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Interactive comment on "Black carbon and mineral dust in snow cover on the Third Pole" *by* Yulan Zhang et al.

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Dear editor,

The manuscript: Black carbon and mineral dust in snow cover on the Tibetan Plateau by Zhang Y.L. et al.

The manuscript number: tc-2017-111

We greatly appreciate the reviewers' constructive comments to improve the paper. We have revised our manuscript according to these comments (blue color in the main text), and hope the revised manuscript is suitable for publication in The Cryosphere.

The “point to point” response to comments are listed as below.

Sincerely yours, Yulan Zhang and Shichang Kang

Response to Referee #1

General opinion: The authors report the observation of light-absorbing impurities in snow over Tibetan Plateau. Based on these field observed data, they calculated the albedo reduction induced by black carbon and mineral dust, and the corresponding impact on snow energy budget. The field data reported in this work are valuable for quantifying the impact of light-absorbing particles on snow albedo and the analysis based on this field data are informative. However, some discussion and conclusions given in this paper are not accurate and need to be modified. This manuscript also contains a lot of types/grammar errors (some obvious errors are listed below) that need to be corrected before this manuscript can be considered for publication. Here are the suggestions/comments that the authors may find useful. Answer: Thank you very much for the comments. We have carefully revised according to the comments. The manuscript has also been improved by a native speaker to reduce the types/grammar errors.

Comments and Questions Page 1 Line 30-32: BC is recognized as an important climate forcer not only because it absorbs sunlight, but also because a large fraction of BC are emitted from anthropogenic sources. Please be more accurate at here. Answer: We have revised as following in the main text (Page 1-2): Atmospheric BC is a distinct type of carbonaceous material from incomplete combustion of biomass/biofuel and fossil fuel. A large fraction of BC is emitted from anthropogenic activities (Bond et al., 2013). Because BC can absorb solar radiation, influence cloud processes, and alter the melting of snow cover and glaciers, it has been considered to be the second most important climate forcer in the Earth’s climate system only after carbon dioxide (Andreae and Ramanathan, 2013; Bond et al., 2013; Ramanathan and Carmichael, 2008).

References: Andreae, M. O., and Ramanathan, V.: Climate's dark forcings, Science, 340, 280−281, 2013. Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schultz, 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., Zender, C. S.: Bounding the role of black carbon in the climate system: A scientific assessment, J. Geophys. Res. Atmos., 118, 5380–5552, doi:10.1002/jgrd.50171, 2013. Ramanathan, V. and Carmichael, G.: Global and regional climate changes due to black carbon, Nat. Geosci., 1, 221-227, doi:10.1038/nego156, 2008.

Page 2 Line 16: ": : : snow covered range" ! snow covered region? Answer: It is "snow covered region". (Page 2, Line 26)

Line 20: "Confirming radiative transfer modeling". It is not very clear to readers what does the authors mean. Please consider revise this. Answer: The sentence has been revised as following (Page 2, Line 23-31): In the European Alps, observed reflectance provided evidence that seasonal input of dust can strongly decrease the spectral properties of snow, in particular, from 350 to 600 nm (Di Mauro et al., 2015, 2017). In a study of two sites on Claridenfirn of the Swiss Alps, Gabbi et al. (2015) showed that mineral dust lowered the mean annual albedo by 0.006–0.011, depending on the location on the glacier, causing a reduction of approximately 142–271 mm in annual mass balance. In the San Juan Mountains of the USA, snow cover duration in a seasonal snow-covered region, was found to be shortened by 18 to 35 days during ablation through surface shortwave RF caused by deposition of disturbed desert dust (Painter et al., 2007). In the upper Colorado River Basin, the daily spring dust RF ranged from 30-65 W m-2, advancing melt by 15-49 days (Skiles et al., 2015). A study of the Mera glacier on the southern slope of the Himalayas even indicated that, when dust concentrations are high, dust dominates absorption, snow albedo reduction, and RF, and the impact of BC may be negligible (Kaspari et al., 2014). The presence of dust in snow suggests a relevant role for BC in darkening the glacier surface.

References: Di Mauro, B., Fava, F., Ferrero, L., Garzonio, R., Baccolo, G., Delmonte, B., Colombo, R.: Mineral dust impact on snow radiative properties in the European Alps combining ground, UAV, and satellite observations, J. Geophys. Res. Atmos., 120, 6080–6097, doi:10.1002/2015JD023287, 2015. Di Mauro, B., Baccolo, G., Garzonio, R., Giardino, C., Massabò, D., Piazzalunga, A., Rossini, M., Colombo, R.: Impact of impurities and cryoconite on the optical properties of the Morteratsch glacier (Swiss Alps), Cryosphere Discuss., doi:10.5194/tc-2017-66, 2017. Kaspari, S., Painter, T. H., Gysel, M., Skiles, S. M., Schwikowski, M.: Seasonal and elevational variations of black carbon and dust in snow and ice in the Solu-Khumbu, Nepal and estimated radiative forcings, Atmos. Chem. Phys., 14, 8089–8103, 2014.

Line 24: "..., but also to" ! but also important/crucial to Answer: Has been revised. (Page 2, Lin35)

Line 26: ": : : is the most sensitive" how could tell it is the most sensitive? Please remove most or provide supporting data. Answer: Removed the "most".

Line 33: ": : : and result in perturbation in" ! : : :and perturb Answer: Has been revised. (Page 3, Line 7)

Line 34: "5 – 25 mm in the snow water equivalent: : :"!5-25 mm snow water equivalent Answer: Has been revised. (Page 3, Line 8)

Page 3 Line 1: "snowpack on the TP is associated with the : : :" by associated you mean the snowpack on the TP is influenced by summer monsoon? Or the snowpack will influence summer monsoon? or both? Please be more accurate here. Answer: Changes in snow cover over the TP have attracted much attention in recent years owing to climate change (Xu et al., 2017). Previous studies have indicated that changes in snow cover across the TP can markedly affect summer monsoons and precipitation over the Indian Ocean (Bai and Feng, 1994; Chen et al., 2000; Vernekar et al., 1995). Through the analysis of spatial and temporal variability of Tibetan snow cover and its relationship with the Indian summer monsoon, Zhao and Moore (2004) showed that there existed an east-west dipole-like correlation pattern between snow cover over the TP and Indian monsoon rainfall that underwent a change in sign around 1985. They also argued that variability in the TP monsoon was responsible for the spatial and temporal variability in the relationship between Tibetan snow cover and the Indian summer monsoon. The relationship between TP snow cover and the East Asian summer monsoon indicated that winter snow cover played an important role in cooling local air temperature through the snow–albedo effect (Xiao and Duan, 2016). However, data analysis demonstrated that persistent effects of winter snow cover were limited to the period from winter to spring over most parts of the central and eastern TP. Therefore, the preceding snow cover over these regions exerted little influence over either the in situ summer atmospheric heat source or the East Asian summer monsoon, because of its short duration. In contrast, the effects of winter or spring snow cover anomalies over the western TP and the Himalayas can last until summer, and these anomalies further influenced the East Asian summer monsoon by modulating moisture transport to eastern China and favoring eastward-propagating synoptic disturbances that were generated over the TP. Here in the main text has been revised as following (Page3, Line 10-13): Changes in snow cover over the TP have attracted much attention in recent years owing to climate change (Xiao and Duan, 2016; Xu et al., 2017). Snow cover on the TP plays an important role on the Asian summer monsoon, and serves as a crucial water source for several major rivers of Asia (Bai and Feng, 1994; Lau et al., 2010; Vernekar et al., 1995; Yao et al., 2012a; Zhao and Moore, 2004).

References: Bai, Y., and Feng, X.: Introduction to some research work on snow remote sensing, Remote Sens. Technol. Appl., 12(2), 59−65, 1994. Chen, Q., Gao, B., Li W., Liu, Y.: Studies on relationships among snow cover winter over the Tibetan Plateau and droughts/floods during Meiyu season in the middle and lower reaches of the Yangtze River as well as atmosphere/ocean. Acta Metall. Sin., 58(5), 582−592, 2000. Lau, W. K. M., Kim, M.-K., Kim, K.-M., Lee, W.-S.: Enhanced surface warm-

ing and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols, Environ. Res. Lett., 5, 025204, doi:10.1088/1748-9326/5/2/025204, 2010. Vernek, A. D., Zhou, J., Shukla, J.: The effect of Eurasian snow cover on the Indian Monsoon, J. Clim., 8, 248–266, 1995. Xiao, Z., and Duan, A.: Impacts of Tibetan Plateau snow cover on the interannual variability of the East Asian summer monsoon, J. Clim., 29, 8495−8514, doi:10.1175/JCLI-D-16-0029.1, 2016. Xu, W., Ma, L., Ma, M., Zhang, H., Yuan, W.: Spatial-Temporal variability of snow cover and depth in the Qinghai-Tibetan Plateau, J. Clim., 30, 1521−1533, doi:10.1175/JCLI-D-15-0732.1, 2017. Yao, T., Thompson, L.G., Mosbrugger, V., Zhang, F., Ma, Y., Luo, T., Xu, B., Yang, X., Joswiak, D. R., Wang, W., Joswiak, M. E., Devkota, L. P., Tayal, S., Jilani, R., Fayziev, R.: Third Pole Environment (TPE), Environ. Development, 3, 52–64, doi: 10.1016/j.envdev.2012.04.002, 2012a. Zhao, H., and Moore, G.W.K.: On the relationship between Tibetan snow cover, the Tibetan Plateau monsoon and the Indian summer monsoon, Geophys. Res. Lett., 31(L14204), doi:10.1029/2004GL020040, 2004.

Line 4-5: “Simulation studies of BC in snow over TP have inherent uncertainties because of the lack of large-area observations of BC data in seasonal snow cover”. This is not correct. Model simulations have inherent uncertainties due to the physics/chemistry/transport schemes used in the models - such as uncertainties in BC emissions sources or deposition rate. Large-area observation of BC in TP will be useful for model evaluation, but it will not help with the inherent uncertainty of the model simulation. Please revise it here. Answer: We agree that large-area observation of BC in TP will be useful for model evaluation. The sentence has been changed to be as following (Page 3, Line15-23): Simulation studies of BC in snow over the TP have inherent uncertainties due to the physics/chemistry/transport scheme used in the models (Gertler et al., 2016; Yasunari et al., 2010, 2013). For example, Kopacz et al. (2011) estimated RF of 5 to 15 W m−2 due to BC within the snow-covered areas of Himalaya and the TP, whereas Flanner et al. (2007) and Qian et al. (2011) estimated peak values of BC effects exceeding 20 W m−2 for some parts of the TP. Menon et al. (2010)

and Ménégoz et al. (2014) proposed that during the last decade BC in snow caused a significant part of the decrease of the snow cover extent or duration observed on the TP during the last decade. Ji et al. (2016b) found a positive surface RF was induced by dust, which caused a decrease of 5–25 mm w.e. over the western TP, Himalayas, and Pamir Mountains from December to May. Large-area observations of BC data in snow cover, which are still seldom in the TP, can be useful for model evaluation and calibration in the future.

Page 4 Line10: " : : : and is dominated by the Indian monsoon" ! A region cannot be dominated by monsoon. Do you mean "affected by"? Answer: It should be "affected by". The sentence has been changed in the main text (Page4, Line27).

Line 11: "Region III has one site (LHG) is located in the northeastern part of the TP"! "Region III has one site (LHG) that is located in the northeastern part of the TP" Answer: Has changed in the main text as following (Page4, Line28-29). Intensified sampling has been carried out in the LHG region within Region III, which is located in the northeastern part of the TP.

Line 15: it seems the snow samples were only collected from the top 5 cm, so how did you calculate the snow albedo for snowpacks thicker than 5 cm? Did you assume the BC/MD mass mixing ratio is constant through the entire snow column? Please clarify this. Answer: We did not measure the BC/MD mass mixing ratio through the entire snow column. Usually, snow samples were collected from the top 5−10 cm. In general, the snow cover is vertically inhomogeneous, and sometimes it is optically thin (Voisin et al., 2012). The stratified structure of snow cover will lead to the discrepancy between computed spectral albedo from semi-infinite snow cover and measured albedo (Grenfell, 1994; Aoki et al., 2000; Zhou et al., 2003; Kuipers Munneke et al., 2008). Recently, the propagation of light in snow with impurities has been extensively investigated with different physical-based numerical models: WW (Grenfell et al., 1994; Jin et al., 2008; Nair et al., 2013), SNICAR (Flanner et al., 2005), PBSAM (Aoki et al., 2000; 2012), GOSWIM (Yasunari et al., 2012; 2014), TARTES (Libios et al., 2013). In this study, we use SNICAR model to simulate the albedo. This simulator is a single-layer implementation of the Snow, Ice, and Aerosol Radiation model (Flanner et al., 2007, 2009), which utilized the two-stream radiative transfer solution (Toon et al., 1989). Therefore, in this study, we only focused on the surface albedo based on SNICAR model which requests a snow depth of 5 cm. When the snow cover was thicker than 5 cm, the input parameter of “snowpack thickness” (Fig. R1) was the observed snow cover depth.

In the main text (section 2.5), we have added the related information. (Page7, Line24-28): In general, the snow cover is vertically inhomogeneous, and sometimes it is optically thin (Voisin et al., 2012). The stratified structure of snow cover will lead to the discrepancy between computed spectral albedo from semi-infinite snow cover and measured albedo (Grenfell, 1994; Aoki et al., 2000; Zhou et al., 2003; Kuipers Munneke et al., 2008). In this study, we usually collected snow samples from the top 5−10 cm. Because the SNICAR model is a single-layer implementation model (Flanner et al., 2007, 2009), the input parameter of “snowpack thickness” was the observed snow cover depth.

Figure R1. The information of SNICAR model input parameters.

References: Aoki, T., Aoki, T., Fukabori, M., Hachikubo, A., Tachibana, Y., Nishio, F.: Effects of snow physical parameters on spectral albedo and bidirectional reflectance of snow surface, J. Geophys. Res, 105(D8), 10219−10236, 2000. Flanner, M. G., Zender, C. S., Hess, P. G., Mahowald, N. M., Painter, T. H., Ramanathan, V., Rasch, P. J.: Springtime warming and reduced snow cover from carbonaceous particles, Atmos. Chem. Phys., 9, 2481–2497, 2009. Flanner, M. G., Zender, C. S., Randerson, J. T., Rasch, P. J: Present-day climate forcing and response from black carbon in snow. J. Geophys. Res., 112, D11202, 2007. Grenfell, T. C., Warren, S. G., Mullen, P. C.: reflection of solar radiation by the Antarctic snow surface at ultraviolet, visible, and near-infrared wavelengths, J. Geophys. Res, 99(D9), 18669−18684, 1994. Kuipers Munneke, P., Reijmer, C. H., van den Broeke, M. R., König-Langlo, G., Stammes, P., Knpa, W. H.: Analysis of clear-sky Antarctic snow albedo using ob-

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servations and radiative transfer modelling, J. geophys. Res- Atmos., 113(D17118), doi:10.1029/2007JD009653, 2008. Voisin, D., Jaffrezo, J.-L., Houdier, S., Barret, M., Cozic, J., King, M. D., France, J. L., Reay, H. J., Grannas, A., Kos, G., Ariya, P. A., Beine, H. J., Domine, F.: Carbonaceous species and humic like substances (HULIS) in Arctic snowpack during OASIS field campaign in Barrow, J. Geophys. Res., 117(D00R19), doi:10.1029/2011JD016612, 2012. Zhou, L., Dickinson, R. E., Tian, Y., Zeng, X., Dai, Y., Yang, Z.-L., Schaaf, C. B., Gao, F., Jin, Y., Strahler, A., Myneni, R. B., Yu, H., Wu, W., Shaikh, M.: Comparison of seasonal and spatial variations of albedos from Moderate-Resolution Imaging Spectradiomater (MODIS) and Common Land Model, J. Geophys. Res, 108(D15), doi:10.1029/JD003326, 2003.

Line 17: how did you measure snow grain size in the field? Please clarify this. Answer: In the field, the snow grains were sprayed on the MIG paper. Then we took a photo by using portable digital microscope (Anyty 3R-MSV500) (Fig. R2a). In the lab, we can measure the snow grain shape and obtain the lengths of a and b (Fig. R2b). Mugnai and Wiscombe (1987) demonstrated that a collection of unoriented non-spheroids produce the same scattering results as spheres, and Grenfell and Warren (1999) showed that the radius of a non-spherical particle was equal to that of a spherical particle that has the same volume-to-surface-area (V/A) ratio. Consequently, V/A ratio was used to transfer the measured snow grain size into the effective grain size. On this basis of field measurement, Hao (2009) proposed two assumptions: 1) The snow particle is an inequilateral spheroid; and 2) The major axis, minor axis, and height of the inequilateral spheroid is denoted by a, b, and c, respectively, in such a way that the relationship a = 2b exists. According to Kokhanovsky and Zege (2004), the effective snow grain radius (Ref) can be calculated equal to the radius of the volume-to-surface equivalent sphere by the following equation (1): R_ef=(3V ÌĚ)/(4A ÌĚ) (1) Where, V ÌĚ=4/3 πrˆ3 and A ÌĚ=πrˆ2, are the average volume and the average cross-section (geometric shadow) area of the snow grains, respectively. And, r is the radius of geometric optics, r=(a+b)/4. Thus, R_ef≈0.35a Eq.1 was then employed to calculate the effective snow grain size.

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We have added related information in the main text (Page 5, Line2-12): For the snow grain size observation, we sprayed the snow grains on MIG paper and took a photo using a portable digital microscope (Anyty 3R-MSV500) to calculate the major and minor axis (Fig. S2). Based on field measurements from previous studies (Mugnai and Wiscombe, 1980; Grenfell and Warren, 1999), two assumptions were proposed: 1) The snow grain particle is an inequilateral spheroid, and 2) The major axis (a), minor axis (b), and height (c) of the inequilateral spheroid are denoted by a, b, and c, respectively, in such a way that the relationship a=2b exists (Hao, 2009). According to Kokhanovsky and Zege (2004), the effective snow grain radius (Ref) can be calculated as equal to the radius of the volume-to-surface equivalent sphere by the following equation (1): R_ef=(3V ÌĚ)/(4A ÌĚ) (1) where V ÌĚ=4/3 πrˆ3 and A ÌĚ=πrˆ2, are the average volume and the average cross-section (geometric shadow) area of the snow grains, respectively. In addition, r is the radius of geometric optics, r=(a+b)/4. Thus R_ef≈0.35a (2)

Figure R2. Snow grain size observation in the field (a) and measurement in the lab (b).

References: Grenfell, T. C., and Warren, S. G.: Representation of a nonspherical ice particle by a collection of independent sphere for scattering and absorption of radiation, J. geophys. Res., 104(D24), 31697–31709, 1999. Hao, X.: Retrieval of alpine snow cover area and grain size basing on optical remote sensing. PhD thesis, Cold and Arid Regions Environment Engineering Research Institute, Lanzhou, China, pp. 103–104, 2009. Kokhanovsky, A. A., and Zege, E. P.: Scattering optics of snow, Appl. Optics, 43(7), 1589–1602, 2004. Mugnai, A., and Wiscombe, W. J.: Scattering of radiation by moderately nonspherical particles. J. Atmos. Sci., 37, 1291–1307, 1987.

Line 24-26: what is the accuracy of the weight you used to measure filter before and after filtration? It seems the author assume BC/OC/MD are the only insoluble particles deposited on the quartz filter, could you please provide more evidence about this? If MD were the only other particle in snow (besides OC and BC), do all MD absorb sunlight? It might be a good idea to include these discussions in the uncertainty analysis.

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Answer: The accuracy of the weight for measurement of filter before and after filtration is less than ±5%. We assumed BC/OC/MD are the only insoluble particles deposited on the quartz filter. Not all MD absorb sunlight. Iron oxide minerals are efficient light scattering and absorption materials which can enhance absorption at UV and visible wavelengths (Di Mauro et al., 2015; Moosmuller et al., 2012; Zhang et al., 2015). Goethite and hematite are the most abundant forms of iron oxides in dust and the major light absorbers in the shortwave spectrum in snow (Wu et al., 2016a). The light absorption by mineral dust in snow is thought to be due to iron oxides (Wang et al., 2013). Two peaks in the first derivative value of the spectra at 430 and 560 nm were determined to be goethite and hematite, respectively. When the iron content reaches a threshold, the iron oxides have little or no impact on the reflectance spectra (Wu et al., 2016a). The fine fraction of glacier dust has a greater abundance of iron (2016b), and the first derivative values of hematite are higher than goethite, indicating that hematite might be concentrated in the fine fraction (2016a). Dust optical properties depend strongly on source material and these properties are designed to represent "global-mean" characteristics as closely as possible (Flanner et al., 2007). The SNICAR model applies the Maxwell-Garnett approximation for combining indices of refractions, assuming a mixture of quartz, limestone, montmorillonite, illite, and hematite. We agree that some dust particles (e.g., those containing a large proportion of strongly-absorbing hematite) can have a larger impact on snow albedo than the dust applied in this work (Aoki et al., 2006; Painter et al., 2007).

We have added related discussion in the section 3.4 as following (Page12, Line25-33): We also have to pay attention to the fact that dust optical properties depend strongly on source material and their properties are designed to represent "global-mean" characteristics as closely as possible (Flanner et al., 2007). The light absorption by mineral dust in snow is thought to be due to iron oxides (Wang et al., 2013), which are efficient light scattering and absorption materials that can enhance absorption at UV and visible wavelengths (Di Mauro et al., 2015; Moosmüller et al., 2012; Zhang et al., 2015). Goethite and hematite are the most abundant forms of iron oxide in dust and

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the major light absorbers in the shortwave spectrum in snow (Wu et al., 2016). The SNICAR model applies the Maxwell-Garnett approximation for combining indices of refractions, assuming a mixture of quartz, limestone, montmorillonite, illite, and hematite. We should note that some dust particles (e.g., those containing a large proportion of strongly absorbing hematite) can have a larger impact on snow albedo than the dust applied in this work (Aoki et al., 2006; Painter et al., 2007).

References: Aoki, T., Motoyoshi, H., Kodama, Y., Yasunari, T. J., Sugiura, K., Kobayashi, H.: Atmospheric aerosol deposition on snow surfaces and its effect on albedo, SOLA, 2013–2016, doi:10.2151/sola.2006-004, 2006. Baccolo, G., Di Mauro, B., Massabò, D., Clemenza, M., Nastasi, M., Delmonte, B., Prata, M., Prati, P., Previtali, E., Maggi, V.: Cryoconite as a temporary sink for anthropogenic species stored in glaciers, Sci. Rep., 7, 9623, doi:10.1038/s41598-017-10220-5, 2017. Di Mauro, B., Fava, F., Ferrero, L., Garzonio, R., Baccolo, G., Delmonte, B., Colombo, R.: Mineral dust impact on snow radiative properties in the European Alps combining ground, UAV, and satellite observations, J. Geophys. Res. Atmos., 120, 6080–6097, doi:10.1002/2015JD023287, 2015. Moosmüller, H., Engelbrecht, J. P., Skiba, M., Frey, G., Chakrabarty, P. K., Arnott, W. P.: Single scattering albedo of fine mineral dust aerosols controlled by iron concentration, Journal of Geophys. Res., 117(D11210), doi:10.1029/2011JD016909, 2012. Painter, T. H., Barrett, A. P., Landry, C. C., Neff, J. C., Cassidy, M. P., Lawrence, C. R., McBride, K. E., Farmer, G. L.: Impact of disturbed desert soils on duration of mountain snow cover, Geophys. Res. Lett., 34, L12502, doi:10.1029/2007GL030284, 2007. Wang, X., Doherty, S., Huang, J.: Black carbon and other light-absorbing impurities in snow across Northern China, J. Geophys. Res. Atmos., 118, 1471-1492, doi:10.1029/2012JD018291, 2013. Wu, G., Xu, T., Zhang, X., Zhang, C., Yan, N.: The visible spectroscopy of iron oxide minerals in dust particles from ice cores on the Tibetan Plateau, Tellus B, 68, 29191, doi: 10.3402/tellusb.v68.29191, 2016a. Wu, G., Zhang, X., Zhang, C., Xu, T.: Mineralogical and morphological properties of individual dust particles in ice cores from the Tibetan Plateau, J. Glaciol., 62(231), 46–53, 2016b. Zhang, X., Wu, G., Zhang, C., Xu, T.,

Zhou, Q.: What is the real role of iron oxides in the optical properties of dust aerosols? Atmos. Chem. Phys., 15, 12159–12177, 2015.

Page 5: Line 6: what is the filter blank for? is this a blank filter? It seems there is some particles on filter blank as well since it weighs more than 0 C/cm-2. Answer: We used the filter blank to detect the sampling and storage processes. It is a blank filter. The blank filters were brought to the field and stored with the filters together. The results showed that the filter blank is much less (1.23±0.38 μg C cm–2) than those in the sampled filters (more than 10 μg C cm–2), indicating the OC/BC data were reasonable.

Line 8: “separately analyzed” ! analyzed separately Answer: Has been changed.((Page6, Line2)

Line 18: “: : : is or not influenced by BC emissions” ! is influenced by BC emissions or not Answer: Has been changed.((Page6, Line21)

Line 23: what is “down-sun”? Answer: It’s type wrong. Spectral albedo measurements were collected using an ASD FieldSpec 4 (FS4) standard-resolution spectroradiometer in the range of 350–2500 nm using the ASD Remote Cosine Receptor (RCR) foreoptic. The RCR foreoptic was mounted to the end of a 91.4-cm rectangular aluminium boom and levelled at a height of 80 cm above the snow surface using a bubble level located at the observer’s end of the boom, collecting sky irradiance when pointed upward and snow irradiance when pointed downward. Spectral albedo was obtained by dividing snow irradiance by sky irradiance from ten consecutive upward and downward measurements collected at site around local solar noon determined using the NOAA SolarNoonCalculator.

We have changed in the main text (Page7, Line2-9). For the selected sites, a general-purpose spectroradiometer (Analytical Spectral Devices (ASD), FieldSpec 4, Inc.), was used to measure the reflectance of snow cover. The ASD FieldSpec 4 instrument is a general-purpose spectroradiometer that is useful for applications requiring the

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measurement of reflectance, transmittance, radiance, or irradiance. The instrument is specifically designed for field environment remote sensing to acquire visible and near-infrared and shortwave infrared spectra. It has 3 nm spectral resolution on the visible/near infrared detector (350–1050 nm, silicon photodiode array), and 10–12 nm resolution on the shortwave infrared detectors (900–2 500 nm, InGaAs). In the field, reflectance was measured at two sites (24K and MD in Table S1) with FieldSpec 4 under clear-sky conditions. These measurements of reflectance were calculated using the standard solar irradiance to get the albedos, which were then used for comparison with simulated albedos.

Line 24: "when the weather was clear"! when the sky was clear. It seems the albedo measurement were made for clear sky only, but later in the albedo comparison, the measured albedo is compared against the albedo calculated using SNICAR for all-sky case. Is this a typo or this is wrong? Answer: Has been changed. The "all-sky" is a type wrong (see Table S2 in supplementary material), we have changed in the main text.

Line 28: "e.g. Doherty et al., 2010": Doherty et al 2010 did not use SNICAR, it only reported the observation in the Arctic. Please remove this citation. Answer: Has removed.

Page 6: Line 9-11: Please revise this sentence. Is this a model or is this just the method you used to calculate snow water melt in this work? Answer: It is a method we used to calculate snow water melt. We have changed the sentence in the main text (Page7, Line31-32). To estimate snow melt due to BC and dust, a method was constructed in which the absorptivity of the snow was multiplied by the daily average incoming shortwave radiation from the automatic weather stations (AWS) set up at the meteorological stations near the sampling sites (Fig. S3) (Schmale et al., 2017).

Line 16: "for clean snow: : :" what is cause of albedo reduction for clean snow case? A different snow grain size due to snow aging? Please be more accurate here. Answer:

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Yes. For clean snow, different snow grain size played an important role on the albedo reduction. We have revised the sentence in the main text (Page8, Line7-8): $\Delta\alpha$ is the albedo reduction caused by BC and dust, for clean snow mainly by different snow grain sizes due to snow aging;

Line 18: "assumed snow depth" what is the assumed snow depth? How did you assume it? Answer: In the following analysis, we assumed the snow depth to be consistent (which is not the reality) for estimating the variations of snow cover durations days in section 3.3. This assumption was based on the snow depth observations from the TP in previous studies (Che et al., 2012; Xu et al., 2017; Zhong et al., 2016). We have changed this sentence in the main text (Page8, Line8).

References: Che, T., Dai, L., Wang, J., Zhao, K., Liu, Q.: Estimation of snow depth and snow water equivalent distribution using airborne microwave radiometry in the Binggou Watershed, the upper reaches of the Heihe River basin, Int. J. Appl. Earth Obs. Info., 17, 23–32, doi:10.1016/j.jag.2011.10.014, 2012. Xu, W., Ma, L., Ma, M., Yuan, W.: Spatial-temporal variability of snow cover and depth in the Qinghai-Tibetan Plateau, J. Clim., doi:10.1175/JCLI-D-150732.1, 2017. Zhong, X., Zhang, T., Zheng, L., Hu, Y., Wang, H., Kang, S.: Spatiotemporal variability of snow depth across the Eurasian continent from 1966 to 2012, Cryosphere Discuss., doi:10.5194/tc-2016-182, 2016.

Line 22: "older wind-packed snow" ! old wind-packed snow Answer: Has been changed.(Page8, Line12)

Page 7: Line 2: Please consider cite paper Doherty et al., 2016. It also reports LAIs in snow in North America. Doherty,S. J., D. A. Hegg, J. E. Johnson, P. K. Quinn, J. P. Schwarz, C. Dang, and S. G. Warren, (2016), Causes of variability in light absorption by particles in snow at sites in Idaho and Utah. J. Geophys. Res. Atmos., 121, no. 9: 4751-4768. Answer: Agree, and has cited this paper.

Line 6-8: How could you tell the LAIs in snow over TP were generated from biomass burning in surrounding region from Table 2? And from Table 2, how could you tell if the fraction of LAIs emitted by biomass/fossil fuel burning in TP is larger than that in the other regions? Please provide more explanations. Answer: Table 2 shows the concentrations of LAIs in snow cover in the TP and other regions. These comparisons indicate deposition of LAIs in the snow over the TP have higher values than other regions. In this section, we will not to discuss their fraction and different sources. Thus, we have revised this sentence in the main text as following (Page8, Line27-29): In comparison (Table 2), the LAIs in snow cover of the TP showed larger values which can be attributed to more deposition from nearby regions around the TP (e.g., South Asia, East Asia, and/or western China) (Lu et al., 2012; Ramanathan and Carmichael, 2008), or to impacts by the soil/dust near the sampling sites.

Line 9-11: How could the ratio of OC/BC be used as a standard to determine the emission sources of biomass burning? What is the OC/BC ratio if all LAIs were emitted from biomass burning or non-biomass burning sources? Answer: Usually, the aerosols emitted from biomass burning have higher OC/EC ratios. For example, Watson et al. (2001) have reported an OC/EC ratio of 14.5 for forest fires; while for the fossil fuel, OC/EC ratio was about 1 (Watson et al., 2001). The OC/EC ratios at Mt. Everest station range from 1.91 to 43.8 with an average of 6.69. Such high ratios are considered to be mainly affected by the strong influence of biomass-burning emissions (Cong et al., 2015a), which is also evidenced by the atmospheric organic acids (Cong et al., 2015b). In the southeastern TP, OC was found to be more abundant during the monsoon season (with OC/EC ratios are 17.67) than in other seasons (e.g. pre-monsoon and winter with OC/EC ratios of 6.29 and 6.45, respectively). These trends can be explained by the emission of plant spores and pollen as well as the formation of greater quantities of secondary organic carbon (SOC) in the periods with the higher OC loadings (Zhao et al., 2013). We have added related information in the main text as following (Page8, Line30-32): Ratios of OC to BC (OC/BC) were used to represent the possible impact of biomass burning in previous studies (Watson et al., 2001; Bond et al., 2013; Cong et al., 2015a, 2016b). Usually, the aerosols emitted from biomass burning have higher OC/EC ratios. For example, Watson et al. (2001) reported an OC/EC ratio of 14.5 for forest fires; whereas for fossil fuel, the OC/EC ratio was approximately 1.

References: Cong, Z., Kawamura, K., Kang, S., Fu, P.: Penetration of biomass-burning emissions from South Asia through the Himalayas: new insights from organic acids, Sci. Rep., 5, 9580, doi:10.1038/srep09580, 2015b. Cong, Z., Kang, S., Kawamura, K., Liu, B., Wan, X., Wang, Z., Gao, S., Fu, P.: Carbonaceous aerosols on the south edge of the Tibetan Plateau: concentrations, seasonality and sources, Atmos. Chem. Phys., 15, 1573-1584, 2015a. Watson, J. G., Chow, J. C., Houck, J. E.: PM2.5 chemical source profiles for vehicle exhaust, vegetative burning, geological material, and coal burning in Northwestern Colorado during 1995, Chemos., 43, 1141–1151, 2001. Zhao, Z., Cao, J., Shen, Z., Xu, B., Zhu, C., Chen, L.-W. A., Su, X., Liu S., Han, Y., Wang, G., Ho, K.: Aerosol particles at a high-altitude site on the Southeast Tibetan Plateau, China: Implications for pollution transport from South Asia, J. Geophys. Res-Atmos., 118, 11360–11375, 2013.

Line 15: “LHG3 AND LHG6 (Figure 3)”, do you mean Figure 1b? Answer: Yes, it should be Figure 1b.

Line 15-21: It seems Figure S2 is an important figure for discussions in this part. If there is no restriction on the number of figures, please consider include this figure in the paper. Answer: Agree, we have included this figure in the main text as Figure 3.

Line 28: “Open burning sourced BC”! BC emitted from open burning sources. Does the BC emitted from open burning sources contain BC emitted from biomass burning? or are they the same? Please be more specific about what you mean by “open burning”. Answer: They are not exactly the same. Here in this study, the results was based on the data of FINN fire emission. Thus, we mean “fire spots or open fire”, kind of biomass burning. We have changed this sentence in the main text as following (Page9, Line19-23): Contributions of BC from open fire burning (a kind of biomass burning) decrease from the southern to the northern TP (Fig. 5). In the Himalayan region, BC from biomass burning sources accounts for half of the BC deposition on snow cover, reflecting the proximity to large sources in South Asia. In the central TP, BC from open fire burning accounts for approximately 30 % of the total, less than from biomass burning evidence from aerosols and glacial snow (Li et al., 2016), maybe indicating a lack of biofuel contributions from our calculation.

Page 8 Line 3-4: “In the southern TP: : :. due to influence of BC sources in the south Asia”. This statement is too vague. Do you mean the total emission is larger in southern Asia? or the BC deposition rate is larger ? or both? This is a major conclusion you have in this work, please be more specific. Answer: Here we mean the total emission is larger in southern Asia (see from the AOD in Fig. R3) rather than the BC deposition rate. We have changed this sentence in the main text (Page9, Line28-33): In the southern TP (MYL), the amount of BC deposition is larger than in the northern TP (NETP) due to the nearby BC sources in south Asia, known to be a regional hotspot of BC-induced atmospheric solar heating (Ramanathan and Carmichael, 2008). Whereas in the central TP (NMC), the amount of BC deposition was higher than in the NETP. This may be because pollutants from the southern side of the Himalayas can traverse the high mountain range not only through the major north-south river valleys but also by being lifted and advected over the Himalayas to reach to the inland TP (Cong et al., 2015b; Lüthi et al., 2015).

Figure R3. MODIS atmospheric optical depth (AOD) fields derived using dark target algorithms over the TP and its surroundings. (http://giovanni.sci.gsfc.nasa.gov).

Line 8: You used SNICAR model to calculate snow albedo for all-sky cases, but the model set up is not stated. For example, what is the cloud fraction for all sky case? As mentioned in the previous comments, the albedo measurement was performed under clear sky, so in what accuracy do you expect this to agree with the SNICAR calculation (Figure 5)? Answer: Here is not the all-sky cases, it should be clear sky. We have changed in the main text.

Line 14: “The deviation between measured and simulated reflectance by MD may be a result of the upper boundary of the SNICAR model in particle dimension". This does not make sense, is the deviation due to upper boundary condition (and what upper boundary condition)? or MD particle size? Please revise. Answer: The difference between measured and simulated reflectance by MD may be caused by the upper boundary of particle size (as shown in Fig. R1, the dust concentrations) in the SNICAR model (Flanner et al., 2007). Thus, we have changed this sentence in the main text (Page10, Lin10-11).

Line 18-19: "This result is import, showing that the SNICAR model simulations can represent albedo changes of snow cover in the Third Pole region". This is a really strong conclusion. I don't think the authors can make this conclusion based on the results shown in this paper. Especially it is unclear to the readers that how did the authors set up the SNICAR calculation. Please remove this or include more details about SNICAR calculation. Answer: Agree, and removed this sentence.

Line 26. As the author said, the BC snow albedo forcing over TP is highly uncertain partly due to the uncertainty in simulated BC concentration. But it is also important to point out that a large fraction of such uncertainty is resulted form uncertainty in simulated snow-cover fraction/snow depth. Please consider including this in the discussion. Answer: Agree, we have added this section in the discussion (Page13, Line1-10). It is further important to note that a large fraction of such uncertainty can also result from uncertainty in the simulated snow-cover fraction/snow depth across the plateau. The TP covers a large area (more than 2.5 million km2) with an average elevation exceeding 4000 m a.s.l. (Yao et al., 2012a). Considerable heterogeneity in the topography and climate has led to complex spatial and temporal snow cover patterns (Xu et al., 2017). Most studies on the snow cover distribution were based on satellite-based observations (Che et al., 2008, 2012). Surface observations of snow depth showed an increase over the TP from 1957–1998 (Ma and Qin, 2012). However, snow cover depth and the number of snow covered days during the current decade under intense climate warming showed a decreasing trend mainly occurring in the southeast TP in winter.

Whereas in spring, snow cover depth showed an increasing trend in the eastern TP (Xu et al., 2017). These differences can also affect the estimation in this study. Nevertheless, the method provides a theoretical approach for evaluating how the presence of LAIs affects the lower parts of the glacier subjected to summer melt.

References: Che, T., Dai, L., Wang, J., Zhao, K., Liu, Q.: Estimation of snow depth and snow water equivalent distribution using airborne microwave radiometry in the Binggou Watershed, the uppwe reaches of the Heihe River basin, Int. J. Appl. Earth Obs. Info., 17, 23–32, doi:10.1016/j.jag.2011.10.014, 2012. Che, T., Li, X., Jin, R., Armstrong, R., Zhang, T.: Snow depth derived from passive microwave remote-sensing data in China, Ann. Glaciol., 49, 145–154, doi:10.3189/172756408787814690, 2008. Ma, L., Qin, D.: Temporal–spatial characteristics of observed key parameters of snow cover in China during 1957–2009, Sci. Cold Arid Reg., 4, 384–393, doi:10.3724/SP.J.1226.2012.00384, 2012. Xu, W., Ma, L., Ma, M., Zhang, H., Yuan, W.: Spatial-Temperal variability of snow cover and depth in the Qinghai-Tibetan Plateau, J. Clim., 30, 1521−1533, doi:10.1175/JCLI-D-15-0732.1, 2017. Yao, T., Thompson, L.G., Mosbrugger, V., Zhang, F., Ma, Y., Luo, T., Xu, B., Yang, X., Joswiak, D. R., Wang, W., Joswiak, M. E., Devkota, L. P., Tayal, S., Jilani, R., Fayziev, R.: Third Pole Environment (TPE), Environ. Development, 3, 52–64, doi: 10.1016/j.envdev.2012.04.002, 2012a.

Page 9 Section 3.3: Why did you pick SW flux of 220, 270 and 310 W m-2? Answer: We selected short-wave radiation from several automatic weather stations (Fig. R4) near the snow sampling sites in region I, II, and III. Table R1 showed monthly short-wave radiation from automatic weather stations near the snow sampling sites during the snow melting season (March-May) when the temperature began to increase. On average, shortwave radiations in March, April, May, and June is about 238, 269, 292, and 271 W m–2, respectively. Short-wave radiation showed the minimum value in March in Tanggula (210 W m–2, lower than the average) and the maximum value in May in Namco (314 W m–2, higher the average). Thus, in order to estimate the impact of input short-wave radiation on the snow cover duration, we gave a range of shortwave radiation from 220 to 310 W m–2.

We have added related information in the main text as following (Page11, Line14-23): Changes of snow cover duration are calculated using a model documented by Schmale et al. (2017) (section 2.6). In Eq. (4), monthly shortwave radiation (SW) input data were obtained from the Automatic Weather Station (AWS) near the snow sampling sites across the TP (Fig. S3). Table S3 shows monthly shortwave radiation data from AWS during the snow melting season (March-May) when the temperature began to increase. On average, shortwave radiation in March, April, May, and June is approximately 238, 269, 292, and 271 W m–2, respectively. Short-wave radiation in March showed the minimum value in Tanggula of the central TP (210 W m–2, lower than the average), whereas in May it showed the maximum value in Namco (314 W m–2, higher the average). Based on these data during the melt season, three scenarios (220, 270, and 310 W m–2)were defined as the minimum, median, and maximum scenarios of input shortwave radiation to estimate its impact on changes of snow cover duration. We have added this information in the supplementary material as Table S3.

Figure R4. Automatic weather stations selected in the Tibetan Plateau.

Table R1. Monthly short-wave radiation from automatic weather stations near the snow sampling sites during the snow melting season.

Line 27: “SD plays an import role” ! SD plays an important role? What do you mean by SD plays a role here? Deeper snow is supposed to melt slower given the same amount of radiative forcing; it is not because snow depths play a role here. Please clarify this point. Answer: We agree that deeper snow is supposed to melt slower given the same amount of radiative forcing. In this study, we calculated the changes of snow cover duration days rather than the total days of snow cover duration. We mean that SD plays an important role on our estimation of numbers of snow cover duration days. Thus, we have changed the sentence in the main text as following (Page11, Line28-29). The result indicated that estimation of changes of snow cover duration days caused by the same level of LAIs was also affected by different SD.

Page 10: Line 13: “However, the results presented in this study : : :. for which these assumptions are not critical”: This is not true. All the quantities listed in this paragraph will influence the snow albedo and most of them will influence the albedo reduction induced by BC. For example: BC-snow internal mixing increases the albedo forcing by 40-60% compared with external mixing (He et al. (2014). The author should discuss the uncertainty of this study resulted from the assumptions they made, instead of claim these quantities will not impact their results. References: He, C., Q. Li, K. N. Liou, Y. Takano, Y. Gu, L. Qi, Y. Mao, and L. R. Leung, 2014: Black Carbon Radiative Forcing over the Tibetan Plateau. Geophy. Res. Lett., 41, 7806-7813, doi: 10.1002/2014GL062191. Answer: Agree, and we have added related discussion in this section in the main text as suggested.

Line 32: “Our study confirms that : : :.. and further reduces snow albedo,: : :.”: this is not true. BC and other LAI can reduce the snow albedo even if the snow aging process is not accelerated. Please revise this. Answer: Agree, and have changed (Page13, Line26). Our study confirms that BC and other water-insoluble LAIs in snow on land and ice can darken the surface, and further reduces snow albedo, and increases the speed of snow cover melt

Figures3: Is the color bar showing height? Please define the color bar and unit. Answer: Yes, the color bar shows the height. We have added the information in the figure caption.

Figure 4: Footprint analyses for six selected sites over the Tibetan Plateau during the winter season (Nov 2015-Feb 2016). LHG and NETP in the northern Tibetan Plateau (Region III), TGL and NMC in the central Tibetan Plateau (Region II), and MYL and SETP in the southern Tibetan Plateau (Region I). (The right color bar means the height (m a.s.l.). The trajectories starting below 500 hPa were taken into account. Black dots: the air parcel did not pass near a fire during the 96 h prior to arrival at the studied

site; Green dots: the air parcel did pass by a fire between -96 h and -48 h, but not afterwards, i.e., the 'contact' to a fire lies back at least 48 h before the air parcel arrived at Renlongba glacier; Magenta dots: contact with fires occurred between -48 h and 0 h before arriving at site; Red dots: contact with a fire before and after -48 h.)

Figure 5: Are MA1-4 measured albedo? Are the dashed lines albedo calculated using SNICAR? Please clarify these details and modify the corresponding text. Answer: In this figure, MA1-4 (solid lines) are measured albedo. Dashed lines mean the albedo calculated using SNICAR. We have added the information in the figure caption.

Figure 6: Measured albedo by ASD (solid lines, MA1-4) and simulated effects of BC and dust on albedo (dashed lines) at the selected snow site on the Tibetan Plateau.

Figure 6-8: please clarify the figure convention in each figure. Do the boxes represent average values from central estimate? For example, in Figure 6, you say the rectangles are central estimate, so what does the box mean? standard deviation of central estimate? maximum and minimum of central estimate? Answer: We have added related information and legend for each figure in the main text.

Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2017-111/tc-2017-111-AC1-supplement.pdf

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Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2017-111, 2017.

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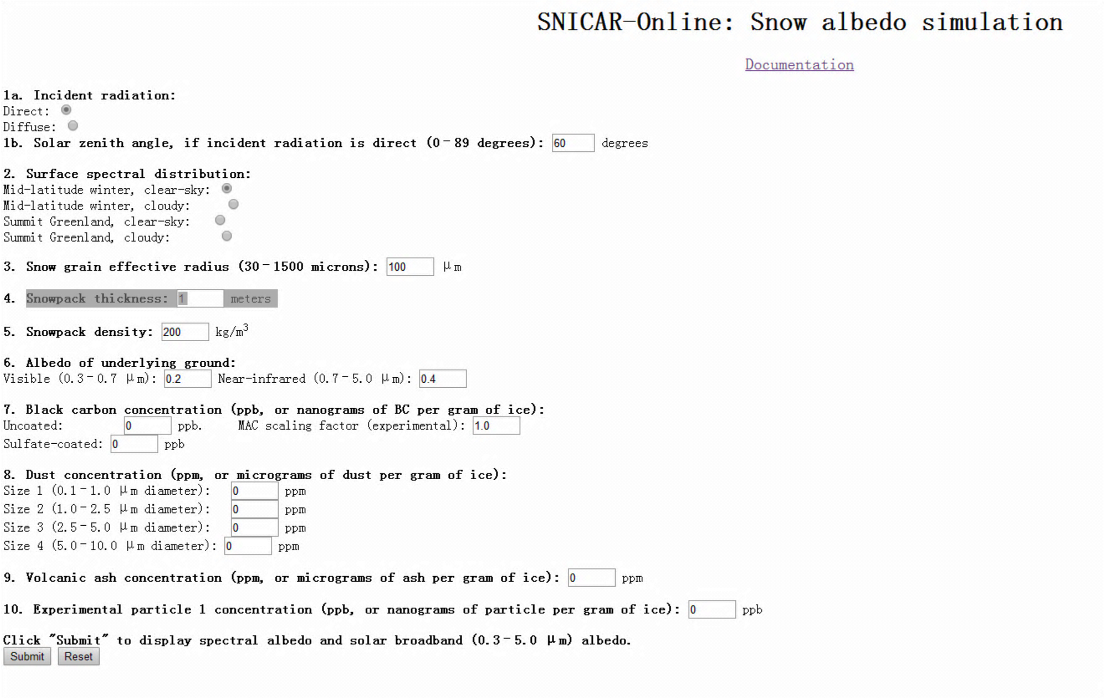
Discussion paper



SNICAR-Online: Snow albedo simulation

Documentation

1a. Incident radiation:
Direct: ●
Diffuse: ○
1b. Solar zenith angle, if incident radiation is direct (0-89 degrees): 60 degrees

2. Surface spectral distribution:
Mid-latitude winter, clear-sky: ●
Mid-latitude winter, cloudy: ○
Summit Greenland, clear-sky: ○
Summit Greenland, cloudy: ○

3. Snow grain effective radius (30-1500 microns): 100 μm

4. Snowpack thickness: 1 meters

5. Snowpack density: 200 kg/m^3

6. Albedo of underlying ground:
Visible (0.3-0.7 μm): 0.2 Near-infrared (0.7-5.0 μm): 0.4

7. Black carbon concentration (ppb, or nanograms of BC per gram of ice):
Uncoated: 0 ppb. MAC scaling factor (experimental): 1.0
Sulfate-coated: 0 ppb

8. Dust concentration (ppm, or micrograms of dust per gram of ice):
Size 1 (0.1-1.0 μm diameter): 0 ppm
Size 2 (1.0-2.5 μm diameter): 0 ppm
Size 3 (2.5-5.0 μm diameter): 0 ppm
Size 4 (5.0-10.0 μm diameter): 0 ppm

9. Volcanic ash concentration (ppm, or micrograms of ash per gram of ice): 0 ppm

10. Experimental particle 1 concentration (ppb, or nanograms of particle per gram of ice): 0 ppb

Click "Submit" to display spectral albedo and solar broadband (0.3-5.0 μm) albedo.

Fig. 1.

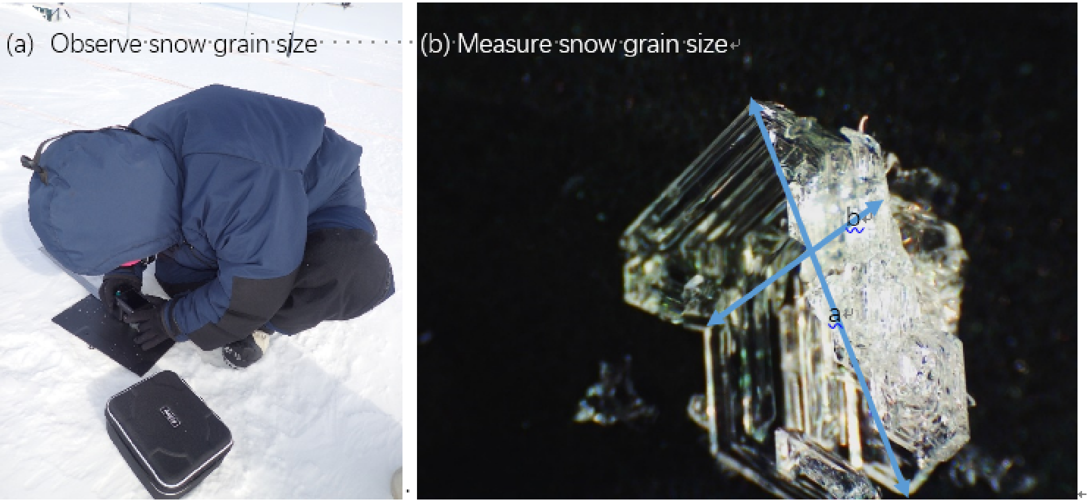
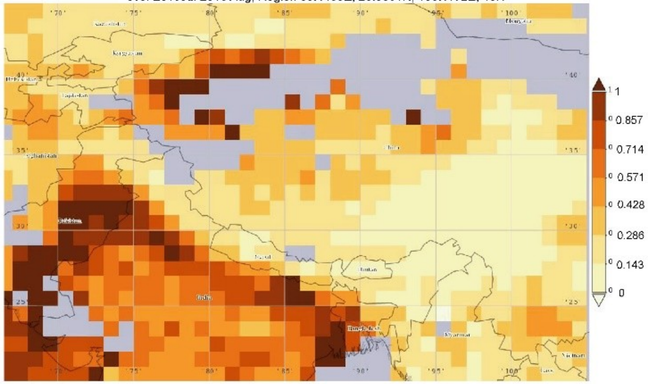


Fig. 2.

(a) Summer

Time averaged map of Aerosol Optical Depth 550 nm (Dark Target) Monthly 1deg. (MODIS-Terra MOD08_M3 v051) over 2015Jul-2015 Aug, Region 66.4453E, 20.0391N, 105.1172E, 45N



(b) Winter

Time averaged map of Aerosol Optical Depth 550 nm (Dark Target) Monthly 1deg. (MODIS-Terra MOD08_M3 v051) over 2014 Dec-2015 Feb, Region 66.4453E, 20.0391N, 105.1172E, 45N

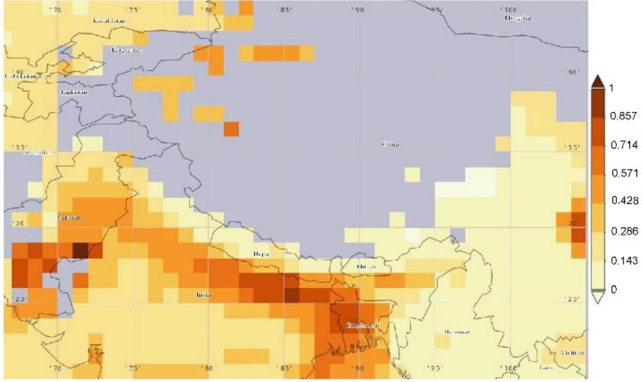


Fig. 3.

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Discussion paper

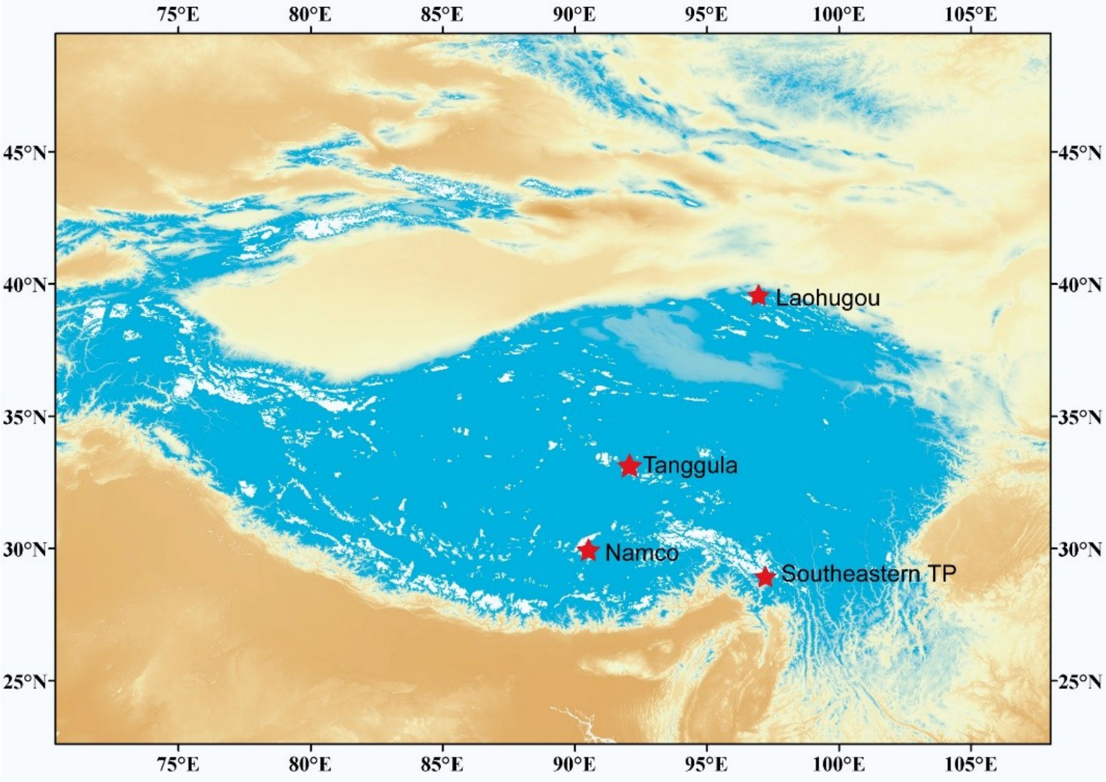

Fig. 4.

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Discussion paper

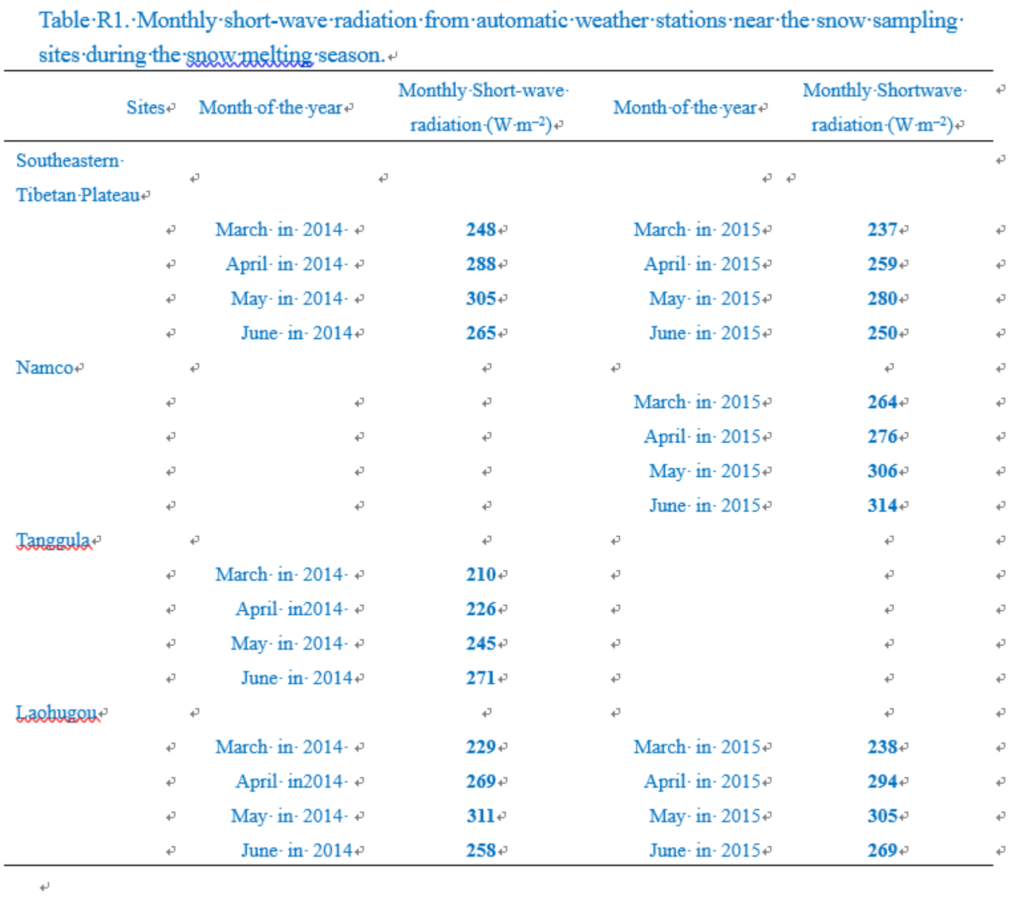

Table R1. Monthly short-wave radiation from automatic weather stations near the snow sampling sites during the snow melting season.

Sites	Month of the year	Monthly Short-wave radiation (W m^{-2})	Month of the year	Monthly Shortwave radiation (W m^{-2})
Southeastern Tibetan Plateau				
	March in 2014	**248**	March in 2015	**237**
	April in 2014	**288**	April in 2015	**259**
	May in 2014	**305**	May in 2015	**280**
	June in 2014	**265**	June in 2015	**250**
Namco				
			March in 2015	**264**
			April in 2015	**276**
			May in 2015	**306**
			June in 2015	**314**
Tanggula				
	March in 2014	**210**		
	April in2014	**226**		
	May in 2014	**245**		
	June in 2014	**271**		
Laohugou				
	March in 2014	**229**	March in 2015	**238**
	April in2014	**269**	April in 2015	**294**
	May in 2014	**311**	May in 2015	**305**
	June in 2014	**258**	June in 2015	**269**

Fig. 5.