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Key Points:
- A new snow albedo model for close-packed snow grains internally mixed with black carbon aerosol is developed
- Close packing reduces albedos for clean and contaminated snow compared with independent scattering and improves modeled snow albedo
- BC-snow albedo effects and albedo feedback are underestimated in climatic analysis and modeling without accounting for snow close packing

Supporting Information:
- Supporting Information S1

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Close packing effects on clean and dirty snow albedo and associated climatic implications

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Abstract Previous modeling of snow albedo, a key climate feedback parameter, follows the independent scattering approximation (ISA) such that snow grains are considered as a number of separate units with distances longer than wavelengths. Here we develop a new snow albedo model for widely observed close-packed snow grains internally mixed with black carbon (BC) and demonstrate that albedo simulations match closer to observations. Close packing results in a stronger light absorption for clean and BC-contaminated snow. Compared with ISA, close packing reduces pure snow albedos by up to ~0.05, whereas it enhances BC-induced snow albedo reduction and associated surface radiative forcing by up to 15% (20%) for fresh (old) snow, with larger enhancements for stronger structure packing. Finally, our results suggest that BC-snow albedo forcing and snow albedo feedback (climate sensitivity) are underestimated in previous modeling studies, making snow close packing consideration a necessity in climate modeling and analysis.

Plain Language Summary Snow plays a critically important role in the Earth climate system and water cycles. It affects not only surface radiative and heat fluxes but also freshwater resources. Previous modeling of snow albedo, a key climate feedback parameter, follows the independent scattering approximation. However, observations have shown that densely packed snow grains (i.e., close packing) are ubiquitous, where the independent scattering among grains may be invalid. This study, for the first time, explicitly accounts for close packing of snow grains and assesses its effects on clean and contaminated snow albedos by developing a new snow albedo model with internal mixing of aerosol and snow grains. We find that compared with the conventional independent scattering approximation, close packing reduces pure snow albedo and also enhances snow albedo reduction caused by black carbon contamination, with larger enhancements for stronger structure packing. Our results suggest that it is imperative to include snow close packing in climate modeling and analysis in order to improve the estimate of black carbon-snow albedo forcing and snow albedo feedback (climate sensitivity).

1. Introduction

Snow plays a critically important role in the Earth climate system and water cycles. It affects not only surface radiative and heat fluxes but also freshwater resources. Snow albedo feedback, the most significant positive amplification of surface temperature increase, strongly enhances warming over polar regions and high mountains [*Qu and Hall*, 2013]. Observations have shown substantial albedo reductions in snowpack contaminated by aerosols [*Qian et al.*, 2015; *Lee et al.*, 2016], particularly black carbon (BC), which has the strongest light-absorbing property [*Bond et al.*, 2013]. Modeling studies also indicated that BC deposition is an important contributor to snow albedo reduction and surface warming over snow-covered regions [*Qian et al.*, 2015], particularly the Tibetan Plateau [*He et al.*, 2014a, 2014b], the Rocky Mountains [*Qian et al.*, 2009], and the Arctic [*Warren and Wiscombe*, 1985; *Qi et al.*, 2017]. In addition to external factors such as impurities and solar zenith angle, internal snow properties can also influence snow albedo, including snow mass/thickness, snow grain size, grain shape, and packing structure [*Warren and Wiscombe*, 1980; *Jacobson*, 2004; *Flanner et al.*, 2007; *Jin et al.*, 2008; *Liou et al.*, 2014].

Previous snow modeling studies have used the conventional independent scattering approximation (ISA) for snow grains [*Warren and Wiscombe*, 1980; *Jacobson*, 2004; *Flanner et al.*, 2007], which assumes that light scattering and absorption of each snow grain is independent of surrounding grains so that the total intensity is the sum of intensity component for each grain. *Wiscombe and Warren* [1980] suggested that ISA is reasonable for pure snow grains in comparison to albedo measurements. However, observations showed that densely packed snow grains (i.e., close packing hereinafter) are ubiquitous [*Colbeck*, 1982], where ISA among grains may be invalid. For example, *Ishiniaru and Kuga* [1982] measured that the extinction coefficient at a visible wavelength for a dense distribution of latex-sphere suspension relative to that for sparse distribution decreases (increases) for high volume fractions when the size parameter is small (large). *Göbel et al.* [1995] observed a decrease in the scattering efficiency (visible and infrared wavelengths) of latex-sphere suspensions and TiO_2 powder grains due to close packing effects, relative to that for ISA. *Kokhanovsky* [1998] found that the scattering efficiency and asymmetry factor of densely packed large particles such as snow grains decrease with their concentrations. Thus, in order to accurately predict and project snowpack change and its climatic impact and feedback, it is imperative to understand and assess the effect of close packing in snow albedo modeling.

Several pioneering efforts have been made to simulate snow close packing effects. Researchers in the electrical engineering field applied quasi-crystalline approximation and dense medium radiative transfer (DMRT) theory to microwave remote sensing of snowpack [e.g., *Wen et al.*, 1990]. DMRT has the same structure as the conventional radiative transfer equation, but the relationship of extinction coefficient, single-scattering albedo, and phase function to optical characteristics of individual particles differs from the conventional ISA. However, their method is not applicable to large size parameters [*Tsang and Ishimaru*, 1987] such as snow albedo calculations at visible and near-infrared wavelengths under the present investigation. *Kokhanovsky and Zege* [2004] further derived a snow model to account for effects of nonsphericity of snow grains and close packing without mixing with aerosols.

In this study, we develop a new snow albedo model for close-packed snow grains internally mixed with multiple BC particles to assess the close packing effect on albedos of clean and BC-contaminated snow and associated climatic effects. We also formulate physical equations to adjust snow albedo calculations without close packing to those with close packing for application to land surface and climate models.

2. Methods

We extend the geometric-optic surface-wave (GOS) approach [*Liou et al.*, 2011, 2014; *Takano et al.*, 2013; *He et al.*, 2015] to compute optical properties of snow grains with close packing structures and inclusion of multiple BC particles. The GOS approach, explicitly resolving complex particle structures, accounts for geometric reflection and refraction, diffraction, and surface wave components (Figure S1 in the supporting information) based on a Monte Carlo photon tracing method and a ray-by-ray integration approach. The GOS approach has been applied to a wide range of particle sizes and shapes, particularly including nonspherical snowflakes mixed with light-absorbing aerosols [*He et al.*, 2014b; *Liou et al.*, 2014]. It produced consistent particle optical properties with those determined from the superposition T-matrix method and laboratory measurements for fractal aggregates with various coating structures [*He et al.*, 2016b] as well as the discrete dipole approximation and finite difference time domain methods for plate and column ice crystals [*Liou et al.*, 2011]. *Liou and Yang* [2016] provided a comprehensive description of the GOS approach and its application.

Specifically, we construct a close-packed snow cube by stacking up a number of individual grain spheres ($N_s = 2^3$, 3^3, 4^3, and 5^3 in this study) with the radius of r_s as shown in Figure 1, where N_s is the number of snow spheres forming a close-packed cube. We then compute an effective geometric cross sectional area (A_s) for the close-packed snow cube by using a Monte Carlo photon tracing method [*Liou et al.*, 2011]. The resulting geometric shadow of the snow cube on a plane perpendicular to incident light beams is

$$A_s(\alpha, \beta) = A[N_a(\alpha, \beta)/N_t] \tag{1}$$

where A (=L^2; L is the cube's maximum dimension) defines the area of a square, which is large enough to cover the geometric cross section of a snow cube. The α and β are the orientation angles of a snow cube with respect to the incident light beam. N_a is the number of photon incident (scattered/absorbed) on a snow cube, depending on its orientation. N_t is the number of total photons used in the photon tracing procedure. We consider an ensemble of randomly orientated close-packed snow cubes and average their geometric cross sections over all directions. Subsequently, we compute extinction and absorption cross sections of the close-packed snow cubes by a ray-by-ray integration approach [*Liou et al.*, 2011]. Diffraction is determined based on the Babinet's principle and the geometric cross section. The surface-wave component is negligible for large particles (size parameters > ~50). Following *Liou et al.* [2011, 2014], we compute single-scattering properties of close-packed snow grains, including optical depth (τ), single-scattering coalbedo ($1 - \varpi$), and

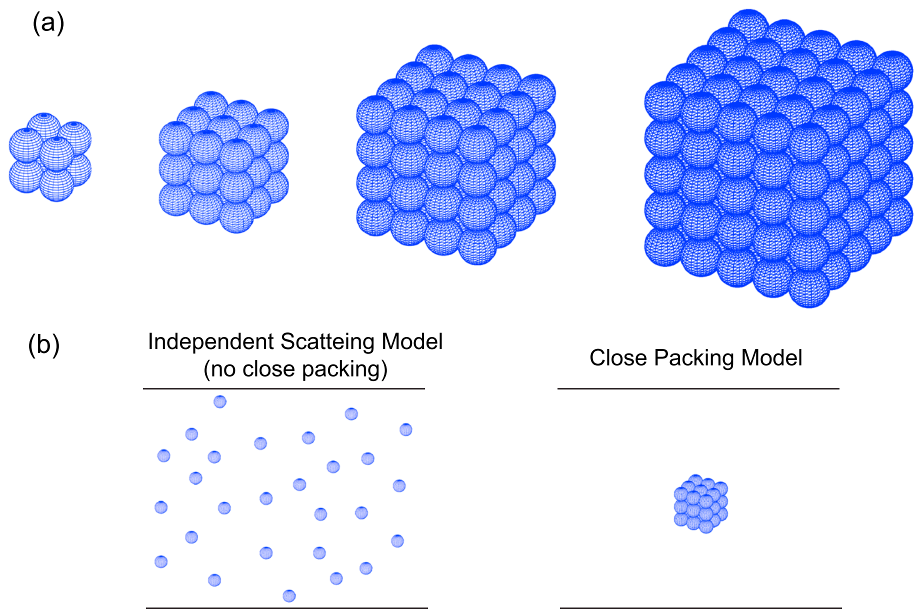

Figure 1. (a) Close-packed snow cubes consisting a number of snow grains/spheres (N_s (n) = 2^3, 3^3, 4^3, 5^3, …, n^3). These close-packed snow cubes are assumed to be randomly oriented in optical calculations. (b) A demonstration of independent scattering model (N_s = 1) and close packing model for the case of n = 3. The actual number of close-packed cubes or independent scattering spheres in a snow layer depends on snow volume and layer thickness. Each close-packed snow cube is assumed to be independent of surrounding cubes.

asymmetry factor (g) and perform radiative transfer computations to obtain snow albedo by using the doubling/adding method [*Takano and Liou*, 1989].

Following the aforementioned procedure, we determine single-scattering properties and albedo of snow grains with ISA. We compute the geometric cross section (πr_s^2) of each snow sphere and sum up over all grains independently to obtain total cross sections ($N_{st}\pi r_s^2$, N_{st} is the total number of independent snow spheres). We further calculate the ratios (f) of the cross section (A_s) of a close-packed snow cube to that of ISA snow ($N_{st}\pi r_s^2$) with the same number of spheres ($N_{st} = N_s$). We find that f = 0.6801, 0.5075, 0.4029, and 0.3338 for n = 2, 3, 4, and 5 ($N_s = n^3$), respectively, independent of snow grain size (r_s). The f value is smaller than 1, because the close-packed snow cube prevents a part of photons from interactions with its inner part (i.e., shadowing effect), resulting in a weaker extinction than the ISA snow with the same number of spheres. We link snow optical depths for close packing (τ') to that for independent scattering (τ) by $\tau' = f\tau$, where f is referred to as optical depth adjustment factor due to close packing effects, assuming the same snow extinction efficiency (= ~2 for large particles) for close packing and ISA. We note that the present study only accounts for a small n ($n < 6$) and the results may not be generalized to cases with a large n (e.g., $n > 10$), which requires further investigations. We also note that snow close packing (changes in grain structures) can also be viewed as volume-equivalent snow spheres with different effective grain sizes. However, we assess the effect of close packing in the present study by explicitly resolving the packing structure rather than using an equivalent effective grain size.

In this study, we perform computations for both clean and BC-contaminated snow with and without close packing effects for fresh (r_s = 100 μm) and old (r_s = 1000 μm) snow. For contaminated snow, we apply a stochastic process [*Liou et al.*, 2014] to generate multiple monodisperse BC spheres with a radius of 0.1 μm randomly distributed inside each snow sphere, with BC concentrations of 100, 250, and 500 ppb in snow for moderately and highly polluted scenarios based on observations [*Qian et al.*, 2015]. We further account for BC particles coated with sulfate (Figure S2), which are ubiquitous in the atmosphere through aging processes [*Schwarz et al.*, 2008; *He et al.*, 2016a] and significantly alters BC optical properties [*He et al.*, 2015]. We assume a core-shell structure for coated BC with a coating thickness of 20 nm to obtain a mass absorption coefficient of ~11.3 $m^2\ g^{-1}$ [*Bond et al.*, 2013]. We use spectral refractive indices of snow from *Warren and Brandt* [2008], BC from *Krekov* [1993], and sulfate from *Toon et al.* [1976]. For albedo calculations, we assume one-layer snow with an optical depth of 960 based on observations [*Jacobson*, 2004] for ISA cases and adjust it for close packing cases using the optical depth adjustment factor (*f*). One advantage of prescribing the snow optical depth is to circumvent the complexity of taking into account the effects of porous space among randomly oriented packed snow cubes and the size of packed snow aggregates on snow mass density and the consequence of optical depth calculations. The underlying surface is set to be a blackbody.

3. Results and Discussions

3.1. Close Packing Effects on Snow Optical Properties and Albedo

Figure 2 shows the single-scattering coalbedo, asymmetry factor, optical depth adjustment factor, and albedo for clean and BC-contaminated fresh snow with ($N_s > 1$) and without ($N_s = 1$; i.e., ISA) close packing at a wavelength of 0.55 μm. Compared to ISA, close packing leads to higher (lower) single-scattering coalbedos (asymmetry factors), with a monotonic increase (decrease) with N_s, for both clean and BC-contaminated snow. The single-scattering coalbedo, albeit small, increases by a factor of 3 with a highly packed structure ($N_s = 5^3$) relative to that without close packing, whereas the asymmetry factor decreases by 10%. The trends are similar for clean and contaminated snow. This suggests that stronger close packing results in stronger snow absorption but weaker forward scattering. However, close packing significantly decreases snow optical depth for a constant snow water equivalent (Figure 2), where it is 50% smaller for moderate packing ($N_s = 3^3$) and 66% smaller for strong packing ($N_s = 5^3$) relative to ISA.

Close packing leads to a small (≤0.01) reduction in pure snow albedo at visible wavelengths (Figure 2), because of the opposite effects from larger single-scattering coalbedos and smaller optical depths versus weaker forward scattering. However, the albedo reduction caused by close packing is larger for BC-contaminated snow than clean snow by up to a factor of 2. Moreover, BC contamination results in a snow albedo reduction by 0.05–0.08 with a concentration of 500 ppb under high pollution (Figure 2), depending on BC coating and close packing (N_s). Previous measurements also showed an albedo reduction of ~0.08 for the same BC concentration in snow [*Hadley and Kirchstetter*, 2012]. The reduction is 40–60% smaller in the case of external mixing of BC and snow [*He et al.*, 2014b]. We find that close packing enhances the BC-induced albedo reduction by up to 15% relative to ISA, with larger reductions for stronger packing, while BC coating further reduces the albedo by ~20% due to a larger single-scattering coalbedo compared with uncoated cases (Figure 2). *He et al.* [2014b] showed a 30–50% larger snow albedo reduction caused by coated BC compared with uncoated BC aggregates, depending on concentration.

Compared with visible wavelength cases, close packing exerts much stronger effects on fresh snow albedo at a near-infrared (NIR) wavelength (Figure S3), where BC contamination shows negligible effects. As close packing becomes stronger (N_s increases), snow albedo reduces by 0.01–0.05, which is a factor of 3–5 larger than that at visible wavelengths. This could affect prediction of snowpack evolution and its radiative effects [*Aoki et al.*, 2011] as well as remote sensing of snow properties using NIR wavelengths [*Li et al.*, 2001].

Figure 3 shows that as close packing becomes stronger, the magnitude and trend for asymmetry factors and optical depths of clean and BC-contaminated old snow at a 0.55 μm wavelength are similar to those in fresh snow cases, whereas the single-scattering coalbedo of old snow is 1 order of magnitude higher than that of fresh snow for all packing cases. As a result, the albedo of pure old snow is lower than that of fresh snow by ~0.03, consistent with previous modeling results [*Wiscombe and Warren*, 1980]. We find that close packing reduces snow albedo by up to 0.01 for pure old snow and up to 0.04 for BC-contaminated old snow, which are much larger than those for fresh snow. Moreover, moderate BC contamination (250 ppb concentration in snow) leads to reductions of 0.11 and 0.13 in old snow albedos for uncoated and coated BC under ISA, respectively (Figure 3), while close packing further enhances the BC-induced albedo reduction by up to 20% for old snow. *Flanner et al.* [2007] simulated a BC-induced reduction of ~0.07 in spectrally averaged (0.3–5 μm) snow albedo for the same concentration of coated BC externally mixed with old snow ($r_s = 1000$ μm) without close packing, which is approximately half of that at visible wavelengths [*Warren and Wiscombe*, 1985].

3.2. Quantitative Albedo Adjustment for Close Packing Effects

We find that calculated snow albedos at a wavelength of 0.55 μm with and without close packing are highly correlated ($R^2 = 0.998$), which decrease with BC concentration and increase with solar zenith angle

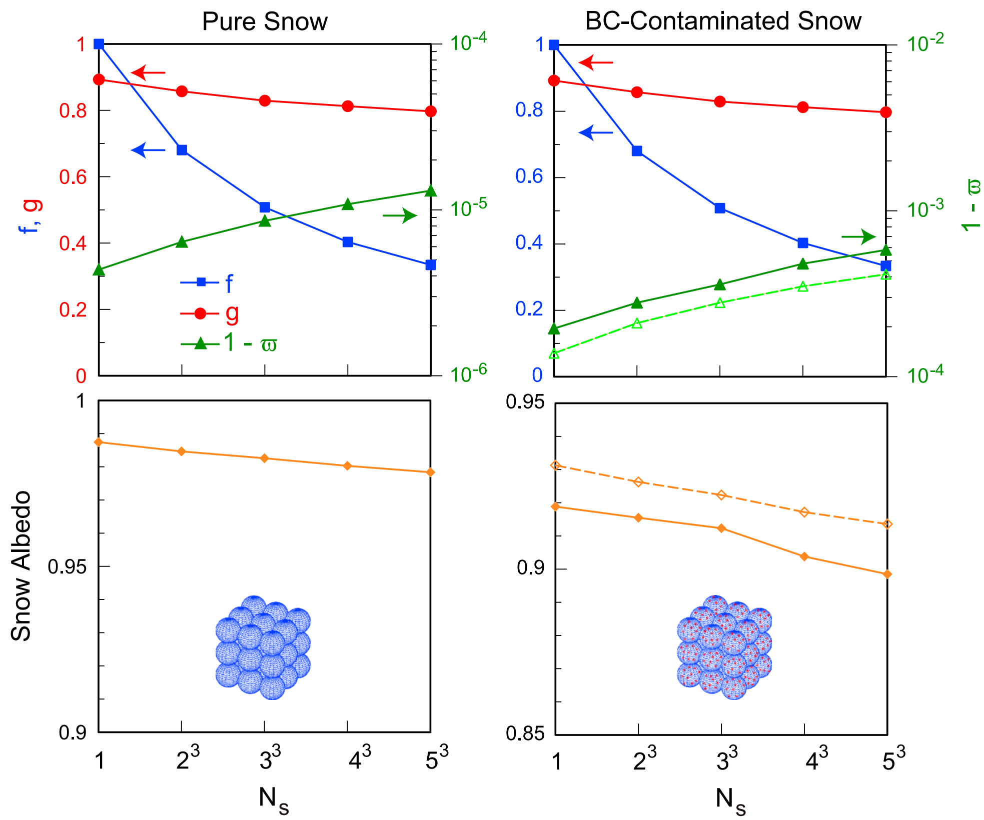

Figure 2. (top row) Single-scattering coalbedo ($1 - \varpi$, green lines), asymmetry factor (g, red lines), and optical depth adjustment factor (f, blue lines) for close-packed snow cubes as a function of the number (N_s) of snow spheres forming the cube. The radius of each snow sphere is 100 μm. Results for both close packing ($N_s > 1$) and independent scattering ($N_s = 1$) snow models are shown. (bottom row) Same as Figure 2 (top row) but for snow albedo at a wavelength of 0.55 μm and a solar zenith angle of 60°. Results for (left column) pure snow and (right column) BC-contaminated snow with a BC concentration of 500 ppb are shown. For contaminated cases, snow grains contain multiple coated (solid lines) or uncoated (dashed lines) BC particles. A close-packed snow cube with $N_s = 3^3$ is shown for demonstration.

(Figures 4a, S4a, S5a, and S6a). It turns out that the strong linear relationship is valid for different N_s values and independent of BC concentration in snow and solar zenith angle. Thus, we develop a linear regression equation to adjust modeled fresh snow albedo without close packing (A_{ncp}) to that with close packing (A_{cp}) as follows:

$$A_{cp} = 1.171 A_{ncp} - 0.178, \quad \left(N_s = 5^3, \text{strong packing}\right) \tag{2}$$

$$A_{cp} = 1.031 A_{ncp} - 0.035, \quad \left(N_s = 3^3, \text{moderate packing}\right) \tag{3}$$

These two equations quantitatively demonstrate snow albedo reduction caused by close packing, applicable to land surface and climate models.

Furthermore, we use the two equations to adjust snow albedo calculations to account for the close packing effect. Figures 4b and S4b show wintertime (December to February) snow albedo during 2007–2009 at Sapporo, Hokkaido, from measurements and model results with and without close packing. We focus on wintertime to avoid effects of substantial snow melting on packing structures. The measured albedo and modeled albedo without close packing (but with snow impurities) are from *Aoki et al.* [2011], while model results with strong and moderate close packing are derived via adjustments from equations (2) and (3), respectively. We find that compared with observations, model results without close packing overestimate snow albedo by 0.021 (mean error (ME)), with a root-mean-square-error (RMSE) of 0.030, whereas accounting for strong (moderate) close packing of fresh snow reduces the ME to 0.004 (0.015) and the RMSE to 0.024 (0.026) (Figures 4b and S4b). Albedo adjustments for close packing of old snow reduce the model-observation discrepancies more (see Figures S5 and S6). Therefore, close packing improves snow albedo

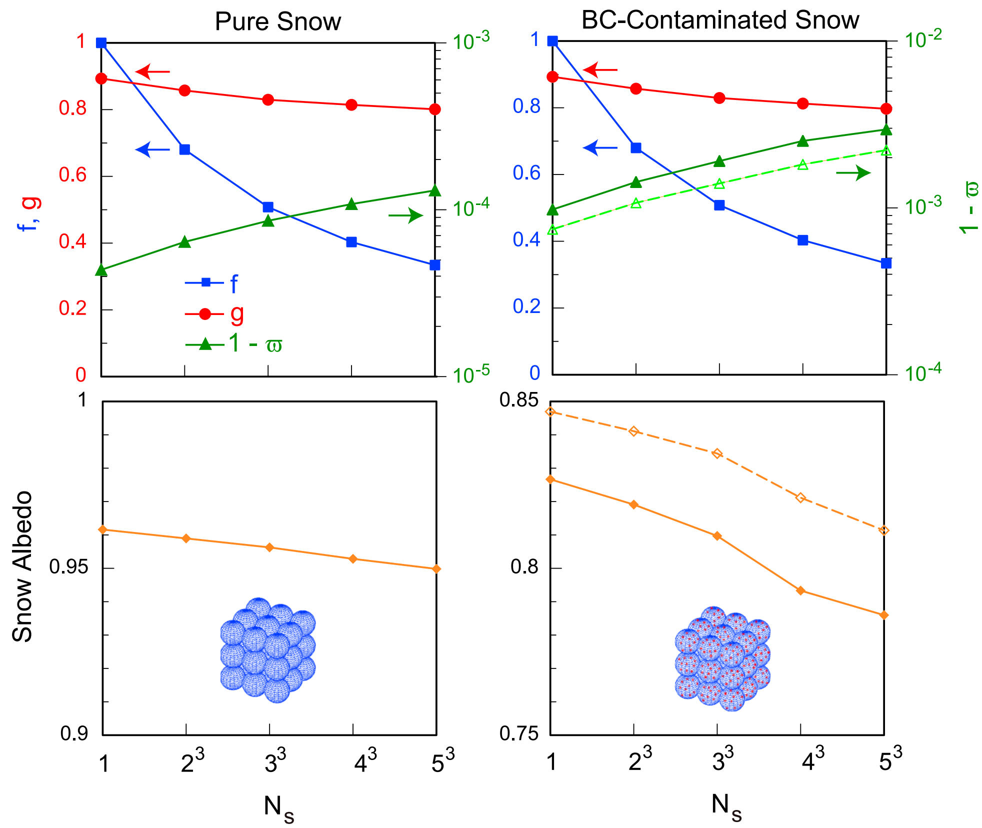

Figure 3. Same as Figure 2 but for a radius of 1000 μm for each snow sphere and a BC concentration of 250 ppb in snow.

simulations, showing important implications to evaluate aerosol effects on snow albedo and snow albedo feedback (see section 4).

3.3. Uncertainty Analysis

We note that a number of factors could introduce uncertainty in quantifying the close packing effect. For example, this effect is significantly affected by the number (N_s) of snow spheres forming the packing snow cube (i.e., packing strength). We account for four scenarios ($N_s = 2^3$, 3^3, 4^3, and 5^3) in this study; however, stronger packing with more snow spheres could occur in real snowpack. In addition, complex structure/shape of close-packed snow grains [see e.g., *Colbeck*, 1982] could be important, which are not accounted for in this study. Recent studies [*Liou et al.*, 2014; *Dang et al.*, 2016] also suggested that grain shape is critical to snow albedo modeling. Other factors, including aerosol-snow mixing state (external versus internal), aerosol composition (BC/dust/others), and aerosol size distribution in snow, likely alter the close packing effect on contaminated snow [*He et al.*, 2014b; *Liou et al.*, 2014]. To the extent that the present modeling results closely match observations as illustrated in Figure 4, it appears that this study has accounted for key close packing factors in snow albedo calculations.

4. Climate Implications

We have shown that close packing, which improves snow albedo simulations (section 3.2), can reduce modeled snow albedo by up to 0.04 compared to ISA, depending on snow grain size, impurity concentration, solar zenith angle, and packing strength (N_s). This albedo alteration due to close packing, viz-a-viz the strong positive snow albedo feedback (SAF) [*Qu and Hall*, 2013], could exert substantial impacts on surface radiative and heat flux and hence temperature and hydrological cycle. Based on an ensemble of climate models without snow close packing, *Hall and Qu* [2006] quantified the sensitivity of snow albedo change to surface air temperature change, which is a key component of SAF. They found a mean springtime sensitivity of $-0.84\%\ K^{-1}$ for Northern Hemisphere (NH) continents, whereas *Fernandes et al.* [2009] showed an

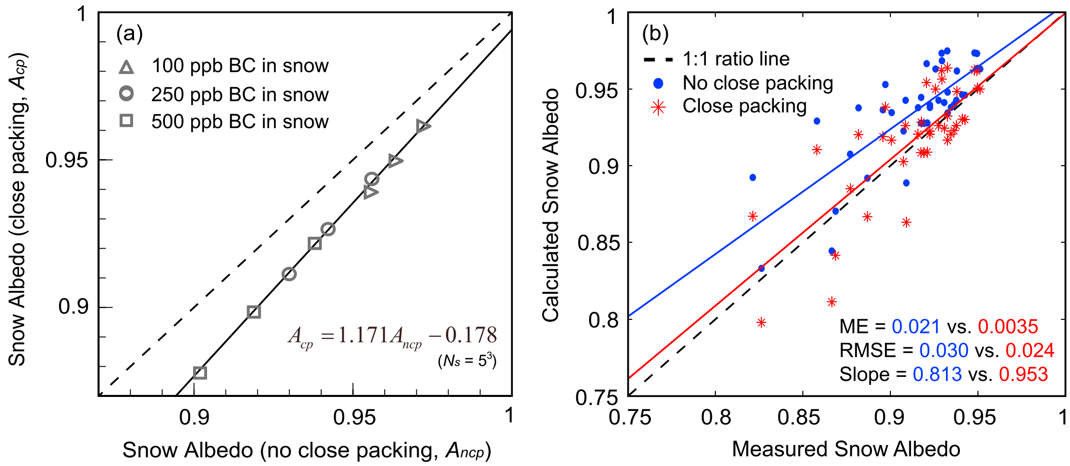

Figure 4. (a) Snow albedo with close packing (N_s = 5^3) as a function of that without close packing at a wavelength of 0.55 μm with a snow sphere radius of 100 μm and contamination by coated BC. BC concentrations in snow are 100 (triangles), 250 (circles), and 500 ppb (squares). For each BC concentration, three solar zenith angles (43°, 60°, and 74°) are used, with an increasing order in albedos. The regression line and equation between snow albedo with (A_{cp}) and without (A_{ncp}) close packing effect are also shown with R^2 = 0.998. (b) Wintertime (December to February) snow albedos (>0.8) during 2007 to 2009 at Sapporo, Hokkaido, from measurements and snow model results without close packing (blue dots). Data are taken from *Aoki et al.* [2011, Figure 8b]. Calculated albedos with close packing (red asterisks) are derived by adjusting those without close packing with the regression equation in Figure 4a. Also shown are regression lines of data points (blue and red) as well as mean error (ME), root-mean-square-error (RMSE), and slope of regression lines of calculated results with and without close packing.

observed sensitivity of −1.11% K^{-1}. *Flanner et al.* [2011] also concluded that climate models substantially undersestimate albedo feedback over the NH cryosphere based on observations. The model-observation discrepancy could be reduced by close packing effects which enhance albedo reductions caused by snow aging (fresh versus old) based on our results, where surface temperature increase is a key driver of snow aging [*Flanner et al.*, 2007].

Following the observed sensitivity, we find that the snow albedo reduction induced by close packing relative to ISA could lead to an increase of up to 0.27 K in springtime surface air temperature over NH continents and even larger for BC-contaminated snow. The surface temperature perturbation by close packing, through the strong SAF, can further affect large-scale atmospheric circulation and hydrological cycle [*Fletcher et al.*, 2009]. Moreover, *Qu and Hall* [2013] found an annual mean climate sensitivity of 0.08 and 0.42 W m^{-2} K^{-1} due to SAF over the globe and NH continents, with highest sensitivities in high mountains and polar regions. However, our results suggest that the climate sensitivity via SAF has been underestimated by previous modeling studies in view of the fact that a higher snow albedo sensitivity to surface air temperature is produced by close packing.

In addition, close packing enhances the BC-induced snow albedo reduction compared with ISA, indicating that the snow albedo effect caused by BC deposition are likely to be underestimated in previous studies. Recent studies, assuming BC-snow internal mixing but without close packing, showed an annual mean BC-induced snow albedo forcing of 0.02–0.08 W m^{-2} globally [*Flanner et al.*, 2012; *He et al.*, 2014b] and 1.5–5.0 W m^{-2} over the Tibetan Plateau [*He et al.*, 2014b]. However, we find that the albedo forcing is up to 20% higher by accounting for snow close packing and that the climatic effect of BC on snow-covered regions could be much larger than previously anticipated. For these reasons, it is submitted that close packing must be incorporated in snow albedo modeling in order to improve predictions of snowpack evolution and aerosol-snow interactions.

Moreover, although ground measurements have measured BC effects on snow albedo changes [*Aoki et al.*, 2011; *Hadley and Kirchstetter*, 2012], *Warren* [2013] pointed out that signals of BC-induced albedo reductions could be difficult to detect by satellites, except over highly polluted areas, because surface albedos retrieved from satellite observations typically have errors of a few percent [e.g., *Stroeve et al.*, 2005, 2013], comparable to albedo reductions caused by BC over the majority of Northern Hemispheric snowpack based on their radiative transfer calculations. Nevertheless, the present results demonstrated that snow close packing, occurring ubiquitously in the real snowpack, could enhance the signals of BC-induced albedo reductions, which increases the detectability of BC effects on snow albedo. Furthermore, in a recent study, *Lee et al.* [2016] indicated that BC can trigger a positive snow albedo feedback and amplify initial albedo reductions, resulting in a detectable albedo change by satellite measurements in a relatively long timescale (e.g., a month).

5. Conclusions

We have developed a new snow albedo model for closed-packed snow grains internally mixed with BC aerosol. Compared with the widely used ISA in previous studies, close packing resulted in higher single-scattering coalbedos but lower asymmetry factors and optical depths for both clean and BC-contaminated snow. Close packing reduced pure fresh snow albedo by up to 0.05 at NIR wavelengths, a factor of 3–5 larger than that at visible wavelengths, while it also enhanced the BC-induced snow albedo reduction and hence albedo forcing by up to 15% for fresh snow and 20% for old snow, with larger enhancements occurring in stronger structure packing. The close packing effect was stronger for larger snow grain size (old versus fresh snow). We further determined quantitative relationships to adjust snow albedo calculations for the close packing effect, resulting in a closer match between albedo simulations and observations than ISA calculations. Our results suggest that the climate sensitivity due to SAF based on ISA has been underestimated, which could affect the evaluation of regional and global hydrological cycle and surface temperature perturbations. Finally, this study highlights the necessity of accounting for snow close packing in assessing the effects of BC on snow albedo and its feedback in the BC-snow system, particularly over polar and mountain regions.

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