Earth's radiation budget, such as tropospheric methane, ozone, and aerosols.

The global distributions of a limited number of atmospheric parameters (including climatically relevant parameters such as ozone and aerosols) and their variabilities will be obtained from satellite observations over long periods of time along with more comprehensive suites of observations over briefer time periods. Satellite data recently obtained and to become available for the first time for methane, tropospheric ozone, and tropospheric aerosols will be analyzed and interpreted in the context of global models and assimilation systems.

The studies will provide an observational- and model-based evaluation of the radiative forcings associated with aerosol direct and indirect effects. These forcing results will contribute to the CCSP climate projections for research and assessment.

Illustrative Research Questions

Driven by the need to have a better predictive understanding of the relationship between the emission sources of these radiatively active gases and their global distributions and radiative forcing, several questions continue to face the research community. More quantitative information is needed to help answer these questions, which include:

- What is the inventory of anthropogenic (i.e., energy, industry, agriculture, and waste) and natural (e.g., ecosystems) emissions sources of CH_4 and N_2O on global and regional scales (see Chapters 7, 8, and 9)?
- What are the causes and related uncertainties of the observed large variations in the growth rates of CH_4 and N_2O abundances?
- What are the global anthropogenic and natural (both biogenic and lightning-related) sources of reactive nitrogen oxides, which are precursors of troposphere ozone?
- How can paleorecords of greenhouse gases and climate variability be used to understand the potential for future climate change (see Chapter 4)?
- What are the trends in mid-tropospheric ozone, particularly in the Northern Hemisphere, and how well can the trends be attributed to known chemical and transport processes?
- How is the oxidative capacity of the atmosphere changing (e.g., OH abundances) and how do these changes affect the radiative forcing impact of greenhouse gas emissions?
- How do changes in the abundance of a principal greenhouse gas (e.g., CH_4) cause a feedback that alters its lifetime or that of another greenhouse gas (see Chapter 7)?
- How do the increasing abundances of greenhouse gases influence the distribution of atmospheric water vapor and its feedback in the radiative balance of the climate system (see Chapter 5)?

Research Needs

Field and laboratory studies, satellite observations, and diagnostic transport/chemical modeling are needed to fully address these questions. Examples of these activities are:

- Satellite, field, laboratory, and modeling studies to develop, evaluate, and improve inventories of global emissions and the potential for emission reductions for CH_4, carbon monoxide (CO), N_2O, and NO_x from anthropogenic and natural sources. This need will be addressed in collaboration with the carbon cycle research element (Chapter 7).
- Global monitoring sites to continue recording the growth rate of CH_4 and its variability. This need will be addressed in collaboration with the Carbon Cycle research element (Chapter 7).
- Field and modeling studies to reduce the uncertainty in the air-sea exchange rate of key gases (e.g., N_2O, CH_3SCH_3, short-lived halocarbons) over important regions of the world's oceans.
- Satellite observations to provide estimates of global distributions of tropospheric ozone and some of its precursors (e.g., NO_x).
- Model studies to simulate past trends in tropospheric ozone to improve the understanding of its contribution to radiative forcing over the past ~50 years.
- Satellite and field studies to characterize how regional- and continental-scale changes in ozone precursor emissions alter global tropospheric ozone distributions, thereby providing tests of and improvement in the representation of ozone-related processes in models.
- Laboratory studies to expand the quantitative descriptions of tropospheric chemical processes, thereby facilitating the continued development of reliable climate models.
- Field and model studies to quantify how changes in NO_x, CH_4, CO, water vapor, and ozone could alter the abundance of the hydroxyl radical, which controls the lifetime of many principal greenhouse gases.

Milestones, Products, and Payoffs

- Observationally assessed and improved uncertainty ranges of the radiative forcing of the chemically active greenhouse gases [2-4 years]. Aspects of this product will be addressed in collaboration with the Climate Variability and Change research element (Chapter 4) and those specifically related to CH_4 and CO_2 with the Carbon Cycle research element (Chapter 7). These improved ranges will be used in formulating future scenarios of radiative forcing, which will be part of CCSP climate projections. As a result, there will be a broader suite of choices (i.e., in addition to CO_2) for decisionmakers to influence anthropogenic radiative forcing, particularly in coming decades.

Question 3.3: What are the effects of regional pollution on the global atmosphere and the effects of global climate and chemical change on regional air quality and atmospheric chemical inputs to ecosystems?

State of Knowledge

Emissions from rapidly industrializing regions of the world have the potential to impact air quality and ecosystem health in regions far from the sources. Paleochemical data from ice cores and snow document past perturbations and demonstrate that even remote areas, such as Greenland, are influenced by worldwide emissions. The anthropogenic contribution to the nitrogen cycle from fossil-fuel combustion and fertilizer production now rivals in magnitude the natural input from nitrogen-fixing organisms and lightning. This additional nitrogen input to the biosphere illustrates how human activities could have important consequences for ecosystem structure and function. The importance of the effect of regional pollution on global tropospheric chemistry has been recognized for some time. Now, the importance of understanding the reverse effect—that of global-scale transport of pollutants or global change on regional air quality—is increasing. A well-recognized example is the enhancement of background global ozone concentrations by anthropogenic emissions.

Illustrative Research Questions

This emerging picture is shaping several questions of importance to society. Some examples of these are as follows:

- What are the impacts of climate change and long-range transport of regional air pollution on water resources, human health, food-producing areas, and ecosystems (see Chapters 6, 8, and 9)?
- How do El Niño-Southern Oscillation (ENSO)-related drought and fires affect regional and global aerosol haze and air quality?
- How do interactions between the biogeochemical cycles of the macronutrients (e.g., carbon and nitrogen) affect greenhouse gas

abundances in the atmosphere and the radiative forcing of the climate system (see Chapters 6 and 8)?
- How do regional changes in atmospheric composition due to biomass burning affect the abundances of greenhouse gases and global nutrient cycles (see Chapters 6 and 8)?
- How do the primary and secondary pollutants from the world's megacities and large-scale, non-urban emissions (e.g., agriculture, ecosystems, etc.) contribute to global atmospheric composition?
- What are, and what contribute to, North American "background" levels of air quality—that is, what levels of pollution are beyond national control?
- What controls the long-range transport, accumulation, and eventual destruction of persistent organic pollutants or the long-range transport, transformation, and deposition of mercury?

Research Needs

These questions are being addressed by measurements of key tropospheric constituents from satellites, airborne platforms, and surface sites. Model analyses and simulations are used to provide a regional and global context for the measurement data set and to address future scenarios. Near-term goals include the following:
- Quantify North American inflow and outflow of reactive and long-lived gases and aerosols using observations with increasing spatial and temporal resolution and project future changes.
- Understand the balance between long-range transport and transformation of pollutants.
- Build and evaluate models that couple the biogeochemical cycles of elements with specific emphasis on carbon and nitrogen compounds.
- Continue baseline observations of atmospheric composition over North America and globally.
- Carry out a detailed global survey of vertically resolved distributions of tropospheric ozone and its key precursor species.
- Carry out studies with atmospheric chemistry models coupled to general circulation models to improve the understanding of the feedbacks between regional air pollution and global climate change.

Milestones, Products, and Payoffs

- A simulation of the changes in the impacts of global tropospheric ozone on radiative forcing over the past decade brought about by clean air regulations [2-4 years]. Aspects of this product will be addressed in collaboration with the Climate Variability and Change research element (Chapter 4).
- Estimates of atmospheric composition and related processes to be used in assessments of the vulnerability of ecosystems to urban growth and long-range chemical transport [beyond 4 years]. Aspects of this product will be addressed in collaboration with the Ecosystems research element (Chapter 8).
- An evaluation of how North American emissions contribute to and influence global atmospheric composition [beyond 4 years].
- A 21st century chemical baseline for the Pacific region against which future changes can be assessed [2-4 years].

Question 3.4: What are the characteristics of the recovery of the stratospheric ozone layer in response to declining abundances of ozone-depleting gases and increasing abundances of greenhouse gases?

State of Knowledge

The primary cause of stratospheric ozone depletion observed over the last 2 decades is an increase in the concentrations of industrially produced ozone-depleting chemicals (e.g., CFCs). The depletion has been significant, ranging from a few percent per decade at mid-latitudes to greater than 50 percent seasonal losses at high latitudes. Notable is the annually recurring Antarctic ozone hole, as well as smaller, but still significant, winter/spring ozone losses recently observed in the Arctic. Reductions in atmospheric ozone levels lead to increased exposure to ultraviolet radiation at the surface, which has harmful consequences for plant and animal life, and human health. In response to these findings, the nations of the world ratified the *Montreal Protocol on Substances That Deplete the Ozone Layer* and agreed to phase out the production of most ozone-depleting chemicals.

Ground-based and satellite measurements show that concentrations of many of these compounds are now beginning to decrease in the atmosphere (WMO, 1999,2003). As the atmospheric burden of ozone-depleting chemicals falls in response to international efforts, stratospheric ozone concentrations should begin to recover in coming decades (see Figure 3-4). However, because of the ongoing changes in atmospheric composition and climate parameters, which began before the onset of stratospheric ozone depletion, the exact course and timing of ozone recovery in the coming decades is not fully known.

Illustrative Research Questions

- How will changes in the atmospheric abundances of greenhouse gases, such as CO_2, N_2O, and CH_4, and the resulting changes in the radiation and temperature balance (e.g., stratospheric cooling), alter ozone-related processes in the stratosphere (see Chapter 7)?
- How will changes in physical climate parameters (e.g., stratospheric winds and temperatures) affect the production and loss of stratospheric ozone and how might these changes in ozone cause a feedback that would alter climate parameters (see Chapter 4)?
- What are the ozone-depleting and radiative forcing properties of the new chemicals chosen to be substitutes for the now-banned ozone-depleting substances?
- How might climate change affect the abundances of very short-lived halocarbon gases of natural origin (e.g., from the oceans) and their contribution to stratospheric ozone depletion?

Research Needs

Improving our understanding of the complex interaction between the ozone layer and the climate system requires further investigations of the processes that interconnect ozone, water vapor, reactive trace constituents (notably chlorine and bromine compounds and reactive nitrogen oxides), aerosols, and temperature. Research needs include the following:
- Extend interagency and international satellite observations of ozone trends, with an emphasis on detecting and attributing ozone recovery.

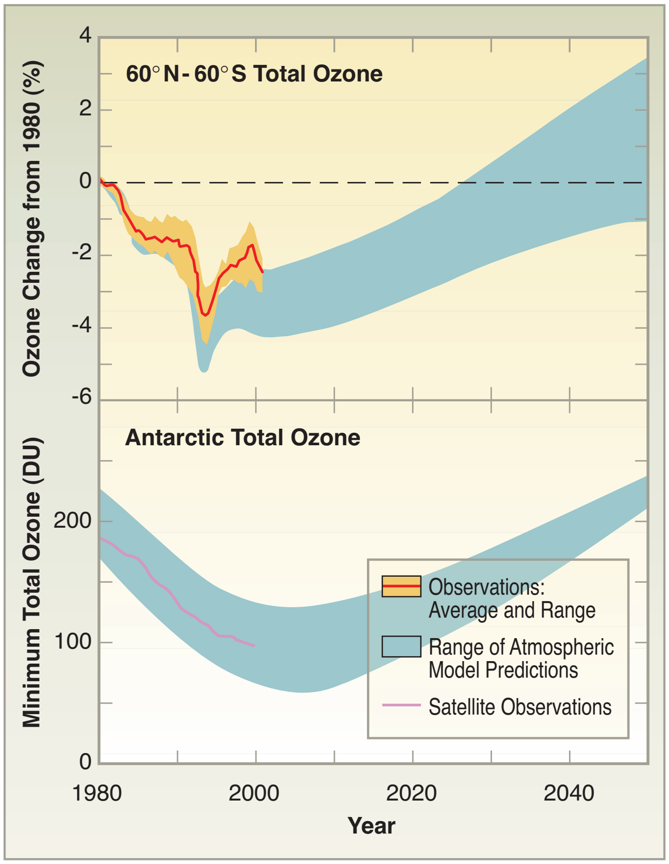

Figure 3-4: Schematic illustrating the estimated recovery of stratospheric ozone in the coming decades. Observations show the decline of global total ozone (top panel) and minimum values of total ozone over Antarctica (lower panel) beginning in 1980. As the abundances of ozone-depleting gases decline in the atmosphere, ozone values are expected to increase and recover towards 1980 and earlier values. The estimated recovery of ozone is shown based on predictions by several atmospheric models which use different assumptions about the composition and meteorology of the future stratosphere. The research needs as outlined in Section 3.4 address reducing the range of uncertainty in ozone recovery estimates. Source: Adapted from WMO (2003). For more information, see Annex C.

- Continue global monitoring of the changes in the abundances of ozone-depleting substances and their substitutes and assessing compliance with the Montreal Protocol.
- Evaluate the impacts on stratospheric ozone and climate forcing of proposed substitute gases with laboratory chemistry and atmospheric models to provide early information to industry prior to large investments in production.
- Maintain and expand measurements of the ozone vertical profile throughout the troposphere and stratosphere in order to obtain a more precise evaluation of the radiative forcing associated with ozone and a more precise detection of stratospheric ozone recovery.
- Use focused aircraft, balloon, and ground-based campaigns, satellite data sets, and chemical transport modeling activities to address:
  - Cross-tropopause transport processes to better understand the ozone-depleting role of the very short-lived (days to months) halocarbon gases that have either been observed in the atmosphere or are proposed for applications that may lead to atmospheric release
  - The response of polar stratospheric cloud formation and ozone-loss chemistry to trends in water vapor and temperature in the stratosphere
  - Stratospheric transport processes to better understand ozone layer responses to climate change.
- Continue monitoring the trends in ultraviolet radiation, particularly in regions of high radiation exposure and high biological sensitivity.

Milestones, Products, and Payoffs

- Updated trends in ozone and surface ultraviolet radiation, analysis of compliance with the provisions of the Montreal Protocol, and model forecasts of ozone recovery [2-4 years].
- Improved quantitative model evaluation of the sensitivity of the ozone layer to changes in atmospheric transport and composition related to climate change [2-4 years].
- Contribute new findings to the 2006 update of the international scientific assessment of stratospheric ozone depletion [2-4 years].
  - This sixth in the series of "operational" products of the ozone science community is key to addressing accountability with respect to ozone depletion—namely, is the outcome expected from international actions being observed?

Question 3.5: What are the couplings and feedback mechanisms among climate change, air pollution, and ozone layer depletion, and their relationship to the health of humans and ecosystems?

State of Knowledge

This question is intended to underscore the explicit need to better understand the relationships that exist between research issues that historically have been treated separately. Understanding the potential consequences of changes in atmospheric composition cuts across a range of important societal issues and scientific disciplines. Atmospheric composition links climate change, air quality, and ozone depletion with human and ecosystem health. The links involve physical processes and feedback mechanisms—some of which are newly recognized and most of which require further study.

Understanding these connections is important for understanding climate change on regional and global scales. For example, research has demonstrated that stratospheric ozone depletion not only causes increased exposure to ultraviolet radiation at the surface, but also exerts a cooling influence on the global climate. Conversely, climate-related changes may cool the lower stratosphere and increase ozone layer depletion in polar regions. Tropospheric ozone, of concern primarily as a component of smog, is not only a local health risk, but also exerts a warming influence on the global climate. Emissions of SO_2 from fossil-fuel combustion not only lead to the formation of acid rain, but also contribute to sulfate-aerosol haze, which exerts a cooling influence on the global climate system.

It is clear that these issues, which initially may have been treated separately by scientists and policymakers, now require a more integrated approach that addresses multiple sources, stresses, and impacts (NASA, 2002).

Illustrative Research Questions

- How do changes in the anthropogenic emissions of NO_x, CO, and VOCs affect the abundance of CH_4 and ozone on regional and global scales (see Chapters 7 and 9)?
- How is air quality affected by changes in climate and weather patterns—for example, changes in ozone resulting from a change in cloudiness, temperature, precipitation, etc. (see Chapter 4)?
- How do the regional and global radiative forcings of aerosols respond to changes in aerosol precursor gases (e.g., sulfur gases, ammonia, and VOCs)?
- What are the common stresses that climate change, ozone layer depletion, and regional air quality exert on humans and ecosystems and do these stresses interact synergistically (see Chapters 8 and 9)?

Research Needs

Research needs, in addition to those given in Sections 3.1 to 3.4, linking atmospheric composition issues to the health of humans and ecosystems are:

- Build and evaluate diagnostic/prognostic models of the coupled climate, chemistry, transport, and ecological systems at the local, regional, and global scales. This need will be addressed in part by products of the Ecosystems research element (Chapter 8).
- Identify and quantify how ecosystems are affected by human activities that change the chemical composition of the atmosphere.
- Build and evaluate models that efficiently represent the behavior of biogeochemical systems and link these models with decisionmaking frameworks.
- Carry out multiple-issue state-of-understanding scientific assessments, in partnership with a spectrum of stakeholders and with the aim of characterizing integrated "If…, then…" options.

Milestones, Products, and Payoffs

- Strengthened processes within the national and international scientific communities providing for integrated evaluations of the impacts on human health and ecosystems caused by the intercontinental transport of pollutants, the impact of air pollutants on climate, and the impact of climate change on air pollutants [2-4 years]. The evaluations will be useful in developing integrated control strategies to benefit both regional air quality and global climate change, and the local attainment of air quality standards [2-4 years]. Aspects of this product will be addressed in collaboration with the Climate Variability and Change (Chapter 4), Carbon Cycle (Chapter 7), and Human Contributions and Responses (Chapter 9) research elements.
- In 2006, the U.S. atmospheric research community will produce the first *State of the Atmosphere* report that describes and interprets the status of the characteristics and trends associated with atmospheric composition, ozone layer depletion, temperature, rainfall, and ecosystem exposure (see Chapters 12 and 13) [2-4 years].
- Diagnostic/prognostic models of the coupled climate, chemistry/transport, and ecological systems [beyond 4 years].

National and International Partnerships

The Atmospheric Composition research focus is linked via cooperation, co-planning, and joint execution to several national and international planning and coordinating activities. A few examples follow:

- **Interagency Programs**: Joint planning [e.g., with the National Aerosol-Climate Interactions Program (NACIP)] is a principal strategy for achieving CCSP objectives.
- **Committee on Environment and Natural Resources - Air Quality Research Subcommittee (AQRS)**: Joint research is conducted on the global/continental scales within the CCSP and on the regional/local scales within the AQRS (e.g., global influences on the "natural background" of air pollutants and linkages with the stakeholders via the AQRS).
- **International Global Atmospheric Chemistry (IGAC)**: IGAC, a core project of the International Geosphere-Biosphere Programme, coordinates several international projects focused on the chemistry of the global troposphere and its impact on the Earth's radiative balance (e.g., the new Intercontinental Transport and Chemical Transformation project, involving Asian, North American, and European researchers).
- **Surface Ocean-Lower Atmosphere Study (SOLAS)**: SOLAS, a new core project of the International Geosphere-Biosphere Programme, will coordinate several international projects focused on the exchange of climate-relevant gases and particles between the troposphere and oceans.
- **World Climate Research Programme/Stratospheric Processes and their Role in Climate (WCRP/SPARC)**: SPARC coordinates international cooperation in research on climate-related aspects of stratospheric science, including efforts aimed at understanding long-term trends in the composition of the stratosphere and upper troposphere.
- **International Assessments**: Atmospheric composition and its role in the radiative forcing of climate and ozone depletion is a key component of international assessments on these topics—performed under the auspices of the Intergovernmental Panel on Climate Change and the United Nations Environment Programme/World Meteorological Organization, respectively. Each involves the participation of a large international body of scientists that represents atmospheric and cross-cutting disciplines.

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