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NEW DIRECTIONS

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New Directions: Atmospheric Brown "Clouds" ☆

In February 1999, over 200 scientists from India, Europe and USA gathered in the islands of the Maldives to conduct the Indian Ocean Experiment (INDOEX). As reported by Ramanathan and coworkers (Journal of Geophysical Research, 106 (2001), 371–399), INDOEX revealed the so-called "brown cloud" phenomenon over the Northern Indian Ocean region with a large impact on the solar radiative heating of the region. The impact on the regional gas phase chemistry of the region, as reported by Lelieveld and coworkers (Science, 291 (2001), 1031–1036), was also large. The fundamental message from INDOEX is that due to long-range transport, what we normally associate with urban haze can span an entire sub-continent plus an ocean basin. The persistence of the haze during the 6 month long dry season, its black carbon content and the large perturbation to the radiative energy budget of the region have significant implications to the regional and global water budget, agriculture and health. The logical implication is that air pollution and climate changes are intricately linked and should be addressed under one common framework (see the ABC concept paper by Ramanathan and Crutzen in http://www-ABC-ASIA.ucsd.edu).

In a related but independent development, Kaufman et al. (Nature, 419 (2002), 215–223) published satellite results for the aerosol optical depth over both land and ocean. These data revealed that pollution aerosols are found in and downwind of all inhabited regions of the planet and each of these hazes spreads over a large region. The data showed a Northern American haze extending all the way into the mid-Atlantic Ocean and Europe; heavy aerosol loading in north and eastern Europe and the Mediterranean Sea; dust plume from Sahara extending across tropical Atlantic; Dust and anthropogenic haze from Mongolia and China extending all the way across the Pacific; and the biomass burning aerosols from Africa and the Amazon region extending into the Atlantic. Thus we should think of the brown clouds of Asia, Africa, North and South America and Europe. Accordingly, we now propose that the phenomenon be referred to as "Atmospheric Brown Clouds" (ABC). Haze instead of cloud is a more correct designation from a purely meteorological definition, but the distinction is subjective, for a haze will become a cloud if the relative humidity reaches saturation. Under the sponsorship of the United Nations Environmental Program (UNEP) an international program entitled ABC, starting with Asia has been created (http://www-ABC-ASIA.ucsd.edu). In what follows we will summarize INDOEX findings and discuss ABC and future research that is needed in this important area.

The equatorial Indian Ocean is a unique natural laboratory for studying the impact of anthropogenic aerosols on climate, because pollutants from South and S.E. Asia is directly connected to the pristine air from the southern hemisphere by a low altitude monsoonal flow into the inter tropical convergence zone (ITCZ). This fact provided the main motivation for INDOEX (http://www-indoex.ucsd.edu/publications/white_paper/). The South Asian brown haze covers most of the Arabian Sea, Bay of Bengal, the Northern Indian Ocean and the South Asian region and extends from about November to May and possibly longer. The brownish haze consists of a mixture of anthropogenic sulfate, nitrate, organics, black carbon, dust and fly ash particles and natural aerosols such as sea salt and mineral dust. Biomass burning and fossil fuel combustion contribute as much as 75% to the observed aerosol.

Why is the haze problem so severe in the tropics? The large increase in emissions of aerosols and their precursors is one important reason. The other important contributor is the unique meteorology of the tropics and the subtropics (including Southern Asia) which leads to a long dry season with minimal rainfall extending from late fall and winter until spring. The dryness precludes the wet removal of haze particles by rain. On the other hand, in the mid and high latitudes, the absence of a long dry season, and seasonally distributed rainfall (and snow fall) cleans the atmosphere more efficiently.

Aerosols, by scattering/absorbing solar and emitting/absorbing long wave (IR) radiation, change the radiation fluxes at the surface and the top of the atmosphere, thereby especially perturbing the atmospheric absorption of solar radiation. These aerosol-induced changes in the radiation budget are referred to as the *direct forcing*. Black carbon, which strongly absorbs solar radiation, plays a major role in the forcing by partially shielding

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the surface from the intense tropical solar radiation. This shielding effect of BC amplifies the surface radiative forcing due to all other manmade aerosols (sulfates, organics, nitrates, fly ash) by a factor of three or more. BC over the Northern Indian Ocean and the Arabian Sea contributes as much as 10–14% to aerosol mass, compared with about 5% in the suburban regions of Europe and Northern America. Lastly, by nucleating more cloud drops, aerosols increase the reflection of solar radiation by clouds, which adds to the surface cooling effect. This effect is knows as the *indirect forcing*. In INDOEX it was shown by direct aircraft measurements (Heymsfield and McFarquhar, Journal of Geophysical Research, 106 (2001), 28653–28673) that the trade cumulus and strato-cumulus clouds in the polluted Arabian Sea had 6 times as many cloud drops as the pristine clouds south of the ITCZ under similar meteorological conditions. Recent studies have also demonstrated that the anthropogenic haze produces copious amounts of smaller drops in convective clouds, thus suppressing precipitation over polluted areas and favoring higher aerosol concentrations in the upper troposphere (Rosenfeld, Science, 287 (2000), 1793–1796).

One of the major and unique accomplishment of INDOEX is that it integrated field measurements with satellite data and aerosol assimilation models to estimate regionally average estimates of the direct and the indirect forcing (Fig. 1). There are three important messages in Fig. 1: First is the fact that the regional radiative perturbations by the anthropogenic aerosols at the surface and within the atmosphere is an order of magnitude greater than that due to the anthropogenic greenhouse gases. This does not imply that the GHGs

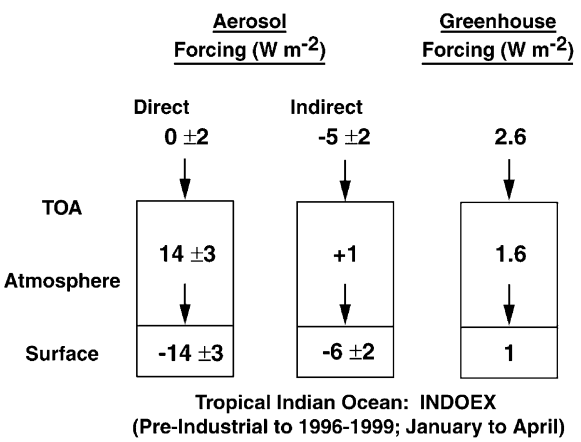

Fig. 1. Comparison of anthropogenic aerosol forcing with greenhouse forcing over the Tropical Indian Ocean for the dry season. The aerosol forcing was estimated from INDOEX data and the greenhouse forcing froma radiation model that uses observed greenhouse gas concentrations. Reproduced from Ramanathan et al. (Science, 294 (2001), 2119–2124).

are not important since they are distributed globally and have century or more long life times while the aerosol is concentrated regionally with lifetimes of the order of a week; what it implies, however, is that regional climate changes may be strongly influenced by absorbing aerosols. The second message is that absorbing aerosols may have a large impact on regional hydrological cycle. Since roughly 50–80% of the solar heating of the ocean is balanced by evaporation, the large reduction in solar radiation reaching the surface (Fig. 1) can lead to a reduction in evaporation which will in turn lead to a reduction in precipitation. The third is that the 50–100% enhancement in the regional solar heating of the lower atmosphere can perturb the monsoonal circulation.

The ABC project. The immediate focus of ABC is Asia. The basic reason is that over 50% of the world's population inhabit this region and the region is experiencing impressive industrial and demographic growth rates, and thus could be very vulnerable to unexpected negative impacts from the haze on health (Smith, Science, 298 (2002), 1847; Stone, Science, 298 (2002), 2106–2107), the hydrological cycle and agriculture. ABC will be setting up about 12 aerosol-climate observatories in the Indo-Asian–Pacific region to fill the urgent need for longer term measurements of aerosols and their sources. The ABC science team (see the ABC website) will integrate these observatories with satellite aerosol data and regional aerosol-chemistry models to assess the aerosol forcing and their impacts on climate, the monsoonal circulation, water budget and agriculture. These data and impact studies will be used by UNEP in collaboration with regional governments to explore solutions and policy options for reducing the brown clouds. One of the main objectives of the ABC program is to increase the capacity in the Asian region for studying such environmental issues and for integrating of the science with impact and policy studies. It is our vision that ABC-Asia will provide the template for ABC-Africa, ABC-Southern America, ABC-Northern America, etc.

Questions and research needs. A number of unresolved basic scientific issues and questions have to be addressed for further progress and these include: the sources of various aerosol species, especially black carbon from biomass and fossil fuel burning; the impact of the absorbing haze on water clouds (is the solar heating decreasing cloudiness or is the formation of more cloud drops enhancing cloudiness in the planet?); Can we document the reduction of sunlight at the surface globally (global darkening?) by absorbing aerosols from radiation budget observations? How much may the planetary albedo have changed during the last 50 years and how much will it be changing in the future? Is the planet becoming wetter due to global warming or drier due to the aerosol related reduction of sunlight at the surface? Is black carbon responsible for the observed

global scale land drying (Hulme and coworkers, Geophysical Research Letters, 25 (1998), 17379–17382)? Have the absorbing aerosols disturbed the regional monsoonal rainfall patterns Asia and Africa? Can increases in absorbing aerosols in the future create different modes of operation, regionally or globally?

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