

A Modelling Approach to Assess the Impact of Black Carbon Deposition on Snow Surface Albedo

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ABSTRACT: Black Carbon (BC) plays a larger role in global climate change by its absorption capabilities. BC deposition in snow are known to reduce the snow albedo and accelerate the glacial melting process, affecting the glacial mass balance of the planet. The Snow, Ice and Aerosol Radiative (SNICAR) model was used to simulate the change in snow albedo resulting from varying concentrations of BC. It was found that the effect of BC deposition on snow surface albedo was maximum in the visible wavelength band. To validate the results of SNICAR, the simulated results were compared with an empirical model. SNICAR simulations also revealed that snow microphysical properties such as the snow grain size also plays a larger role in reducing the snow albedo, thereby accelerating the snow melting process.

KEYWORDS: black carbon, SNICAR, albedo, simulation, visible wavelength

I. INTRODUCTION

Carbonaceous particles constitute a major part of the atmospheric aerosol community. They exist in two forms, organic carbon (OC) and elemental carbon (EC), more commonly known as black carbon (BC). Combustion processes such as vehicular exhaust, biomass burning and coal combustion form the major sources of such aerosol particles. The presence of carbonaceous particles in the atmosphere, specifically BC alters the radiation budget of the atmosphere to a large extent, by strongly absorbing solar radiation ranging from visible to NIR regions [1]. BC alters the radiative balance of the Earth primarily in three ways – by heating up the atmosphere in the vicinity of the aerosols [2], by decreasing the snow albedo and accelerating glacier melting [3], and by acting as cloud condensation nuclei, altering the precipitation patterns [4]. Out of all the three, the radiative perturbation of BC is relatively stronger on the snow albedo reduction. Snow, being the most reflective surface is significantly affected by the presence of BC on its surface [3]. BC deposition on snow darkens the snow, thereby decreasing its albedo and heating up the snowpack leading to a faster snow melt. The impact of BC on snow albedo has been a very popular topic of research in environmental and atmospheric sciences in the recent years in the mid-latitudes. This is because the glaciers in the Himalayas and Tibetan Plateau are receding at a faster rate than the polar regions due to its proximity from the BC emission sources. Investigations carried out in the Himalayan region indicated the loss in glacier area from almost 6000 glaciers covering an aerial extent of 20,000 km², which is almost half of the glacier-covered area in the region and these investigations suggest that the glaciers are losing at average 0.4% area per year [5,6,7]. Investigations conducted on glaciers and snow covers across different parts of the Himalayas and Tibetan Plateau have shown significant accumulation of BC in the glaciers and seasonal snow. Ming et al. (2009) reported average concentration of 72 ppb for surface snow samples collected from the Nam Co region in Central Tibet in the winter of 2011 [8]. In 2012, field campaigns conducted across Northern China revealed concentrations of black carbon as high as 567 ppb [9]. Earlier studies have found that even a slight concentration 40 ppb of BC in new snow or 10 ppb coarse grained BC in aged snow has the potential to reduce the snow's spectrally averaged reflectance by 1% - 3% at the visible wavelength [3]. Xu et al. (2015), reported that the surface albedo of the glaciers decreased by more than 5% along the Himalayan mountain range and 1.4% over the entire Tibet, providing a positive local feedback to the enhanced global warming [10]. However, sufficient information

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on the spatial distribution of BC in snow is not yet available due to the difficulties and uncertainties in measurement techniques. This led to the development of physically based snow albedo models, which can be coupled with other climate models such as the Global Circulation Model (GCM), in order to better understand the radiative impact of BC on snow. Studies carried out using these models revealed that although BC has a larger effect on snow albedo reduction, snow microphysical properties such as the snow grain size also play a very important role. It was found that BC in combination with an increase in the snow grain size amplifies the radiative effect of BC on snow.

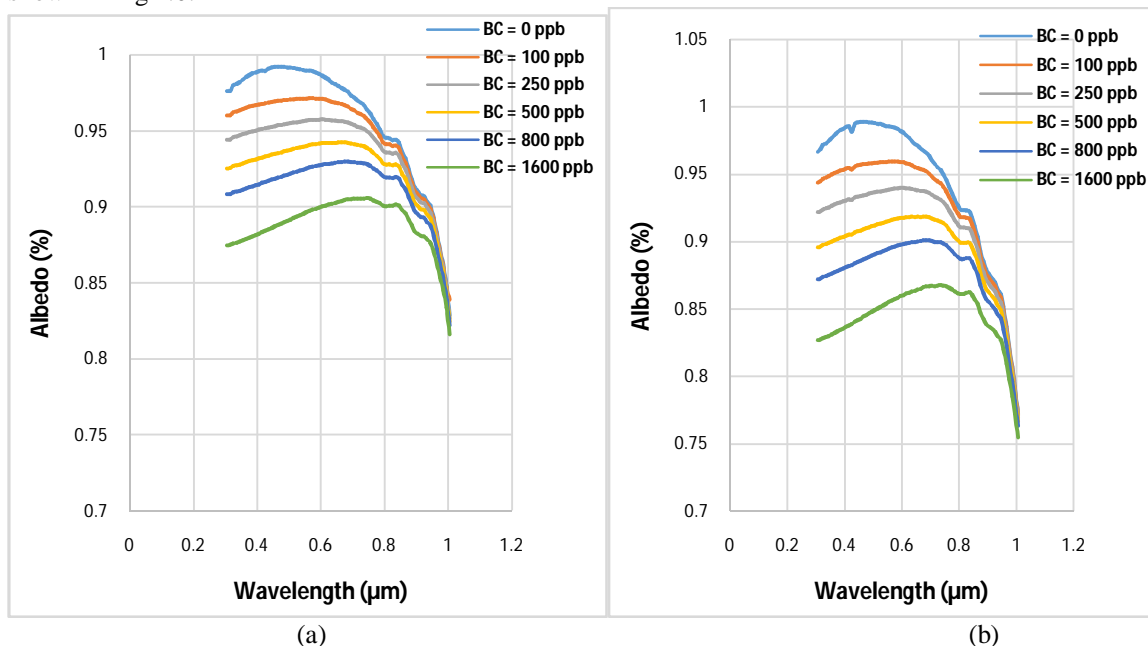
This paper presents a study conducted using one such snow albedo model named Snow, Ice and Aerosol Radiative (SNICAR) model. The effect of BC on the snow albedo has been simulated using SNICAR and its radiative perturbation over the visible region of the solar spectrum has been observed. Additionally, the effect of BC in combination with increase in snow grain size has also been studied.

II. METHODOLOGY

We used the SNICAR model [16] for simulating the albedo change due to BC concentration ranging from 0 – 1600 ppb over the visible wavelength band of the solar spectrum. The model was run for direct incident radiation under Mid-Latitude clear sky conditions and a solar zenith angle of 60° . The snowpack thickness and the snowpack density were taken as 1 m and 300 kg/m^3 (for aging snow). The albedo of the underlying ground in the visible and near infrared band were fixed at the default values of 0.2 and 0.4 respectively [11]. The mass absorption cross section (MAC) of BC was also set to the default value of 1.0 [12]. The BC concentration used for the simulation was considered “uncoated”, denoting the absence of sulphate influence on the BC particles. The snow grain radius (R_{eff}) was initially assumed to be $50\mu\text{m}$, which were later on, progressively increased to $100\mu\text{m}$ and $150\mu\text{m}$, so as to study the combined effect of BC and snow grain growth. It is to be noted here that the albedo feedback only due to BC and snow grain size has been considered in this study. The influence of dust and other such particles has been ruled out.

III. RESULTS AND DISCUSSION

The simulations in SNICAR were initially carried out for pure snow i.e. snow with no BC concentration. Thereafter, BC with concentration of 100 ppb, 250 ppb, 500 ppb, 800 ppb and 1600 ppb were simulated with a snow grain radius (R_{eff}) of $50\mu\text{m}$, $100\mu\text{m}$ and $150\mu\text{m}$. The albedo response due to the above concentration of BC on the snow albedo is shown in Fig 1.0.



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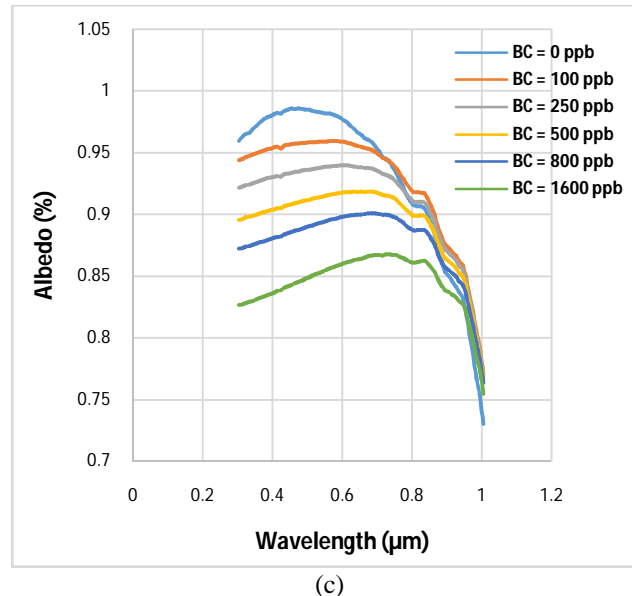


Fig 1.0 Snow albedo response for (a) $R_{eff} = 50\mu m$, (b) $R_{eff} = 100\mu m$; and (c) $R_{eff} = 150\mu m$

It is evident from Fig 1.0 that the snow albedo decreases with increasing concentration of BC. In Fig 1.0 (a), the average spectral albedo for pure snow was found to be 0.98, which with increasing concentration of BC reduced to 0.89 for $BC = 1600$ ppb and $R_{eff} = 50\mu m$. Similarly it can be observed from Fig 1.0 (b) and (c) that with increasing BC concentration the spectral albedo of snow reduces significantly. This observation was found to be consistent with many studies, which confirm the BC induced radiative forcing over snow surface albedo [13,11,12]. The simulated results also reveal that the albedo of both pure and BC contaminated snow coincides at wavelength greater than $0.7\mu m$. This indicates that the radiative perturbation of BC is highest in the visible region and gradually reduces as the wavelength increases. This may be due to the fact that snow is partially absorptive in the NIR region of the solar spectrum [13]. In order to validate the simulated results from SNICAR, the albedo values of BC concentration ranging from 0 – 1600 ppb were simulated and matched with an empirical model developed by Hadley and Kirchstetter to estimate the albedo reduction owing to BC in snow [13]. The model has been derived from a least squares fit of the data from experiments conducted on lab scale with varying concentration of BC and snow grain sizes. The model equation is – $\Delta\alpha_{BC} = 0.0035BC^k$, where $k = 0.295(R_{eff}^{0.114})$. BC concentration and R_{eff} are expressed in units of ppb and μm , respectively. The simulation parameters in SNICAR were kept the same as the previous simulations and only the snow grain size was varied. The first simulation was carried out for $R_{eff} = 50\mu m$ and matched with the empirical results, followed by simulation with $R_{eff} = 100\mu m$ and $150\mu m$. The results of the comparative analysis are shown in Fig 2.0.

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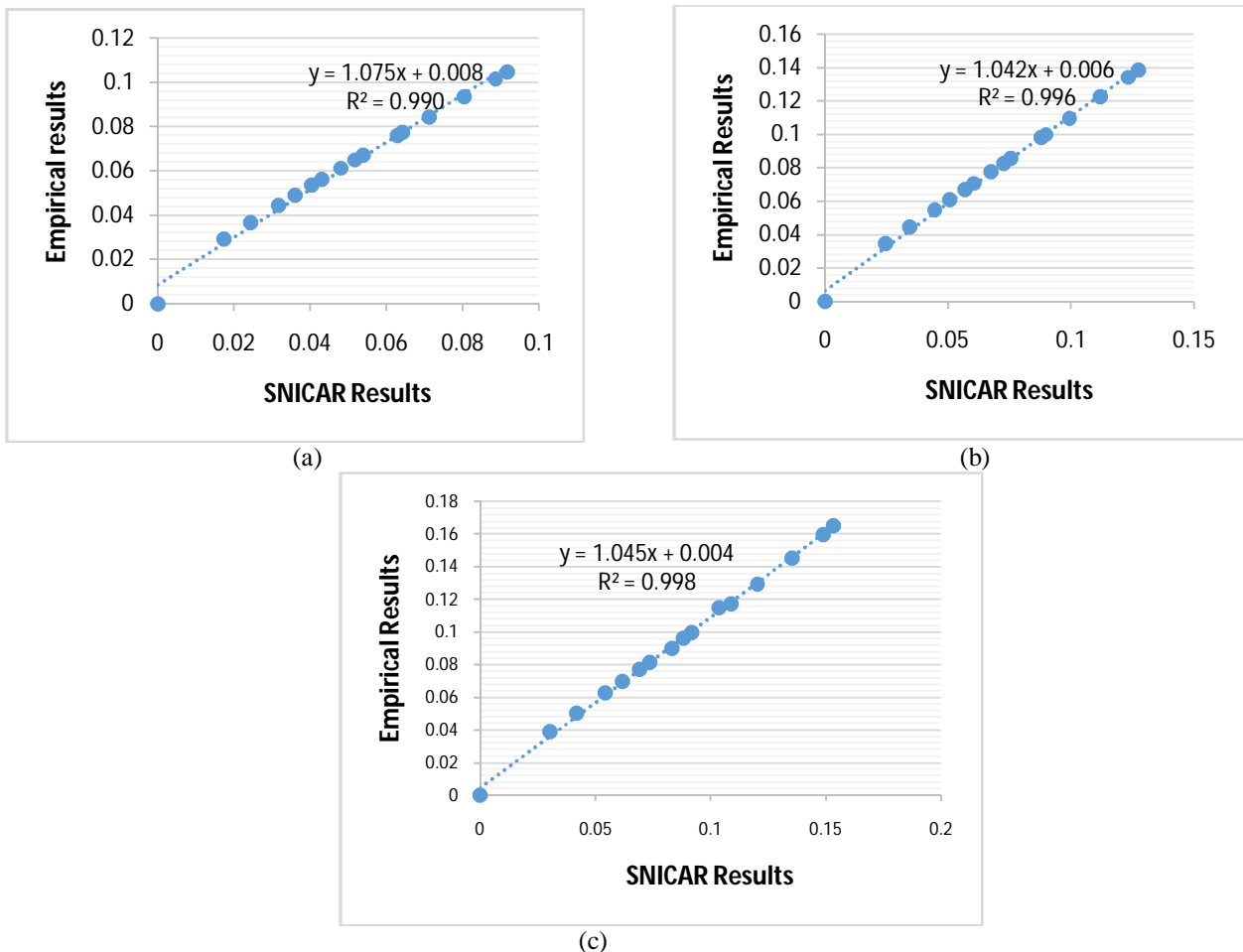


Fig 2.0 Correlation between simulated results of SNICAR and Empirical model for– (a). $R_{\text{eff}} = 50\mu\text{m}$; (b) $R_{\text{eff}} = 100\mu\text{m}$; and (c) $R_{\text{eff}} = 150\mu\text{m}$

It can be observed from Fig 2.0 that for all the snow grain sizes the simulated results using SNICAR and the results from the empirical model showed a very strong correlation. However it was found that the correlation seemed to be stronger in larger grains as compared to smaller grains. From Fig 2.0 (a) to (c), as we increased the snow grain size from 50 - 150 μm , keeping for the same level of BC contamination, the coefficient of determination increased from 0.9906 to 0.9985. Therefore it can be concluded that SNICAR model can be satisfactorily used to simulate the effects of BC on snow albedo, in the absence of albedo measuring instruments, and this observation has been verified by many researchers through site measurements as well as laboratory experiments [14,13,15]. Additionally, it has been observed from Fig 1.0 that for the same concentration of BC, with an increase in size of snow grains the spectral albedo of snow decreases. This effect is shown in Fig 3.0

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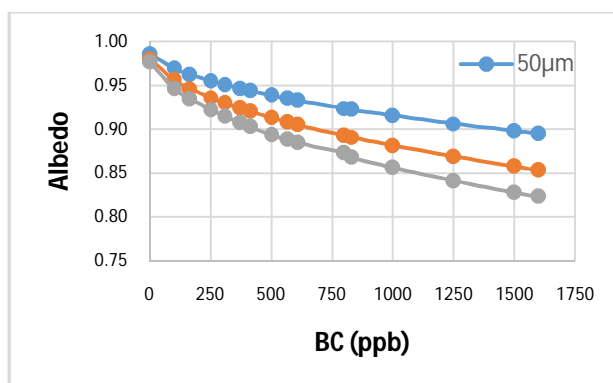


Fig 3.0 Snow albedo v/s BC for different snow grain sizes

From Fig 3.0, it was observed that the albedo of pure snow when the size of snow grain was 50µm came out to be approximately 0.99. Increasing the snow grain size to 100µm the simulated albedo value changes to 0.98, which means that there is a relatively 1% decrease in the albedo owing to the increase in snow grain size and without any influence of BC. Similarly let us take the example of a snow grain of size 50µm contaminated with a BC concentration of 500 ppb. The albedo value at 50µm is found to be 0.94 and when the size grain size increases to 100µm the albedo value reduces to 0.91 i.e. a 3 % decrease in the albedo value. When the snow grain increases to 150µm, the albedo value reduces to 0.89 indicating a further 2% reduction. Therefore it is evident from the above results that snow microphysical properties such as the snow grain size plays a larger role in accelerating the effect of BC in reducing the snow albedo and causing glacial recession, as predicted in previous studies (Hadley and Kirchstetter, 2012; Wang et al., 2014)

IV. CONCLUSION

BC concentration simulated in SNICAR revealed that the BC deposition on snow has a profound effect on the snow albedo, especially in the visible wavelength region. With the increase in wavelength, snow becomes absorptive and the radiative perturbation of BC becomes insignificant. By comparing the simulated albedo values with an empirical model, it has been observed that the SNICAR values show very good agreement with the empirical model values and the correlation increases with increasing snow grain size (R_{eff}). Snow microphysical properties such as the snow grain size, also plays a larger role in affecting the snow surface albedo in combination with BC. For the same concentration of BC in snow, it was found that an increasing the snow grain size from 50 – 150µm, the albedo may be reduced by up to 15%.

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