

## SIDEBAR 5.2: RADIATIVE FORCING BY BLACK CARBON IN THE ARCTIC—P. K. QUINN, A. STOHL, A. BAKLANOV, M. G. FLANNER, A. HERBER, K. KUPIAINEN, K. S. LAW, J. SCHMALE, S. SHARMA, V. VESTRENG, AND K. VON SALZEN

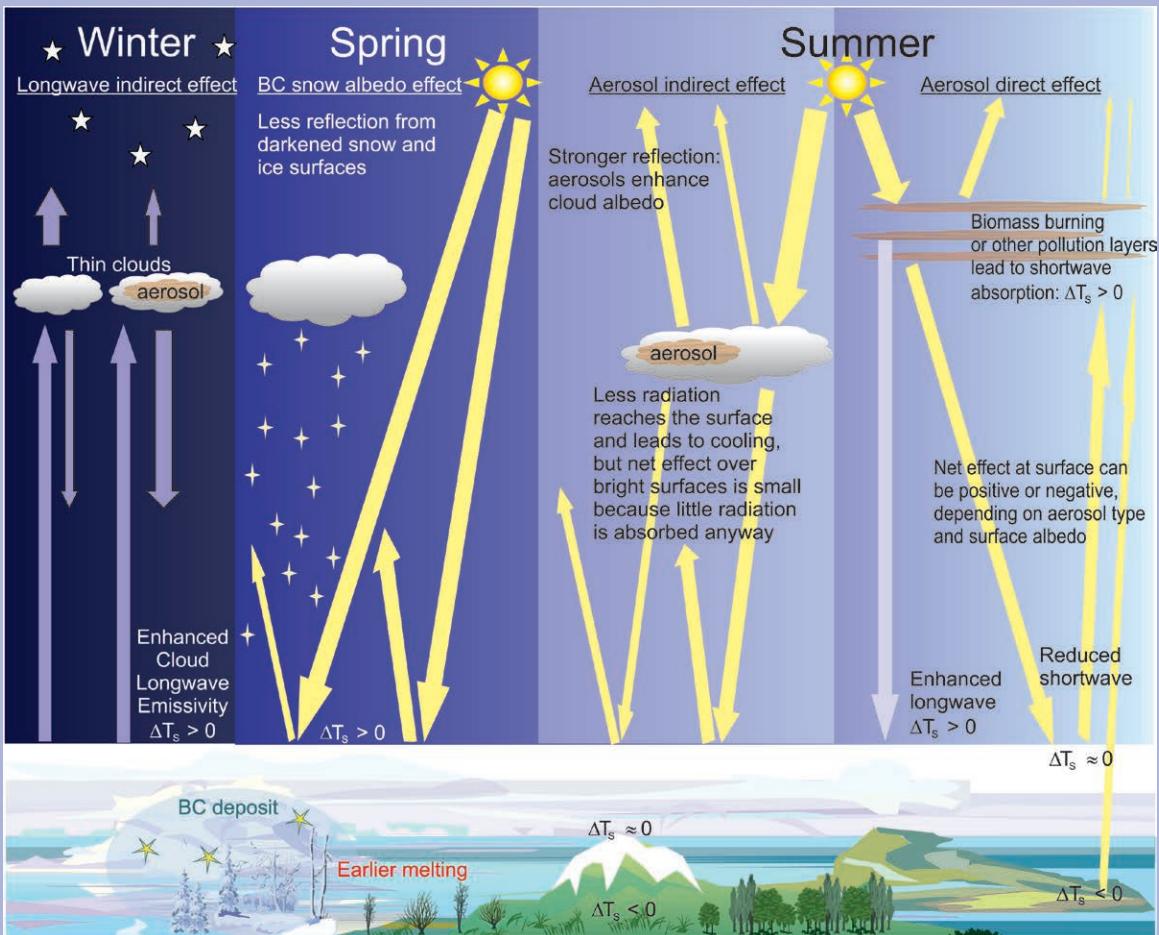
Black carbon (BC) is the most efficient atmospheric particulate species at absorbing visible light. Consequently, it exerts a warming effect that contrasts with the cooling effect of purely scattering aerosol components such as sulfate. However, pure BC particles rarely occur in the atmosphere. Soon after emission, BC becomes mixed with other components such as sulfate and organics. BC-containing particles can have either a warming or a cooling effect on climate depending on their altitude and the albedo of the underlying surface relative to the albedo of the BC haze itself. The albedo of the haze depends on the relative amounts of all of the chemical components present, their mixing state, and whether they primarily scatter or absorb light. BC-containing aerosols, unlike greenhouse gases, are short-lived, with a lifetime in the atmosphere on the order of days to weeks. While recognizing that reductions in CO<sub>2</sub> emissions are required for long-term mitigation of Arctic warming, it has been suggested that reducing emissions of BC could reduce projected global mean warming and slow the rate of warming in the short term in the Arctic (Shindell et al. 2012; Bowerman et al. 2013).

Atmospheric BC concentrations in the Arctic have declined since the 1990s (Sharma et al. 2013), and the BC content of Arctic snow is now no higher than it was thirty years ago (Clarke and Noone 1985; Doherty et al. 2010), but BC-containing aerosols will likely continue to influence Arctic climate through several different forcing mechanisms. Atmospheric BC can directly warm the Arctic atmosphere by absorbing solar radiation that would otherwise have been reflected back to space or absorbed by the surface (far right panel in Fig. SB5.4). The added atmospheric heating subsequently increases the downward longwave radiation to the surface and decreases the temperature difference between the surface and the atmosphere, thereby warming the surface. With the highly reflective snow and ice surfaces typical of the Arctic, even a moderately absorbing aerosol can lead to a heating of the surface–atmosphere column. The average daily radiative efficiency of atmospheric BC (units of W g<sup>-1</sup>) in the Arctic summer is greater than in most other environments because of the long sunlight exposure and presence of highly reflective clouds, snow, and sea ice (e.g., Cess 1983). As summer progresses and open water appears within the sea ice cover, and melt ponds form

on the ice surface, the direct forcing efficiency by atmospheric BC decreases because the surface becomes less reflective. Similarly, it is reasonable to expect that forcing by atmospheric BC will become weaker as snow, sea ice, and glacier extent and surface albedo decrease under a warming climate (Flanner et al. 2009).

BC deposited to snow and ice surfaces enhances the absorption of solar radiation at the surface and warms the lower atmosphere, which can initiate snow and ice melt earlier in the season (left center panel in Fig. SB5.4). Even very low BC concentrations (ppb) of deposited BC have an impact because the absorptivity of BC is about five orders of magnitude greater than ice at visible wavelengths. In addition, multiple scattering in surface snow greatly increases the path-length of photons and the probability that they will encounter non-ice particles (Warren and Wiscombe 1980). Snow darkening drives an equilibrium temperature response, per unit of radiative forcing, several times that of CO<sub>2</sub> (Koch et al. 2009). This large impact occurs because all of the energy associated with the forcing is deposited directly into the snow and ice covers, components of the Earth system responsible for powerful positive feedback (e.g., Robock 1983; Hansen and Nazarenko 2004).

Radiative forcing by BC can also result from the impact of aerosols on cloud distributions, lifetime, and microphysical properties. By increasing the number of cloud droplets and decreasing cloud droplet size, aerosols can lead to an increase in reflectivity and cloud optical thickness (first indirect effect) and to an increase in cloud lifetime and a decrease in precipitation (second indirect effect; e.g., Twomey 1977). Both of these changes result in greater reflection of solar shortwave radiation back to space and a cooling at the surface (right center panel in Fig. SB5.4). In contrast, when the cloud droplet number concentration of thin Arctic liquid-phase clouds is increased through interaction with anthropogenic aerosols, the clouds become more efficient at trapping and re-emitting longwave radiation, which results in a warming at the surface (Garrett and Zhao 2006; far left column in Fig. SB5.4). BC can also impact clouds through semi-direct effects associated with atmospheric heating. Depending on circumstances, BC-induced heating can either stabilize the atmosphere and increase low-level cloud formation (Hansen et al. 2005), inhibit cloud formation, or increase



**FIG. SB5.4. Forcing mechanisms in the Arctic due to black carbon.**  $\Delta T_s$  indicates the surface temperature response.

the evaporation rate of clouds (e.g., Ackerman et al. 2000; Jacobson 2010). Simulating these indirect and semi-direct effects remains a challenge for global-scale models, especially in the Arctic. Both the sign and magnitude of the net forcing due to nonlinear interactions between BC and clouds in the Arctic are uncertain.

Further complicating the impact of BC on Arctic climate is that forcing exerted by BC outside of the Arctic can result in changes in energy transport through the atmosphere and oceans to the Arctic (Shindell and Faluvegi 2009). For example, BC-heated air masses can travel from midlatitudes to the Arctic.

In the past few years there has been a concerted effort by the scientific community to quantitatively estimate the climate impacts of BC, both globally and within the Arctic

(e.g., Bond et al. 2013; Quinn et al. 2008). Currently, there is no single appropriate environmental indicator to assess the Arctic climate response to changes in emissions of BC and co-emitted species including organic carbon and sulfate. Hence, only an integrated evaluation will reduce the large uncertainties and improve estimates of BC's climate impacts. Such an evaluation requires accurate emission inventories of local and remote sources, long-term monitoring and process-oriented measurements, and global models capable of realistic transport of BC to the Arctic and depositional losses en route and within the Arctic. In addition, models must accurately capture feedbacks induced by BC, including those associated with snow, glacier, and sea-ice loss, cloud changes, and dynamical changes.