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Air pollution and climate change both reduce Indian rice harvests

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An ever-changing mix of anthropogenic pollutants alters the chemical and physical properties of the atmosphere and thereby causes potentially negative impacts on human society. To establish a robust cause-and-effect chain, all the way from a particular kind of emission to its economic and/or social impacts, remains a transdisciplinary tour de force with several risks of failure along the way. The first major link along such a chain, that between increased aerosol loads ("atmospheric brown clouds," or ABC) over the Indian subcontinent, globally increasing greenhouse gas (GHG) concentrations, and regional changes in temperature, rainfall, and surface-near radiation, requires consideration of chemical and physical processes, ranging in scale from microscopic particles to atmospheric flows across the entire continent and its surrounding oceans. However, even if a changing environment near the ground can be attributed to anthropogenic emissions, it is still another matter to prove and quantify the second crucial link: to the existence of attributable impacts on society. For example, it may be shown that the changing atmosphere affects crop growth in some way, but does it also impact the farmer's livelihood in some way? Ever since it had been shown that aerosols block some incoming radiation, and therefore might reduce direct warming effects from GHG (1), it had been a common notion that ABC and GHG could have locally counteracting effects. For rice yields in India, an innovative study by Auffhammer *et al.* (2) in this issue of PNAS provides compelling evidence that ABC and GHG both have reduced historical rice harvests well below the levels to be expected otherwise. The study has profound implications for ongoing and future efforts to improve both climate and air quality.

Vulnerability of Indian Agriculture to Global Climate Change

During recent decades, climate change has been identified as a very serious environmental problem for South Asia, with particularly high vulnerability being noted for the agricultural sector (3). Even a small change in climate may result in high social vulnerability, for at least two reasons: first, many crops rely on the regular return of Monsoon rainfall (4), a system that has fluctuated widely in the past, and, second, the economic potential to adapt is very low for most Indian farmers (5). Recent warming (≈0.44°C since 1930) has impacted crop yields through several mechanisms associated with direct temperature as well as changes in water availability (6). Most published impact assessments rely on biophysical crop model simulations that, despite substantial advances in development and good correspondence to experimental results, could still over- or underestimate the sensitivity. For example, these models rarely account for changes in water use efficiency under higher atmospheric CO_2, nor do they reflect changes in crop area due to reduced water resources for irrigation.

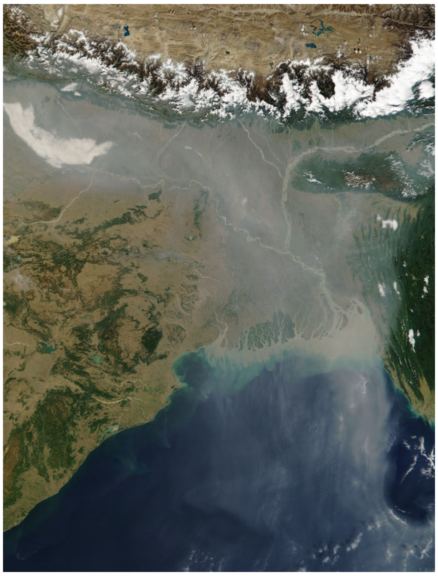

Fig. 1. Haze above Northern India and Bangladesh, observed from the Terra satellite's MODIS instrument on December 4, 2001 (image courtesy of NASA, Visible Earth, http://visibleearth.nasa.gov).

Climate model simulations show that GHG increases alone, in the absence of aerosols, would have caused even more rapid warming than has been observed, perhaps at double the current rate (7). Impacts from this warming could be expected to scale with temperature. Could, therefore, the "dimming" caused by ABC reduce the regional impacts of climate change? Answering this question requires a careful study of all climatic aspects of ABC and then a quantitative analysis of the major factors affecting agricultural output, a task for which currently no single crop model exists.

Climatic Impacts of Atmospheric Brown Clouds

Despite remaining open questions, the basic mechanisms linking regional climatic conditions in South Asia to ABC are known from a combination of measurement campaigns and model simulations (7). First, the radiation budget is strongly affected by the presence of haze (Fig. 1), which reduces direct radiation at the surface (land or ocean, approximately -10 to -15 W m^{-2}, during the 1990s) and warms the troposphere by approximately the same amount of energy. On average, the net solar forcing at the top of the atmosphere changes by <1 W m^{-2}, but much higher values may occur between January and May. Particularly during this period, substantial dimming of solar radiation occurs, a progressive reduction of net radiation arriving at the plant canopy, bare soil, or water surface (approximately -0.4 W m^{-2} a^{-1}, 1960–1990). It leads to a reduction in surface evaporation, particularly over the ocean (-5 to -10%, with higher values between January and April). A further consequence is surface cooling, which reduces the warming trend that would have been attributable to GHGs (0.76 ± 0.1 K) between 1930 and 2000 to approximately half its value. The altered energy balance also weakens the latitudinal Monsoon-generating gradient in sea surface temperature due to the stronger cooling in the ABC-affected Northern Indian Ocean (by ≈25% since 1950) and reduces vertical moisture transport in the troposphere (expressed by a decrease in convective instability from 1979 to 2003 by 15%). Together, these mechanisms are linked to an observed decrease in Monsoon rainfall (≈5% for 1930–2000) and to some increase in climatological droughts (7).

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The Combined Impact of Brown Clouds and Greenhouse Warming

Despite this evidence, linking the climatic changes in recent decades to societal impacts is not straightforward. Total agricultural output, providing 24% of India's gross domestic product and 57% of its employment (8), is affected by numerous factors besides climate, in particular the improved access to technology that has occurred since the beginning of the "green revolution." Overall, production increases steadily and has done so for decades despite a reduction in agricultural area since 1980, approximately balancing the growth in demand caused by a growing human population. The vulnerability assessment therefore must relate to the deceleration of growth, considering the complete set of influences from changing direct and scattered radiation, temperature, water availability, and technology development on yield and cultivated area. Despite some indications that crop growth is likely impacted by ABC (9), there is currently no simulation model that successfully integrates these factors at a scale appropriate for the analysis.

Focusing on rice as a key crop in India, Auffhammer *et al.* (2) resort to a statistical model, taking into account the observed harvests (as a function of cultivated area and weather) and the area cultivated (as a function of the previous years' area, prices, and weather). Their approach yields two equations, fitted individually by multivariate regression to data from nine Indian states, for each year from 1972 to 1998. Among a larger set of weather variables tested, June–September rainfall and October–November minimum temperatures were found to have significant influence on rice yield. As expected, higher rainfall ensured both larger areas to be cultivated and higher yield, whereas higher nighttime temperatures reduced yield (6). Differences between regions and socioeconomic potential was accounted for by the separate parameters in the different states.

The so-derived model was then used in a factorial design that allowed the identification of the potential effects of separate removal of ABC and of GHG warming from rice harvests during recent decades.

June–September rainfall and October–November minimum temperatures were found to have significant influence on rice yield.

The parallel climate model (PCM) (10) was first run with the full effects of ABC and GHG, giving good agreement with observations. Two additional simulations were then made, one with removed ABC effects and a second with fixed temperatures. Due to the combined equations for yield and cultivated area, as a function of climate, the statistical model could be expected to provide both biophysical and economic impacts of the two alternative scenarios. Removing ABC increased both rainfall and temperature; however, in agricultural terms, the rainfall effect was more important, generating significantly higher outputs than under conditions of both ABC and (less) warming. Over the period studied, ABC-attributed harvest reductions alone are estimated to have grown from $\approx$4% during the 1970s to $>$10% during 1985–1998 (2). When, in addition to ABC effects, the global warming trend was removed altogether, then harvests increased even further, making a clear case of combined negative impacts of haze and climate change.

Can We Learn From History?

The important combined effect of ABC and GHG on historical rice harvests makes a compelling case for a broader effort toward the reduction of air pollution as well as greenhouse gas emissions. Auffhammer *et al.* (2) are careful to point out that their model cannot be applied directly to other crops or to other regions. However, they first demonstrate that one very large economic activity in India has already seen considerable damage, with no likely perspective for a better future. Indeed, earlier work had already shown why failures of the all-important monsoon system are likely to be more frequent given the steady weakening of temperature gradient above the Indian ocean, which had been linked to ABC and climate change (7, 11). One does not need to go far back in history to find striking images of the human suffering associated with large famines in India.

The study leaves no uncertainty concerning the urgent need for regional and global mitigation efforts against aerosol as well as GHG emissions. Many inefficient combustion reactions produce both ABC and GHG, and switching to other technologies could generate substantial economic benefits, including the reduction of direct damage from air pollution (which was not part of this analysis). The way toward adaptation to the unavoidable impacts nevertheless remains problematic. Observation-based statistical models such as that of Auffhammer *et al.* (2) do not scale into a world of much higher ABC and GHG because nonlinear mechanisms are to be expected (11). Ultimately, process-based rather than statistical models of the integrated effects of atmospheric, ecological, and socioeconomic changes will have to indicate future pathways of global and regional change. Before application in a policy context, such approaches will have to match the power of historical analysis.

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