nal cortex—as envisaged in one formulation of the interference model (*13*).

Different implementations of the interference model have placed the velocity-controlled oscillators in other brain regions, such as the medial septum (*14*), and do not necessarily require membrane potential oscillations to be present in the entorhinal cortex (some degree of theta-band modulation of grid cell firing would be expected). Heys *et al*. did observe membrane potential oscillations of medial entorhinal cells, but at frequencies below the normal theta range (1 to 2 Hz), raising the possibility that oscillatory interference might be occurring at lower frequencies. These findings may be indicative of differences in the nature of neuronal oscillations between species. For instance, hippocampal theta-band oscillations in humans have a much lower frequency than in rats (*15*). Alternatively, a shift to lower-frequency oscillations might avoid unwanted interactions with the processing of bat echolocation epochs which occur at 6 to 12 Hz. Indeed, at least one species of bat shows theta-like modulation in hippocampal neurons when echolocating (*7*).

It may be that the adaptations that allow bats to function in, and encode, 3D space have dramatically altered the way they path integrate—as such, their grid cells may be functionally different from those in rodents and humans. Characterizing grid cells in flying bats will help to answer some of these questions.

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CLIMATE CHANGE

Climate's Dark Forcings

Uncertainties about the properties and amounts of atmospheric black carbon complicate efforts to understand its regional and global effects on climate.

Meinrat O. Andreae[1,2] and V. Ramanathan[2,3]

The black soot coming out of the tailpipes of diesel trucks is a nuisance familiar to every highway traveler. Soot also endangers the health of untold numbers of women and their families exposed to smoke from traditional cookstoves burning biofuels and coal. But in addition to irritating our noses and lungs, this pollutant, also known as black carbon (BC), is the strongest absorber of solar radiation in the atmosphere. The magnitude of global warming from BC, as well as its regional effects, has been the subject of intense debate. In a recent comprehensive assessment, Bond *et al*. (*1*) have synthesized available model results and observations, and propose a "best estimate" for BC's global climate forcing. Their estimate is almost twice as high as values commonly discussed (*2*). What causes such large discrepancies between estimates, and what are the implications for the global and regional climate effects of BC?

Unlike greenhouse gases, BC is not a single, chemically defined substance with constant physical properties. In addition to the aggregates of nanometer-scale carbon spherules traditionally thought of as BC, the atmosphere contains light-absorbing organic or "brown" carbon (BrC) (*3*). BrC may account for 15 to 50% of light absorption in the atmosphere and in snow and ice (*1*, *4*, *5*) and has different optical properties and source and sink patterns from BC. In addition to combustion sources, especially biomass burning, BrC is also produced by atmospheric chemical reactions, a source not considered in emission inventories.

BrC is sometimes included implicitly in climate models constrained by BC measurements, because different BC measurement techniques may include some or all BrC. However, most models have ignored BrC absorption and, as a result, concluded that the combination of BC and nonabsorbing organic carbon leads to net cooling. This has been challenged by two recent studies (*5*, *6*). It is essential to improve measurement techniques for BrC and to include it explicitly in models.

BC (including BrC) influences climate through numerous mechanisms. In addition to causing atmospheric heating and surface dimming, BC-containing aerosols affect cloud optical properties and precipitation behavior. This in turn affects the energy budget of the atmosphere (*7*). The global net BC forcing is obtained by integrating over all mechanisms. Because most earlier studies have included only a subset of mechanisms, one must be very careful when making comparisons.

Bond *et al*.'s "all mechanisms" forcing estimate of +1.1 W m^{-2} (with a large uncertainty) is about twice as high as that of UNEP/WMO (*2*), mostly because of higher values for the absorption by BC in the atmosphere. Yet, their estimate of 0.88 W m^{-2} for the forcing from light absorption by present-day BC is almost identical to that from a previous study (0.9 W m^{-2}) (*8*). This agreement is instructive, because the two studies use atmospheric models, but are otherwise based on very different approaches.

Ramanathan and Carmichael's estimate (*8*) is based on satellite and ground-based light absorption data from the AERONET network of more than 140 sites around the world. In contrast, Bond *et al*. derive absorption estimates from emission inventories and atmospheric models. They initially obtain values lower than supported by observations; only when they scale up their results to agree with the AERONET data do the two studies converge. This suggests that underestimation of atmospheric BC absorption by as much as a factor of three is the primary culprit for the lower forcing estimates in most earlier models. Either the models are missing a major BC

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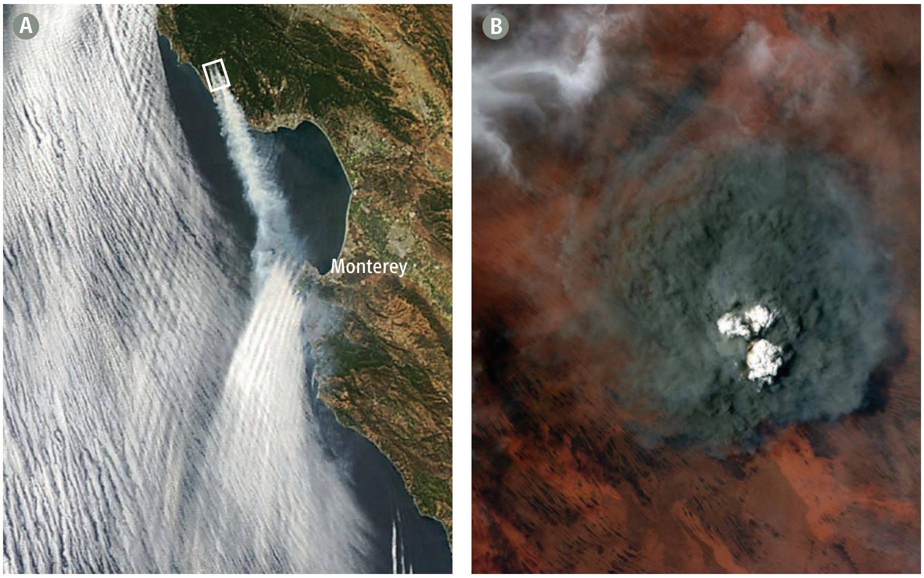

Smoke properties and cloud interactions. (**A**) The smoke from the 12 August 2009 fire (white box) northwest of Santa Cruz, California, is light colored because it burns in moist vegetation. Interaction of the smoke plume with clouds off the Monterey Peninsula (center) increases the reflectance of the clouds. (**B**) The smoke from a fire in extremely dry vegetation in the Great Victoria Desert, Australia (near 29°S, 129°E), on 17 January 2013 is nearly black. A bright cumulus cloud rises from the top of the plume.

CREDIT: (PANEL A) NASA/GSFC, MODIS RAPID RESPONSE; (PANEL B) NASA/C. HADFIELD

source or the emission inventory values are not applicable worldwide.

Summing up all forcing terms may be appropriate for a global estimate, but the relative importance of the individual effects differs between regions, especially when considering the effects on precipitation. Furthermore, the regional net forcing from a source such as biomass burning can even change sign from region to region (see the figure). Climate change will be more sharply felt at the regional scale and through changes in water availability than through an increase in average global temperature.

Because BC is concentrated near its sources, it introduces spatial gradients in solar heating of the atmosphere and surface. Over South Asia, this differential dimming of the surface weakens the north-south gradient in the solar heating of the Indian Ocean and the land-ocean contrast in surface solar heating. The net effect is a weakened monsoon circulation and a reduction in evaporation, reducing the amount of water available for rainfall (*8*).

These coupled ocean-atmosphere processes act on seasonal time scales. On shorter time scales, BC warms the troposphere above 3 km, intensifying monsoon circulation (*9*) and modulating intraseasonal monsoon variations (*10*). Furthermore, the aerosol particles that contain BC reduce precipitation efficiency in small clouds but enhance it in deep clouds and make the clouds grow taller (*7*). The resulting vertical redistribution of heat affects monsoon circulation and tropical precipitation.

The combined radiative, microphysical, and dynamical effects of absorbing aerosols may explain observed changes since the 1950s in the Indian and East Asian Monsoon and the Sahelian drought (*1*, *8*, *9*). On an even larger scale, model results suggest that BC is to a great extent responsible for the observed expansion of the tropical belt and the poleward shift of the tropical jet and extratropical storm tracks (*11*). In Earth's cold regions, heating of the air and darkening of snow by BC may accelerate Arctic sea ice retreat and melting of Himalayan glaciers (*1*, *12*). If, as concluded by Bond *et al.*, BC absorption has been strongly underestimated in previous models, the regional effects may be much larger than models have assumed. A reexamination is urgently required.

Like all climate change assessments, the conclusions of Bond *et al.* are based mainly on models. However, the representation of aerosol and cloud processes in climate models has severe shortcomings. The increasing complexity of recent model versions does not necessarily imply improved model skill. Better observational constraints are needed at all scales, from aerosol microphysics to global satellite studies of cloud properties.

Is BC mitigation, as suggested by UNEP/WMO, worth the effort, given the large uncertainties in BC forcings? Most BC sources coemit other species, such as organic particles and SO_2, which have a negative forcing. The forcings from BC and these other species nearly cancel each other in present models (*1*), mainly because of the large cooling effect of open biomass burning. However, BC from diesel and coal burning may have a substantial net warming effect despite cooling from coemitted species (*13*). In California, BC concentrations fell by 50% from 1988 to 2008, largely as a result of diesel emission reductions (*14*), whereas coemitted species showed no trends. Mitigation could thus target diesel exhaust, as well as traditional cookstoves that burn biofuels.

The potentially large effects on regional precipitation and circulation and on glacier melting offer further incentives to mitigate BC. However, the strongest motivation may come from the expected health benefits. An estimated 3.5 million deaths annually are attributed to household air pollution from solid fuels and an additional 3.1 million deaths to ambient particles, including BC (*15*). Finally, the discussion about BC and other short-lived climate forcers must not obscure the 38-billion-ton and growing gorilla in the room—the amount of CO_2 emitted annually into the atmosphere—which needs to be cut sharply and promptly to avoid accelerating climate change.

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