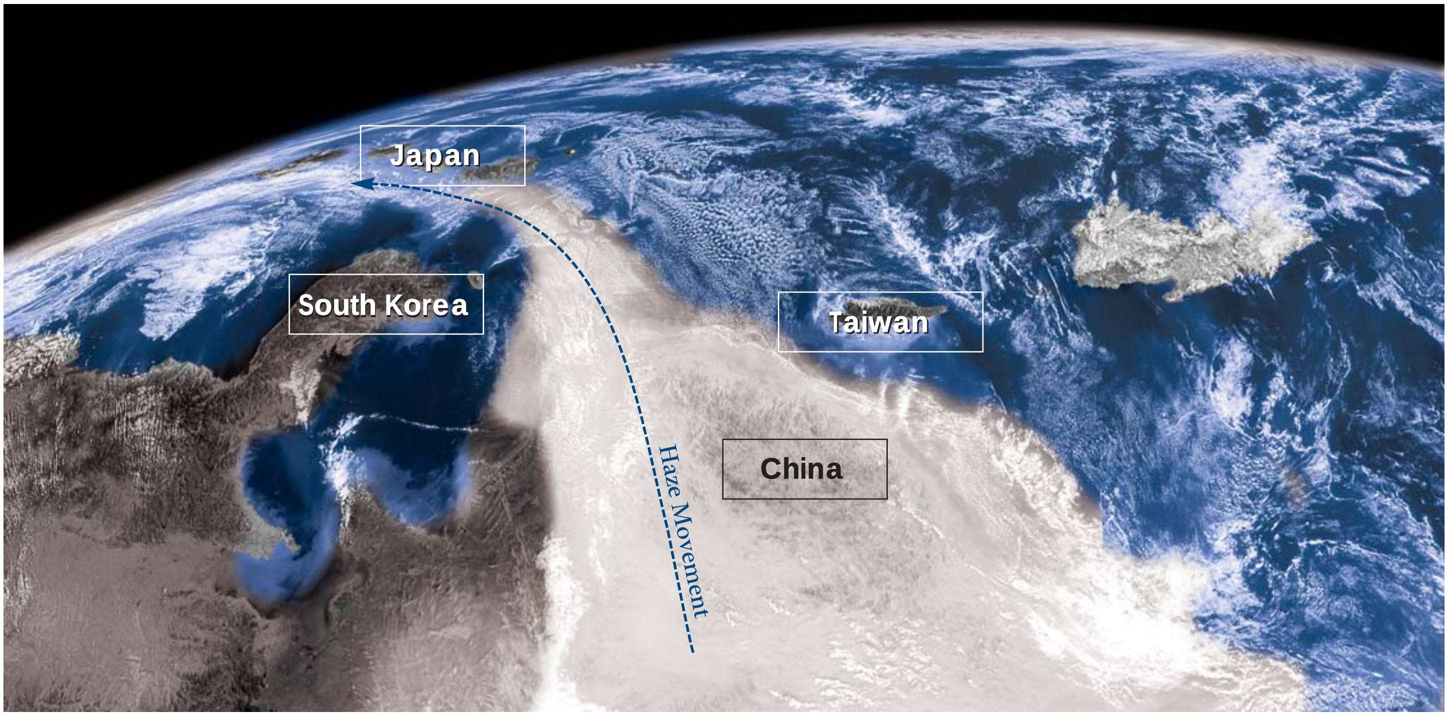

Satellite image of brown haze flowing across the East China Sea past the Korean Peninsula and northeastward toward Japan. Image courtesy of the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE.

Global Warming

Veerabhadran Ramanathan

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The effect of greenhouse gases on global warming is, in my opinion, the most important environmental issue facing the world today. Our knowledge of the underlying causes of climate change is growing, but the problem brims with uncertainties, raising serious scientific and ethical questions.

In studies of global temperatures, one question always arises at the outset: When did humans become a major force in modifying the climate system? My own timetable begins in the 1950s, when the world's population increased by over 60 percent, resulting in a perceptible impact on many indices of change. With high-precision observations, my late colleague, Dave Keeling, produced the single most important times-series data set for the study of global change. He demonstrated that the amount of carbon dioxide in the atmosphere increased by about 20 percent since the time he began his work in the mid-1950s. If you take one million molecules of air, approximately 375 will be carbon dioxide. Compare this with the fact that in the last four hundred thousand years, the amount of CO_2 concentration has never been larger than 290 parts per million.

The rapidity of the increase leaves little doubt that human impact is the cause. What lies behind such a significant increase in a relatively short time? The lifetime of carbon dioxide is over a century. If today you release a can of CO_2, roughly 25 – 35 percent of it will still be with us a hundred years from now.

What happens to this CO_2? The air carries it around until it covers the entire planet like a blanket of gases. In fact, no matter where we measure – the Arctic, the Antarctic, the surface, or 20 miles above the surface – we detect the increase in CO_2. Fossil-fuel combustion and biomass burning are the major sources for this increase.

Why should we worry about this blanket of added CO_2 and other greenhouse gases? The fundamental energy source for the planet is sunlight. However, not all of the solar energy is absorbed: about 30 percent is reflected back to space by clouds, the atmosphere, and land and sea surface, including sea ice, ice sheets, and the like. The planet is warmed by the remaining 70 percent and, in turn, reradiates the heat as infrared energy (also known as thermal energy or heat radiation). Over the long term, climate is governed by the balance between the incoming solar heating and the cooling associated with the outgoing infrared energy. The added CO_2 upsets this balance by absorbing and reemitting the infrared energy. In this process, the blanket of CO_2 acts just like a wool blanket on a cold night by trapping the outgoing infrared heat within the surface-atmosphere system and causing the planet to become warmer.

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110 years ago by the Swedish Nobelist Svante Arrhenius. In the mid-1970s a series of complications began to unfold, leading to the realization that carbon dioxide was not the only cause of global warming. Mario Molina and Sherwood Rowland's research on the impact of chlorofluorocarbons (CFCs) on the ozone hole led to my investigations on the potential greenhouse effect of CFCs. Our research revealed the unexpected result that adding one molecule of CFC to the atmosphere would have the same greenhouse effect as adding more than ten thousand molecules of CO_2. The fact that CFCs, which are relatively rare in the atmosphere, could be such a powerful force in global warming was initially met with disbelief. But as other researchers reproduced our findings, a Pandora's box of greenhouse gases, including methane, ozone, halocarbons used as refrigerants and propellants, and nitrous oxide from fertilizer, began to open.

We could no longer ignore the effect of greenhouse gases and our sense that global warming would occur much earlier than we might have imagined. My work with climatologist Roland Madden some twenty-five years ago revealed that the impact of global warming would become discernible by the year 2000. Meeting in 2001, the Intergovernmental Panel of Climate Change, consisting of a group of over a thousand scientists, confirmed our prediction.

Coincident with the greenhouse gas warming is the appearance of atmospheric brown clouds. If greenhouse gases are the ultimate end product of fossil fuel and CO_2, then particulates in the air represent an intermediate phase. A brown haze is generally associated with urban areas, but in 1999, the Indian Ocean Experiment (INDOEX), involving more than two hundred scientists, focused on a brown cloud that spans an entire continent and ocean. As coleader of this experiment (with P. J. Crutzen), which deployed six aircraft and two ships with several tens of instruments, I had the opportunity to observe from the C-130 aircraft the brown clouds spreading from South Asia and blanketing most of the North Indian Ocean. We then used satellite data to show that the South Asian brown haze occurs every year generally between November and May. It consists of a 3 km mixture of anthropogenic (human-produced) sulfates, nitrates, organics, black carbon, dust and fly ash particles, and natural aerosols such as sea salt and mineral dust. Measurements from aircraft, ships, and surface stations involved in the experiment found that biomass burning and fossil-fuel combustion contribute as much as 75 percent to the observed aerosol.

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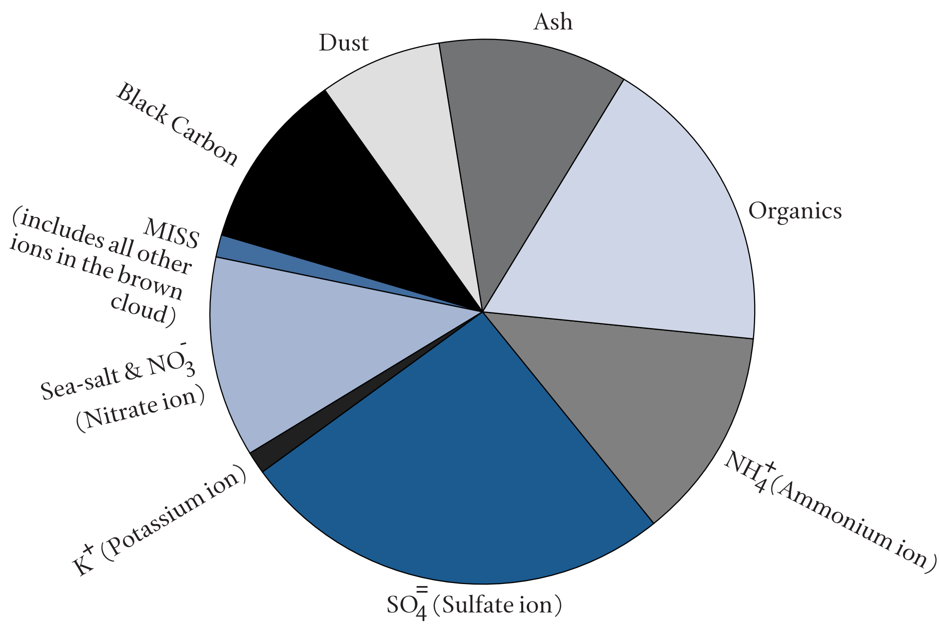
Black carbon is probably the most insidious component of the haze as far as health is concerned; it is also the most important factor in terms of climate change. During the INDOEX campaign we deployed a suite of high-precision radiometers to discover that black carbon and other absorbing particles in the brown haze over the Indian Ocean and the Arabian Sea reduced sunlight by as much as 10 – 15 percent. The sunlight-reduction effect at the surface was larger by a factor of two or more than estimated by climate models. In terms of the ocean surface, black carbon in the brown haze reduces the average radiative heating by as much as 10 percent and enhances atmospheric solar radiative heating by as much as 50 – 100 percent.

Composition of a brown cloud



Aerosols also produce more cloud drops, which increase the reflection of solar radiation by clouds, adding to the surface-cooling effect; and decrease the size of cloud drops and suppress precipitation.

The link between aerosols and precipitation represents an added complication. As emissions from fossil fuel and black carbon have increased, monsoonal rainfall and surface sunlight have decreased. Modeling research conducted by us with the climate-system model developed by the National Center for Atmospheric Research in Boulder, Colorado, indicates that three factors may contribute to the drying effect. First, sunlight provides the energy to evaporate water from the ocean, causing rainfall. With reduced sunlight the evaporation from the ocean decreases and, as a result, the rainfall decreases. Second, as solar absorption by black carbon heats the atmosphere, it cools the surface by shielding it from the sun. This redistribution of sunlight causes warmer air to overlie the colder surfaces, suppressing rainfall. Finally, the brown haze appears to slow summer monsoonal circulation, leading to a reduction in precipitation over South Asia. These findings are important reasons for reducing air pollution.

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Lest you think that air pollution is a confined problem, I want to emphasize that long-range wind transport means that pollution on the East Coast of the United States is going across the Atlantic to Europe, European pollution is traveling to Asia, and Asian pollution is coming back to America. To better understand how atmospheric brown clouds impact the environment, climate, and the quality of life, we have launched a project to integrate scientific findings with impact assessment. With support from the United Nations Environment Program and the National Oceanic and Atmospheric Administration, we are working with scientists from Sweden, Germany, China, India, Japan, and other Asian countries to develop a system of strategically located ground-based observatories in the Indo-Asian and Pacific regions to monitor atmospheric pollution. Together with satellite data and periodic aircraft measurement, these observatories will document changes in aerosol content, pollutant gases, and some greenhouse gases, enhancing the predictive capacities of climate models. We hope that in time this work will revolutionize how we look at the atmosphere.

However, we continue to face a number of uncertainties in our efforts to predict climate change. First, by the beginning of the next century, the global population will reach about nine billion, and people in the developing world will be striving to achieve Western standards of living. Their efforts will result in enormous amounts of atmospheric pollutants and other stresses on the environment.

Second, there are the unsolved questions surrounding the rate and masking of global warming. The extent of global warming is not fully reflected in the Earth's *surface* temperatures. The additional heat trapped by the increase in greenhouse gases from the late nineteenth century to the present time has committed the planet to a global warming in the range of 1°C to 3°C. We have realized only a fraction (25 – 50 percent) of this warming. Some of this warming has been masked by the dimming due to brown clouds, and the remaining heat is stored in the depths of the ocean to be released later. Through the process of convective overturning, oceans transfer infrared energy to their deepest layers and hold the heat, delaying the impact of global warming. Whether this stored heat will warm the atmosphere in a few decades or a few centuries is unknown. The delay of the warming by decades to centuries by the flywheel effect of ocean mixing, when combined with the century or more lifetime of CO_2 (and molecules of other greenhouse gases) in the atmosphere, presents policymakers with the central moral dilemma of the global-warming problem. Every decade we delay in taking action, we are committing the planet to additional warming that future generations have to deal with.

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The masking effect is equally troubling. We now know that the surface-cooling effect of aerosols may have masked as much as 50 percent of the global warming caused by greenhouse gases, presenting a serious dilemma for the global community: If we attempt to reduce air pollution because of its effect on health, we may see an amplification of global warming. At the same time, if greenhouse gases are curbed because of our concerns about global warming, the brown clouds may weaken the Earth's water cycle, particularly the monsoonal rainfall in Asia, leaving us with conflicting options involving those regions negatively impacted by global warming and those negatively impacted by air pollution.

Although we talk about global averages in discussions of global warming, we cannot forget the marked changes that also occur at the regional level, affecting most severely the poorest people on Earth. International cooperation among scientists and among nations will be essential if we are to effectively address the formidable political, social, and ethical consequences of global warming. Among the many obvious reasons for the urgent need for international collaboration is the fact that the developed nations are the major contributors to the greenhouse gases while the developing nations are the major sources for particles in the brown clouds. ■