Black Carbon is one of the main anthropogenic compound affecting the climate system: Bond et al. (2013) suggest the total climate forcing of black carbon through all forcing mechanisms to reach +1.1 W m⁻², with a quite elevated uncertainty of ≥90% (bounds of +0.17 to +2.1 W m⁻²). This estimate refers to both direct and indirect atmospheric effects, but also the impact of BC on snow albedo, which has been found to strongly impact the climate system. Anthropogenic BC currently deposited on snow reduces the snow cover duration from several days in the Northern Hemisphere (Ménéguz et al., 2013). Such forcings are linked with the effect on snow cover extent and temperature of the last decades and expected for the next century (Brutel-Vuilleum et al., 2007). The Himalayan region host extended glaciers and is snow-covered during a large part of the year: its atmosphere is strongly affected by BC anthropogenic emissions, taking place both in the Indian plain and in the quite crowded mountainous areas. Consequently, atmospheric BC concentration reaches very high rates in this region (Ramanathan et al., 2007), even at elevated areas (Bonasoni et al., 2008). Here, we use a global climate model with a stretched grid, to reach a fine resolution over the Himalaya, in order to quantify the effect of BC deposition on the snow cover duration. The temporal variation and the order of magnitude of the aerosol concentration in the snow are confronted to an ice core record performed in a Nepalese glacier. Finally, we estimate the surface radiation and the temperature change associated with the BC deposition on the snow in the Himalaya.

Aerodynamic deposition: from ice core measurements to large scale simulations

An ice core was extracted from the Mera glacier (6476m a.s.l., N27°43', E86°52', 5552 m a.s.l.) to reconstruct the aerosol fluxes in this region over the period 2000-2010. BC shows a strong seasonal deposition cycle in the snow, with a maximum during pre-monsoon season (Fig. 2). Dust deposition is more constant over the year. The BC content in the snow ranges between 10 and 50 µg.l⁻¹, whereas dust concentration reaches thousand times higher levels. Due to the relatively coarse resolution of our climate model, we cannot compare directly the observed and the modeled aerosol concentration in the snow. The grid cell located over the Mera Peak is too low in altitude, and therefore to warm, to allow snowfall in our simulation. 50 km more on the North (in the Mt Everest region), the grid cell surface altitude reach 5552 m a.s.l., which allow to simulate a permanent seasonal snow cover. Here, the seasonal variations of BC and dust cannot compare directly the observed and the modeled aerosol concentration in the snow.

Impact of aerosol deposition on the snow cover duration and energy balance

We performed 4 simulations with the global climate model LMDZ (Hourdin et al., 2006), coupled with a detailed aerosol module INCA. Two simulations were run with a standard coarse-gridded resolution (96x144) stretched grid, with a zoom on the Himalaya (see Fig. 5). For each resolution, we performed two simulations with a detailed snow abedo scheme (Wiscombe and Warren, 1980): One using the BC deposition computed from the INCA model aerosol, and another without BC in the snow (see Table 2). In the following, we analyze the difference between these pairs of simulation to quantify the climate effects of BC on snow.

Performing experiments with the aerosol - climate model LMDZ-INCA

We performed 4 simulations with the global climate model LMDZ (Hourdin et al., 2006), coupled with a detailed aerosol module INCA. Two simulations were run with a standard coarse-gridded resolution (96x144) stretched grid, with a zoom on the Himalaya (see Fig. 5). For each resolution, we performed two simulations with a detailed snow abedo scheme (Wiscombe and Warren, 1980): One using the BC deposition computed from the INCA model aerosol, and another without BC in the snow (see Table 2). In the following, we analyze the difference between these pairs of simulation to quantify the climate effects of BC on snow.

Snow cover duration estimated from satellite and models

A fine resolution appears essential to simulate the observed snow cover duration (Fig. 6, NSIDC, IMS data).

We simulated that anthropogenic aerosol emissions bring large amounts of pollutants in the Himalayan snow. The BC content in the surface snow reach its maximum value during the spring, with values ranging between 10 and 500 µg.kg⁻¹ (Fig. 7a). The BC deposition induces a reduction of the snow cover duration of 1 to 8 days per year over large areas of the Western Himalayas and the Karakorum (Fig. 7b). The snow cover is largely less extended in the Tibetan plateau, in Central and Eastern Himalaya, where the BC forcing is therefore less visible. Such forcing cannot be estimated with coarse gridded climate models, who generally overestimate both snow cover and BC forcing in these regions. BC deposition on snow induces an increase of solar radiation at the surface which reaches an annual mean of 1 to 3 W.m⁻² in the high altitude areas of the Himalaya (Fig. 7c).

Our simulation indicate that anthropogenic aerosol emissions bring large amounts of pollutants in the Himalayan snow. The BC content in the surface snow reach its maximum value during the spring, with values ranging between 10 and 500 µg.kg⁻¹ (Fig. 7a). The BC deposition induces a reduction of the snow cover duration of 1 to 8 days per year over large areas of the Western Himalayas and the Karakorum (Fig. 7b). The snow cover is largely less extended in the Tibetan plateau, in Central and Eastern Himalaya, where the BC forcing is therefore less visible. Such forcing cannot be estimated with coarse gridded climate models, who generally overestimate both snow cover and BC forcing in these regions. BC deposition on snow induces an increase of solar radiation at the surface which reaches an annual mean of 1 to 3 W.m⁻² in the high altitude areas of the Himalaya (Fig. 7c). Two main processes explain such forcing: (1) the reduction of the snow albedo induced by BC deposition, (2) the decrease of the snow cover duration, increasing a strong increase of solar radiation at the surface which reaches an annual mean of 1 to 3 W.m⁻² in the high altitude areas of the Himalaya (Fig. 7c).

Aerosol deposition: from ice core measurements to large scale simulations

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