Intercontinental Transport of Air Pollution:

Relationship to North American Air Quality

A Review of Federal Research and Future Needs

Air Quality Research Subcommittee
of the
Committee on Environment and Natural Resources
CENR

April 2001

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The May and July 2000 meetings of the Air Quality Research Subcommittee of the Committee on Environment and Natural Resources (CENR) focused on a discussion of federal research related to the intercontinental transport of air pollution, with an emphasis on how it relates to North American air quality. This report provides a brief summary of the current state of science as discussed at these meetings, with some additional material that was not presented at the meetings due to time constraints. A complete and comprehensive review of the science related to intercontinental transport is clearly beyond the scope of this report. Rather, the report provides a brief overview of the science, identifying key knowledge and capability gaps, and is intended as an information piece to guide the development of future federal research programs relative to air quality. The Air Quality Research Subcommittee discussions are coordinated with the Global Change Research Subcommittee, which coordinates research on the global aspects of this and many other phenomena. This report is a scientific and programmatic document, as the preceding Subcommittee reports have been, and is not intended to represent governmental policy.

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1.0 Executive Summary

Globalization is increasing environmental as well as economic interdependence. Industrialization of the developing world means higher energy consumption and more pollution. Many air pollutants remain in the atmosphere long enough to be transported over intercontinental distances. Four such pollutants that have implications for human health, global climate, regional environmental quality, and sustainable economic development are:

- Ozone and ozone precursors
- Airborne particles
- Mercury
- Persistent Organic Pollutants (POPs)

The international community recognizes the importance of this problem and has taken steps to control trans-boundary transport of air pollution through a number of accords. The United States is a party to at least four different agreements and one pending agreement that address this problem.

The development of effective environmental policy related to this issue requires an understanding of the factors that control the emission, transformation, distribution, and effects of long-lived air pollutants. The science needed to provide information for such policy development falls into four broad areas:

- Source / receptor relationships
- Transport/transformation processes
- The role of natural emissions
- The effect of climate

There is a substantial body of research that has addressed the problem of intercontinental transport of air pollution. Much of the U.S. research on this topic is coordinated with the international research community and their efforts through the International Global Atmospheric Chemistry Project (IGAC). U.S. Federal coordination is achieved through the Global Change and the Air Quality Research subcommittees of the Committee on Environment and Natural Resources (CENR) and the U.S. Global Change Research Program (USGCRP).

Research has shown that there is significant transport of natural and anthropogenic airborne material from Africa to North and South America, from Asia to North America, from North America to Europe, and from Europe and Asia to the Arctic. For example, satellite images and aircraft measurements have shown that large quantities of Saharan dust are transported across the North Atlantic in distinct layers associated with the passage of frontal systems. African dust is detected routinely at a monitoring site in Miami. This dust affects large areas of the Eastern and Southern U. S. and has implications for attainment of local particulate matter (PM) standards. Further, biomass burning in Africa contributes large quantities of ozone to the atmosphere of the Southern Hemisphere. Ozone, ozone precursors, and particulate mater from pollution sources along the East Coast of North America have been observed in the remote Atlantic and at European ground stations. Investigators at the Mauna Loa Observatory, on the island of Hawaii, routinely see evidence of long range transport of natural and anthropogenic aerosols and trace

gases originating over Asia. Asian pollution has been observed off the West Coast of the United States. Researchers have shown that haze in the Arctic is caused by anthropogenic emissions traveling 8,000-10,000 km from their source regions in Eastern Europe. Investigators have shown that biomass burning, caused by both human activities and natural processes, results in significant regional pollution and may have impacts on atmospheric chemistry and global climate.

Intercontinental transport of air pollution is a global issue that requires a global solution. U.S. Federal research in this area is part of an international effort. Groups like IGAC/ITCT (Intercontinental Transport and Chemical Transformation) are essential to develop a global research agenda. Some of the U.S. Federal agencies with significant involvement in research into long range transport phenomena are: National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), Environmental Protection Agency (EPA), and National Institute for Standards and Technology (NIST).

The research activities necessary to illuminate intercontinental pollution transport phenomena and issues in the future fall into six categories:

- Emissions: The quality of emissions estimates is highly variable throughout the world. Emphasis needs to be placed on improving estimates of emissions in the developing countries and from both deliberate and uncontrolled biomass burns. The quantification of emissions in remote marine areas (ships, airplanes, and biogenic) is another important area where information is lacking.
- Process Studies: The key to a more complete characterization of intercontinental transport of air pollution is an improved understanding of the atmospheric processes that control the transport, transformation, and fate of these pollutants.
- Models: There are three-dimensional models that couple transport and chemical processes on a global scale. Efforts need to be continued to improve the overall performance of these models through the incorporation of new procedures that represent the current understanding of the underlying science and through validation through more extensive observations.
- Observing Systems: The databases provided by the intensive field campaigns provide a comprehensive snapshot over a relative short period. These programs will need to be augmented by longer-term observations that provide a larger spatial and temporal context. Better and more comprehensive long-term ground-based and space-borne observing systems will need to be developed.
- Climate Effects: Couplings between the atmosphere, the chemistry of trace species, climate, the oceans, and biological systems are not known well enough to predict how changes in one system will influence the other. Efforts must continue to improve the understanding of the effects of variations in climate on these systems.
- Assessments: Periodic assessments that describe the current understanding of the science related to intercontinental transport of air pollution are needed to insure an effective research program and to facilitate communication with the decision makers in the policy community.

2.0 Introduction

The Earth has but one atmosphere. Airborne pollutants are transported to remote environments if they have sufficiently long lifetimes. No place on Earth is untouched by these compounds. Observations made at monitoring sites in the Antarctic show deposition of particulate carbon and increasing levels of carbon dioxide (CO_2). Analyses of the tissue of killer whales hunting in the North Pacific show the accumulation of pesticide residues. Chlorofluorocarbons are found throughout the atmosphere. And, radioactive fallout from nuclear testing and the Chernobyl accident are found on every continent.

Long-range transport of anthropogenic pollution is not a new phenomenon. Copper levels measured in ice cores from glaciers in Greenland increase suddenly in layers approximately 2500 years old. This increase is attributed to the emissions from crude smelting methods used for copper production in Europe and Asia. Ice cores from mid-latitude glaciers throughout the world show clear evidence of the onset of the industrial revolution. Eskimos observed arctic haze caused by industrial pollution from Europe before they had first contact with explorers.

The development of a global economy has effects beyond raising standards of living. We are in an era of increasing environmental as well as economic interdependence. Industrialization of the developing world means higher energy consumption and more pollution. The implications of this growth for human health, global climate, regional environmental quality, and sustainable economic development are significant.

2.1 Air Pollutants that can be Transported Over Long Distances

Many of the pollutants that are monitored and regulated at local and regional levels can be transported long distances from their sources. The amount of time that a pollutant will stay in the atmosphere is determined by its reactivity (loss rate by reaction with hydroxyl radicals etc.) and removal rate (dry and wet deposition). Atmospheric lifetimes vary widely (Figure 2.1), both among pollutants and throughout the atmosphere.

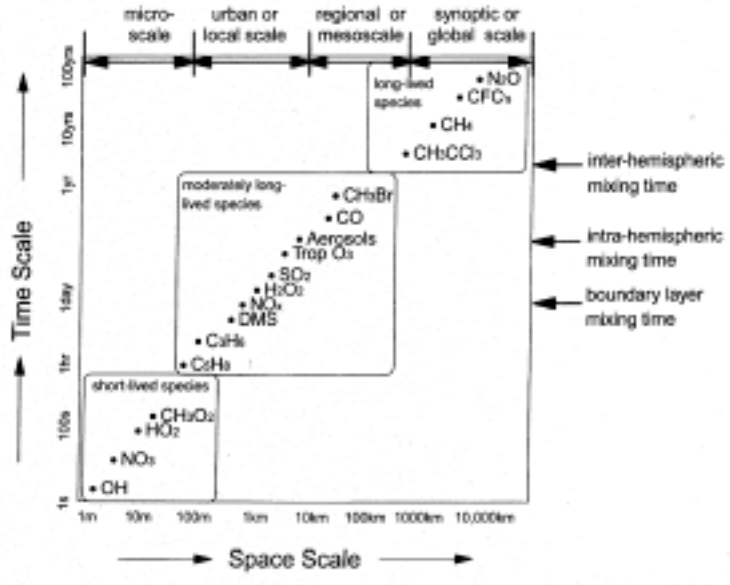

Figure 2.1 Spatial and temporal scales of variability of a number of key constituents of the atmosphere [NRC,1998].

This report addresses four pollutants or types of pollutant that are transported over intercontinental distances and have global environmental effects:

- Ozone and ozone precursors
- Airborne particles
- Mercury
- Persistent Organic Pollutants (POPs)

2.1.1 Ozone and ozone precursors

Ozone is a secondary pollutant. It is formed in the troposphere through a complex non-linear photochemical oxidation process involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. The pathways of the reactions and the resulting products are highly dependent on the relative abundance of the precursor species. These precursor compounds have natural as well as anthropogenic sources. Nitrogen oxides are produced by lightning and in soils. Trees produce significant amounts of VOCs in the form of terpenes such as isoprene. However, throughout much of the world anthropogenic production of these compounds dominates natural production, particularly in the case of NO_x. The relative abundance of NO_x and VOCs determines if there is net ozone production or net ozone destruction.

The ozone chemical cycles have implications for global climate. Tropospheric ozone is the third-most important greenhouse gas, after carbon dioxide and methane. An increase in ozone abundance results in positive radiative forcing. The relative abundance of ozone and the precursor species also control the oxidizing capacity of the troposphere and therefore the lifetimes of many pollutant species. The production of secondary aerosols through the oxidation of sulfur dioxide (SO_2) to sulfate (SO_4^{2-}) and NO_x to nitrate (NO_3^-) is also related to the oxidation cycle.

Long-range pollution transport means that increases in Asian emissions may make attainment of air quality standards in the U. S. and Europe more difficult. Model studies, using a scenario where Asian emissions triple between 1985 and 2010, show:

- Global mean O_3 levels increasing 8 to 10% [Collins et al., 2000]
- O_3 increases over Europe in summer of 10 to 20 ppb [Jonson et al., 1999]
- Mean increases of 1-3 ppb ozone in the Eastern U.S and 2-6 ppb in the Western U.S. [Jacob et al., 1999]

These increased background levels would more than offset any gains achieved by reducing U.S. or European emissions of NO_x and hydrocarbons by as much as 25%.

The chemistry of the troposphere is linked to the state of the global climate. There will be interactions between changes in climate and the oxidation reactions that produce ozone. Increases in temperature will accelerate the decomposition of reservoir species such as peroxyacetylnitrate (PAN). These species are chemically stable and allow NO_x to be transported over long distances, but decompose to reactive forms at higher temperatures. Increasing temperatures will result in increasing humidity. Water vapor is a greenhouse gas and a source of hydroxyl radical (OH). Increases in the atmospheric abundance of OH can result in net

production or destruction of O_3 depending on ambient NO_x levels. The response of biological systems to climate change could alter the natural emission of important trace species such as terpenes and sulfur compounds. Changes in temperature can also affect the demand for electricity and its associated emissions as well as evaporative losses from automobile fuel systems. The results of these interactions are uncertain. Couplings between the atmosphere and the chemistry of trace species, climate, and biological systems are not known well enough to predict how changes in one system will influence the other.

2.1.2 Airborne particles

Airborne particles deposit to the surface very slowly, thus they can remain airborne for long periods and be transported over intercontinental distances. Primary particulates are released from industrial processes, from natural and anthropogenic biomass burning, and from the entrainment of mineral dust into the atmosphere. Secondary particulates are formed from oxidation of gas-phase primary pollutants or from the condensation of semi-volatile species. Model studies indicate that as much of 40% of the SO_2 emissions from North America, Europe, and Asia may be transported to the free troposphere [Chin and Jacob, 1996]. Sulfate aerosol particles can act as cloud condensation nuclei (CCN). Clouds formed around sulfate aerosol have different radiative properties than those formed with other CCN. Increases in sulfate aerosol abundance may result in more clouds or clouds that reflect incoming sunlight more efficiently and cause a net reduction in the solar radiation reaching the Earth's surface. Some anthropogenic organic aerosols, such as carbon black or soot, absorb radiation and can result in positive radiative forcing.

Both primary and secondary aerosols have significant public health and climatic implications. An increase in global background aerosol levels would reduce the effectiveness of local controls on emissions of particles and particle precursors (e.g., sulfur dioxide – SO_2). Increased aerosol loads can change the global radiation budget both directly and through the formation of clouds. The increased presence of particles can also have effects on the chemistry of the troposphere and stratosphere by modulating the incoming radiation and by providing surfaces where heterogeneous chemical reactions can occur.

Climate changes can also result in conditions that could affect the aerosol loading of the atmosphere. Changes in precipitation patterns may increase the size of deserts and result in more mineral dust in the atmosphere. Warmer ocean temperatures could increase the natural sulfur released into the atmosphere by plankton.

2.1.3 Mercury

Gaseous and particulate mercury are emitted into the atmosphere from both natural and anthropogenic sources. Once in the atmosphere, mercury can be transported over local, regional, or even global scales depending on the form of mercury and meteorological conditions. Inorganic mercury (Hg^{2+} e.g., mercury chloride, $HgCl_2$) in the gas and particulate phases is very soluble and deposits readily, so deposition is fairly high in close proximity to sources of these forms of mercury. On the other hand, elemental mercury (Hg^0) is relatively insoluble, deposits slowly and therefore can traverse the globe. The mercury that remains in the atmosphere for long periods will become a part of the global “background.” The global reservoir of atmospheric

mercury has grown by a factor of between 2 and 5 since pre-industrial times, but the current trend is uncertain (Boening, 2000).

Atmospheric mercury, once deposited onto land, can be reemitted into the atmosphere, taken up by plants, or transported to water bodies by surface runoff. In water, anaerobic bacteria convert mercury into methylmercury, a very potent neurotoxin. Methylmercury can bio-accumulate more than a million-fold in the aquatic food chain (Schroeder and Munthe, 1998). Human consumption of fish with high concentrations of mercury increases the risk of adverse health effects including mental retardation, cerebral palsy, deafness, blindness, and dysarthria in those exposed in utero as well as sensory and motor impairment in exposed adults. According to the National Academy of Sciences, more than 60,000 children born each year may suffer learning disabilities due to mercury (National Research Council, 2000). The persistence of mercury and the bioaccumulation of toxic organic mercury compounds in the aquatic food chain has raised concern of the local and long-range atmospheric transport of mercury as the linkage between anthropogenic mercury emissions and high methylmercury concentrations in fish.

In February 2001, the United Nations Environment Programme (UNEP) Governing Council passed a resolution calling for "a global assessment of mercury and its compounds to be presented to the Governing Council at its session in 2003." This assessment will compile existing information on sources, concentrations, transport and transformation pathways, impacts, and control technologies and policies and present options for future actions by the Governing Council and Global Ministerial Environment Forum.

2.1.4 Persistent Organic Pollutants

The final category of pollutants to be considered here, Persistent Organic Pollutants (POPs), is made up of organic compounds that resist photolytic, chemical and biological degradation; have low solubility in water; and high solubility in lipids, or fats. These properties allow POPs to have a long lifetime in the environment, collect in biological tissue, and concentrate in organisms at the top of the food chain. Given these properties and the fact that these substances can often exhibit toxicity at relatively low concentrations, POPs can pose significant risks to the health of humans and ecosystems. Human health effects due to exposure to POPs may include reproductive and developmental abnormalities and increased risks of cancers. While a large number of substances have these general characteristics, attention has focused on a relatively small group of substances that have enjoyed wide commercial use, either as pesticides (e.g., DDT, Mirex) or industrial chemicals (e.g., PCBs, HCBs), or are released to the environment as byproducts of industrial processes (e.g., Dioxin). Many of these substances are subject to regulation in the U.S. and other industrialized countries. A number of substances, listed in Table 2.1, have been the subject of several international agreements that ban or severely restrict use or environmental release of these substances. For the chemical products on this list, substitutes are believed to exist for all except DDT. While largely banned in the U.S., DDT has a unique application as a malarial control agent, and its use for this purpose is not restricted under these agreements.

Table 2.1 Persistent Organic Pollutants addressed by International Agreements

Aldrin[1,2]	Hexachlorocyclobenzene (HCH) [1]
Chlordane [1,2]	Hexabromobiphenyl [1]
Chlordecone [1]	Hexachlorobenzene (HCB) [1,2]
Dichlorodiphenyltrichloroethane (DDT) [1,2]	Mirex [1,2]
Dieldrin [1,2]	Polycyclic biphenyls (PCB) [1,2]
Endrin [1,2]	Polycyclic aromatic hydrocarbons (PAHs) [1]
Heptachlor [1,2]	Toxaphene [1,2]
Polychloro Dibenzodioxins/furans (PCDD/Fs) [1,2]	

[1] Addressed in the 1998 Aarhus Protocol of the 1979 LRTAP Convention
[2] Addressed in the Stockholm Convention (expected to be signed May 2001)

2.2 International Agreements Related to Intercontinental Transport of Air Pollution

The international community strives to control transboundary transport of air pollution through a number of accords. The United States is a party to at least four different agreements and one pending agreement that address the intercontinental transport of air pollutants.[1] These five agreements, which are described in further detail in Appendix A, are, in chronological order:

- the 1979 Convention on Long Range Transboundary Air Pollution (LRTAP Convention)
- the 1985 Vienna Convention for Protection of the Ozone Layer and 1987 Montreal Protocol
- the 1991 Arctic Environmental Protection Strategy
- the 1992 United Nations Framework Convention on Climate Change
- the Stockholm Convention on Persistent Organic Pollutants (signing is planned for May, 2001)

Through these agreements, the United States government is committed to reducing the intercontinental transport of a number of air pollutants and their associated adverse environmental impacts. As our knowledge of intercontinental transport processes increases, it is likely that additional international agreements will be proposed and developed to address this type of transboundary pollution problem.

2.3 Information Needed to Support Decisionmaking

It is obvious from the discussion above that the long-range transport of air pollution is a complex and multi-faceted issue with significant consequences for human health and sensitive ecosystems. Clearly, transboundary, and even intercontinental, flows of pollutants already

[1]The United States has a number of bilateral and trilateral agreements with Canada and Mexico that address the transboundary transport of pollutants within North America.

contribute to a number of environmental problems, such as the deposition of persistent pollutants to water bodies. With increasing emissions associated with the global spread of industrialization, the contribution of these flows to environmental problems in the United States could become an obstacle to achieving our own domestic environmental goals.

The development of effective environmental policy related to intercontinental transport of air pollution requires an understanding of the factors that control the emission, transformation, distribution, and effects of long-lived air pollutants. The science needed to support such policy development falls into four broad areas and can be expressed in terms of a series of questions that need to be answered.

2.3.1 Source/receptor relationships – How does the pollution from one region influence the air quality of another region hundreds and thousands of kilometers away? Specific science questions include:

- What is the frequency of transport and the magnitude of impact of pollution (ozone, PM, mercury and POPs) from:
  - Africa to North America,
  - Africa to Southern Hemisphere,
  - North America to Atlantic and Europe,
  - Asia to remote Pacific and Western U. S., and
  - Eastern Europe and Asia to Alaska, Canada, and the Arctic?
- What is the contribution of Northern Hemisphere continental sources to the global/Northern Hemisphere ozone, PM, and mercury budgets?

2.3.2 Transport/transformation processes – What are the primary atmospheric processes that determine the concentration, composition, and distribution of pollution throughout the globe? Specific science questions include:

- How much NO_x is exported from the continents and what are the transport mechanisms responsible?
- What are the in-situ anthropogenic sources of NO_x in the remote troposphere (aircraft and ships) and their relative effectiveness in ozone formation?
- How much particulate matter is exported as a function of season from the continents and what are the transport mechanisms responsible?
- What are the sources (natural and anthropogenic), chemical composition and production mechanisms for aerosols in the remote troposphere (aircraft and ships)?
- What are the nature, magnitude, and spatial distribution of the changes in visibility of airborne chemicals transported into the remote marine atmosphere?
- On a seasonal basis, how far are gaseous and aerosol contaminants emitted from the continents over the Northern Hemisphere transported during their atmospheric lifetimes?
- How is the deposition of gaseous and aerosol contaminants influenced by meteorological and topographical conditions, and air-surface exchange processes?
- How do persistent climatological features, such as the Siberian High, the Aleutian Low, sub-tropical high-pressure cells, and the inter-tropical convergence zone (ITCZ) effect intercontinental transport and chemical transformation?

- How do topographically altered wind patterns, deep convection, and precipitation effect intercontinental transport and chemical transformation?
- What is the role of layered pollution in the remote marine troposphere in intercontinental transport and chemical transformation?
- What is the importance of chemical processing on aerosols?
- What is the role of nighttime/wintertime chemistry in intercontinental transport and chemical transformation?
- What is the fate of gaseous mercury during the polar sunrise?
- How is the re-emission of deposited mercury and POPs affected by meteorological and topographical conditions and air/water interface processes?

2.3.3 The role of "natural" emissions – To what extent do natural emissions contribute to the global pollution background? Specific science questions include:

- What is the contribution of biomass burning contaminants (CO, NO_x, VOCs, soot) emitted from Southeast Asia, Siberia, and North and Central America to continental pollution in the Northern Hemisphere?
- What is the significance of biomass burning aerosols in long-range chemical transport?
- What is the significance of dust-borne chemical transport?
- How much NO_x can be attributed to natural sources?
- How will the suspension, transport, and deposition of dust chemicals be altered by desertification exacerbated by human activities?
- How much mercury can be attributed to geogenic sources and biomass burning?

2.3.4 The effect of climate – How will climate variability and predicted long-term climate change influence the frequency and severity of long-range transport episodes and trends in regional air quality?

- How does climate variability (including seasonal variability) and predicted long-term climate change affect the natural emissions including:
  - VOC emissions from forests,
  - NO_x emissions from soils, and
  - fugitive dust from arid regions (deserts)?
- What is the variation of biomass burning contamination from year to year? How will climate change affect the frequency and severity of biomass burning?
- How do present-day ozone levels compare with those in pre-industrial times?
- How do these atmospheric contaminants in the oceanic regions affect regional and global climate?

3.0 Insights from Past Research

The study of intercontinental transport of air pollution is and has been a global effort with contributions from individual researchers and research institutions around the world. Most of the major field campaigns are international collaborations that bring together resources and capabilities from a variety of countries. A complete and comprehensive review of all of these efforts is clearly beyond the scope of this report. Rather, this report will look at intercontinental transport from a North American perspective. The report will focus on the impact of North American emissions on global air quality and, conversely, the impact of global emissions on air quality in North America. What follows is a brief overview of the science, highlighting the role of U.S. research, with the goal of identifying key knowledge and capability gaps.

3.1 Research Approach

The current understanding of the magnitude of intercontinental transport of air pollution and the underlying processes has resulted from a number of complementary approaches, each providing a different perspective and a unique contribution.

- ***Ground-based monitoring*** **–** The analysis of data from remote monitoring sites has provided valuable information on long-term trends in global pollution. Insights into the possible sources of measured pollution can be obtained through the use of air mass back trajectory analysis. The value of these sites is greatly enhanced when the surface-based measurements are augmented by regular measurements of vertical pollution profiles using instrumented aircraft, sondes, LIDARs etc.

- ***Intensive field campaigns*** **–** These studies, which use instrumented aircraft and surface platforms (ships and ground sites), have been carried out over the years by various international teams. The studies have been used to improve the understanding of atmospheric processes and to identify the influence of particular sources. In general, the individual studies have tended to focus on either gas-phase or heterogeneous processes.

- ***Model simulations*** **–** The last two decades have seen significant improvements in computer models that simulate atmospheric processes on a global scale. These chemical/transport models (CTMs) incorporate mathematical representations of the key processes that reflect current understanding. These models have proven to be invaluable tools for the design and execution of intensive field campaigns as well as for the analysis of data from both intensive and long-term measurement programs. They have also been used to forecast the impact of future emission and climate changes on distant air quality.

- ***Satellite observations*** **–** In many ways, satellites are the ideal tools to observe the global distribution of pollutants in the atmosphere. They provide unparalleled coverage, reaching areas of the globe that are difficult or impossible to study from the surface. These platforms are capable of measuring a rapidly growing list of compounds, and

techniques have been developed to provide information on vertical distributions in addition to the routine column measurements.

3.2 Research Coordination

U.S. federal research related to intercontinental transport is coordinated through two of the Committee on Environment and Natural Resources (CENR) subcommittees: the Air Quality Research Subcommittee and the Subcommittee on Global Change. The U.S. Global Change Research Program (USGCRP) serves as the umbrella organization for much of the research. "The USGCRP seeks to provide a sound scientific understanding of the human and natural forces that influence the Earth's climate system- and thus provide a sound scientific basis for national and international decisionmaking on global change issues. The USGCRP seeks to observe, understand, predict, and assess the critical natural and human-induced dynamic states and trends of the Earth's global environmental system across a wide range of time and space scales."[2]

Much of the U.S. research is coordinated with the international research community and their efforts through the International Global Atmospheric Chemistry Project (IGAC). IGAC is a core project of the International Geosphere – Biosphere Program (IGBP) that was established in response to the growing concern about the chemical changes in the global atmosphere and their potential impacts on humanity. The aims of IGAC are to:

- Develop a fundamental understanding of the processes that determine atmospheric composition.
- Understand the interactions between atmospheric chemical composition and biospheric and climatic processes.
- Predict the impact of natural and anthropogenic forcing of the chemical composition of the atmosphere.

At the inception of IGAC, it was recognized that the composition and chemistry of the atmosphere are dependent on climatic, ecological, geophysical, and anthropogenic variables. A systematic study of the atmosphere must be able to account for the complex interactions among all these variables. However, over the globe, these variables are strongly dependent on location. For these reasons, five major regions were defined as research foci: marine, tropical, polar, boreal and mid-latitude regions.

Recently, IGAC re-focused its structure into three main subject areas: biosphere-atmosphere exchange, photochemistry, and atmospheric aerosols. In addition, IGAC has moved away from regional concepts toward a more global perspective. In this context, it was natural to coordinate regional activities concerned with photochemistry within a single framework that has a global dimension and both gas-phase and particulate-phase science objectives. The new combined program is called Intercontinental Transport and Chemical Transformation (ITCT). As the name implies, the initial focus of ITCT is to investigate intercontinental transport of anthropogenic pollution and to determine the chemical transformation that occurs during this transport. An

[2] US Global Change Research Program web site, http://www.gcrio.org/ocp2001/

important goal of this research is to estimate how the transport of pollution from one continent can influence the air quality in another. The investigation will be initially focused in the Northern Hemisphere that contains most of the world landmasses, where most of the world's population resides, and where most of the anthropogenic pollution is generated.

3.3 Studies of Intercontinental Transport in the Northern Hemisphere

Atmospheric scientists have observed significant transport of natural and anthropogenic airborne material from Africa to North and South America, from Asia to North America, from North America to Europe, and from Europe and Asia to the Arctic. Some of this research is discussed in the following sections.

3.3.1 Africa to North America

Large quantities of Saharan dust are transported across the North Atlantic in distinct layers associated with the passage of frontal systems. Intense heating of the desert, particularly in the summer, forms a 5-6 km deep mixed layer over the desert known as the Saharan air layer (SAL). Strong pressure gradients cause winds that pick up soil dust particles and mix them throughout the SAL. These easterly moving systems carry the dust to the North African coast where the SAL rises above the marine mixed layer [Karyampudi et al., 2000]. The dust layer exhibits a distinct frontal boundary that can be seen in sharp gradients of humidity, temperature and dust concentration measured by aircraft and as cloud lines visible in satellite images (Figure 3.1). These fronts extend hundreds of km along the leading and southern edges of the systems.

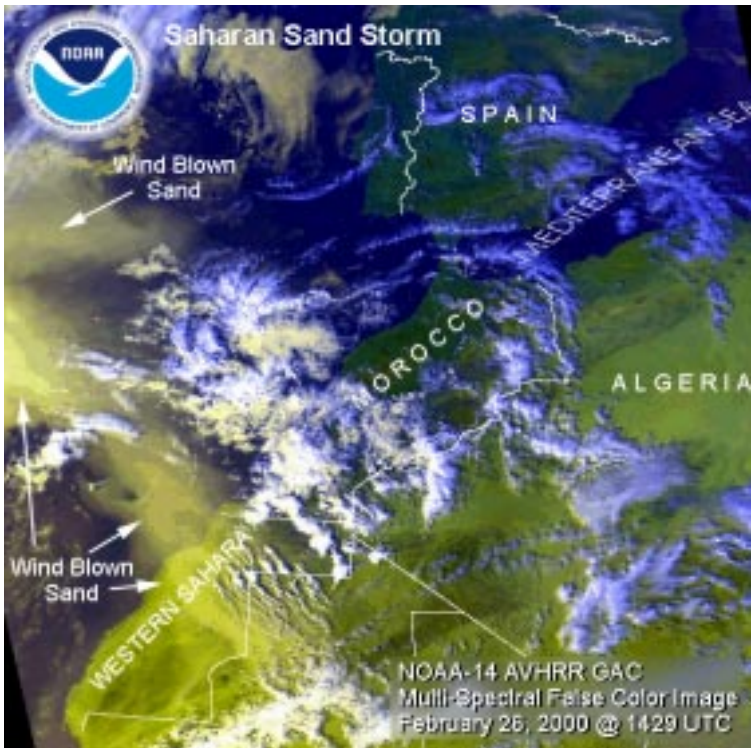

Figure 3.1 AVHRR satellite image showing a dense area of airborne dust flowing off the coast of western Africa.

Aerosol samples have been collected at a monitoring site in Miami during the last 23 years [Prospero, 1999]. Episodes when African dust is the primary component in these samples were observed when the site was under the influence of onshore winds. A large portion, 30 to 50%, of the African dust mass in these samples is in particles in the respirable size range of less than 2.5 mm. This dust affects large areas of the Eastern and Southern U. S. and has implications for

attainment of local PM standards. These frontal systems and the dust they transport may also be connected to the formation of tropical storms.

3.3.2 Africa to Southern Hemisphere

Biomass burning in Africa contributes large quantities of ozone to the atmosphere of the Southern Hemisphere [Fishman et al., 1991]. Ozone concentrations derived from satellite data and balloon borne ozone sondes show seasonal fluctuations of O_3 over the tropical Atlantic. Maximum O_3 values occur in the southern hemispheric winter and persist through the spring (July-October). The observations of high O_3 levels coincide with the African dry season when there is widespread biomass burning. The satellite observations show a seasonal plume of O_3 at tropical latitudes, over the Atlantic, transported west of the continent by the prevailing winds. At higher southern latitudes, a plume of O_3 has been observed extending from Africa eastward for 7500 km, almost reaching Australia. Elevated levels of CO and CH_4 correlated with this biomass burning and high O_3 are observed at sites throughout the Southern Hemisphere.

3.3.3 North America to Atlantic and Europe

There is a large concentration of pollution sources along the East Coast of North America. Ozone, ozone precursors, and particulate mater have been observed in the remote Atlantic and marine air at European ground stations. Particulate matter from Canadian forest fires has been observed in Greenland. One study found levels of ozone as high as 100 ppb in the free troposphere over Europe [Stohl et al., 1999]. The investigators concluded that the ozone was photochemically produced in the boundary layer over Eastern North America. They speculate that this polluted air mass was lifted and transported in a coherent stream by the warm airflow at the leading edge of a low pressure system known as a warm conveyor belt.

Other investigators have made direct observations of a similar mechanism over North America and the Atlantic. Using measurements of the chemical composition and physical state of air masses around mid latitude cyclones, they concluded that the air streams in these cyclones transport pollution from the continental boundary layer of North America to the troposphere over the North Atlantic [Cooper et al., 2000]. Their observations show that the warm air that precedes low pressure systems carries trace gases. As the warm air moves over the Atlantic, this air can be trapped over the water, locking the polluted air in the marine boundary layer. If, however, there is a sea breeze or a stationary cold front, the polluted air can rise over the marine boundary layer and form an isolated layer, generally less than 1 km thick, which is isolated from the marine boundary layer. Globally, most long-range pollution transport probably is transported by this mechanism and in these types of mid-tropospheric layers.

NARE - North Atlantic Regional Experiment

The *North Atlantic Regional Experiment* (NARE) was established by the International Global Atmospheric Chemistry (IGAC) project to study the chemical processes that are occurring in the remote marine environment of the North Atlantic. NARE planning meetings have been held in July 1989 in Norwich, England; September 1990 in Chamrousse, France; April 1991 in Boulder, Colorado; and April 1992 in Montreal, Canada to articulate the science objectives and to develop plans for future activities. This regional activity is investigating the processes that determine the fate of continental emissions as well as the processes that deliver these emitted compounds and

their oxidation products to the remote free troposphere. In the course of these studies, NARE has addressed intercomparisons, calibrations, shared standards, and protocol for data sharing and archiving.

The initial focus of NARE has been to determine the impact of emissions of pollutants that lead to the production of tropospheric ozone. The objective of NARE is to investigate the chemical and transport processes that shape the distribution of ozone over the North Atlantic and to estimate the impact of human-influenced emissions from North America, Europe, and Eurasia on the production of tropospheric ozone and related parameters on a hemispheric scale. The research needed to meet this objective has involved measurements of the distribution and trends of ozone and related parameters in the North Atlantic region, determination of the sources of this ozone and the elucidation of the processes responsible for ozone formation.

The goals of the NARE program are:

- To assess the long range transport of photochemically active compounds and/or their products and determine the impact of this transport on hemispheric air quality.
- To ascertain the effect of these compounds on the oxidative properties and radiation balance of the atmosphere.
- To estimate the amounts of these compounds that are deposited in this marine environment and to determine the impact of this deposition on surface sea-water chemistry marine biological processes.

A series of intensive field experiments (listed below) have been conducted, employing heavily-instrumented research aircraft from the U.S., Canada, and the U.K.

- Summer of 1993
- Winter (1993-1994)
- Winter/Spring (1995-1997)

Chemical and meteorological measurements have been conducted at a number of ground stations over a period of several years to provide context for the field intensives. The routine measurements have been augmented during intensive periods to compliment the airborne measurements. NARE surface sites include the following:

- Cape Sable, Nova Scotia, Canada
- Sable Island, Nova Scotia, Canada
- Cape Pine, Newfoundland, Canada
- Cape Norman, Newfoundland, Canada
- Mace Head, Ireland
- St. Barbara, Terceira, Azores, Portugal

NARE research involves scientists from several countries, including Canada, France, Germany, the United Kingdom, and the United States. Support for the U.S. participation has come from several federal agencies: National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), Department of Energy (DOE), and Environmental Protection Agency (EPA). The research team includes a large number of university scientists, both from the U.S. and abroad.

Some of the more significant findings from the NARE experiments are:

1. Ozone from North America dominates ozone distribution in North Atlantic during the summer

Surface measurements have shown that ozone pollution from North America is easily detectable 1500 km downwind from the North American source region [Parrish et al., 1993]. Subsequently, surface measurements located 3000 km downwind from the sources established that North American pollution enhances O_3 levels in the central North Atlantic, in the spring [Parrish et al., 1998].

2. Mechanism for the transport of North America pollution to the North Atlantic

Meteorological measurements show that during the summer, inversions can effectively isolate the marine boundary layer from the lower midtroposphere aloft, where the majority of the pollutants are transported in highly stratified layers [Angevine et al., 1996].

3. The role that fronts play in transporting continental pollution

The primary direction for transport of North American pollution to the North Atlantic in the summertime is toward the northeast. In general terms, this can be viewed as the result of the prevailing westerly winds developing a southerly component as air masses come under the influence of the clockwise circulation of the Bermuda-Azores high. However, warm sector flow ahead of advancing cold fronts has been identified as the most important process for the transport of pollution from the urbanized U.S. East Coast to the North Atlantic [Merrill and Moody, 1996; Berkowitz et al., 1996]. This mechanism provides a means to rapidly and effectively transport large amounts of relatively short-lived pollution over long distances.

4. The role that the oxides of nitrogen (NO_x) and volatile organic compounds (VOCs) play in the O_3 budget of the North Atlantic troposphere

In the remote, marine troposphere, the concentrations of carbon monoxide (CO) and methane (CH_4) are adequate to support significant photochemical ozone formation. However, whether this photochemistry produces rather than destroys ozone is determined by the amount of NO_x available [Fehsenfeld and Liu, 1993].

5. The seasonal variation of the anthropogenic influence on the tropospheric O_3 budget

All of the NARE summertime studies in the western North Atlantic have found a positive correlation between CO and O_3. This positive correlation demonstrates that anthropogenic pollution produces ozone in the summer, as discussed above. However, in the wintertime a negative correlation between CO and O_3 is observed, both at surface sites [Parrish, 1993] and in the free troposphere [Parrish et al., 1998; 2000a]. This negative correlation demonstrates that anthropogenic pollution provides a sink for ozone in the winter.

AEROCE - Atmosphere-Ocean Chemistry Experiment

AEROCE was a comprehensive multi-disciplinary and multi-institutional research program that focused on a number of aspects of the atmospheric chemistry over the North Atlantic Ocean. AEROCE began in 1988 and ended in 1998. A major objective was to gauge the impact of anthropogenic sources on the chemical and physical properties of the atmosphere, to assess the consequences of the perturbations on natural processes including climate, and, through the use of models, to predict the longer-term effects.

The AEROCE program followed two sampling strategies: (1) a continuous measurement program at stations including Bermuda, Barbados and Ireland that produced a climatological data set for selected trace gases (such as O_3 and CO), the chemical and physical characteristics of aerosols and precipitation, and associated radiative effects; (2) intensive field programs that incorporated a much more extensive measurement protocol of aerosols and gases. These field programs included observations made from the Wyoming Kingair aircraft, making possible the identification of layers containing pollutants such as CO, NO_x, volatile organic compounds (VOC's) and aerosol particles. The complex chemical signals (interleaved layers) could only be understood in the context of the meteorological situation diagnosed with three-dimensional trajectories and animation of satellite image loops.

Major Findings from AEROCE included new insights on:

1. *Chemistry/air quality and meteorology*
   - AEROCE results have made a significant contribution to our understanding of the chemistry of midlatitude cyclones in the North Atlantic region that is increasingly impacted by human activity. AEROCE has demonstrated that the periodicity and pulsation of the fluxes of many measured chemical species can only be meaningfully assessed by high frequency, if not real time, sampling strategies.
   - The seasonal cycles of the concentrations of pollution-derived elements in aerosols at Bermuda were found to be mainly driven by transport and not strongly related to variations in source emissions. Spring maxima in pollutants were caused by rapid transport from North America while fall maxima were the result of air that was slowly transported from North America by large high-pressure systems that stagnated over the lower Mid-Atlantic States.
   - The natural process of tropopause folding brings ozone down from the upper atmosphere. Injection of ozone from the upper troposphere and lower stratosphere is more regular and stronger than previously thought. Pollution over North America produces ozone that can be transported eastward. In AEROCE these two sources could be distinguished. Linked frontal systems result in the transport of both natural ozone and continental pollutants to the free troposphere and Marine Boundary Layer over the North Atlantic Ocean.
   - Showed the impact of long range transport on air quality in the Southeastern and Gulf Coast States. During the summer months, African dust is a major sub-2.5 μm diameter aerosol in this region. This has important implications for air-quality enforcement. Although African dust in itself will not cause an exceedance of the new standard, dust in concert with local pollution aerosols could well exceed the new standards. The high concentrations of sub-2.5 μm African dust in the southeastern United States could have an impact on respiratory health in the Southeastern States.
2. *Radiation and climate*
   - AEROCE has shown that anthropogenic emissions, through increased ozone concentrations and aerosol loading, have a major impact on the radiative properties of the of the atmosphere over the remote North Atlantic Ocean and thus on climate forcing.
   - Mineral dust is the dominant light scattering aerosol over a large region of the tropical and subtropical North Atlantic.
   - Long-range dust transport is linked to large-scale climate processes. Dust concentrations vary greatly from year to year. They increase sharply (a factor of 3-4) during periods of

severe drought. The long-term record at Barbados has been shown to be highly correlated with the North Atlantic Oscillation (NAO).

- The linking of the AEROCE mineral dust record to the absorbing aerosol product from the TOMS satellite data has shown that the major dust sources are associated with topographical lows in arid regions. Dust does not necessarily imply arid conditions; the aridity must follow upon a relatively recent (in a geological sense) pluvial period.

3. *Biogeochemical cycles*

- AEROCE has provided a basis set for the parameterization of current and future atmospheric chemical models and biogeochemical budgets of the NAO.
- AEROCE provided estimates of anthropogenic impacts on the atmospheric S and N cycles. For example, in the sulfur cycle, it was shown that human activities accounted for a maximum of 85-90% of the sulfate aerosol (multi-year average in the westerly winds at Mace Head, Ireland). Nitrogen inputs to the surface ocean via wet deposition can lead to episodic enhancements in primary production.
- Long-term trends in pollutant transport were documented. At Bermuda, the AEROCE data suggest that there has not been a substantial change in the concentration of (aerosol) nonsea-salt sulfate and nitrate in aerosols and precipitation over the period 1988-1998, although a slight downward trend is suggested. Over this time period the SO_2 emissions in the US have decreased about 15-20%. Such a small change would not be readily discernable because of meteorological variability. In contrast, the annual-mean aerosol lead concentrations decreased by an order of magnitude since the 1970s (based on early measurements on Bermuda) and a factor of four since the 1980s during AEROCE. Similar changes in lead concentrations were observed in seawater from the North Atlantic.
- Atmospheric transport can be linked to water column processes. Annual variations in the sediment trap fluxes in the Sargosso Sea were linked to changes in the atmospheric transport efficiency from source regions in Africa as opposed to changes in the strengths of the dust sources. The hypothesis that African dust has dramatically impacted the nitrogen nutrient cycle in the central North Atlantic has been developed. The large temporal-spatial variability of African dust could provide a strong modulation to N-nutrient production budgets in the Atlantic. Also, the iron associated with the dust serves as an essential micronutrient.

3.3.4 Asia to remote Pacific and Western U. S.

Mauna Loa Observatory

The Mauna Loa Observatory is located in the middle of the Pacific on the island of Hawaii. The observatory site is on the Mauna Loa Volcano at an elevation of 3400 m and is generally above the marine boundary layer. Investigators routinely see evidence of long range transport of natural and anthropogenic aerosols and trace gases originating over Asia at this site. Over the past two decades they have seen 6 to 26 springtime Asian dust episodes per year. These episodes last from a few hours to a week. Trajectory calculations indicate the dust takes 5 to 10 days to reach Mauna Loa from the Asian continent and travels a distance of approximately 10,000 km. Observations of elevated levels of anthropogenic trace gases such as CH_4, CO_2, sulfate, and black carbon are coincident with the dust episodes. In addition to mineral dust from soil, the analyses

show that about half the material in the aerosol samples is anthropogenic. The species they have detected include sulfur, carbon black, and enhanced trace metals. They also observe anthropogenic trace gas pollution events in the absence of Asian dust and during other seasons. Trajectory analyses for these events indicate that the likely sources of the trace gases are in southern Asia. Investigators instituted weekly airborne flask sampling profiles upwind of the Hawaiian Islands in June 1999. Most of these profiles reveal elevated layers of pollution up to several km thick often occurring above the marine boundary layer. Trajectory analyses indicate the pollution originates in south Asia and takes approximately 10 day to reach Hawaii [Schnell, 2000].

North American Observations

Asian pollution has been observed off the west coast of the United States. Radon measurements made in the early eighties have shown events where Asian continental air is transported to the west coast of North America in approximately three days [Kritz et al., 1990]. The investigators in this study proposed a transport mechanism where radon rich surface air is carried to the free troposphere above the Asian continent in the convection cells of thunderstorms. Once in the troposphere it is transported rapidly eastward. Other investigators conducted an experiment over the open ocean off the northwest coast of the United States during 3-12 May 1985 [Andreae, et al., 1988]. They collected samples in post-frontal maritime air masses and measured natural and anthropogenic sulfur and nitrogen compounds and radon decay products. The radon decay products and trajectory analysis suggested these air masses had been transported from Asia in 4-8 days. Nonsea-salt sulfate concentrations decreased with altitude in the boundary layer and then increased again in the free troposphere. They concluded that the sulfate in the free troposphere is dominated by transport of anthropogenic pollution from Asia and that long-range transport at mid-tropospheric levels is an important mechanism for global scale transport of pollution. Dust storms have been tracked by satellite from Asia to the west coast of the United States where the dust plume was sampled over California [Perry et al., 1999]. Two separate layers of dust were detected, one between the altitude of 6 and 10 km and another centered at an altitude of 3 km. Calculated trajectories of this plume showed this plume originating over Asia and were verified by satellite data.

Measurements of anthropogenic Asian pollution and dust pollution have also been made at land sites in the continental United States and Alaska. Point Arena is a coastal measurement site in Northern California, 180 km north of San Francisco, that is dominated by flow off the Pacific. Investigators measured light hydrocarbons, ozone, peroxyacetylnitrate (PAN), HNO_3, NO_{3^-}, NO_x, NO_y, and meteorological parameters for 10 days in late April and early May of 1985. The chemical composition and trajectory analysis suggested that the observed anthropogneic species originated from emissions in Asia and that the Asian pollution was transported at high altitudes [Parrish et al. 1992]. Similar observations were made at the Cheeka Peak observation site in NW Washington State [Jaffe et al., 1999]. During Observations made in March and April of 1997 CO, O_3, PAN, nitrate, radon, aerosols and NMHCs were detected that were attributed to Asian emissions using analysis of radon decay produces and trajectory analysis.

Pacific Exploratory Mission

The Pacific Exploratory Mission (PEM) is a series of field experiments designed to determine the extent, impact, and mechanisms of pollution transport from the Asian continent. PEM West A took place during September-October 1991 [Hoell et al., 1996]. PEM West B took place in February and March 1994 and coincided with the time of maximum impact of Asian outflow on the Pacific Rim region [Hoell et al., 1997]. PEM Tropics took place in September-October 1996. Four important findings from the PEM program were:

- During the winter and early spring the meso-scale meteorology results in strong rapid transport from the Asian continent to the remote Pacific and North America.
- Chemical composition of tropospheric air throughout the Pacific Rim region is influenced by Asian outflow.
- Long-range pollution transport occurs primarily in coherent layers in the free troposphere.
- Pollution transport to the free troposphere shows evidence of occurring through mechanisms involving vertical convection in humid air.

Two important meteorological features influence atmospheric transport of pollution from Asia. These are the semi-permanent subtropical high over the Pacific, and the resulting Japan jet. These features exhibit strong seasonal characteristics. During the winter and spring, the period covered by the PEM West B campaign, the high pressure system is located over the central North Pacific and the Japan jet and results in strong westerly flow from Asia at all coastal locations north of about 20^{o} N. The high is displaced eastward and the wind speeds decrease during other times of the year. During these periods, the region under the influence of the jet moves to areas north of about 40^{o}N. The late summer and early fall, the time of PEM West A, is also a period of enhanced convection and vertical mixing and the Asian offshore flow is influenced by cyclones, some of typhoon strength, which disrupt established flow patterns and enhance large scale vertical mixing.

Comparison of the chemical composition of air sampled in similar locations during the two PEM West programs reveals seasonal differences in transport. The levels of anthropogenic trace species measured near the Asian coast during PEM West B (winter/spring) were 0.1 to 2 times higher than in similar locations during PEM West A (summer/fall). However, the chemical ratios of these species were similar, indicating that the degree of photochemical processing of pollution in the two seasons was approximately the same. At sites thousands of kilometers from the coast, both the concentrations and chemical ratios were substantially larger in PEM West B compared to PEM West A. This implies that transport is faster and more direct in the winter/spring regime. Transport velocities are expected to be 2 to 3 times higher in the winter than the fall. The trace species composition of these air masses did not show evidence of significant photochemical aging because of rapid transport time. Samples collected off the West Coast of the United States in PEM West B exhibited sizable influences from Asian outflow at all altitudes. Investigators determined that air masses sampled off the United States coast were transported from Asia in 3 days. These data show that the magnitude and long-range impact of Asian outflow on United States is significant [Gregory et al., 1997].

In both PEM West A and B a similar distribution of anthropogenic pollutants was observed at altitudes of 8-10 km. Combustion-derived species were detected while water-soluble trace species and aerosols were depleted. This composition suggests a mechanism in which ground-level emissions are lofted to the upper troposphere by wet, convective systems that strip water-soluble components. This vertical convective transport was followed by westerly advection and seems to be a process that occurs throughout the year [Talbot et al., 1997].

The observations during PEM Tropics showed enhanced concentrations of CO, hydrocarbons, and sometimes ozone in coherent layers north of 15^{o} N. Two distinct types of layers were observed. In the marine boundary layer, exhibited CO and other evidence of anthropogenic input and trajectories analysis showed the pollution layers were from Asia or further upwind. No biomass-burning signature was detected. The layers observed above 3 km were different in character. CO correlated with methylene chloride. This correlation is evidence of input from biomass burning. Trajectories calculated for these layers indicate the air masses originated south of 30^{o}N. There was also some evidence of possible contributions to ozone and PAN levels from Europe or the Middle East [Logan 2000].

In all three PEM missions there were observations of significant layers of pollution both in the boundary layer and the free troposphere. The thickness of the layers was on the order of 1 km and they had a horizontal spread on the order of 1000 km. There were observations of stratospheric air, sometimes mixed with trapped pollution. Stratospheric intrusion creates stabilized layers that trap buoyant plumes. Buoyant plumes can be forced to spread horizontally. These layers have an important effect on the thermal structure of the atmosphere. Dry subsiding air is stabilized by differences in radiative cooling. There are higher water vapor concentrations at the bottom of these layers, which causes a significantly greater radiative cooling at the bottom of the layer than at the top. Layers transported in the free troposphere will eventually be brought to the boundary layer by large-scale sinking motions in anti-cyclonic regions [Stoller et al., 1999].

PHOBEA

The recently conducted Photochemical Ozone Budget of the Eastern North Pacific Atmosphere (PHOBEA) aircraft campaign off the northwest coast of the United States in April-May 1999 (http://weber.u.washington.edu/~djaffe/phobea/) revealed layers of high ozone and aerosols transported across the north Pacific from the Asian continent.

Modeling

Several groups have used global 3-D Chemical Transport Models to estimate the current and future impact of Asian emissions on U.S. air quality. Berntsen et al. (1999) were able to reproduce the observed enhancements in CO and PAN in the Northwest U.S., and indicated that the ozone over the western U.S. was also enhanced. Other model simulations [Jacob et al., 1999] appear to support this conclusion and, also, indicate that significant enhancements in the average ozone concentration over the Western (2-6 ppb) and Eastern (1-3 ppb) United States might occur if Asian emissions of ozone precursors are significantly increased. Asian emissions of the ozone precursor NO_x are expected to grow two- or three-fold in the next several decades. The period of maximum impact was predicted to be April-June. Yienger et al. (2000) used a CTM to estimate

the Asian contribution to ambient ozone arriving over central California for 1990 and projected 2020 NO_x emission levels. The model predicts that the Asian contribution to surface ozone in 1990 will be a modest 5-6 ppb ozone during late spring and summer but will jump to 10-20 ppb by the year 2020. This may be enough to push some areas in the U.S. over the threshold of non-compliance. The Asian signal is much stronger aloft, and it is typically subsidence from this reservoir that maintains the Asian pollution signal in the boundary layer.

The NOAA CTM has been shown to be capable of simulating the frequency, magnitude, and dynamic characteristics of episodic CO transport to North America from Asia (Figure 3.2).

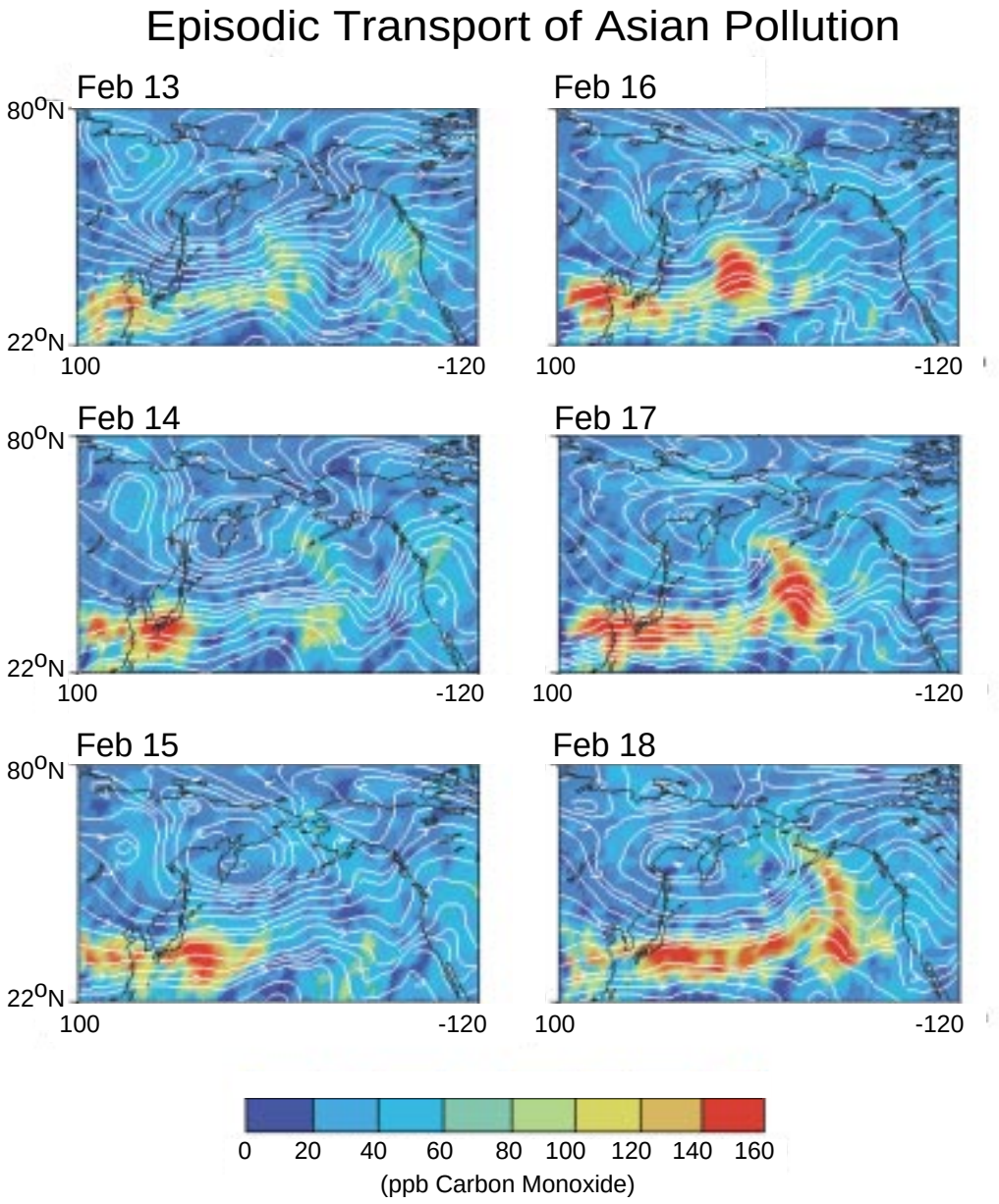

Figure 3.2 This figure presents 6 daily snapshots (model simulations) of CO that was emitted in Asia and, after being lifted to the middle of the troposphere [~500mb], is now being transported over the Pacific Ocean toward the U.S. by synoptic weather patterns [Yienger et al, 2000].

In addition to supporting the development of comprehensive Eulerian models, the EPA has also funded analyses of forward and backward trajectories involved in intercontinental transport. Backward trajectories are useful for indicating the source regions that are likely to influence a given receptor location. Figure 3.3 shows the probability of an air mass traveling from a source region to three West Coast receptor sites derived using backward trajectory analyses. Forward trajectories are useful for describing the meteorological processes that entrain pollutants aloft, enabling intercontinental scale transport. Figure 3.4 shows the output of a 3-D inert tracer simulation using the MAQSIP model to simulate the transport of emissions from the Gobi Desert across the Pacific [Hanna et al., 2000].

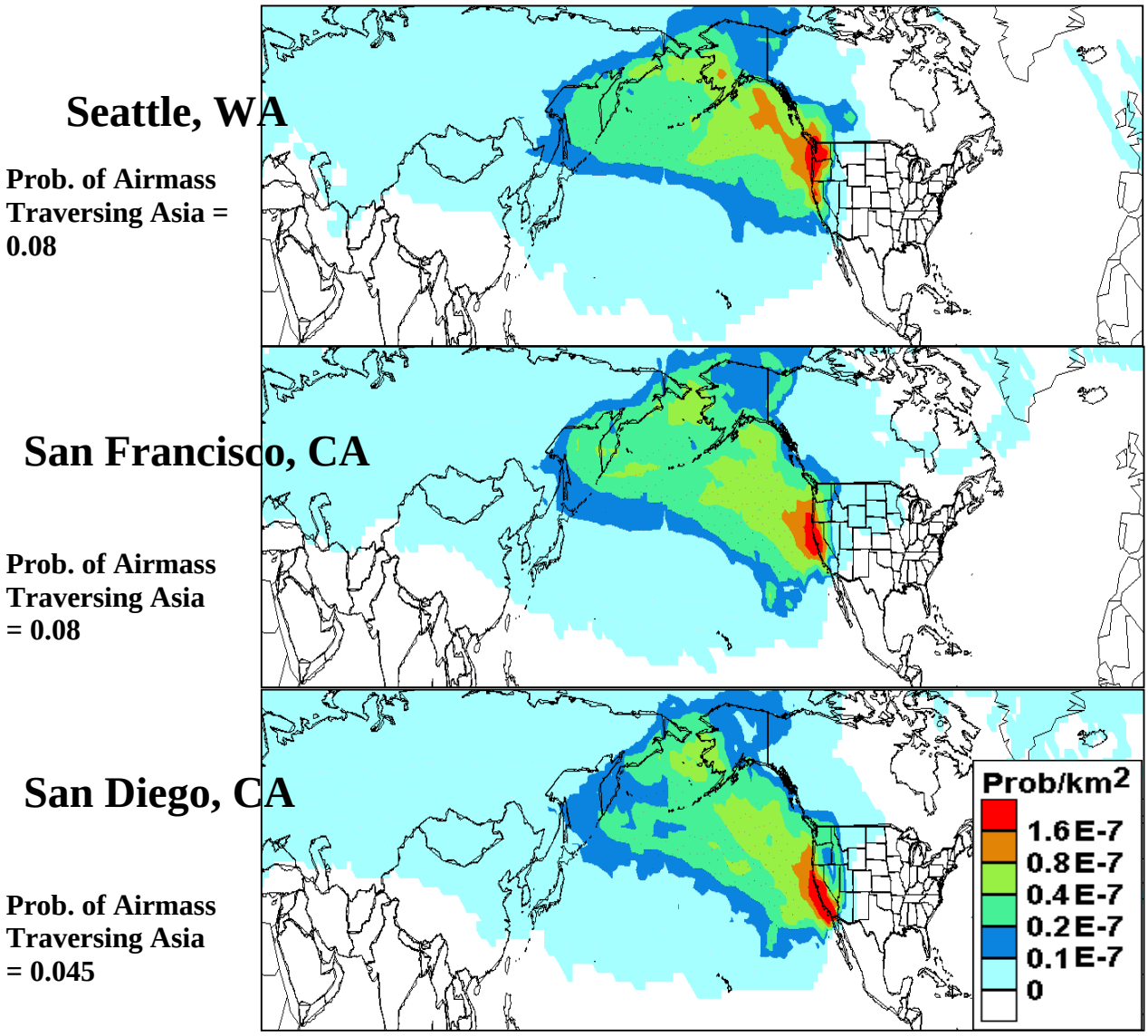

Figure 3.3 Probabilities of source regions for air masses reaching West Coast receptor sites produced using backward trajectory analyses. [Husar and Schichtel, 2000]

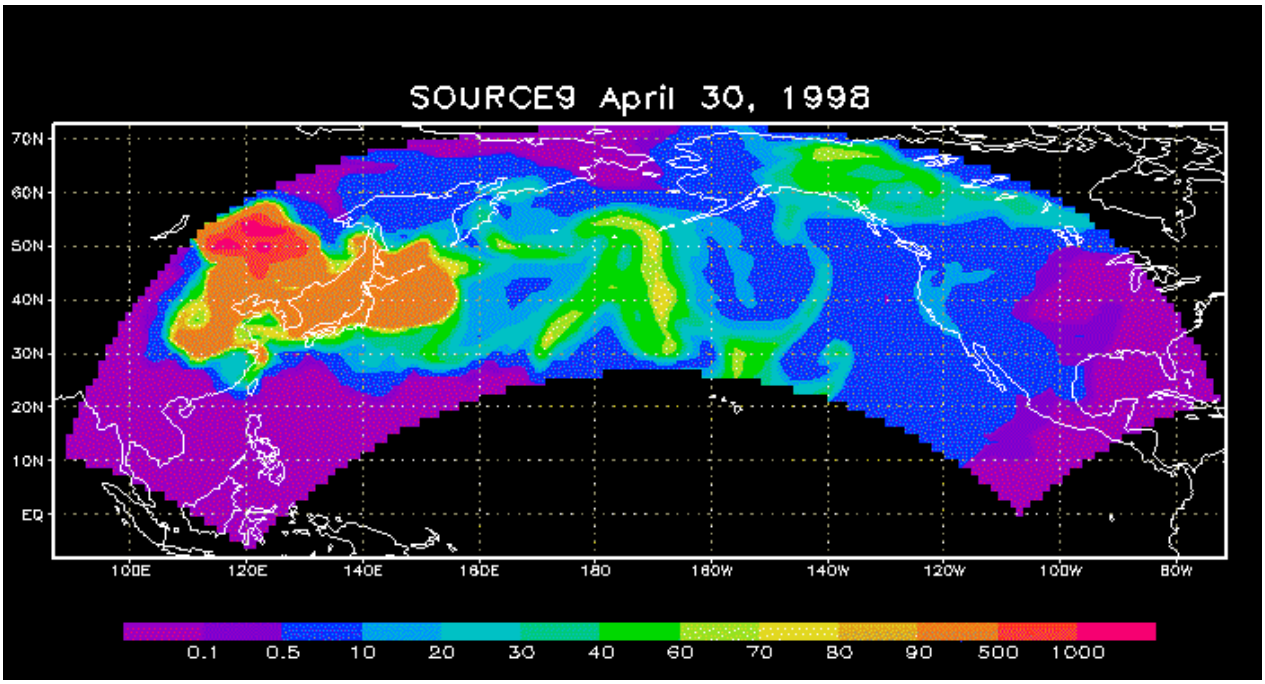

Figure 3.4 Surface layer concentrations of an inert tracer emitted in Asia predicted after 15 days of simulation [Hanna *et al*., 2000].

3.3.5 Eastern Europe and Asia to Alaska, Canada, and Arctic

Arctic Gas And Aerosol Sampling Program (1982-1992)

The Arctic Gas and Aerosol Sampling Program (AGASP) was a decade-long University of Colorado/National Oceanic and Atmospheric Administration program studying the origins, nature and climatic effects of Arctic haze [Schnell, 1984]. At the initiation of the project in 1982, the haze observed from December to May each year was thought to be local air pollution or dust from the Gobi desert. Using three well-instrumented aircraft flying from bases in Alaska, Greenland, Canada and Norway in the springs of 1983, 1986, 1989, and 1992, it was established that the Arctic haze consisted of high concentrations of anthropogenic gases and aerosols from Europe and the Soviet Union that flowed into and stagnated in the Arctic basin north of the polar front. On some occasions, this highly polluted region covered an area 2-4 times the area of the United States.

The Arctic haze was transported in visually distinct layers throughout the troposphere. In one case, six distinct layers of air pollution of differing characteristics were measured above the Barrow, Alaska Atmospheric Baseline Observatory. All of these pollution layers had traveled at least 8,000-10,000 km from their source regions in Eastern Europe/Russia. On some flights out of Alaska it was possible to determine the outlines of separate, distinct smoke plumes (probably from large coal fired power plants) that had traveled for two weeks and at least 8000 km without mixing or diluting appreciably.

Some of the more notable findings of the AGASP program are:

- Arctic haze is air pollution from Eastern and Western Europe that inundates the Arctic basin during the winter and spring traveling up to 10,000 km.
- This pollution may be found throughout the troposphere in concentrations equal to or exceeding the annual average pollution levels measured in polluted urban areas in the United States.
- The concentration of the pollution aloft is generally 2-4 times the concentration measured at the surface.
- Black carbon (soot) concentrations above Barrow, Alaska can exceed the annual averages measured in the Denver Brown Cloud.
- Heating rates in the haze were measured at up to 0.2 $^{0}Kday^{-1}$ and spectral optical depths of 2 in distinct layers.
- Complete tropospheric ozone destruction beneath the Arctic boundary layer across the Arctic basin was discovered and subsequently shown to be a halogen-mediated reaction.

At the NOAA long-term monitoring site at Barrow Alaska, it has been recently documented that the incidence of Arctic Haze (air pollution from Western and Eastern Europe) has decreased by 50% over recent years.

AMAP - Arctic Monitoring and Assessment Program

The Arctic Monitoring and Assessment Program (AMAP) began in 1991 under the international Arctic Environmental Protection Strategy (see Appendix A) and in 1996 became one of five working groups under the Arctic Council (see http://www.arctic-council.org/). The first phase of AMAP, which ran from 1991 to 1996, was focused on the development of an assessment of the concentrations and effects of selected anthropogenic pollutants in Arctic ecosystems and communities. This assessment, which was published first on paper in 1998 and on CD-ROM in 2000 [AMAP, 2000], contains a number of important conclusions regarding the impact of intercontinental transport of pollutants on the Arctic:

- Over much of the Arctic, the levels of POPs cannot be related to known use and/or releases from potential sources within the Arctic and can only be explained by long-range transport from lower latitudes.
- Of the heavy metal contamination in the Arctic, industrial sources in Europe and North America account for up to one-third of the deposition, with maximum input in winter.
- Sulfur and nitrogen compounds from sources associated with industries, energy production and transport in areas remote from the Arctic result in low but widespread levels of these contaminants throughout the Arctic.
- Regulatory actions in Europe and North America are reducing the sources of some POPs, heavy metals, sulfur and nitrogen contaminants.

The second phase of AMAP is focused on the development of several assessment reports on specific pollution issues. The U.S. government has responsibility for the development of reports on the environmental effects of climate change (joint lead with Norway), ultraviolet radiation, and heavy metals. As part of the planning effort for the heavy metals assessment, the EPA hosted an international workshop on "Heavy Metals in the Arctic" in Alaska in 1999 [AMAP, 1999]. Currently, EPA is developing a database for the Phase II assessment and will hold a second international workshop on "Heavy Metals in the Arctic" in Virginia in June, 2001.

3.4 Biomass burning

Biomass burning on a wide scale causes significant regional pollution, often with deleterious impacts on the health and safety of the local population. On a global scale, biomass burning may have significant impacts on atmospheric chemistry and global climate. Loading of the atmosphere with nitrogen oxides (NO_x = NO+NO_2), carbon monoxide (CO), black and organic carbon, mineral ash, and volatile organic compounds, in addition to greenhouse gases such as nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), contributes to air pollution, global warming, and acid rain.

Biomass fires are the result of both human-influenced and natural processes. Fire-management practices, particularly in the tropical and subtropical regions, are one of the most significant contributors to worldwide emissions from biomass fires. With a growing population, the demand for land use is increasing, and the challenge of assessing the role of biomass burning in atmospheric chemistry, climate, and terrestrial ecology is becoming increasingly important. However, natural wildfires that result from lightning strikes can also be important. For example, Wotawa and Trainer, 2000 have estimated that, on average, emissions from fires in the boreal forests of North America contribute approximately 17% to U. S. carbon monoxide emission annually. Particulate material from these fires has been seen as far away as Greenland [Currie, et al., 1998]. These "wildfires" are modulated by regional climate variability and are most prevalent during periods of decreased precipitation.

3.5 Measurement Methods – Development and Testing

Our understanding of the atmospheric processes responsible for intercontinental transport is dependent upon, and in some cases limited by, the ability to accurately characterize the state of the atmosphere in terms of chemical composition and physical characteristics. Many of the measurement programs described above included a measurement development and/or evaluation component that has resulted in many significant improvements. NASA organized a series of measurement programs to specifically address this issue. The Chemical Instrument Test and Evaluation missions, CITE-1 (1983, 1984), CITE-2 (1986) and CITE-3 (1989) provided rigorous, double-blind instrument intercomparisons for measurements of odd nitrogen and sulfur species in several ecosystems. These missions established the scientific validity of the measurements and the database.

3.6 Summary of Major Field Campaigns

The insights presented in this section come from a number of intensive field campaigns and long-term monitoring efforts conducted by research organizations throughout the world. Many of the more significant U.S. research programs have been described in the preceding sections. These are summarized below in Table 3.1 and Figure 3.5.

Table 3.1 Field campaigns related to intercontinental transport of air pollution

Field Mission	(Locale)	OBJECTIVES
ABLE-1	Barbados	Boundary layer chemistry and dynamics - precursor
ABLE-2A	Brazil	Boundary layer study of $CO/O_3/NO_x$ - dry season
ABLE-2B	Brazil	Boundary layer study of $CO/O_3/NO_x$ - wet season
ABLE-3A	Alaska	Photochemistry and biogenic sources of tropospheric gases
ABLE-3B	Canada	Photochemistry and biogenic sources of tropospheric gases
AEROCE	North Atlantic	Assess impacts of anthropogenic pollution on atmospheric processes
AGASP	Remote European Arctic	Arctic haze
AMAP	Arctic	Assessment of pollution impacts on Arctic ecosystems
CITE-2	West Coast-U.S.	Test and intercomparisons: nitrogen budget experiments
CITE-3	Tropical Atlantic	Intercomparisons of sulfur budget experiments
NARE	North Atlantic	Transport and photochemistry in continental outflow
PEM-West-A	Western Pacific	Photochemistry and transport of gases and aerosols
PEM-West-B	Western Pacific	Photochemistry and transport of gases and aerosols
PEM-Tropics A	South Central Tropical Pacific	Ozone and sulfur photochemistry/transport of gases and aerosols
PEM-Tropics B	Central and Eastern Tropical Pacific	Ozone and sulfur photochemistry/transport of gases and aerosols
PHOBEA	Eastern North Pacific	Photochemistry in marine and coastal air
TRACE-A	Tropical Atlantic	Transport and photochemistry of ozone in the tropics
TRACE-P	Western Pacific	Transport and photochemistry of gases and aerosols

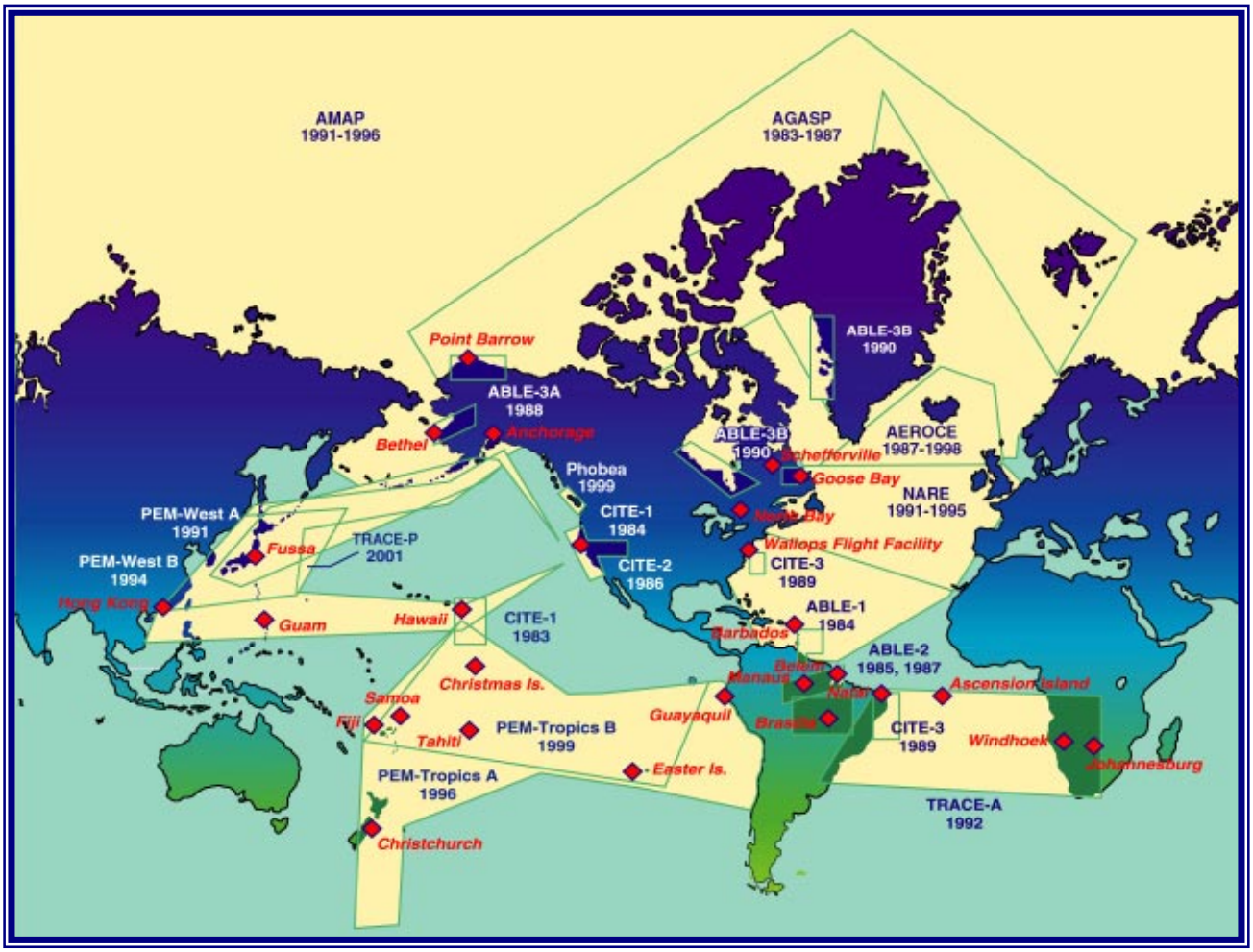

Figure 3.5 Major U.S. field campaigns related to intercontinental transport of air pollution.

4.0 Current and Proposed U.S. Federal Research

Many of the research programs described in the previous section are ongoing, with strong collaborations among the U.S. federal agencies, the private sector, and the international research community. Some of the past efforts are being refocused under IGAC's ITCT research program. What follows is a brief description of programmatic objectives and research activities (ongoing and planned) for each agency involved in research on intercontinental transport of air pollution.

4.1 National Aeronautics and Space Administration (NASA)

NASA provides nearly continuous global observations of tracers of long-range transport through the space-based missions of its Earth Science Enterprise. The purpose of NASA's Earth science research is to observe the global Earth environment, to understand the mechanisms that underlie natural and human-induced environmental changes in the global environment, and to identify consequences for life on Earth. NASA's Earth science research contributions emphasize large regional-to global-scale phenomena, seasonal and longer period responses leading to irreversible changes, processes with significant impacts or large uncertainties, and capability to model the present state and variations of the global environment. NASA tries to continually infuse new sensor and platform technology into observational studies, and to expand the capability and precision of modeling efforts.

The instruments flown in NASA's space-based missions typically have multi-species measurement capabilities and multiple science objectives. No single observing system (ground, aircraft-based, or space-based in any orbit) addresses all time and space scales that are important to tropospheric chemistry and long-range transport. Consequently, an integrated observing strategy brings the greatest understanding of the complex processes that occur in the troposphere.

4.1.1 Ozone and Aerosol Transport

Several space-based sensors observe the transport of ozone in the atmosphere. NASA's Total Ozone Mapping Spectrometer (TOMS) has provided the global total column (single vertical layer) ozone measurements since 1978 from various satellites approximately once per day over the total globe at about 40 x 40 km^2 horizontal resolution. The ozone distribution is a product of the analysis of spectral radiance at ultraviolet wavelengths. Due to a satellite failure, a gap from 1994-1996 exists in the measurements, but TOMS is currently operational. Analytical techniques have been developed to separate out the stratospheric component of the total column of ozone, and studies of the "tropospheric residual" have provided insight into the effects of meteorological conditions (wind systems, weather fronts, and the jet stream) on long-range transport of pollutants [Fishman and Balok, 1999].

Additional vertical definition in the ozone measurements is expected from the Tropospheric Emission Spectrometer (TES), a high-spectral-resolution infrared-imaging Fourier transform spectrometer on NASA's Aura platform due to launch in 2003. TES has 0.5 x 5 km^2 horizontal resolution, 2-6 km vertical resolution for ozone, and a revisit time of once every 4 days. The

Ozone Mapping Instrument (OMI) on NASA's Aura platform will provide ozone distributions at coarser (13 x 25 km^2) horizontal resolution every day with 8 km vertical resolution.

Aerosol distributions (optical thickness) can also be determined from spectral radiance measurements in the ultraviolet. TOMS provides aerosol distributions on the same time and space scales as the ozone distributions. In addition, dense aerosols may be observed from space using visible wavelength imagers. Dramatic images of large scale smoke palls, dust storms, and pollution continue to be obtained from space-based imagers including SeaWIFS, MISR, MODIS, and ASTER. Although these imagers are primarily focused on surface (land and ocean) observations, they provide an easily understood context for measurements of aerosol from fires, dust storms, and volcanic eruptions. Aerosol distributions vary by season, and throughout the day, driven by wind systems with intense diurnal variations. In addition to indicating long-range transport, trajectory analysis can identify the origin of the aerosol emissions. Aerosol also has significant effects on solar insolation, visibility, and atmospheric chemistry.

NASA is developing LIDAR techniques to measure the detailed vertical structure of ozone and aerosol in the atmosphere. A prototype aerosol LIDAR (LITE) has flown on the Space Shuttle, and NASA's PICASSO-CENA mission will provide continuing profiles of aerosol and cloud layers from space beginning in 2004.

In addition to these tracers of transport, NASA's suite of Earth observing instruments also regularly provides measurements of other trace constituents. The GOME instrument on a European Space Agency satellite infers tropospheric NO_2 (a pollution gas) from rapid variations in the total column NO_2 measurement. OMI on NASA's Aura platform will provide similar measurements beginning in 2003. NASA has measured the global distribution of CO, an excellent intercontinental tracer of industrial activity and biomass burning, since the early 1980's, first with the MAPS instrument on the Space Shuttle, currently with the Canadian Space Agency's MOPITT instrument on NASA's Terra platform, and continuing with TES on the Aura platform in 2004.

Concurrently, atmospheric chemistry and transport models are being developed to guide mission planning for aircraft and space-based missions, to integrate observations on many different time and space scales, and to develop predictive capabilities. Various data sources are used to evaluate the fidelity of the model in representing atmospheric processes and to complement the science studies being investigated with the model. The overall objective of this work is to improve the understanding of atmospheric chemistry and transport processes and to translate that understanding into improved predictive models for use in global change studies.

NASA provides tools for studies of long-range transport to identify dilution, reaction, and deposition of trace constituents in the atmosphere. Both observations and models are applied to study the processes that act upon these constituents, and to enable predictions of the state of the atmosphere. NASA supports the national interest in identifying long-range transport for treaty compliance, air quality regulation, and human health.

4.1.2 Global Tropospheric Experiment (GTE)

In 1984, the National Academy of Sciences recommended initiation of a Global Tropospheric Chemistry Program in recognition of the central role of atmospheric chemistry in global change. Envisioned as the U. S. national component of an international research effort, the Global Tropospheric Chemistry Program entails the systematic study, supported by numerical modeling, of biological sources of atmospheric chemicals; global distributions and long-range transport of chemical species; and reactions in the troposphere that lead to the conversion, redistribution, and removal of atmospheric chemicals. The Global Tropospheric Chemistry Program is part of a comprehensive international research effort coordinated through the IGAC.

The long-range goal of the Global Tropospheric Experiment (GTE) is to contribute to scientific understanding of human impacts on the chemistry of the global troposphere. Changes in chemical composition of the troposphere on a global scale have been well documented during the last two decades, providing a baseline from which to observe changes and giving rise to concern that these chemical changes in the troposphere, which are expected to increase as population increases and economic activity expands, will lead to changes in the Earth's climate. The connection between atmospheric chemical composition change and climate change is a major focus of NASA's Earth Science Enterprise.

Since there are no boundaries within the earth's atmosphere, gases produced on one continent can easily be transported around the globe, often in a matter of days. The GTE utilizes aircraft that are instrumented for measurements of a wide range of atmospheric parameters and species as flying laboratories. However, the GTE also draws heavily upon satellite observations of meteorology, land use, and atmospheric chemical species to aid in experiment design and in the scientific analyses of results obtained from aircraft and ground-based measurements. The simultaneous measurements of trace gases from airborne platforms, augmented by the ground and space measurements, provide important process information to the atmospheric chemistry models being developed for predictions of climate change. Understanding the chemical processes in the troposphere on a global scale is critical to predict, and potentially ameliorate, harmful man-made changes to the global environment.

Long-term observations from ground sites and satellites provide important continuous monitoring of the temporal trend of atmospheric composition but are limited in terms of spatial coverage (ground sites) or the suite of species that are measurable (satellites). Aircraft missions complement surface and satellite observations by providing a detailed investigation of the dynamical and chemical processes affecting atmospheric composition over specific geographical regions. Aircraft experiments provide "ground truth" for satellite measurements and explore in detail the processes responsible for the observed distributions.

Since 1984, guidance for the GTE field studies has come from planning meetings that define a series of field studies conducted through the NASA Tropospheric Chemistry Program, and coordinated with other national and international studies. The field measurements have included studies of the tropical forest, Arctic tundra, instrument intercomparisons, global distributions, and long-range transport.

Participants in the series of *ad hoc* planning meetings, representing a broad cross-section of the international atmospheric chemistry community, are collectively the architects of the NASA GTE field programs. They include Daniel Albritton, Hajime Akimoto, Helmuth Bauer, Jack Calvert, Mary Anne Carroll, Ralph Cicerone, David Crosley, Robert Duce, Douglas Davis, Dieter Ehhalt, Fred Fehsenfeld, Jack Fishman, Robert Harriss, Daniel Jacob, Volker Kirchhoff, Pablo Lagos, Don Lenshow, Shaw Liu, Antony Mayer, Robert J. McNeal, Volker Mohnen, Luiz Molion, Jarvis Moyers, Reginald Newell, Stuart Penkett, Joyce Penner, John Ritter, Michael Rodgers, Sherry Rowland,Wolfgang Seiler, Hanwant Singh, Anne Thompson, and Steve Wofsy.

Several of the intensive field campaigns described in the previous section (CITE, TRACE, PEM) were conducted under the GTE umbrella. Several new studies are underway or planned for the near future:

ACE-Asia

The Intensive Operations Period (IOP) of the Aerosol Characterization Experiment (ACE) is taking place in the Spring, 2001. It is during springtime that offshore transport of aerosols from the Asian Continent, especially dust, occurs most frequently. The overall goal of ACE-Asia is to increase our understanding of how atmospheric aerosol particles influence the radiative and cloud nucleating properties of the atmosphere. Aerosol layers are being investigated with the use of satellite remote sensing and surface and airborne measurements. In addition to longer-term ground and satellite measurements, measurements of chemical and physical aerosol properties and their radiative impacts are being made at many locations and altitudes during the IOP. The IOP for ACE-Asia has been designed to overlap with that of TRACE-P and there will be several joint missions between the two teams of scientists. The primary U.S. support for ACE-Asia comes from NSF, NOAA, and the Office of Navel Research (ONR).

BIBLE

The Biomass Burning and Lightning Experiment (BIBLE) Phase C, conducted by the Japanese Earth Observation Research Center (EORC), National Space Development Agency of Japan (NASDA) made measurements in the Western Pacific during December 2000 that provided data supplemental to the TRACE-P mission. The goal of BIBLE was to study tropospheric chemistry (natural and anthropogenic processes) in the tropical Asia/Pacific region. Measurements of ozone, ozone precursors and other photochemical quantities were made aboard a Gulfstream II aircraft. In addition, BIBLE Phase C made measurements of lightning over the Western Pacific during the ferry flights to and from Northern Australia and Indonesia.

PEACE

The Pacific Exploration of Asian Continental Emission (PEACE) mission, also conducted by EORC/NASDA, will take place in May 2001 and will also provide data complementary to TRACE-P. Using the Gulfstream-II aircraft mentioned in the previous section, PEACE will make measurements of the seasonal excursion of the continental outflow from Asia.

TRACE-P

TRACE-Pacific or TRACE-P, scheduled for April 2001, has major objectives to determine the chemical composition of the Asian outflow over the western Pacific in spring in order to understand and quantify the export of chemically and radiatively important gases and aerosols and their precursors from the Asian continent, and to determine the chemical evolution of the Asian outflow over the western Pacific in spring in order to understand the ensemble of processes that control the evolution. TRACE-P will use two NASA aircraft, the DC-8 (ceiling 12 km) and the P-3B (ceiling 7 km) operating out of Yokota Air Force Base (near Tokyo, Japan) and Hong Kong.

Supporting measurements for TRACE-P are intended to place the aircraft observations in a broader temporal and spatial framework. Ozonesondes have proven to be particularly valuable for that purpose in past GTE missions. TRACE-P will include a program of intensified launches at three established ozonesonde sites and a Japan mainland site such as Tateno. Ozonesondes will be launched once a week from March 2000 to March 2002 (one year before to one year after the mission) and twice a week during the mission.

Measurements at coastal sites, islands (Cheju, Lanyu, Oki), and from ships will also be important for extending the aircraft observations in TRACE-P. Key species to be measured include ozone, aerosols, CO, and hydrocarbons. It is expected in the framework of APARE that the Asian partners to NASA will play a leading role in the operation of these surface measurements.

Space-based observations from the Measurement of Pollution In The Troposphere (MOPITT) and the Global Ozone Monitoring Experiment (GOME) instruments should be of considerable value for interpretation of the TRACE-P data. MOPPITT (launched into polar orbit in 1999) will provide global distributions of CO vertical profiles including multiple levels in the troposphere. GOME (in polar orbit since 1995) is expected to provide operational data for tropospheric ozone columns by the time of the TRACE-P mission.

4.2 National Oceanic and Atmospheric Administration (NOAA)

NOAA is augmenting IGAC's ITCT activities by developing capabilities to better quantify the transport of pollution into and from North America. Emissions from North America can impact European air quality. In addition, pollutants transported into the U.S. become part of the "background" that defines a limit for air quality management. The research is focused on the long-lived pollutants, CO, ozone, and fine particles. The research attempts to define the location of the sources of the pollutants and determine the nature of those sources. These sources include natural sources, such as forest fires, volcanoes, and wind-blown dust; manmade sources, such as transportation and heavy industry; and in-route sources, including ships and aircraft. Research conducted to date has focused on modeling studies of impacts from biomass burning and transport from Asia to North America and measurements and modeling of transport and chemistry in the North Atlantic region (NARE). The proposed research will investigate transport across the Pacific and Atlantic Oceans and North Polar Region. In addition, the chemical

transformation and deposition that may occur in the oceanic and polar regions will be studied. The program will:

- conduct airborne exploratory studies of airflow from the Pacific into the western U.S. in early 2001,
- develop surface monitoring capabilities and deploy an intensive field study in 2002 to investigate and quantify trans-Pacific transport,
- build on existing modeling efforts to quantify transport of pollution from Asia to North America, and
- analyze existing data and conduct further measurements to determine the influence of biomass burning.

NOAA serves as the U.S. Co-chair (with Japan and the United Kingdom) of ITCT.

4.2.1 Exploratory Field Study in 2001

During January and February 2001 NOAA operated two aircraft over the Pacific as part of the weather research program. The Gulfstream G-IV operated out of Hawaii while the WP-3 Orion was deployed to California. The areas of operation of the two aircraft (mid to eastern Pacific) are within the primary transport pathways of pollution between Asia and North America. In addition, the mid-Pacific is a region of intense stratosphere-troposphere exchange associated with breaking Rossby waves. These programs offer the opportunity to carry out an exploratory study of the pollutant concentrations and transport in this region.

4.2.2 Development of surface monitoring capabilities

In order to better track the long-range transport of pollution to and from North America and to monitor the change in the pollutant distributions with time, additional surface monitoring sites and upgrades to existing sites are planned.

Azores

Two measurement sites are planned for the Azores in the central North Atlantic Ocean. These projects are outgrowths of the CO, ozone, and nitrogen oxides measurements made at Terceira Island in 1993 [Peterson et al., 1998; Parrish et al., 1998]. The Pico Exploratory Atmospheric Chemistry Observatory (PEACO) is a planned two-year study of atmospheric chemistry in the lower free troposphere (FT) over the Azores. The measurements will be made at the summit of Pico mountain on Pico Island at an altitude of 2200 m, a height that is frequently in the free troposphere according to ozone soundings made at the adjacent island of Terceira [Oltmans et al., 1996]. Despite the significant logistical and organizational difficulties involved in operating on a mountaintop with no existing access or electrical power, measurements are scheduled to begin in early summer 2001. Government permission has been received to set up the site and make measurements for a 2-year period.

The primary objectives of the measurements are to quantify the impact of continental outflow on the budget of ozone over the North Atlantic and to assess the relative importance of ozone and ozone precursor export. However, it is expected that the measurements will be used for a variety of other purposes, including aerosol studies. Initially, the measurements will include carbon monoxide (CO), ozone, and standard meteorological observations. Future measurement

additions include black carbon, nonmethane hydrocarbons, and nitrogen oxides. Space and electrical power are quite limited and instruments must be remotely monitored and controlled.

The Portuguese Meteorological Institute is planning a long-term Global Atmospheric Watch (GAW) site in the marine boundary layer (MBL) in the Azores. The value of an Azores GAW site was mentioned in a recent WMO informal report ("Final Report of the Consultation of Experts on Carbon Monoxide Instrumentation for Remote GAW Sites, Geneva, 8-10 September 1999"). Measurements at this site, in conjunction with the mountaintop measurements, will allow the investigation of FT/MBL exchange and the budgets of ozone and its precursors in the MBL of the central North Atlantic.

NOAA Baseline Observatories

The NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) operates long-term atmospheric observatories at Pt. Barrow, Alaska and Mauna Loa, Hawaii. Presently, the measurements are aimed at climate forcing and ozone-depleting agents such as CO_2, CH_4, O_3, N_2O, CFC's, aerosols and solar incoming and upwelling radiation. In addition, persistent organic pollutants and mercury have been added recently at Barrow. Measurements at the observatories will be enhanced as part of the ITCT Program. During Spring 2001, a pilot intensive will be held at Mauna Loa (Springtime Transport of Effluents from Asia to Mauna Loa – STREAM) during which additional measurements such as continuous CO, persistent organic pollutants, mercury, nitrogen oxides, aerosol chemistry, and hydrocarbons (Proton Transfer Mass Spectrometry and GC-MS instruments) will be conducted. The results of this pilot campaign will be used to evaluate possible observatory participation during the proposed 2002 intensive field study.

Northwestern U. S. Pacific Coast

An initial study of the factors that influence the air quality on the western fringes of the United States will be undertaken during the spring of 2002 at sites that will be identified and developed during 2001. A possible site would be Trinidad Head, CA, where CMDL presently operates both a Dobson ozone spectrophotometer and an ozonesonde station. In addition, the NASA Advanced Global Atmospheric Gases (AGAGE) program measures various chlorofluorocarbons (CFCs) at this site. Both programs operate through cooperation with Humboldt State University. CMDL plans to expand its background measurements of air-quality parameters at this site in the future and to work with other agencies and universities to develop a distributed baseline observatory on the west coast of the U.S.

4.2.3 Field Study in 2002

During Spring 2002, NOAA will conduct airborne measurements of the concentrations of ozone, fine particles, their precursors, the photochemical intermediates, and other photochemical products, as well as other atmospheric parameters. The study will be based on the U.S. West Coast, and will investigate how inflow from the Pacific basin affects the chemical processing and removal of compounds of anthropogenic origin that influence the regional budgets of ozone and fine particles downwind over the continental U.S.

4.2.4 Modeling

NOAA is using a global chemistry-transport model (GCTM) developed by the Geophysical Fluid Dynamics Laboratory (GFDL) and a suite of regional chemistry, transport, and assessment models to study the transport, transformation, and fate of air pollution on a global scale. These tools are being applied in two areas of research that are particularly germane to the problem of intercontinental pollution transport.

The GFDL/GCTM is currently being used to diagnose the episodic nature of trans-Pacific air pollution transport. Analysis of flow and tracer fields reveals that, after venting from the Asian boundary layer, pollution parcels sometimes remain in highly discrete synoptic structures all the way across the Pacific Ocean. The new ground-based and airborne measurements of pollution in the Pacific Basin that will result from the research programs described above will provide a rigorous test of model performance and capability. The models will be used to aid in the planning of future field studies and in the interpretation of the data from the intensive and longer-term monitoring efforts, leading to a better understanding of the contribution of Asian emissions to air quality in North America.

4.2.5 Biomass burning

Several research projects will be undertaken to better understand the contribution of biomass burning to global pollution:

- Long-term CO measurements data will be investigated to search for inter-annual variability consistent with seasonal variations and magnitude of high-latitude fires.
- Determine the influence of NO_X and VOC emissions for high-latitude fires on summertime ozone levels over North America.
- Determine the chemical composition of gases and fine particles emitted by these fires and the chemical evolution of those emissions once they enter the atmosphere.
- Determine the influence of these aerosols on hemispheric climate forcing and variability with particular emphasis on the their impact in the North Polar Region.
- The GFDL GCTM will be used to quantify the impacts of biomass burning on tropospheric concentrations of CO, NO_x, and O_3 throughout the world.

4.3 National Science Foundation (NSF)

4.3.1 ACE (Aerosol Characterization Experiment) – Asia

The International Global Atmospheric Chemistry Program (IGAC) has planned a series of Aerosol Characterization Experiments (ACE) that integrate *in-situ* measurements, satellite observations, and models to improve our understanding of the climate forcing due to aerosol particles. ACE-Asia is the fourth in this series of experiments. The three primary objectives of ACE-Asia are to:

1. Study the physical, chemical, and radiative properties of major aerosol types in Eastern Asia and the Northwest Pacific region and investigate the relationships among these properties,
2. Quantify the interaction between aerosols and radiation in the region, and

3. Quantify the physical and chemical processes controlling the evolution of the major aerosol types and their properties.

ACE-Asia scientists are simultaneously measuring chemical and physical aerosol properties and their radiative impacts at many locations and altitudes during the Intensive Operations Period in the Spring, 2001. It is during springtime that offshore transport of aerosols from the Asian Continent, especially dust, occurs most frequently.

The international ACE-Asia observing facilities include instruments at ground stations throughout Asia and aboard several aircraft and research vessels. Flight plans and ship operations are directed to sample regional aerosol features under varying meteorological conditions and distances from shore. These measurements provide data to test and refine radiative transfer and chemical transport models that are used to quantify aerosol radiative forcing. Organic, inorganic and elemental tracers are used to assess the contributions of different sources to the measured aerosol concentrations.

Results from ACE-Asia will improve our ability to understand how atmospheric aerosols influence the chemical and radiative properties of the Earth's atmosphere. They will also help us understand how future changes in aerosol concentration and composition may influence changes in the Earth's climate system as a whole.

ACE-Asia is an international field experiment with participation from Australia, China, United Kingdom, France, Germany, Japan, Korea, Russia, Chinese Taipei, and the United States. The Operations Center from which scientists are directing the U.S. aircraft studies is located at Iwakuni, Japan. The U.S. contribution to ACE-Asia is being supported primarily by NSF, NOAA, and ONR.

Details of the ACE-Asia project can be found at: http://saga.pmel.noaa.gov/aceasia/

4.3.2 Photochemical Ozone Budget of the Eastern North Pacific Atmosphere II (PHOBEA II)

During the first phase of the Photochemical Ozone Budget of the Eastern North Pacific Atmosphere (PHOBEA I), relatively high background average mixing ratios of ozone were found in the eastern North Pacific atmosphere and at the surface in Washington state. Simultaneous measurements of CO, PAN, NMHCs, aerosol scattering and absorption, combined with isentropic trajectories, suggest that anthropogenic emissions from Asia can be transported to the west coast of the U.S. in a relatively short time (as little as 5 days). These measurements will be extended in PHOBEA II to help understand the nature of the sources for the air that arrives at the West Coast of North America. Ground and airborne measurements are being made, beginning in the spring of 2001, to coincide with ACE-Asia and TRACE-P. Vertical profiling of CO, O_3, NMHCs, and aerosol scattering will be carried out throughout the year to provide an important complement to the ground-based sampling. The primary goal of this project is to understand the sources for ozone, ozone precursors, and fine particles in the North Pacific coastal atmosphere.

4.4 Environmental Protection Agency (EPA)

Given that domestic sources of emissions are the primary cause of air pollution problems in our country, the primary focus of air quality research and management efforts at the Environmental Protection Agency (EPA) is the protection of human health and environmental quality through the management of emissions sources within the United States. However, the EPA recognizes that transboundary, and even intercontinental, flows of pollutants already contribute to a number of environmental problems, such as mercury and POPs contamination in the Arctic and in the Great Lakes and other U.S. water bodies. With increasing emissions associated with the global spread of industrialization, the contribution of these flows to environmental problems in the United States could become an obstacle to achieving our own domestic environmental goals. In 1997, EPA promulgated new standards for ozone and particulate matter that lowered the compliance levels for these pollutants in response to new health effects research. The recognition that health effects can be associated with air pollution levels lower than was previously believed has heightened the interest in a better quantification of the impact of the "global background" and transported pollution on U.S. air quality.

To improve the EPA's efforts to address these issues, an International Transport of Air Pollutants (ITAP) Working Group has been formed within the agency, co-chaired by the Office of Air and Radiation and the Office of International Activities. The main purposes of this working group are to:

- share information across EPA programs
- identify opportunities and needs for coordination
- provide a focal point for interaction with organizations outside the EPA
- identify potential domestic and international policy gaps and opportunities
- identify capabilities, resources, and structures needed to effectively address ITAP issues

The activities addressed by the ITAP Working Group include international policy development, technology and information transfer, control technology development, emissions characterization, modeling and assessment, and ambient monitoring. The activities that are related most directly to intercontinental transport phenomena are described below.

The EPA is a key component of the U.S. Government's participation in the five international agreements that address issues related to the intercontinental transport of air pollutants, which were discussed earlier. EPA personnel are involved at both the policy and technical level in each of these international efforts. To foster additional international cooperation on issues of intercontinental transport, EPA, with additional contributions from a number of governmental agencies in the U.S. and Canada, sponsored the First International Conference on the Trans-Pacific Transport of Atmospheric Contaminants, held in July, 2000, in Seattle [Wilkening, Barrie, and Engle, 2000]. The EPA is helping to organize a similar conference on the transport of photooxidants and fine particles across the North Atlantic and Arctic, which will take place in Spring, 2001, as part of the U.S. participation in the LRTAP Convention.

4.4.1 EPA Research

The EPA is conducting a series of ambient monitoring studies to better understand the behavior of mercury in the atmosphere and the potential for very long-range transport. These studies involve the use of new measurement techniques to determine the relative concentrations of the various chemical (elemental and ionic) and physical (gaseous and particulate) forms of mercury in the atmosphere. These new techniques are being applied in surface and aircraft measurements to help apportion the deposition in the Florida Everglades between local and distant sources; in surface measurements in Point Barrow, Alaska, to study the observed depletion of atmospheric mercury during polar sunrise; and in surface measurements at Cheeka Peak, Washington, to characterize trans-Pacific transport. Future studies are being planned in the Ohio River Valley, to examine differences between local and distant sources, and at Mauna Loa, to characterize intercontinental and global transport processes.

The information from these measurement studies is being used to develop and evaluate a chemical mechanism for mercury that has been incorporated into EPA's Community Multiscale Air Quality model (CMAQ), a state-of-the-art Eulerian regional atmospheric fate and transport model [Byun and Ching, 1999]. Through an international model comparison study being conducted under the auspices of the LRTAP/EMEP program, the CMAQ mercury mechanism is being compared to other models of mercury chemistry being developed by U.S. and international experts. Eventually these models will help apportion observed deposition between domestic emission sources and foreign emission sources that contribute to the global circulation of mercury [Bullock, 2000; MSC-E, 2000].

Lastly, the EPA, through a number small individual grants and cooperative agreements, is examining the potential for integrating remote sensing and surface measurements to characterize inter-continental transport. Examples include work EPA is doing with Battelle's Pacific Northwest National Laboratory and the UNEP/GRID Center in Sioux Falls, South Dakota, to explore how remote sensing information available from satellites can be integrated with surface measurements to address large scale transport phenomena, including intercontinental scale transport [Engle-Cox, DeFelice, and Falke, 2000]. The complementary nature of satellite and surface observations is shown in Figure 4.1, which compares a GOES satellite image to surface observations from the IMPROVE network during an April, 1998 dust event originating in the Gobi Desert. The transport of dust from the Gobi and Taklimakan deserts has also been documented using Probabilistic Transport Pathway Analysis (Husar and Schichtel 2000).

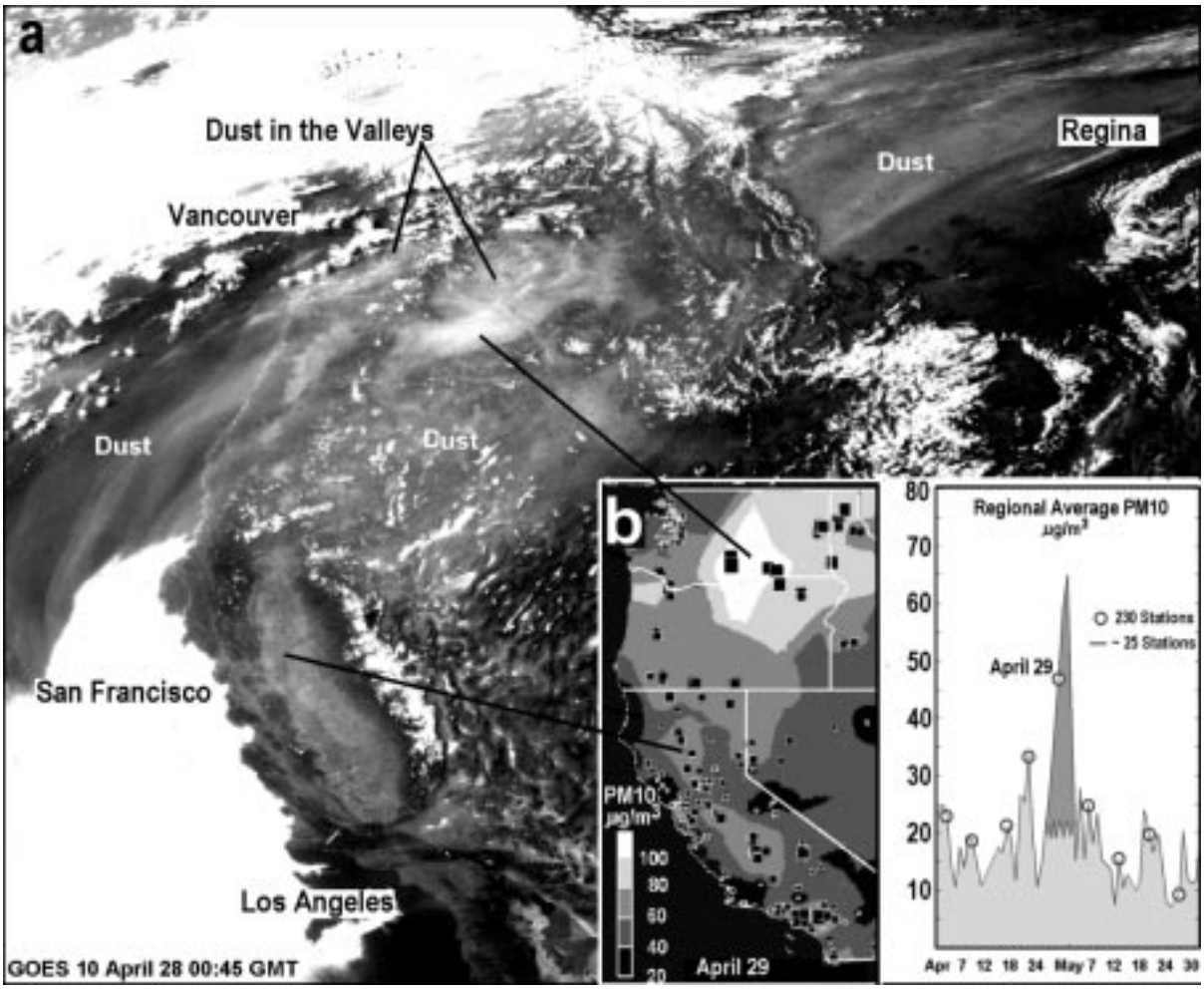

Figure 4. 1 Fine particle transport as shown by a GOES satellite image (a) and IMPROVE surface observations (b) as a result of an April, 1998 dust storm in the Gobi Desert. [Husar and Schichtel, 2000]

4.5 National Institute of Standards and Technology (NIST)

NIST conducts research related to intercontinental transport of air pollution as part of a program to develop and apply novel aerosol collection strategies, unique metrologies, reference materials, and metrics of uncertainty to help address regional and national air quality issues. All current and planned NIST research in this area is collaborative and multi-institutional, and involves significant meteorological challenges. One project is the collection and measurement of air and particle samples from large experimental crown fires, where objectives include relating compositional and morphological data to variables such as meteorology, fuel type, burn intensity, and collection site. Another project involves a comprehensive study of seasonal patterns of natural and anthropogenic species in air and snow transported to Summit, Greenland. Key issues are the identification of source types, source regions, temporal history, air-to-snow transfer functions, and the treatment and reporting of measurement uncertainties related to these issues.

5.0 Research Needs

This report is intended as a broad overview of what is known about intercontinental transport of air pollution and the role of U.S. Federal research in developing the science needed to inform effective policy development. Clearly, a great deal is already known and programs are in place to insure continued progress. However, in an effort to insure that all the key information gaps are being addressed and that opportunities for interagency collaboration are identified, it is instructive to list the research needs that were identified by the Air Quality Research Subcommittee.

It should be emphasized that the U.S. research program must be viewed in the international context. Intercontinental transport of air pollution is truly a global issue that requires a global solution. U.S. Federal research in this area is part of a larger effort, which places a premium on international cooperation and collaboration and underscores the role that groups like IGAC/ITCT must play in developing a global research agenda.

5.1 Emissions

The quality of emissions estimates is highly variable throughout the world. The quantification of existing impacts and projection of changes in the future are dependent upon reliable estimates of both anthropogenic and natural emissions. Work must continue to better quantify existing emissions and methods for forecasting future emissions. A particular emphasis should be placed on improving estimates of emissions in the developing countries and from both deliberate and uncontrolled biomass burns. Emissions in remote marine areas (ships, airplanes, and biogenic) is another important area where more information is needed.

5.2 Process Studies

The key to a more complete understanding of intercontinental transport of air pollution is an improved understanding of the atmospheric processes that control the transport, transformation and fate of these pollutants. These processes are the ones that link source and impact areas. Intensive field campaigns employing ground networks, remote sensing, and instrumented ships and aircraft have provided invaluable insights into these processes. Several such research programs have been described and additional studies will be needed if we are to explore a broad enough range of meteorological conditions and emission distributions to have confidence in the understanding of the key phenomena.

5.3 Models

Three-dimensional models that couple transport and chemical process on a global scale are available. However, these models are somewhat limited in their ability to resolve fine-scale processes such as ship plumes. The skill of these models is not fully known, since there have been only limited data sets against which to evaluate their predictions. Models are essential in the design and interpretation of results from intensive field experiments. They are also essential for the prediction of impacts associated with future emission changes. Therefore, we must be sure that the models reliably simulate the key atmospheric processes and that we understand the accuracy of their predictions. Additional measurements from both routine monitoring stations and intensive studies are needed for the evaluation of model performance. Efforts must continue to improve the overall performance of these models through the incorporation of new procedures that represent the current understanding of the underlying science.

5.4 Observing systems

The rich databases provided by the intensive field campaigns provide a comprehensive snapshot of a relatively short period. To be effective these programs must be augmented by longer-term observations that provide spatial and temporal context. These longer-term trends are provided by ground-based and space-borne observing systems.

- **Ground-based monitoring networks –** coordinated measurements of key pollutants at remote locations around the world provide information on trends in background pollution levels. These measurements can be coupled with back trajectory analysis to provide information on sources and transport corridors. By combining measurements over several years, it is possible to assess trends and to more accurately quantify relative contributions of local and distant sources. The current global monitoring network is very sparse, making it very difficult to properly quantify the impact of transported pollution in many regions. The use of profiling techniques (sondes, remote sensing, aircraft, etc.) to augment the surface measurements has proven to be a valuable addition. If possible, additional surface-based monitoring sites need to be established and, where possible, the capability to provide routine pollution profiles above the sites needs to be developed.

- **Satellites** - complement the detailed ground networks and airborne process studies, and provide observations in data-sparse regions of the planet. Satellites can provide nearly world-wide coverage for specific compounds and aerosols, and provide continuing observations during multiple seasons and years. Trace gases and aerosols could be observed from space with time resolution approaching that of weather satellites, although these observations are not in the present plans. Such data would provide new knowledge in the global spatial domain, uniquely identifying the sources and observing real time transport of pollution, and providing the means to directly validate transport models. Exciting new sensors are planned for future platforms and retrieval techniques are being developed and evaluated for existing and planned sensors. Major advances in

understanding are anticipated in areas where continuous satellite data are combined with surface-based observations, either from routine or intensive measurement campaigns and modeling advances.

5.5 Assessments

Periodic assessments that describe the current understanding of the science related to intercontinental transport of air pollution are needed to insure an effective research program and to facilitate communication with the decisionmakers in the policy community. A mechanism should be established to support the conduct of such assessments and communicate the results to interested stakeholders.

6.0 Additional Reading

There are four other reviews of the research needs related to intercontinental transport of air pollution that relate to the efforts of the CENR Air Quality Research Subcommittee. The purpose and scope of each is quite different. However, they provide additional perspectives on this important issue.

6.1 "Intercontinental Transport and Chemical Transformation" (IGAC white paper)

IGAC (see Section 3.2 for more information) has proposed a comprehensive research program to address intercontinental pollution transport. The program, which is called Intercontinental Transport and Chemical Transformation (ITCT), provides a framework for international cooperation and collaboration. The objectives of the program are:

- To investigate intercontinental transport of manmade pollution, with an emphasis on ozone, fine particles, and other chemically active "greenhouse" compounds;
- To determine the chemical transformation that occurs during this transport.

The broad elements of the program approved by the IGAC Scientific Steering Committee are described in a white paper "(ITCT)" that is available on the web at http://www.al.noaa.gov/WWWHD/pubdocs/ITCT/.

6.2 "Global Air Quality" (NRC Report)

The National Research Council's (NRC's) Committee on Atmospheric Chemistry, with support from the US Global Change Research Program, NASA, and EPA, has initiated a study of the linkages between regional/global changes in atmospheric composition, climate change, and U.S. air quality. More specifically, the Committee was asked to[3]:

- "Review projections of how future global industrialization, urbanization, and other human activities could alter regional and global atmospheric composition and chemistry over the next century."
- "Discuss how these global chemical changes could affect atmospheric radiative forcing and impact U.S. air quality."
- "Describe the gaps in scientific understanding that currently impede our ability to accurately assess such changes."
- "Identify the observational data that are most critical for detecting and documenting these chemical changes, characterize the capacity of current observational systems to collect such data, and suggest ways that these systems can be enhanced or better integrated to provide the necessary observations."
- "Identify any other research needs related to this issue and, where appropriate, discuss what types of institutional arrangements (on both the

[3] National Research Council, charge to the Committee on Atmospheric Chemistry

national and international level) would be most effective for carrying out this work."

A NRC report detailing the recommendations of the Committee is expected in mid-2001.

6.3 "The Atmospheric Sciences Entering the Twenty-First Century" (NRC Report)

In 1998 the National Research Council's Board on Atmospheric Sciences and Climate prepared a report entitled "The Atmospheric Sciences Entering the Twenty-First Century" [NRC, 1998], that reviews the benefits that atmospheric sciences have provided to the Nation and charts a path for the future. In outlining a scientific strategy for atmospheric chemistry the authors identify four overarching research challenges that bear directly on intercontinental transport of air pollution.

- "Document the chemical climatology and meteorology of the atmosphere, particularly their variability and long-term trends,…"
- "Develop and evaluate predictive tools and models of atmospheric chemistry through a synthesis of information gathered from process-oriented field studies, laboratory experiments, and other observational efforts;…"
- "Provide assessments of the efficacy of environmental management activities;…"
- "Be holistic and integrated in the study of the Environmentally Important Atmospheric Species and of the chemical, physical, and ecological interactions that couple them together."

These authors also identify a number of specific "Disciplinary Research Challenges" and associated "Infrastructure Initiatives" that must be addressed to meet future information needs.

The recommendations contained in this NRC report are reflected in the specific recommendations related to intercontinental transport of air pollution included in the "Research Needs" section of this CENR/AQRS white paper.

6.4 "Long-Range Atmospheric Transport and Effects of Contaminants in the North Pacific Region: Knowledge, Concerns & Research Needs" (The Aljoya Consensus Statement)

Over 100 experts from the North Pacific region met in Seattle, Washington, USA from July 27-29, 2000 for the First International Conference on Trans-Pacific Transport of Atmospheric Contaminants. Individuals from Canada, China, Japan, Russia, South Korea, and the United States attended. The objectives were to: 1) discuss the state of science on long-range transport of atmospheric contaminants in the North Pacific region, 2) identify research needs, and 3) promote a network of individuals and organizations. The conference produced a Consensus Statement (http://www.epa.gov/oia/iepi/transpac.htm) that summarizes key findings and implications of existing research and identifies research needs related to three key questions:

1) What are the contributions of anthropogenic emissions in Asia, Europe, and North America to atmospheric contaminant concentrations and deposition in the Pacific region and how will these change in the future?
2) How do atmospheric concentrations and deposition of contaminants affect terrestrial and marine ecosystems and human health in the Pacific region?
3) How do atmospheric contaminants in the Pacific region affect regional and global climate?

The conference concluded by calling for cooperative development of a “Pacific Environmental Research Strategy” to promote a common scientific understanding of long-range transport of atmospheric contaminants in the Pacific region.

7.0 References

ACE-ASIA For additional information, visit the program web site at: http://saga.pmel.noaa.gov/aceasia/index.html

AGASP The program has produced in the region of 200 reviewed publications, many of which appear in 5 dedicated issues of scientific journals and two books on the subject (*Geophys. Res. Lett*., *11*, #5, 1984 (23 papers); *Atmos. Environ.*, *19*, #12, 1985 (23 papers); *Atmos. Environ.*, *23*, #11, 1989 (24 papers); *Atmos. Chem.*, *9*, #1-3, (23 papers); *Atmos. Environ.*, *27A*, #17/18, 1991 (35 papers); Arctic Air Pollution, Stonehouse, Cambridge Press, 1986; Pollution of the Arctic Atmosphere, W. T. Sturges, Elsevier, 1991.)

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Appendix A: International Agreements Related to Intercontinental Transport of Air Pollution

As was discussed earlier, the United States is a party to at least five different agreements or ongoing negotiations that address the intercontinental transport of air pollutants. The five agreements are described in further detail below.

1979 Convention on Long Range Transboundary Air Pollution

The 1979 Convention on Long Range Transboundary Air Pollution (or LRTAP Convention) and the associated eight protocols address the transboundary fluxes of sulfur, nitrogen oxides (NO_x), volatile organic compounds (VOCs), ozone, ammonia, heavy metals (HM), and persistent organic pollutants (POPs) [see http://www.unece.org/env/lrtap/]. There are 47 parties to the LRTAP Convention, which encompasses the United States, Canada, and all of Europe and is administered by the United Nations Economic Commission for Europe (UNECE). Each of the agreements under the LRTAP Convention is listed in Table A-1, along with the status of U.S. participation in each agreement. The LRTAP protocols may be divided into two generations. The 1985 1st Sulphur, 1988 NO_x, 1991 VOC, 1998 HM, and 1998 POPs Protocols comprise the first generation and are focused on establishing fixed ceilings or uniform decreases in emissions of the named pollutants. The second generation of protocols began with the 1994 2nd Sulphur Protocol, which was intended to minimize the cost of decreasing emissions to a level necessary to achieve steady-state levels of pollutant loadings, known as critical loads, below which no ecological or human health damage occurs. The 1999 Multi-Effects Protocol extended this critical load concept to apply simultaneously to acidification, eutrophication, and ground-level ozone impacts associated with emissions of sulfur (sulphur), nitrogen oxides, ammonia, and volatile organic compounds.

The current focus of activity under the LRTAP Convention is the implementation of the existing protocols. However, the technical assessment and research bodies under the Convention have begun to prepare for future protocols that will add to the list of controlled POPs, apply the critical load concept to heavy metals, and extend the mix of pollutants addressed under the Multi-Effects Protocol to include fine particles.

An essential part of the critical load approach as applied under the LRTAP Convention is the development of source/receptor relationships that allow the impacts in one country to be attributed to emissions in another. To date, source-receptor relationships have only been defined between the countries in Europe. However, during the negotiation of the Multi-Effects Protocol, the potential for intercontinental transport of air pollutants was raised out of concern that ozone precursors may travel from North America to Europe and contribute to exceedances of critical levels for ozone. As a result, the Preamble of the Multi-Effects Protocol acknowledges the "potential for transport between continents and the need for further study with regard to that potential." Furthermore, Article 8 of the Protocol calls for parties to engage in cooperative research "on the chemistry of the free troposphere and the potential for intercontinental flow of pollutants."

As a result of this commitment, the EPA, in coordination with EMEP and Environment Canada, has agreed to host a workshop in the Spring of 2001 to explore the current state of knowledge with respect to the transport of photooxidants and fine particles across the North Atlantic and Arctic. While it is not yet clear how important the intercontinental flow of pollutants is to achieving the goals of the LRTAP Protocols, it is likely that these pollutant flows will have to be accounted for in future policy negotiations.

Table A-1 Status of agreements under the Convention on Long-Range Transboundary Air Pollution

Agreements under the LRTAP Convention	Location First Signed	Date First Signed	Entry into Force	Number of Signatories	Number of Ratifications	U.S. Signed	U.S. Ratified
Convention on Long-Range Transboundary Air Pollution (LRTAP)	Geneva	1979	1983	33	47	Yes	Yes
Protocol on Long-Term Financing of the Cooperative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollution in Europe (EMEP)	Geneva	1984	1988	22	38	Yes	Yes
Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes By At Least 30 Per Cent (1st Sulphur)	Helsinki	1985	1987	19	21	–	--
Protocol Concerning the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes (NOx)	Sophia	1988	1991	25	26	Yes	Yes
Protocol Concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes (VOC)	Geneva	1991	1997	23	17	Yes	--
Protocol on Further Reduction of Sulphur Emissions (2nd Sulphur)	Oslo	1994	1998	28	22	–	--
Protocol on Persistent Organic Pollutants (POPs)	Aarhus	1998	--	36	1	Yes	--
Protocol on Heavy Metals (HM)	Aarhus	1998	--	36	1	Yes	--
Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone (Multi-Effects)	Gothenburg	1999	--	31	--	--	--

1985 Vienna Convention for Protection of the Ozone Layer and 1987 Montreal Protocol

The United States is a party to the 1985 Vienna Convention and 1987 Montreal Protocol, which address the protection of the stratospheric ozone layer and the control of the production, use, and emissions of ozone depleting substances (see http://www.unep.ch/ozone/home.htm). Chlorofluorocarbons (CFCs) and other ozone depleting substances remain in the atmosphere for a long time and circulate globally. Characterizing the intercontinental transport of these pollutants has not been a central issue in the development or implementation of these agreements. However, a better understanding of the processes that govern intercontinental transport of air pollutants may be helpful in attributing observed concentrations to source regions as a method for verifying compliance with the Montreal Protocol.

1991 Arctic Environmental Protection Strategy

In 1991, the eight Arctic countries—United States, Canada, Russia (then the Soviet Union), Norway, Sweden, Finland, Denmark, and Iceland—agreed to cooperate in the implementation of an Arctic Environmental Protection Strategy (AEPS), which includes cooperative research on pathways, sinks, and effects of pollution in the Arctic; assessment of potential environmental impacts of development activities; and consideration and implementation of pollution control measures to reduce adverse impacts to the Arctic environment. As part of AEPS, the Arctic Monitoring and Assessment Program (AMAP), coordinated by a secretariat in Norway, conducts monitoring and modeling studies of the transport and fate of heavy metals and persistent organic pollutants into and within the Arctic (see http://www.amap.no/). AMAP has demonstrated that most of the heavy metals and persistent organic pollutants found in the Arctic originate on the continental land masses further south and are carried to the Arctic by intercontinental and circum-polar transport processes. Since 1997, AEPS activities have been subsumed under the Arctic Council. The Arctic Council, formed in 1996, consists of representatives from the same eight Arctic countries and is supported by a secretariat at the U.S. State Department (see http://arctic-council.usgs.gov/).

1992 United Nations Framework Convention on Climate Change

The United States is a party to the 1992 United Nations Framework Convention on Climate Change (UNFCCC), which addresses emissions and impacts of carbon dioxide and other greenhouse gases (see http://www.unfccc.de/). As in the case of stratospheric ozone depletion, the characterization of the intercontinental transport of air pollutants is not essential to the development or implementation of this agreement. However, understanding of the intercontinental transport of ozone, aerosols, and other trace pollutants that affect the earth's radiative balance may be very important for explaining and predicting regional and global scale climatic changes. The importance of this linkage between tropospheric air pollutants and global climate is expected to be addressed in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report, scheduled to be completed in 2001 (see http://www.ipcc.ch/).

Stockholm Convention on Persistent Organic Pollutants

The United States was an active participant in the negotiation of a United Nations Convention on Persistent Organic Pollutants (see http://www.chem.unep.ch/pops/). The negotiations were successfully concluded in December, 2000, in South Africa, and the final treaty is expected to be signed in May, 2001, in Stockholm. The Convention focuses on reducing the environmental impacts associated with the production, use, release, and disposal of twelve chemicals or chemical classes: DDT, aldrin, dieldrin, endrin, chlordane, heptachlor, hexachlorobenzene, mirex, toxaphene, polychlorinated biphenyls (PCBs), dioxins and furans. Many of these substances are subject to very long-range transport, sometimes involving deposition and subsequent re-emission, often referred to as "hopping." As a result of such transport processes, emissions in other parts of the world can lead to environmental damage and human health effects

from the use of these substances even in countries (or on continents) where these substances have been banned or are highly controlled. Characterizing the intercontinental transport processes that can lead to adverse impacts is important to raise awareness and build support for actions to decrease the use and emissions of these substances worldwide. An improved understanding of these processes will be especially important once the final treaty is in effect, as countries evaluate additional substances to be added to the treaty.

Appendix B: Committee on Environment and Natural Resources (CENR) Subcommittee on Air Quality Research

The CENR is charged with improving coordination among Federal agencies involved in environmental and natural resources research and development, establishing a strong information-transfer link between science and policy, and developing a Federal environmental and natural resources research and development strategy that responds to national and international issues. There are five research subcommittees under the CENR:

- Air Quality
- Ecological Systems
- Global Change
- Natural Disaster Reduction
- Toxics and Risk

The Air Quality Research Subcommittee has articulated two major goals in its Strategic Plan:

- to enhance the effectiveness and productivity of U.S. air quality research, and
- to improve information exchange between research and policy on air quality issues, including the scientific knowledge base for air quality standards and assessing compliance

Dan Albritton of NOAA chairs the Subcommittee, which includes representatives from the following departments and agencies:
Department of Agriculture - Agricultural Research Service
Department of Agriculture - Cooperative State Research, Education, and Extension Service
Department of Agriculture - Natural Resources Conservation Service
Department of Agriculture - U.S. Forest Service
Department of Commerce - National Institutes of Science and Technology
Department of Commerce - National Oceanic and Atmospheric Administration
Department of Defense
Department of Energy
Department of Health and Human Services - Center for Disease Control and Prevention
Department of Health and Human Services - National Institutes of Health
Department of Housing and Urban Development
Department of State
Department of the Interior - National Park Service
Department of the Interior - U.S. Geological Survey
Department of Transportation - Federal Aviation Administration
Department of Transportation - Federal Highway Administration
Environmental Protection Agency
National Aeronautics and Space Administration
National Science Foundation
Office of Management and Budget
Office of Science and Technology Policy
Tennessee Valley Authority