Anonymous Referee #2

Received and published: 1 January 2021

The authors investigated the BC coating effects based on the core/shell Mie theory and the radiative transfer model SNICAR. The paper is generally well-written. It is good for the climate models to consider the BC enhancement on albedo reduction due to the BC coating effects. It is also nice to give options for different core/shell ratios. However, I feel the content is not abundant enough and have some comments below for the authors to consider.

R: Thank you very much for the positive evaluations and valuable comments. We have added more contents in the manuscript according to your suggestions and addressed all comments very carefully as detailed below.

1. In section 3.1, it is not clear to me why the absorptive shell reduce the BC enhancement compared with the non-absorptive shell. And the authors should explain what is the lensing effect.

R: When BC is coated with the non-absorptive shell (or the absorptive shell), the light absorption by the BC core can be enhanced, because the shell acts as a lens and focuses more photons onto the core than would reach it otherwise (i.e. lensing effect) (Bond et al., 2006). In addition, the BC light absorption enhancement (E_{Abs}) for absorptive shell may differ from that for non-absorptive shell due to either (i) modification of the photon path through the coated particle due to the absorptive shell, thus causing fewer photons to be focused towards the BC core, or (ii) absorption of photons by the absorptive shell, thus causing fewer photons to reach the core. In this case, the total absorption by the coated particle will be conserved (i.e. it does not matter whether a photon is absorbed within the shell or the core), but the magnitude of E_{Abs} has been decreased. When E_{Abs}>1, this indicates that photons at that wavelength are still being focused onto the core due to the lensing effect. However, when E_{Abs}<1, this is an indication that the enhancement due to the lensing effect is overwhelmed by absorption by the absorptive shell, similar results have been reported by Lack and Cappa (2010). We have added these discussions in Section 2.1.1 at Page 6 Lines 19-21 and revised the sentences Section 3.1 at Page 13 Lines 6-16.

References:

Bond, T. C., Habib, G., and Bergstrom, R. W.: Limitations in the enhancement of visible light absorption due to mixing state, J Geophys Res-Atmos, 111, 10.1029/2006jd007315, 2006.

Lack, D. A., and Cappa, C. D.: Impact of brown and clear carbon on light absorption enhancement, single scatter albedo and absorption wavelength dependence of black carbon, Atmos Chem Phys, 10, 4207-4220, 10.5194/acp-10-4207-2010, 2010.

2. In section 3.2, actually the E_1-w, E_alpha, and E_delta_alpha tell the same story. And the impact of BC coating on spectral characteristics should be consistent with that on broadband characteristics. To make the story full, I suggest the authors present the direct numbers of snow albedo of various snow cases, e.g. fresh snow, old snow, of different snow depths, with different BC concentrations and core/shell ratios, other than the ratios as E_...

R: The reason why we mainly discussed $E_{1-\omega}$, E_{α}, and $E_{\Delta\alpha}$ is snow albedo can be effectively affected by various factors, such as snow grain size, LAP content, solar zenith angle, which has been widely discussed and verified through model simulation and experimental measurements by previous studies (e.g. Hadley and Kirchstetter, 2012; Wang et al., 2017; Warren and Wiscombe, 1980). The use of $E_{1-\omega}$, E_{α}, and $E_{\Delta\alpha}$ can make us focus on the impact of BC coating effect on snow albedo, which has been successfully used by previous study (He et al. 2018c). Yet, we agree with the referee's opinions that the direct numbers of snow albedo of various snow cases are still important for the research community. Hence, according to your suggestions, we have revised the figures, which not only show $E_{1-\omega}$, E_{α}, and $E_{\Delta\alpha}$, but also show the direct numbers of snow albedo under various snow cases, e.g. snow grain radius from 100 to 500 μm, BC concentrations from 0 to 1000 ng g^{-1}, core/shell ratios from 1.2 to 2.5, and two different coating materials (non-absorbing and absorbing materials):

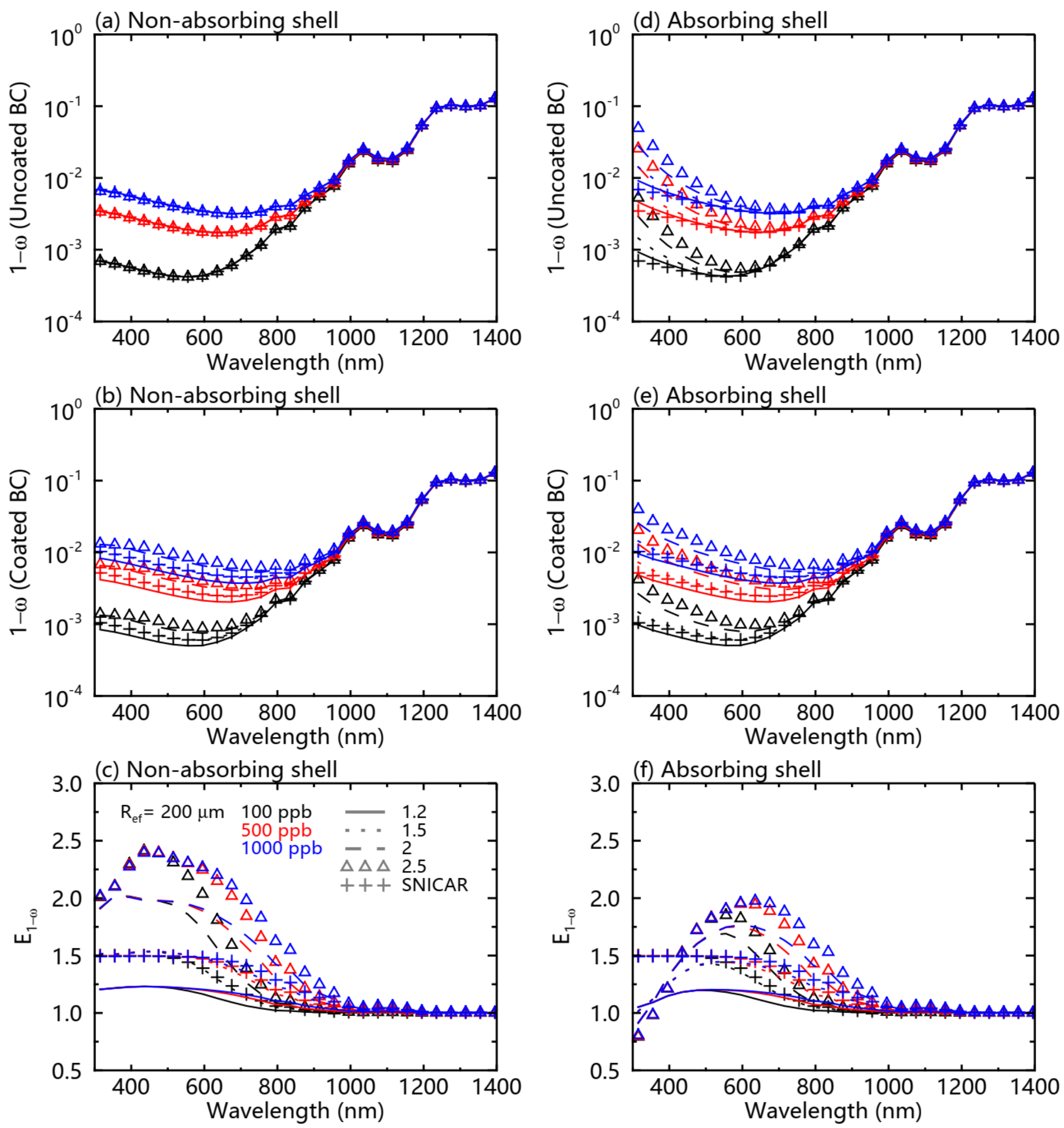

Figure 2. Snow single-scattering co-albedo (1–ω) as a function of wavelength, with different BC concentrations and core/shell ratios for (a) uncoated and (b) coated BC with an assumption of a non-absorbing shell. (d) and (e) are same as (a) and (b), respectively, but with an assumption of an absorbing shell. (c) shows the ratios of snow single-scattering co-albedo ($E_{1-\omega}$) for coated versus uncoated BC with an assumption of a non-absorbing shell. (f) is same as (c), but with an assumption of an absorbing shell. The snow grain radius was assumed to be 200 nm.

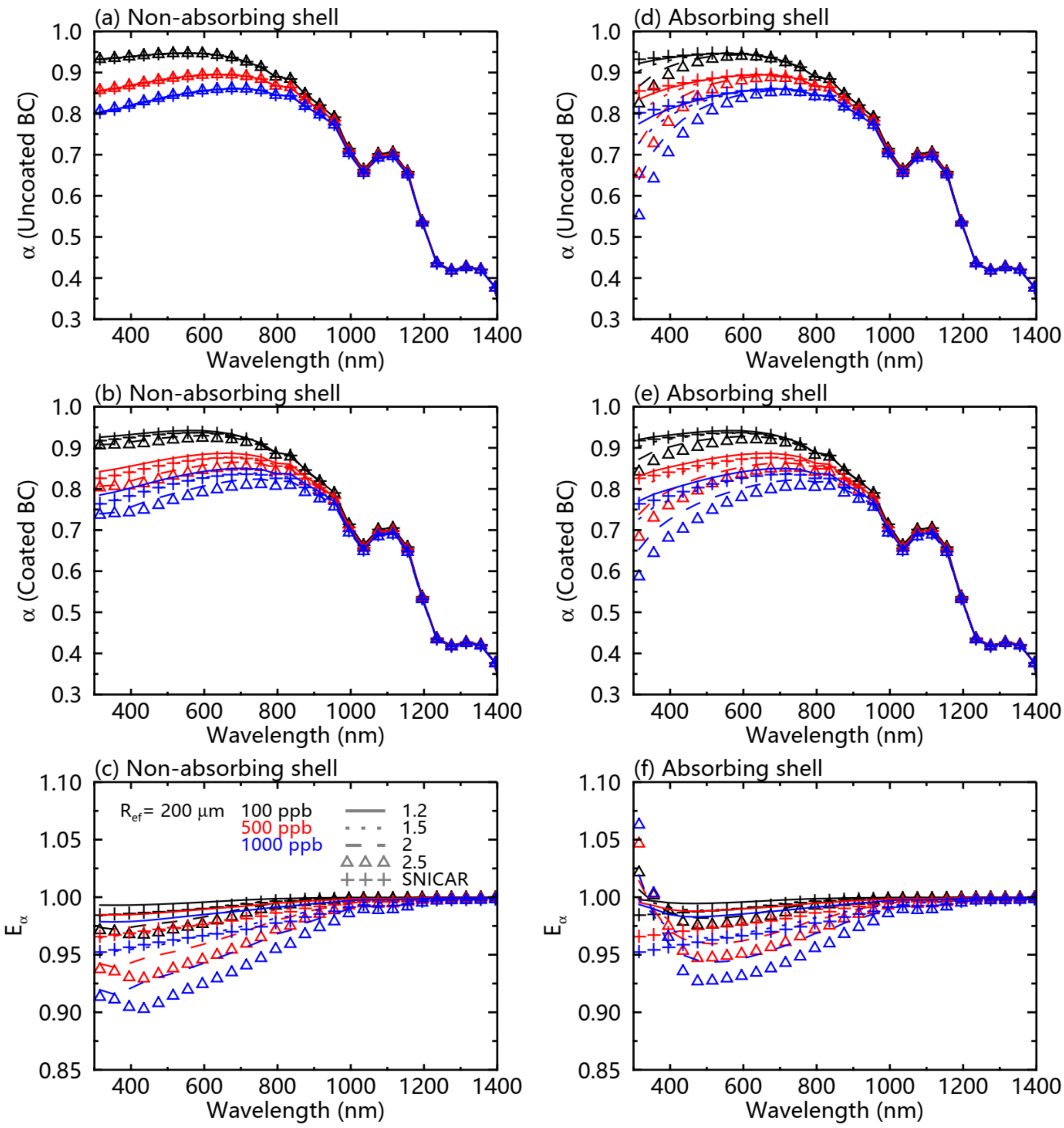

Figure 3. Same as Figure 2, but for snow albedo (α).

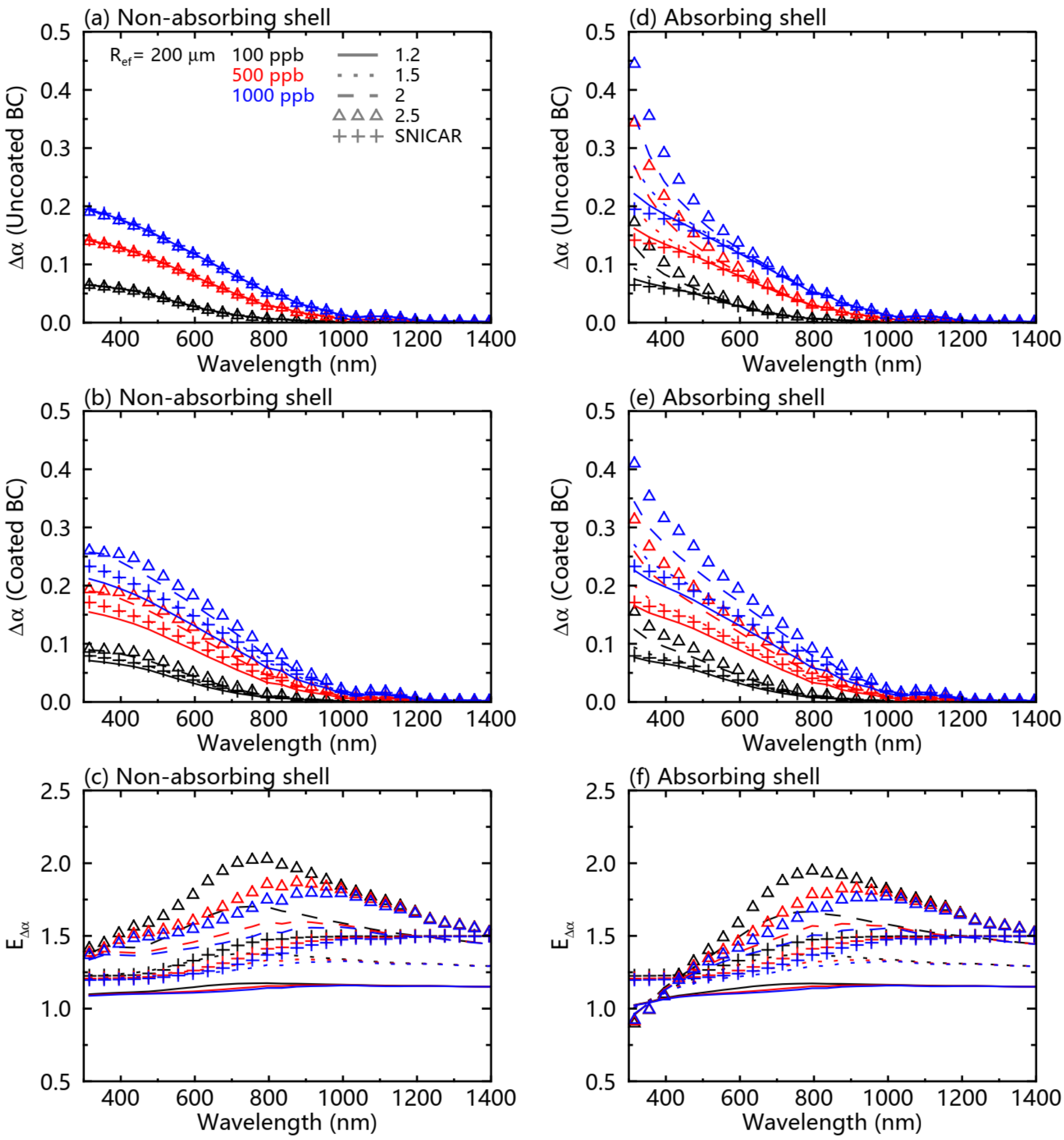

Figure 4. Same as Figure 2, but for snow albedo reduction (Δα).

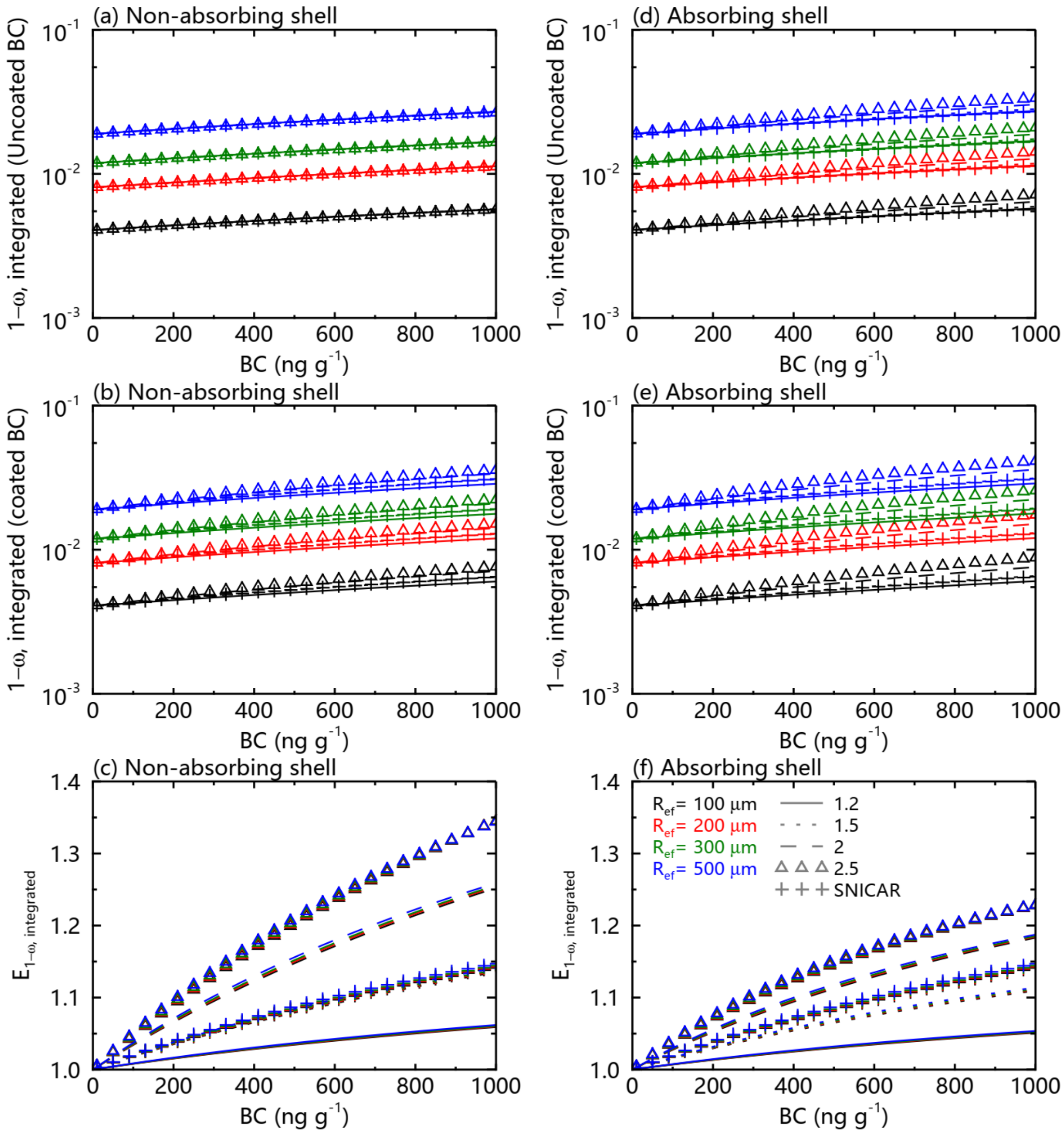

Figure 5. The spectrally weighted snow single-scattering co-albedo ($1\text{-}\omega_{\text{integrated}}$) over 300–2500 nm of a typical surface solar spectrum at mid–high latitude from January to May, for (a) uncoated and (b) coated BC with an assumption of a non-absorbing shell. (d) and (e) are same as (a) and (b), respectively, but with an assumption of an absorbing shell. (c) shows the ratios ($E_{1-\omega,\ \text{integrated}}$) of spectrally weighted snow single-scattering co-albedo for coated versus uncoated BC with an assumption of a non-absorbing shell. (f) is same as (c), but with an assumption of an absorbing shell.

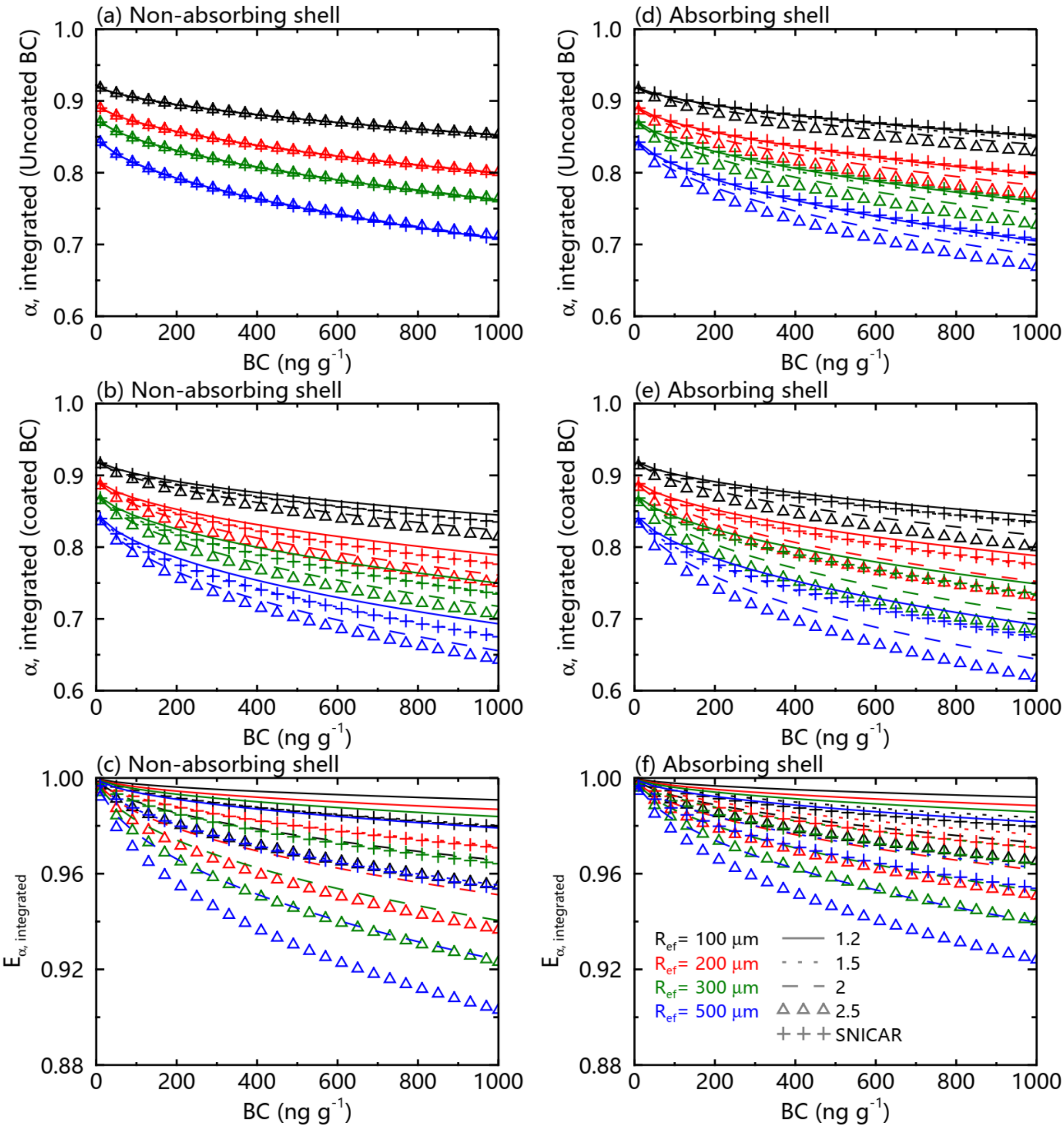

Figure 6. Same as Figure 5, but for snow albedo ($\alpha_{\text{integrated}}$).

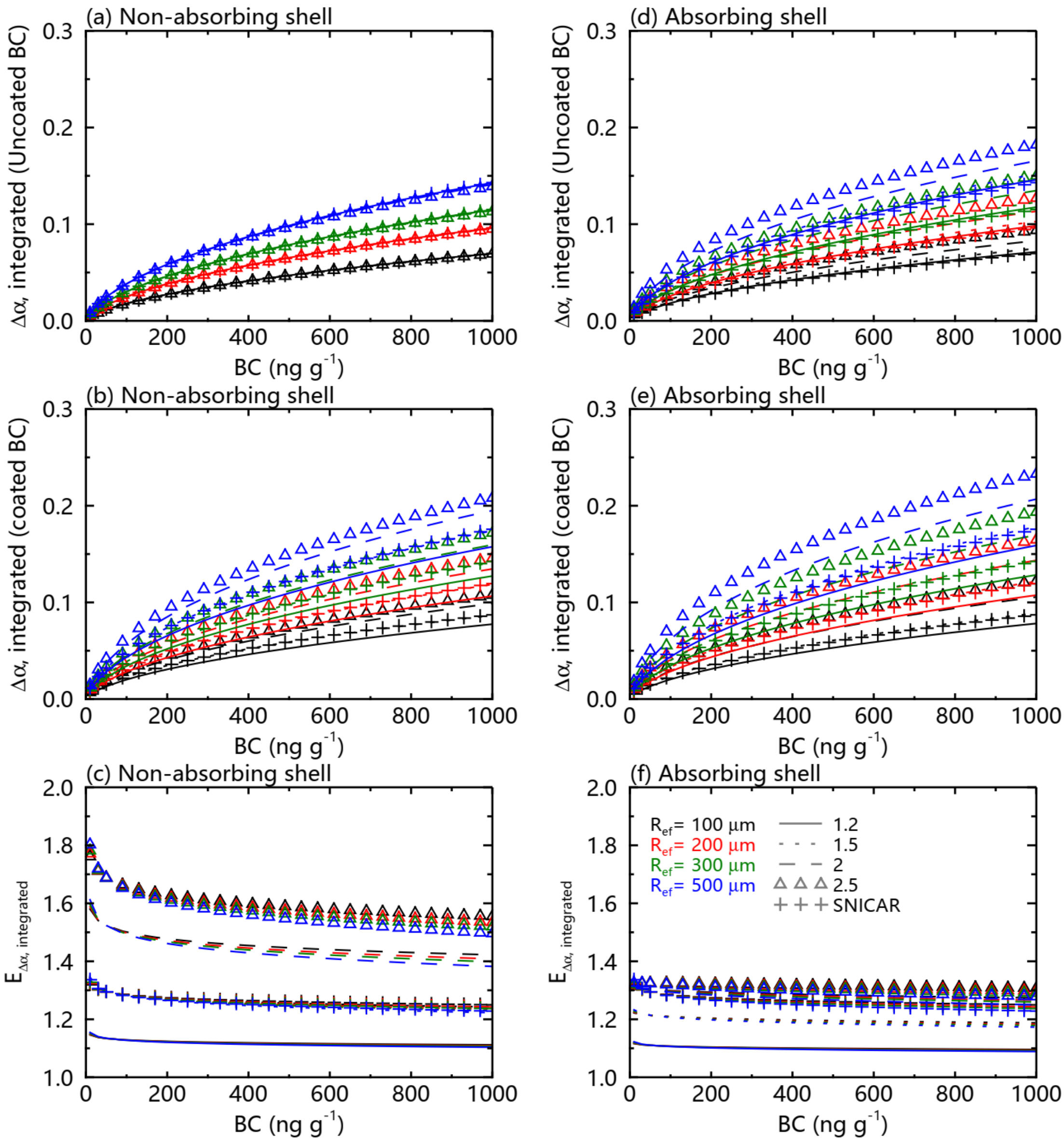

Figure 7. Same as Figure 5, but for snow albedo reduction ($\Delta\alpha_{integrated}$).

In addition, we have moved Figure S5 to Figure 10 to compare the direct numbers of snow albedo reduction and radiative forcing by coated versus uncoated BC for measurement-based estimate of coating effect in Section 3.6.

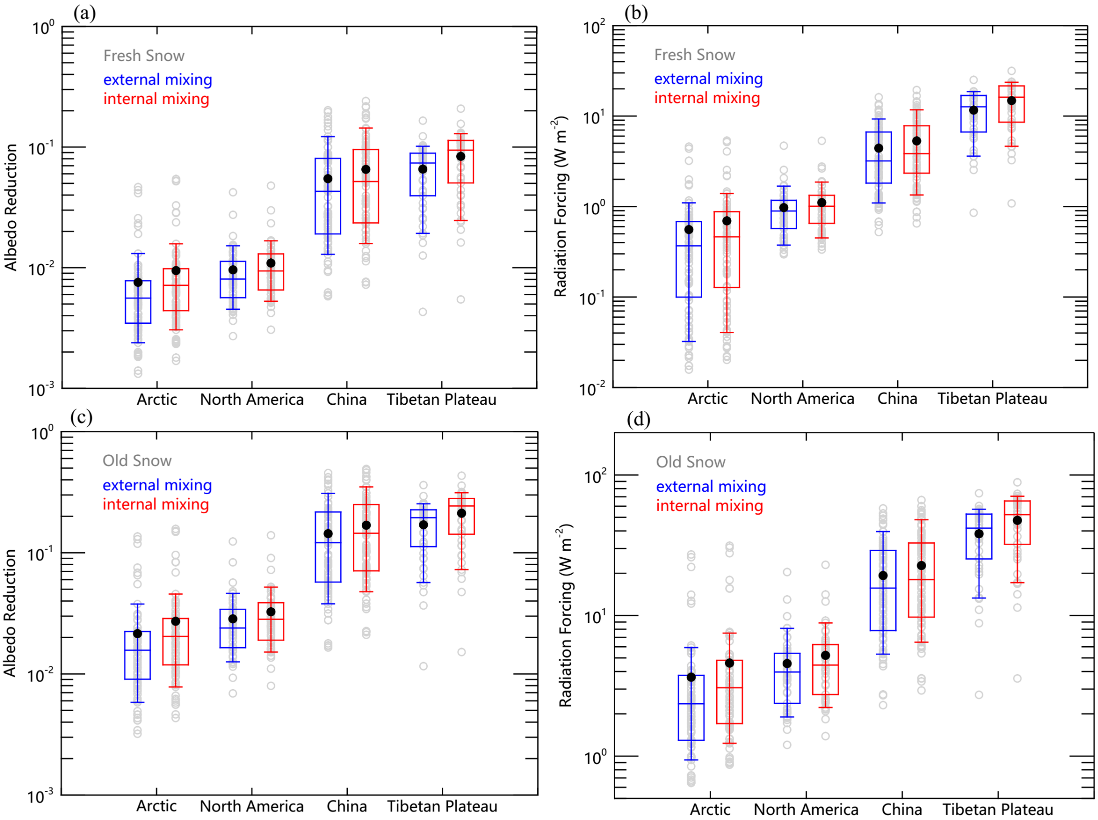

Figure 10. Statistical plots of (a) albedo reduction, and (b) radiative forcing, in different regions for fresh snow. (c) and (d) Same as (a) and (b), but for old snow. The boxes denote the 25th and 75th quantiles, horizontal lines denote the 50th quantiles (medians), solid dots denote averages, and whiskers denote the 10th and 90th quantiles. In situ data is shown as gray circles.

The detailed contents added in the text can been seen in the revised manuscript in Section 3.2, 3.3 and 3.6.

References:

Hadley, O. L., and Kirchstetter, T. W.: Black-carbon reduction of snow albedo, Nat. Clim. Change, 2, 437-440, 2012.

He, C. L., Liou, K. N., Takano, Y., Yang, P., Qi, L., and Chen, F.: Impact of Grain Shape and Multiple Black Carbon Internal Mixing on Snow Albedo: Parameterization and Radiative

Effect Analysis, J Geophys Res-Atmos, 123, 1253-1268, 2018c.

Wang, X., Pu, W., Ren, Y., Zhang, X. L., Zhang, X. Y., Shi, J. S., Jin, H. C., Dai, M. K., and Chen, Q. L.: Observations and model simulations of snow albedo reduction in seasonal snow due to insoluble light-absorbing particles during 2014 Chinese survey, Atmos. Chem. Phys., 17, 2279-2296, 2017.

Warren, S. G., and Wiscombe, W. J.: A Model for the Spectral Albedo of Snow. 2: Snow Containing Atmospheric Aerosols, J. Atmos. Sci., 37, 2734-2745, 1980.

3. In section 3.3, the authors argued that SNICAR consider the BC coating effect of an intermediate core/shell ratio. Well, what is the result of this simplification?

R: The result of this simplification that didn't consider the impact of coating materials and core/shell ratio on the BC coating effect only presented a small variation of 1.23–1.31 for $E_{\Delta\alpha,\ integrated}$. In contrast, our study explicitly resolved the optical properties of coated BC in snow. Our results indicate that a 'BC coating effect' enhances the reduction of snow albedo by a factor of 1.1–1.8 for a non-absorbing shell and 1.1–1.3 for an absorbing shell, depending on BC concentration, snow grain radius, and core/shell ratio. As a result, this simplification may lead to possible biases of -10% to 50% in snow albedo reduction calculation. We have added these discussions in the text at Page 18 Lines 11-16.

4. It is good for the authors to discuss the uncertainties of imaginary RI values of OC and BC particle sizes in section 3.4. The question is how large the uncertainty is as 1% for E_alpha and 13% for E_delta_alpha? Bias of direct snow albedo is more straightforward.

R: According to Equation 2, the uncertainty for $E_{\alpha,\ integrated}$ is equivalent to that for snow albedo and the uncertainty for $E_{\Delta\alpha,\ integrated}$ is equivalent to that for snow albedo reduction. As a result, the uncertainties for snow albedo and snow albedo reduction are 1.4% and 13.9%. We have added this clarification in the text at Page 19 Lines 12-15.

5. In section 3.5, the authors mentioned the overestimated albedo as around 0.06 in the polluted snow and argued that the new parameterization of BC coating can reduce this overestimation to 0.02. I feel this statement is too strong, as there is huge uncertainty in the measurements of LAPs in snow. It is good for the climate models to have an option for BC coating effects but I suggest not exaggerate this part.

R: Thanks for your suggestions. We have removed the sentences about "the overestimated albedo as around 0.06 in the polluted snow and argued that the new parameterization of BC coating can reduce this overestimation to 0.02.". In addition, we have revised the sentences about the application to climate models as follows:

"On the other hand, although most global climate models (GCMs) account for coated BC in the atmosphere, they barely consider the coating effect for BC in snow (Bond et al., 2013). In addition, different GCMs apply different types of snow radiative transfer models, which means that one physical mechanism responsible for the BC coating effect in snow cannot be suitable for all GCMs. Hence, our parameterizations are good for the climate models to have an option for BC coating effects in snow." from Page 21 Lines 20-21 to Page 22 Lines 1-5

References:

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Karcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zender, C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, J. Geophys. Res.-

Atmos., 118, 5380-5552, 2013.