The global effects of ASIAN HAZE

A thick layer of aerosols just discovered above the Indian Ocean by an international team may be a far-reaching influence on climate systems

The more people there are, and the higher their standard of living, the greater the pressure on natural resources. As the world population may double in a few generations, with Asia in the lead, the urgent question is whether the earth can sustain such developments. Of concern here is the rapid increase of air pollution in Asia and, more especially, the hitherto unknown existence of a persistent winter haze extending over much of the northern Indian Ocean, from the Arabian Sea to the Bay of Bengal.

The layer of haze was the discovery of the Indian Ocean Experiment (Indoex), an international field experiment that has been collecting surface and atmospheric data over the tropical Indian Ocean since 1996. It is a major effort. Two ships, four aircraft, and a number of satellites share the task with a ground-based surface station, located on Kaashidhoo, an island of the Maldives south of India [Fig. 1]. Malé, the capital of the Maldives, is a highly strategic location because the winter monsoon carries polluted Asian air over it in a steady northeasterly flow, so that the observational platforms downwind of the source regions were in a good position to trace emissions, chemical transformations, and global pollution exports.

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Indoex has cost $25 million and involved more than 150 scientists from India, France, Germany, the Netherlands, and Sweden, as well as the United States. Support for the U.S. component was provided mainly by the National Science Foundation and the Department of Energy, with participation by NASA and the National Oceanographic and Atmospheric Administration.

Most of the haze consists of aerosols ranging in size from tens of nanometers to a few micrometers. Chemically, the particles are a complex mix of sea salt, sulfates and nitrates, mineral and agricultural dust, soot, fly ash, and organic substances. About 60 percent or more result from human activity. As these aerosols scatter and absorb solar radiation, they are a major source of uncertainties in predictions of global warming. Studies modeling their activity suggest that they may offset a significant fraction of the global warming due to increased greenhouse gases.

Emissions of primary pollutants

Primary pollution emissions may be short- or long-lived. The first species affect only regional air quality, whereas the second upset the global balance of radiation energy in the atmosphere [Table 1]. The radiation energy balance has three components: the sunshine entering the atmosphere from above; the sunshine reflected into space by the surface-atmosphere system below; and the difference between the two, which is the net solar energy absorbed by the planet. The third component is the infrared energy emitted into space. On a global and long-term (about 10 years) average, the sunlight absorbed

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is nearly balanced by the infrared radiation sent into space by the planet.

The short-lived compounds last for a matter of hours up to several months. The gases included can be toxic, especially when they are highly concentrated and close to their source. The chief examples are sulfur dioxide, carbon monoxide, nitrogen oxides ($NO_x = NO+NO_2$), and a host of non-methane hydrocarbons.

The long-lived category includes gases that can outlast a century. The main long-lived compounds are carbon dioxide, methane, nitrous oxide (NO_2), and chlorofluorocarbons. Owing to their slow removal rate, they accumulate in the atmosphere, and they disperse globally because large-scale mixing typically takes months within a hemisphere to a year betweem hemispheres. Because these gases absorb infrared radiation, less of this energy is emitted into space. The ability of these gases to reduce the infrared emission to space is popularly known as the greenhouse effect.

Human activities also result in the injection of microscopic particles called aerosols, such as elemental carbon (soot) and dust, which also perturb the global radiation energy budget.

The gas that contributes most to global change is CO_2. Nearly 300 billion metric tons of carbon have been emitted by machinery since the Industrial Revolution began. Roughly half remains at large in the atmosphere, as the lifetime of carbon dioxide is about a century. As a consequence, the atmospheric carbon dioxide reservoir has grown by nearly 30 percent since the steam engine's arrival. In these days, the use of liquid and solid fuels (mainly oil and coal combustion) contributes about equally, adding up to 75–80 percent, whereas natural gas combustion contributes 15–20 percent. The remainder (about 5 percent) results from cement production.

By far the greatest single contributor to CO_2 emissions from fossil fuels is the United States with 1450 teragrams of carbon per year, followed by China with approximately 920 TgC/yr (1 Tg = 10^{12} g). India is fifth on the list with about 270 TgC/yr. Russia, Japan, and several western European countries, such as Germany, the UK, and Italy also rank among the top 10 emitters of carbon dioxide.

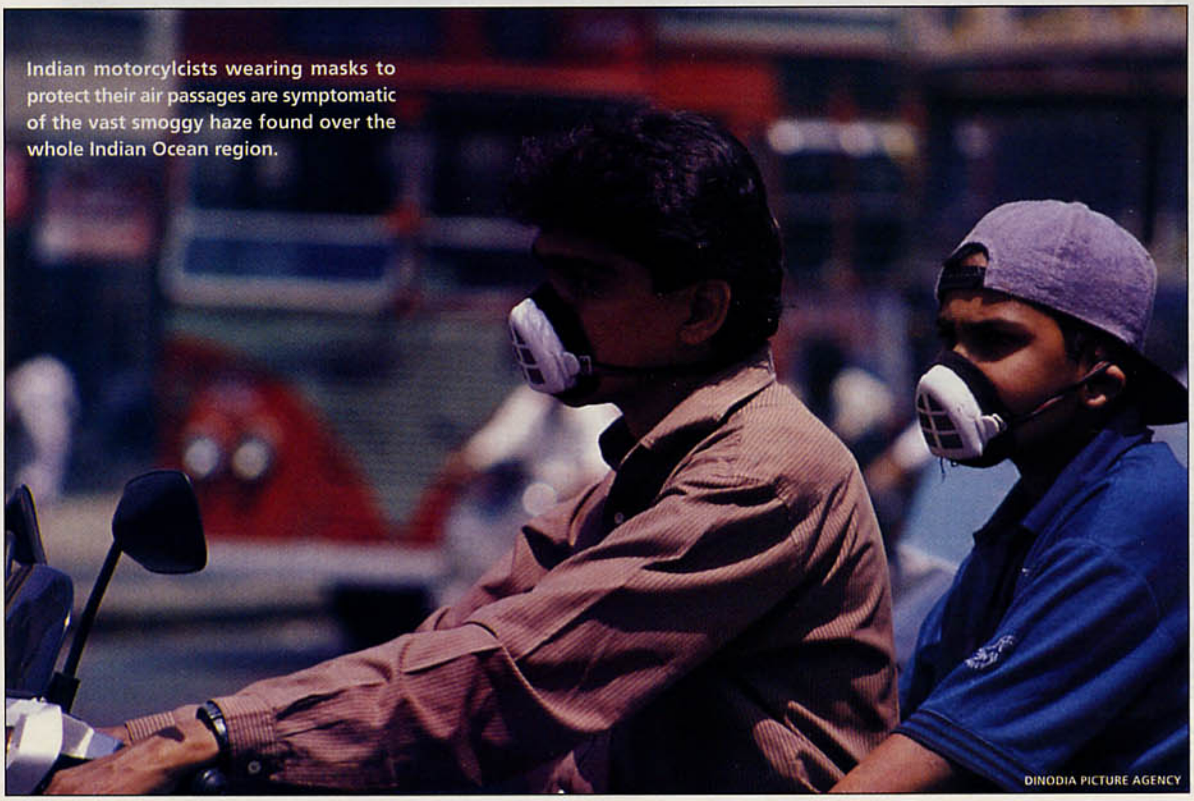
There is one important difference, though. The per capita carbon dioxide emission in most top 10 countries exceeds two million grams of carbon annually, whereas in China and India it is far less—in China, three-quarters of a million grams and in India, about three-tenths of a million. Undoubtedly, the fossil fuel consumption and per capita carbon dioxide emissions of Asian countries will grow in the next decades. It is also evident that this increased carbon dioxide emission, mostly due to coal combustion, will be associated with the release of other pollutants, such as hydrocarbons, carbon monoxide, sulfur dioxide, nitrogen oxides, and soot.

Chemical formation of secondary pollutants

Secondary pollutants are formed within the atmosphere through chemical processes. Prime examples are ozone and nitric and sulfuric acid.

Ozone is a photochemical oxidant that has unhealthy effects on people and crops. It is a by-product of the atmospheric breakdown of hydrocarbons and carbon monoxide under the influence of short-wave solar radiation (hence *photo*chemistry). Ozone formation is catalyzed by nitrogen oxides. Therefore, the mixture of exhaust gases from combustion processes, which includes all the ingredients of photochemical smog, very efficiently produces ozone, especially at low latitudes and during summer at middle latitudes.

The atmospheric transformation of nitrogen oxides and sulfur dioxide produces nitric and sulfuric acid, respectively. These compounds contribute to acid rain. Sulfuric acid condenses onto aerosol particles in the atmosphere because it



Indian motorcylcists wearing masks to protect their air passages are symptomatic of the vast smoggy haze found over the whole Indian Ocean region.

has a low vapor pressure. Since aerosols usually contain water and other solutes, the sulfuric acid dissociates into sulfate. Rain rids the atmosphere of sulfate aerosols, so that they endure on average for only a few days in humid regions—at middle latitudes, say—whereas they can hang around for weeks in the dry subtropics.

The numerous other types of "man-made" aerosols include nitrates, organics, soot, and agricultural dust. In addition, there are natural aerosols such as sea salt, mineral dust, and sulfates. In spite of the fact that the sulfates and most other aerosols last for a matter of days or weeks only, they can be so abundant in the polluted atmosphere that they affect the climate, competing with the long-lived greenhouse gases.

Sources of temperature change

The ways in which these aerosols can perturb the climate are complex. For instance:

- Sulfates, organics, and nitrate aerosols scatter short-wave solar radiation and thus increase the amount of sunlight reflected into space. In effect, the aerosols make the planet look brighter. Hence, an increase in these aerosols tends to cool the earth's surface and the atmosphere, a phenomenon called negative climate forcing.
- Soot, on the other hand, whether from fossil fuel or biomass combustion, absorbs sunlight that would have otherwise reached the surface; thus it tends to heat up the atmosphere and cool the surface.
- Although the aerosols absorb infrared radiation, their greenhouse effect is much smaller than their effect on the solar radiation.
- Aerosol particles, especially sulfate particles, play an important role in the atmosphere because droplets of water tend to form around them in clouds. The cooling effects of the sulfates might even be strengthened because increasing aerosols add to the number of cloud droplets, which makes the clouds brighter and the earth cooler (assuming an unchanged amount of liquid water in the clouds). Moreover, with more cloud droplets competing for the same amount of water, the drop size becomes smaller and as a result the cloud may become less efficient at raining.

The Indian Ocean Experiment has collected data on the effects of pollution on the radiation balance of the atmosphere, and the data is being currently analyzed.

The Inter-Tropical Conversion Zone

Indoex has been involved in making a large number of measurements over the tropical Indian Ocean since 1996 and will continue through 2001. A high point was the intensive field phase during the first three months of 1999, which included observations made on the ground, at sea, in the air, and in space.

Two of the aircraft involved flew from Malé. One was a C-130 from the National Center of Atmospheric Research in the United States, equipped to measure aerosols and radiation. It detected a brownish aerosol layer up to an altitude of 1–3 km. From combined surface, ship, and satellite observations it was inferred that the aerosol layer extended over much of the Indian Ocean to 5 °S latitude, the location of the Inter-Tropical Convergence Zone (ITCZ). This zone is a region of deep convection that demarcates the meteorological northern from the southern hemisphere.

Due to the large uncertainties in using satellite data to retrieve aerosols over land, the aerosol concentrations over the Indian subcontinent have not been calculated with precision. But the limited surface data suggest the aerosol layer over the subcontinent will compare with that over the Arabian Sea and Bay of Bengal.

Limited analysis of the data suggest that aerosols stemming from industry and other forms of human activity can contribute as much as 70 percent to the total aerosol burden. More detailed analyses are required to understand the spatial and temporal variations in and relative importance of man-made and natural aerosols.

Indeed, by penetrating the Inter-Tropical Conversion Zone into the southern hemisphere, the aircraft observed a tremendous contrast between clean and polluted air masses across the Indian Ocean. Man-made aerosols can reduce solar radiation reaching the Indian Ocean by as much as 10 percent. This changes the atmospheric radiation profile such that solar heating of the ocean is much

1. Origins and extent of atmospheric pollution

	Long-lived greenhouse gases				Short-lived air pollutants				
Type of pollutant	CO_2	CH_4	N_2O	CFCs [a]	CO	NMHC	NO_x	SO_2	Soot
Sources in 1990s (teragrams per year of carbon or nitrogen or sulfur dioxide)									
Industrial and fossil-fuel related	5500	125	1.3	0.65 (1990)	125	120	25	70	7
Tropical agricultural and biomass burning [b]	1600	275	3	—	400	70	10	2	6
Natural	—	200	7.5	—	160	750	10	20	—
Volume mixing ratios									
Pre-industrial (about 1850)	280 ppm	750 ppb	270 ppb	0	Unknown				
Present (1990s)	360 ppm	1730 ppb	310 ppb	0.8 ppb [a]	50–500 ppb	2–10 ppb	0.05–5 ppb	0.05–5 ppb	1–103 ngC/m³
Lifetimes and rates of increase									
Atmospheric lifetime	50–200 years	8 years	120 years	50–100 years	2–3 months [c]	Hours-weeks [c]	1–2 days [c]	A few days [c]	Days-weeks [c]
Annual rate of increase in 1990s	0.5%	0.5%	0.2%	0.5%	Regionally variable				

NMHC = non-methane hydrocarbons Ppm, ppb = parts per million/billion by volume

Source: Indoex

[a] These are chlorofluorocarbons CFC-11 and -12, phased out under the Montreal Protocol. The mixing ratio for CFC-11 is declining by 0.3 percent per year, for CFC-12 increasing by 0.7–1 percent per year.
[b] But large-scale fertilization and afforestation may remove 1600 Tg of carbon per year from the atmosphere.
[c] Ranges indicate clean background air to regional pollution.

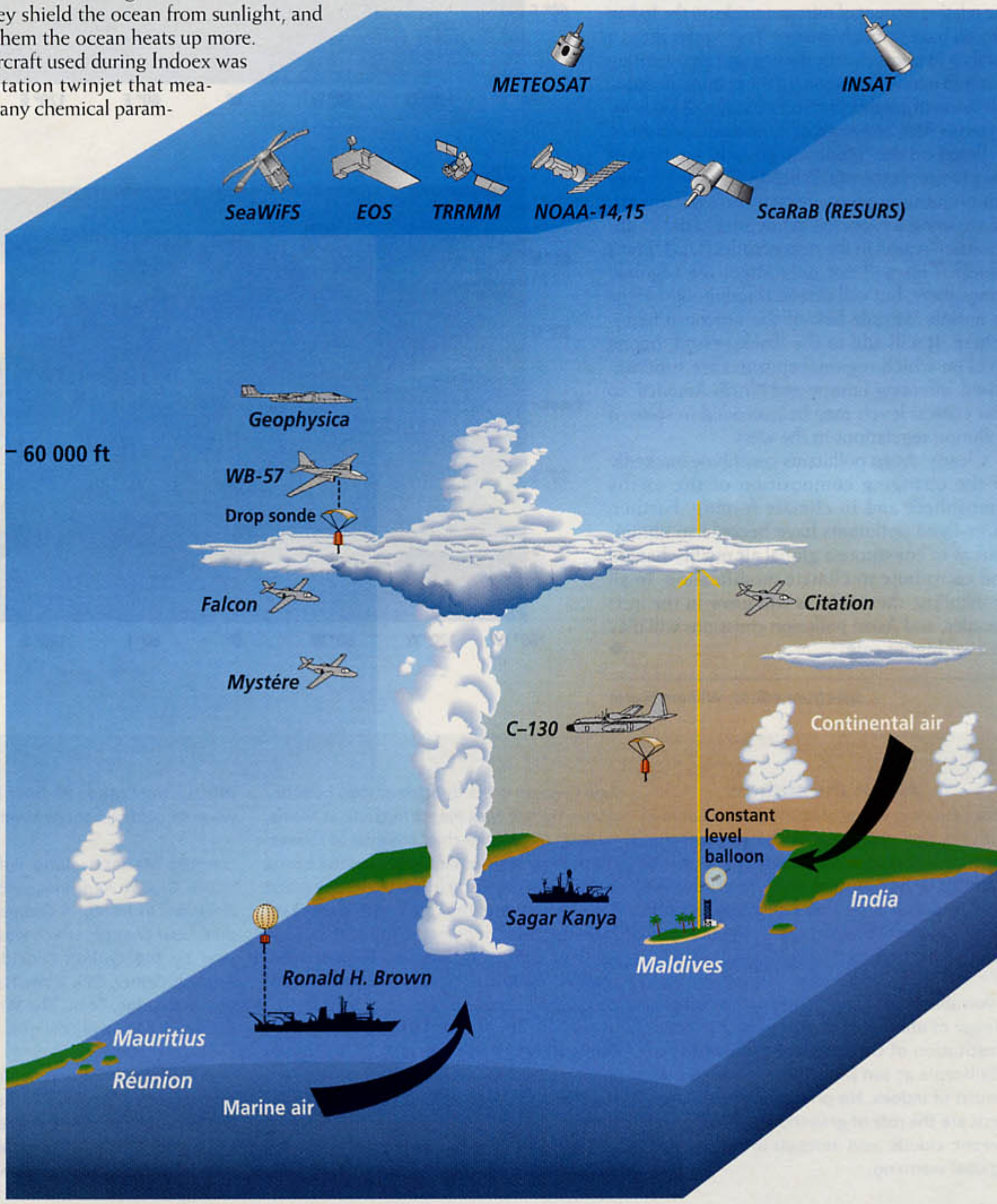
reduced, while in the lower atmosphere containing the haze layer, it is greatly enhanced, which raises a number of environmental questions:

- Do the Indian Ocean aerosols amplify the greenhouse warming or mitigate it?
- Can they suppress turbulent mixing in the boundary layer? Suppression of mixing can worsen the pollution buildup in the boundary layer and hamper the exchange of energy and moisture between sea and air.
- How does the reduction of solar radiation influence life processes in the surface of the ocean?
- Does less water evaporate from the ocean surface when aerosols reduce the amount of sunlight reaching the ocean? This question arises because the balance between absorbed solar radiation and evaporation of moisture is close.
- Can the aerosol solar heating burn off the trade cumulus clouds? They shield the ocean from sunlight, and with fewer of them the ocean heats up more.

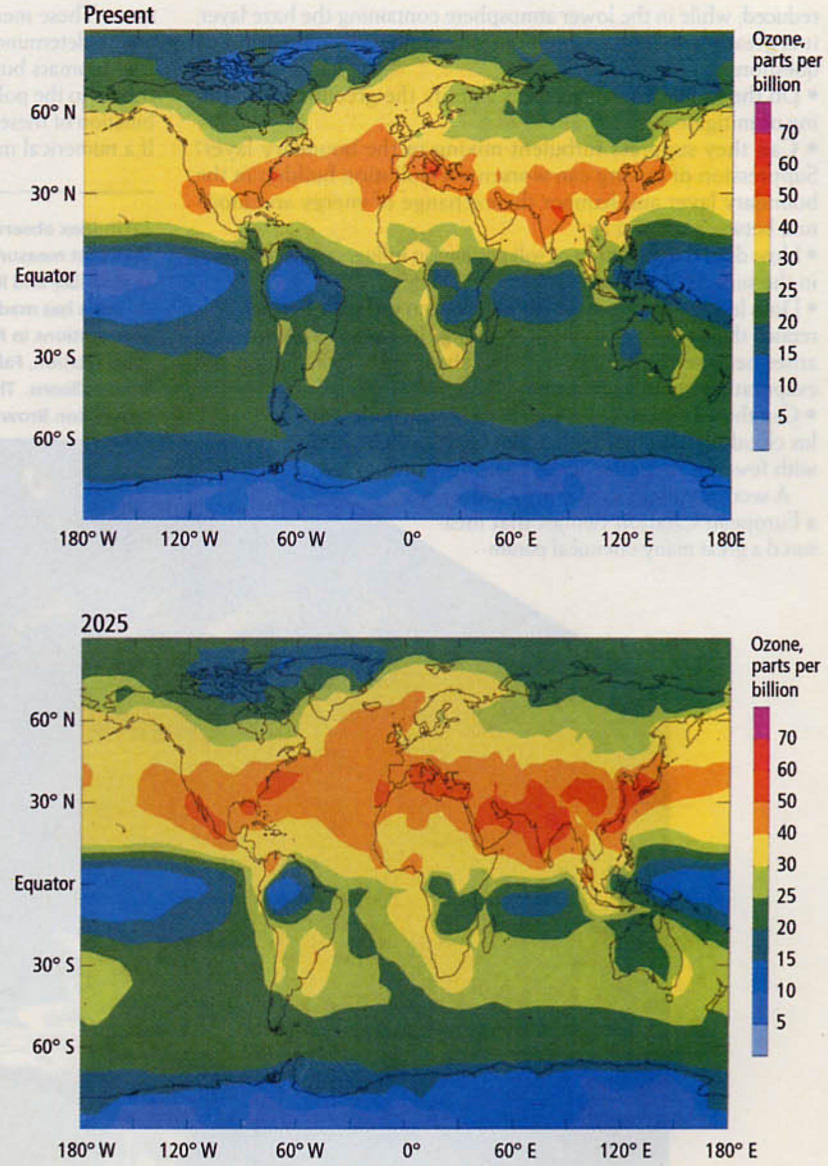
A second aircraft used during Indoex was a European Citation twinjet that measured a great many chemical parameters. These measurements are used to identify pollution sources and to determine levels of photochemical pollution. They indicate that biomass burning, coal combustion, and transportation contribute to the pollution of the air above the Indian Ocean. The combination of these sources burdens air quality throughout the region. If a numerical model of the atmosphere is applied, the impact of

[1] Indoex observational sites and platforms start with a tier of satellites that measures reflected and emitted radiation from earth in several visible and IR wavelengths at a resolution of several kilometers.

India has made available the research vessel Sagar Kanya and surface stations in Mauritius, Mount Abu, and Trivandrum. Europe supplies Citation, Falcon, Mystère, and Geophysica aircraft, plus constant-level balloons. The United States provides a C-130 aircraft, the research vessel Ron Brown, and the Kaashidhoo Climate Observatory.



[2] **Annual mean ozone mixing ratios near the surface of the globe are shown for the present atmosphere [above] and predicted from a numerical model for 2025 [below]. The 2025 prediction is based on the "moderate growth" scenario of the Intergovernmental Panel on Climate Change. Note that the critical level of ozone, above which crops and natural vegetation are damaged, is often defined as 40 parts per billion by volume in the growing season.**



these sources of pollution on large-scale ozone formation can be assessed. It appears that ozone in photochemical smog develops analogously to smog in western countries [Fig. 2], except that the relative amount of nitrogen oxides in the Indian Ocean haze is much smaller. The oxides act as a catalyst in photochemical smog and are a limiting factor in ozone formation. In the coming decades, when use of combustion technology will likely increase in Asia, emissions of these oxides will grow.

Based on the "moderate growth" scenario of the Intergovernmental Panel on Climate Change (an ongoing process of scientific assessment), ozone smog is expected to intensify in the southern Asian region in the next decades [Fig.2, lower panel]. This will not only affect the regional atmosphere, but will extend throughout the low to middle latitude belt of the northern hemisphere. It will add to the "background" ozone level on which regional episodes are superimposed, affecting Europe and North America, so that critical levels may be exceeded in spite of pollution regulations in the west.

Clearly, Asian pollutants contribute markedly to the changing composition of the earth's atmosphere and to climate forcing. Further, short-lived pollutants have become so ubiquitous as to constitute a global air quality hazard and contribute to climate modification. In all probability, these effects will grow in the next decades, and Asian pollution emissions will play an ever bigger role. ◆

Spectrum editor: William Sweet

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To probe further

Two authors of this article, V. Ramanathan and P.J. Crutzen, and score of others, are listed as authors of *Indian Ocean Experiment* (INDOEX), 1996, the University of California at San Diego's Center for Clouds, Chemistry and Climate (C4) publication #162 and INDOEX publication #3. Both are available at www-c4.ucsd.edu and www-indoex.ucsd.edu

Gregory Marland along with four others wrote *Global, Regional, and National CO_2 Emissions* In *Trends: A Compendium of Data on Global Change*, which was published this year by the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn. The World Wide Web address is cdiac.esd.ornl.gov.

In press from Krishnan Rajeev, V. Ramanathan, and Jens Meywerk is "Regional aerosol distribution and its long-range transport over the Indian Ocean" (December issue of the *Journal of Geophysical Research*, 1999).