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Review article

When smoke gets in our eyes: The multiple impacts of atmospheric black carbon on climate, air quality and health

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Abstract

With both climate change and air quality on political and social agendas from local to global scale, the links between these hitherto separate fields are becoming more apparent. Black carbon, largely from combustion processes, scatters and absorbs incoming solar radiation, contributes to poor air quality and induces respiratory and cardiovascular problems. Uncertainties in the amount, location, size and shape of atmospheric black carbon cause large uncertainty in both climate change estimates and toxicology studies alike. Increased research has led to new effects and areas of uncertainty being uncovered. Here we draw together recent results and explore the increasing opportunities for synergistic research that will lead to improved confidence in the impact of black carbon on climate change, air quality and human health. Topics of mutual interest include better information on spatial distribution, size, mixing state and measuring and monitoring.

Keywords: Black carbon; Air quality; Climate change; Aerosols

Contents

1. Introduction

It may come as something of a surprise that the atmosphere around and above us contains not only gases, but millions of tonnes of solid matter. The particles comprising this load range in size from molecular clusters a few nanometres in diameter to veritable rocks many tens of micrometres across. Black carbon (BC) is an important anthropogenic contribution to this load, giving 5–10% of the mass of this particulate in urban areas of US and Europe, but 10–14% of the mass over the Northern Indian Ocean (Ramanathan and Crutzen, 2003). It presents a hazard to human life in two ways: having the potential to affect both our climate and our health. It has even been suggested that concentrating solely on reducing black carbon emissions might provide a "quick fix" for global warming (Jacobson, 2002). In the Public Health field, BC is becoming recognised as a key player in the adverse effect of inhaled pollutants on the body. One environmental impact of BC close to sources in the urban environment can be seen in Fig. 1, which shows BC deposited on the lower levels of buildings in Venice.

A wide variety of definitions of BC exist, independently developed for ease of measurement or monitoring. The climate community defines "BC" as the component of atmospheric aerosol that absorbs visible radiation. This is comprised of

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Fig. 1. The impact of BC deposition on buildings in Venice. The upper levels are more exposed to wind and rain such that the BC has been much reduced. At low levels the BC persists. Photographs taken by E. Highwood, August 2004.

elemental carbon (EC) and some organic carbon (OC) species. In terms of air quality, BC is usually considered as a component of PM10 (particles up to 10 micrometres in diameter). However, a more detailed size description is often necessary and particles are often described as belonging to ultrafine, fine and coarse modes. The source of the 12 Tg/year of BC emitted into the atmosphere (IPCC, 2001) is primarily combustion, including fossil fuel and biomass burning, and so sources tend to be geographically restricted to the surface in regions of human population (see Fig. 2), the exception being aircraft emissions which are released directly into the upper troposphere and although having a small impact on mass, can have a large influence on the number of small BC particles (Hendriks et al., 2004). In urban areas, where approximately 47%[1] of the global population live and work, combustion-derived particles are the most numerous particles by number (MacNee and Donaldson, 2003). Particles from diesel powered road vehicles alone account for 15% of PM10 and 45% of PM0.1 in the UK (AQEG, 2004).

BC is abundant in the lower atmosphere, having been detected over oceanic regions (Kristjansson, 2002) and in the Arctic stratosphere (Baumgardner et al., 2004), far away from most known sources. The transfer of BC from the surface and boundary layers of the atmosphere to the troposphere is affected by urban area design and by meteorology. BC and other aerosols generally remain in the troposphere for only a few weeks. They are removed by precipitation and by gravitational settling or sedimentation. This leads to an atmospheric distribution which is spatially very inhomogeneous on scales from a few hundreds of metres to thousands of kilometres.

Historically, the implications of BC emissions for health and for climate change have been treated separately, with little recognition of common interests and impacts. Increasingly however, these areas of environmental research are encountering common uncertainties and needs for research tools. It is therefore timely to consider recent results and how future research could be made mutually beneficial.

2. The climate impact of black carbon

Four ways by which BC affects climate have been proposed.

- The *direct effect*: BC scatters and absorbs solar radiation, such that an increase in BC decreases the planetary albedo and reduces the solar radiation that reaches the ground by as much as 25 W m^{-2} (or around 5%) (Krishnan and Ramanathan, 2002) thus contributing to so-called “global dimming” (Stanhill and Cohen, 2001). This leads to changes in surface fluxes of heat and moisture (Ramanathan et al., 2001) and ultimately to changes in the dynamics of the atmospheric boundary layer. The change in the surface radiation can be up to 3 times that at the top of the atmosphere.
- The *indirect effect*: BC nucleated or scavenged within other aerosols can alter the microphysics of clouds, changing droplet size for example.
- The *semi-direct effect*: Studies over the Indian ocean, South America, and in models suggest that a layer of BC increases the atmospheric heating rate by as much as 1 to 3 K per day (Ackerman et al., 2000; Koren et al., 2004; Johnson et al., 2004) and alters humidity profiles, therefore affecting whether cloud can persist or even form.
- The *indirect surface albedo effect*: surface deposition of BC onto snow and ice crystals can lead to melting of the ice, and warming.

A key estimate of the relative importance of each of these effects can be obtained by comparing their influence on the global mean energy budget of the planet—their “radiative forcing”. (Radiative forcing was used as a comparative measure by the Intergovernmental Panel on Climate Change. A positive global mean radiative forcing tends to mean a warming of the planet. Radiative forcing is easier to calculate than say a temperature change, since only a radiative transfer code is required, rather than the complexity and expense of a full climate model. However, for the indirect and semi-direct effects, the calculations do require at least part of the climate model; that which simulates the impact of aerosols on cloud. It has recently been argued that some radiative forcings are more effective at producing a surface temperature change than

[1] United Nations Press Release http://www.un.org/News/Press/docs/2000/20000324.pop757.doc.html.