

Global Air Quality and Pollution

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The impact of global air pollution on climate and the environment is a new focus in atmospheric science. Intercontinental transport and hemispheric air pollution by ozone jeopardize agricultural and natural ecosystems worldwide and have a strong effect on climate. Aerosols, which are spread globally but have a strong regional imbalance, change global climate through their direct and indirect effects on radiative forcing. In the 1990s, nitrogen oxide emissions from Asia surpassed those from North America and Europe and should continue to exceed them for decades. International initiatives to mitigate global air pollution require participation from both developed and developing countries.

When the first measurements of high concentrations of CO over tropical Asia, Africa, and South America were made available by the MAPS (Measurement of Air Pollution from Satellite) instrument launched in 1981 on the space shuttle *Columbia* (1), it became clear that air pollution was an international issue. Those images showed not only that industrial air pollution from fossil fuel combustion could affect regional and global air quality, but that emissions from biomass burning (forest fires, agricultural waste burning, and vegetable fuel combustion) were important as well, confirming the hypothesis of Crutzen *et al.* (2). This meant that people in less developed countries, as well as residents of industrialized and rapidly growing developing countries, could suffer from air pollution generated elsewhere. Another illustration of the global character of air pollution came from measurements of tropospheric ozone made by the TOMS (Total Ozone Mapping Spectrometer) and SAGE (Stratospheric Aerosol and Gas Experiment) instruments on the *Nimbus 7* satellite (3). Once again, the impact of biomass burning on regional ozone concentrations was demonstrated, in addition to that of industrial pollution. More recently, observations of various tropospheric air pollutants such as NO₂, SO₂, and HCHO by GOME (Global Ozone Monitoring Experiment) and SCHIAMACHY (Scanning Imaging Absorption Spectro-Meter for Atmospheric ChartographY) (4) and of CO by MOPITT (Measurement of Pollution in the Troposphere) (5) have revealed pollution on a global scale. Edwards *et al.* (6) obtained a picture of the processes affecting tropospheric O₃ production over Africa and the Atlantic, combining the data on TOMS O₃, MOPITT CO, and GOME NO₂. Aerosols are another cat-

egory of air pollutants that can be viewed from satellites. Examples of the global distribution of anthropogenic and natural aerosols derived from MODIS (Moderate-Resolution Imaging Spectrometer) on the *TERRA* satellite have been given by Ramanathan *et al.* (7) and Kaufman *et al.* (8). Nakajima *et al.* (9) derived global distributions of aerosol particle number and cloud microphysical parameters, using the AVHRR (Advanced Very High Resolution Radiometers) remote sensing data, and Higurashi and Nakajima (10) showed the distribution of four major aerosols types (soil dust and carbonaceous, sulfate, and sea-salt aerosols) in the East China Sea region using SeaWiFS (Sea-viewing Wide Field-of-view Sensor) data. These studies show that satellite data can be useful for revealing climatic and environmental implications of global air pollution.

Global air-quality issues exist only in regard to those pollutants whose atmospheric lifetimes are long enough (on the order of 1 week) for them to be transported at least to another continent. One such trace gas is tropospheric ozone, a potent greenhouse gas (11) that also is toxic to humans, animals, and plants. Because the atmospheric lifetime of ozone is 1 to 2 weeks in summer and 1 to 2 months in winter (12), ozone produced in a polluted region of one continent can be transported to another continent all year long. Hemispherical transport, whose characteristic time scale is about 1 month, can occur in all seasons except summer. Figure 1 shows how model-calculated surface O₃ during the growing season (May through August) in the Northern Hemisphere has increased between 1860 and 1993 (13). According to this analysis, the concentration of surface O₃ over the mid- and high-latitude Eurasian and North American continents was 15 to 25 parts per billion by volume (ppbv) in 1860 but has increased to 40 to 50 ppbv even in relatively

remote areas, and from 10 to 15 ppbv to 20 to 30 ppbv over the mid- and high-latitude Pacific Ocean. One example of the spatial extent of global ozone pollution is that the average concentration of ozone in remote areas of East Asia is already high enough to jeopardize agricultural and natural ecosystems there (14). It is easily seen, then, how the elevation of background levels of ozone by long-range transport can cause the addition of ozone produced locally or regionally, in amounts that would not otherwise have been critical, to exceed air-quality standards or critical levels (15, 16). This makes small increments of ozone concentrations caused by contributions from other continents an issue of great concern (17).

The atmospheric lifetime of CO is also long enough (1 to 2 months on average) to allow intercontinental transport and hemispheric air pollution. Because a significant portion of CO pollution is from automobiles and biomass burning (13), its intercontinental transport is usually more easily captured by observation than is that of ozone (18). Because the concentration of OH in remote areas is mainly controlled by CO, and the concentration of OH in the atmosphere determines the lifetimes of most atmospheric trace gases, including greenhouse gases such as CH₄ and HCFC (13), global pollution by CO is worrisome because of its effect on the oxidizing capacity of the atmosphere.

Another important aspect of global air pollution is the impact of aerosols on climate (7, 19). Aerosol lifetimes are approximately 1 to 2 weeks (19), which is significantly shorter than that of ozone. Therefore, aerosols have a more uneven distribution than ozone, both horizontally and vertically, and are more concentrated near their source regions over continents and in the boundary layer. The more uneven distribution of tropospheric aerosols causes highly heterogeneous radiative forcing, which can lead to climate effects occurring regionally as well as globally (7, 19). From the perspective of air quality, background concentrations of anthropogenic aerosols in remote areas are much lower than those considered dangerous by air-quality standards, because of their shorter lifetimes, and intercontinental transport is more episodic than for ozone.

Studies of transboundary air pollution led to the investigation of possible intercontinental transport (20) and hemispheric air pollu-

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tion (21). Trans-Pacific transport of trace gases from Asia to North America has been reported most frequently (18, 22–26). Transport of Asian dust has been clearly identified in several events backed up by model analysis (27, 28). Although trans-Pacific transport of surface ozone has not been captured by observation, modeling studies have revealed that the Asian outflow enhances the concentration of surface ozone in the United States by a few ppbv (17).

Trans-Atlantic transport of O_3 and CO from North America to Europe during the period from 1990 to 1995 has been investigated (29) using data from Mace Head, on the west coast of Ireland, but relatively few episodes have been identified. Results from a chemical transport model and backward trajectories have shown that North American pollution contributes an average of approximately 5 ppbv to surface O_3 at Mace Head and about 2 to 4 ppbv over Europe in summer (up to 5 to 10 ppbv during some events) (30). The influence of North American pollution on European air quality is seen most frequently in the free troposphere (31, 32).

Transport of European outflow across Eurasia to Asia has scarcely been studied. A study of backward trajectories has shown that a substantial amount of air from Europe arrives over East Asia in winter and early spring (33). Analyses of surface O_3 and CO data obtained at Mondy, a remote mountain site in eastern Siberia south of Lake Baikal, have shown that air masses transported from Europe have average concentrations of O_3 that are 2 to 3 ppbv higher, and of CO that are 6 to 14 ppbv higher, than those arriving from other regions (34). Surface measurements of trace gases over Siberia have been made using the trans-Siberian Railroad between Moscow and Vladivostok (35, 36). Measurements of air pollutants over Eurasia made using commercial airlines have revealed high concentrations of O_3 in the upper troposphere (37, 38). Export of nitrogen oxides (NO_x), an important precursor of O_3 in the troposphere, from the polluted boundary layer and its production by lightning are the major sources over polluted continents and the clean ocean, respectively (39).

Wild and Akimoto (20) have studied the intercontinental transport and chemical transformation of O_3 between North America, Europe, and Asia using a global chemical transport model. Figure 2 shows the annual zonal, column, and meridional mean difference in O_3 mixing ratios (in ppbv) due to a 10% increase in emissions of three anthropogenic precursors of O_3 , NO_x , CO, and volatile organic compounds over East Asia, the United States, and Europe. The

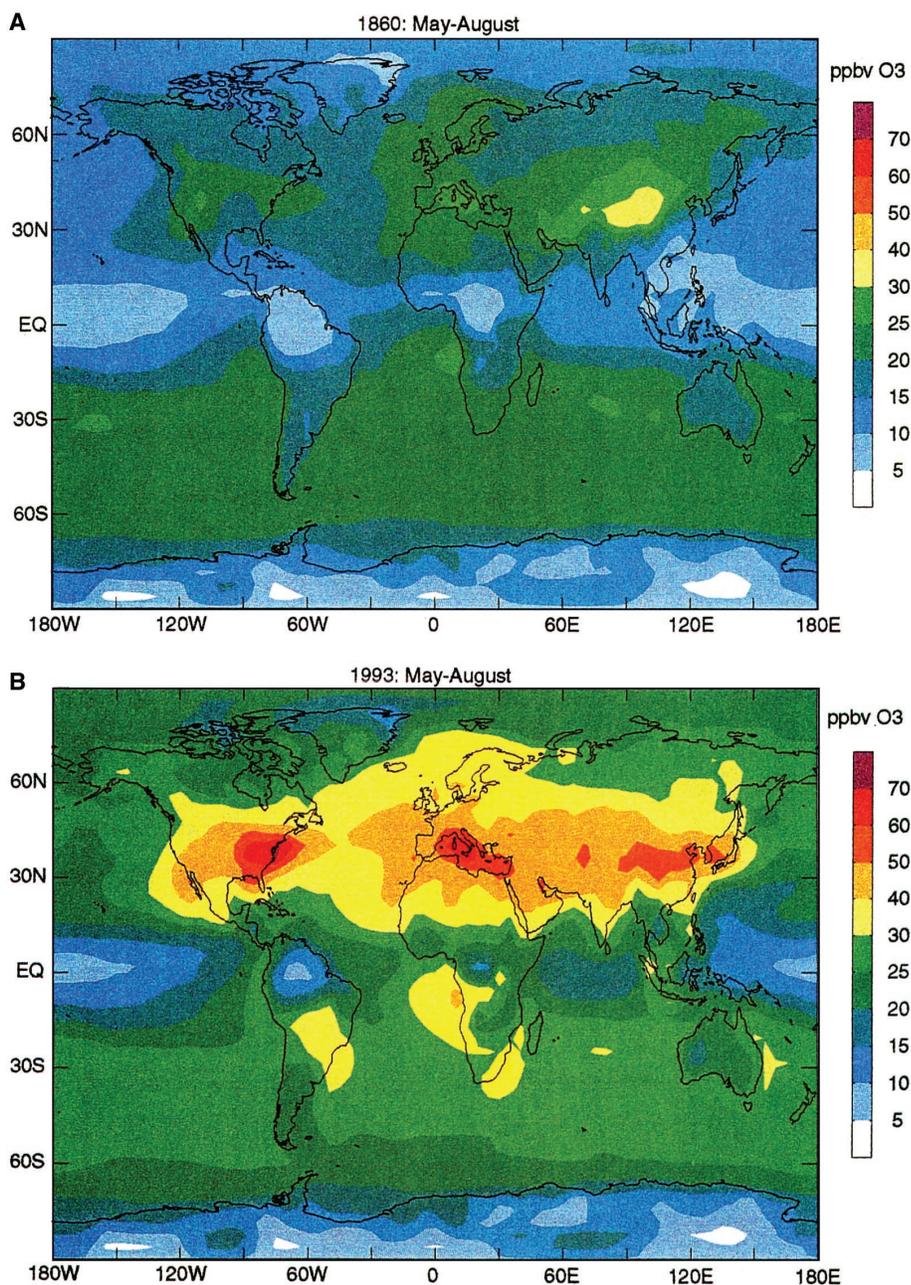


Fig. 1. Model-calculated surface O_3 during the growing season in the Northern Hemisphere (May through August) in (A) 1860 and (B) 1993 (13).

meridional mean values (Fig. 2, right) highlight the elevated concentrations of O_3 above the polluted boundary layer and downwind of the region. Vertical transport processes move O_3 and its precursors emitted from East Asia close to the tropopause and effectively spread O_3 through the upper troposphere on a hemispheric scale, over North America and Europe as well. Thus, intercontinental transport of O_3 from East Asia occurs mostly in the middle and upper troposphere. In contrast, vertical transport

of O_3 and its precursors is very weak in the case of European emissions, and downwind O_3 is confined to the boundary layer and middle troposphere. Thus, intercontinental transport of O_3 from Europe affects mainly near-surface O_3 concentrations in East Asia. European emissions produce the greatest enhancements over northern polar regions, whereas East Asian emissions occur sufficiently far south to affect the upper troposphere in the tropics and Southern Hemisphere as well (Fig. 2, left). Emissions

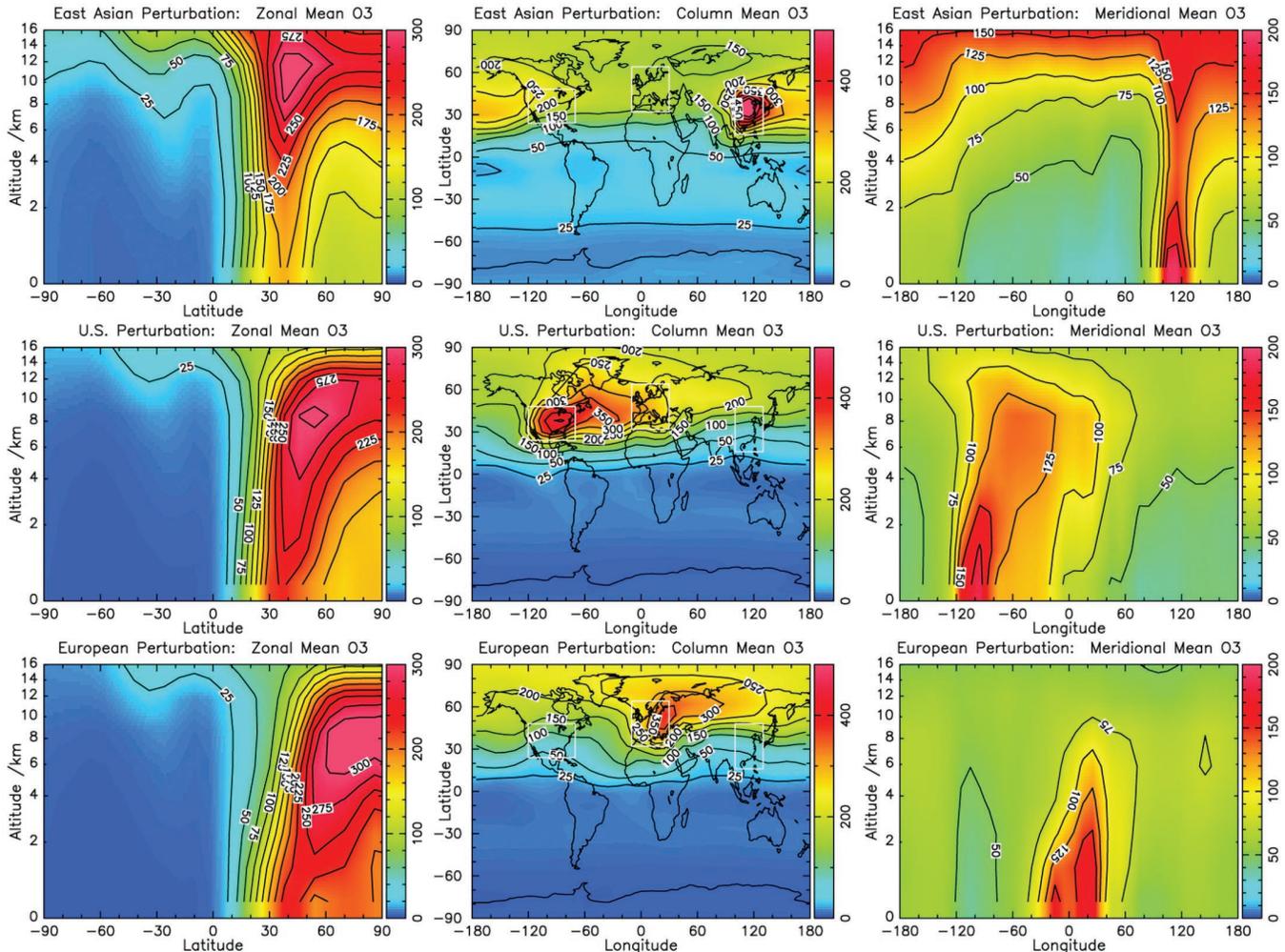


Fig. 2. Annual zonal (left column), column (center column), and meridional (right column) mean difference in O₃ mixing ratio (in ppbv) due to 10% increased emission of precursors over East Asia (top row), the United States (middle row), and Europe (bottom row) (20).

Fig. 3. Changes in anthropogenic NO_x emissions over North America (United States and Canada) (41), Europe (including Russia and the near and middle East) (42), and Asia (East, Southeast, and South Asia) [solid squares, (44); open squares, (45)]. The extrapolated line for Europe in the 1970s is based on OECD data (43).

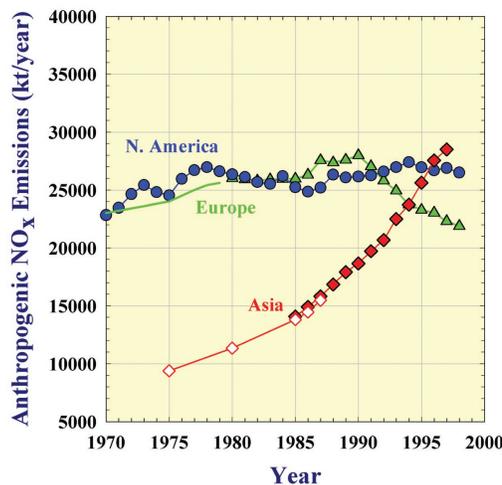


Figure 3 shows the recent trend in NO_x emissions by continent in the Northern Hemisphere (40). Emissions from North America include those from the United States and Canada (41); European emissions include those from Russia and middle and near-East Asia (42, 43); and Asian emissions include those from East, Southeast, and South Asia (44, 45). Emissions from North America and Europe (including adjacent regions) have been nearly equal since the 1980s and have each remained near 25 to 28 Tg/year. After 1990, an apparently decreasing trend in NO_x emissions from Europe is thought to be due to stringent emission controls in Western European countries. In contrast, Asian emissions, which contributed only a minor fraction of global emissions during the 1970s, have increased rapidly since then and surpassed emissions from North America and Europe in the mid-1990s. This situation is expected to continue for at least the next couple of decades (46). In addition, future increases of emissions from Africa and

from the United States have an effect between that of East Asia and Europe for vertical, meridional, and zonal transport (Fig. 2, middle

row). Thus, the O₃ from the United States affects Europe in the boundary layer and middle and upper troposphere.

South America, because of the economic growth there, would make global air quality more of an issue in the Southern Hemisphere, a region where only biomass burning has been considered important so far.

Finally, the importance of megacities as sources of regional and global pollution is worth noting. Megacities may be defined as metropolitan areas with over 10 million inhabitants, although there is no precise accepted threshold, and population estimates are not necessarily based on the same areas of reference. In 2001, there were 17 megacities according to United Nations statistics (47). With rapid growth of the world's population, particularly in developing countries, and continuing industrialization and migration toward urban centers, megacities are becoming more important sources of air pollution from associated mobile and stationary sources. Air quality in megacities is thus of great concern, as illustrated by a study in Mexico City (48). Although the health effects of air pollution on the inhabitants of megacities are a serious social problem, its regional and global environmental consequences are also of great concern. Therefore, local, regional, and global air-quality issues, and regional and global environmental impacts, including climate change, should be viewed in an integrated manner.

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Modern Global Climate Change

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Modern climate change is dominated by human influences, which are now large enough to exceed the bounds of natural variability. The main source of global climate change is human-induced changes in atmospheric composition. These perturbations primarily result from emissions associated with energy use, but on local and regional scales, urbanization and land use changes are also important. Although there has been progress in monitoring and understanding climate change, there remain many scientific, technical, and institutional impediments to precisely planning for, adapting to, and mitigating the effects of climate change. There is still considerable uncertainty about the rates of change that can be expected, but it is clear that these changes will be increasingly manifested in important and tangible ways, such as changes in extremes of temperature and precipitation, decreases in seasonal and perennial snow and ice extent, and sea level rise. Anthropogenic climate change is now likely to continue for many centuries. We are venturing into the unknown with climate, and its associated impacts could be quite disruptive.

The atmosphere is a global commons that responds to many types of emissions into it, as well as to changes in the surface beneath it. As human balloon flights around the

world illustrate, the air over a specific location is typically halfway around the world a week later, making climate change a truly global issue.

Planet Earth is habitable because of its location relative to the sun and because of the natural greenhouse effect of its atmosphere. Various atmospheric gases contribute to the greenhouse effect, whose impact in clear skies is ~60% from water vapor, ~25% from carbon dioxide, ~8% from ozone, and the rest from trace gases including methane and nitrous oxide (N₂O). Clouds also have a greenhouse effect. On average, the energy from the sun received at the top of the Earth's atmosphere amounts to 175 petawatts (PW) (or 175 quadrillion watts), of which ~31% is

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