Dec22, 2017

Dear editor,

Thank you and the reviewers very much for all your time and efforts regarding our manuscript (***tc-2017-111: Black carbon and mineral dust in snow cover on the Tibetan Plateau***). We have carefully revised the manuscript according to the reviewers' comments. Detailed responses are in blue in the main text. We also included the revised version below with changes shown in blue. We hope that you and reviewers find the revisions appropriate and adequate.

Yours sincerely,

Yulan ZHANG and Shichang KANG

General comments:

- It is unclear what "footprint analysis" means. Please replace with "back trajectory analysis" in all instances or define what you mean by footprint if they are not the same.

Answer: Thanks and agree, and have revised in the main text.

- Data available upon request does not meet TC policy. You need to provide your BC and LAP data here as supplementary information or provide a DOI containing the data per TC policy: http://www.the-cryosphere.net/about/data_policy.html#data_availability

Answer: We have provided the data of light-absorbing particulates in this study as a supplementary information.

Referee comments:

- Referee #1's comment on page18 (page 10 line 13) seems not to have been addressed. You need to address this on page 13.

Referee #1's comment [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. (Page 12, Line 31-33).

``````BC in the atmosphere tended to mix with OC and inorganic salts during aging enhancing its absorption (Gustafsson and Ramanathan, 2016). He et al. (2014) noted that BC-snow internal mixing
``````

increases the albedo forcing by 40–60 % compared with external mixing, and coated BC increases the forcing by 30–50 % compared with uncoated BC aggregates, whereas Koch snowflakes reduce the forcing by 20–40 % relative to spherical snow grains.```````

- Referee #2 comment #1: Please mention this as a source of uncertainty in your analysis (section 3.4) in the main text.

Referee #2 comment #1 [My first and foremost concern is that samples were collected in November and December, and yet they are attempting to quantify the impacts of light absorbing particulates on melt. This does not make sense to me and if I misunderstood this it is because it is not made clear in the manuscript. Although the sample collection timing may be after the summer monsoon, these samples do not represent the impurities that are present during the ablation season- and therefore it is inappropriate to use these values to quantify reduction in snowpack duration. Particularly for dust, which tends to deposit in the spring when source regions dry out (peak radiative forcing by dust in snow is observed from MODIS imagery over the Himalayan region in April and May).]

Answer: Agree, we have added the related information in the main text in section 3.4 (Page 12, Line 22-28).

These samples were collected during winter season when the snow cover were more stable and continuous, which might not represent the true impurities as these during the ablation season. However, during melting season, because of the poor accessibility on the snowpack in the TP, it was hardly to collect the snow cover samples. Besides, considerable heterogeneity in the topography and climate has led to complex spatial and temporal snow cover patterns (Xu et al., 2017). Discontinued snow cover during melting season may be a problem to represent the true impurities in snow. Thus in our study, we gave an estimation based on the different snow grain size and density, rather than the fixed data. More work needs to do to fill in gaps in the future.

- Page 5 lines 10-12: You describe grain size, but not snow depth or density measurements. Please describe methods for all measurements, as requested by the reviewers.

Answer: In this study, snow depth was measured using a ruler. Snow density was measured using weighing method of specific volume of snow. We have added these information in the main text of section 2.2 (Page 5, Line 4-5).

- Page 7 lines 24-28: The lines in blue do not answer the reviewer's question. Did you assume uniform BC throughout the snow depth? It looks like that is the only option in the inputs. If so, what sort of error does this represent?

Answer: In this study, BC was assumed to be uniform throughout the snow depth as described in the SNICAR model. This model is a single-layer implementation model (Flanner et al., 2007, 2009). Due to melting processes, BC may be accumulated on the snow surface, while in the subsurface of snow pack, BC concentration was lower. In SNICAR, the vertical distributions of BC in snow is not consider. Lacking a radiative transfer approximation for BC, Flanner et al. (2007) assume snow forcing acts homogeneously over snow-covered and snow-free ice. This crude assumption probably underestimates forcing. Because the SNICAR cannot provide the scenarios of BC in vertical distribution, we couldn't estimate the errors caused by BC's distribution in snowpack.

- Page 9 line 19: “kind of biomass burning” Can you be more explicit here? I’m still not sure what you mean by “open”.

Answer: In this study, the open burning of biomass data we used include “wildfire, agricultural fires, and prescribed burning, and dose not included biofuel use and trash burning” (Wiedinmyer et al., 2011). Thus, we have changed in the main text (Page9, Line19-20). We also explained it in the section 2.4 (Page 6, Line 30-31).

Unclear wording or missing information. Much of this is in the methods section, which has improved somewhat, but I think still will not satisfy the reviewers concerns on this point. Specific comments are below.

Answer: Thank you very much for all the comments. We have carefully learned these suggestions, and revised in the main text.

- Page 2 line 12: insert “a wavelength ( ) of” before 440 nm. Elsewhere, insert “ = “ before any number representing a wavelength.

Answer: Agree, and added the related information before the number representing a wavelength.

- Page 2 line 25: 142 – 271 mm of what? Snow or ice mass?

Answer: In the study (Gabbi et al., 2015), maximum deviations in annual mass balance due to Saharan dust were up to -142 mmw.e. yr^{-1} for the upper and -271 mmw.e.yr^{-1} for the lower measurement site in individual years. Thus in this study, it means a range of 142 – 271 mm water equivalent. We have added the information in the main text (Page 2, line 27).

- Page 2 line 27: “days during ablation through” doesn’t make sense. Please check this and reword.

Answer: We have changed this sentence in the main text.

“```` be shortened by 18 to 35 days during ablation period due to surface shortwave RF caused by deposition of disturbed desert dust”

- Page 2 line 31: It doesn’t make sense that the presence of dust suggests a relative role for BC. Dust and BC have different sources.

Answer: Agree, they have different sources. Here “the relevant role” means both of BC and dust can reduce snow surface albedo and darkening the surface. We have changed this sentence in the main text. “The presence of dust in snow suggests it also plays an important role in darkening the glacier surface.” (Page 2, Line 33)

- Page 4 lines 28-29: You characterize region I and II, but not region III. What characterizes region III and differentiates it from I and II? What do you mean by “intensified sampling”? What is “LHG”?

Answer: The stable oxygen isotope ratio ($\delta^{18}O$) in precipitation is an integrated tracer of atmospheric moisture worldwide. In the previous study in the Tibetan Plateau (Yao et al., 2013; Tian et al., 2007), the researchers have established a database of precipitation $\delta^{18}O$ and use different models to evaluate the climatic controls of precipitation $\delta^{18}O$ over the Tibetan Plateau. The spatial and temporal patterns of precipitation $\delta^{18}O$ and their relationships with temperature and precipitation reveal three distinct domains, respectively associated with the influence of the westerlies (northern Tibetan Plateau, region III), Indian

monsoon (southern Tibetan Plateau, region I), and transition in between (region II). Therefore, we have added related information in the main text (Page 4, Line 26-28).

The "intensified sampling" here means systematic sampling for a whole winter season. We deleted the word "intensified" in the sentence.

"LHG" means the Laohugou No.12 glacier region, we have added the information in the main text (Page 4, Line 24).

- Page 4 line 30: Is "LHG" the same as region III?

Answer: "LHG" is not the same as region III. LHG is located in the Region III, it can represent the snow samples we collected in the region III. We have changed the sentence in the main text (Page 4, Line 30-31).

- Page 5 line 6: Is there a region you mention (c) but don't use it in the equations below?

Answer: We don't use c in the equations. Thus we revised this sentence in the main text (Page 5, Line 9).

- Page 5 line 17: This is too qualitative. What is the mass fraction of dust compared to BC and OC?

Answer: In the Tibetan Plateau, Zhang et al. (2016) showed the dust number concentrations in snowpit from different glaciers (as shown in Table 2 in the publication). The average density of upper crust is about 2.8 g cm^{-3}. Median size of the dust in snow of the Tibetan Plateau is about 3 μm (d) (Xu et al., 2010). Thus, the equivalent sphere volume $V = (4/3)\pi(d/2)^3$.

Therefore, the mass concentration of dust in snow of the Tibetan Plateau is about hundreds of μg g^{-1} based on number concentrations. The unit of BC and OC in snow is ng g^{-1}, which means around three magnitudes lower than the mass concentration of dust. Thus, in this study, the mass fraction of dust is larger than 90% compared to BC and OC (see the Supplementary data).

We have revised this sentence in the main text (Page 5, Line 20-21).

Table 2. Mean values of $\delta^{18}O$ (‰), major ions (ng/g), and microparticles (10^3 /mL) in studied snowpits.

Sites	$\delta^{18}O$	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	NO_3^-	Microparticles
TS	−8.84	140	213	59.4	194	1159	256	593	359	894
LH	−11.94	149	163	30.9	345	1855	364	547	356	740
MS	−17.97	75.9	118	40.0	49.4	506	110	109	154	197
GL	−10.67	176	142	31. 8	85.0	1186	263	376	291	170
ZD	−17.14	352	210	146	76.1	1658	363	444	256	562
ER	−18.53	327	163	108	27.5	194	392	419	109	36.5
DML	−17.12	14.7	19.6	20.6	30.5	129	30.5	29.2	52.9	205
YL	−12.00	207	229	65.2	53.5	1003	245	459	220	116

References:

Xu, J., Ho u, S., Qin, D., Kaspari, S., Mayewski, P.A., Petit, J. R., Delmonte, B., Kang, S., Ren, J., Chappellaz, J., Hong, S.: A 108.83-m ice-core record of atmospheric dust deposition at Mt. Qomolangma (Everest), Central Himalaya, Quaternary Research, 73: 33−38, 2010.

Zhang, Y., Kang, S., Zhang, Q., Gao, T., Guo, J., Grigholm, B., Huang, J., Sillanpää, M., Li, X., Du, W., Li, Y., Ge, X.: Chemical records in snowpits from high altitude glaciers in the Tibetan Plateau and its surroundings, PLoS ONE, 11(5), e0155232, doi:10.1371/journal.pone.0155232, 2016.

- Page 5 line 24: which is it, 580 or 80? Why one or the other?

Answer: In the protocol of IMPROVE-A for analysis of OC and EC, different temperature plateaus were used to obtain the signals of OC or EC on the filters. Thus in the main text, we have revised this sentence (Page 5, Line28-31).

- Page 5 line 27: How was the carbon converted to methane?

Answer: Fig. R1 of DRI carbon analyzer block diagram shows the analyzer operates by: (1) liberating carbon compounds under different temperature and oxidation environments from a small sample punch taken from a quartz-filter, (2) converting these compounds to carbon dioxide (CO_2) by passing the volatilized compounds through an oxidizer (MnO_2 at 912 °C), (3) reduction of the CO_2 to methane (CH_4) by passing the flow through a methanator (firebrick impregnated with nickel catalyst at ~550 °C in a stream of hydrogen), and (4) quantification of CH_4 by a flame ionization detector (FID).
We have revised this sentence in the main text (Page 6, Line 1-3).

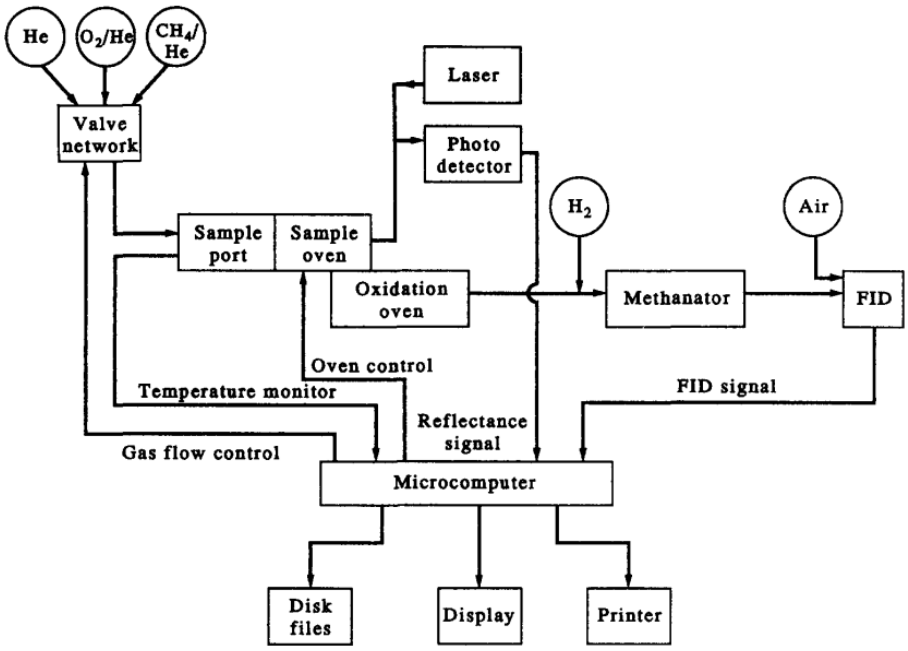

Fig. R1 DRI thermal/optical carbon analyzer block diagram. (Chow et al., 2004)

References:

Chow, J.C., Watson J. G., Pritchett, L. C., Pierson, W.R., Frazier, C A., Purcell, R.G.: The DRI thermal/optical reflectance carbon analysis system: description, evaluation and applications in U.S. air quality studies. Atmos. Environ., 27(8): 1185−1201, 2004.

- Page 5 line 31: Is this the range for the detection limit? 750 seems high.

Answer: The value of 750 µg C cm^{-2} is the detection range (maximum). The detection limit of total carbon is 0.93 µg C cm^{-2}. Detection limit of total organic carbon is 0.82 µg C cm^{-2}, and the total elemental carbon is 0.19 µg C cm^{-2}.

- Page 6 line 17: need units for the numbers 0 and 75

Answer: The unit is "°N". We have added in the main text. (Page 6, Line 22)

- Page 7 line 9: What is "standard solar irradiance"? Does this mean you don't have observations of surface irradiance? Remove "to get the albedos".

Answer: In this study, we don't have observation of surface irradiance. Thus, we use "reference/standard solar irradiance", which is the power per unit area received from the Sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument. Irradiance on the Earth's surface depends on the tilt of the measuring surface, the height of the sun above the horizon, and atmospheric conditions. Absorptance, reflectance, and transmittance of solar energy are important factors in material degradation studies, solar thermal system performance, solar photovoltaic system performance, biological studies, and solar simulation activities. These optical properties are normally functions of wavelength, which require the spectral distribution of the solar flux be known before the solar-weighted property can be calculated. To compare the relative performance of competitive products, or to compare the performance of products before and after being subjected to weathering or other exposure conditions, a reference standard solar spectral distribution is desirable.

We have deleted the words "to get the albedos".

- Page 7 line 22-23: provide units for all variables.

Answer: We have added the units in the main text (Page 7, Line 28-30).

- Page 7 line 31: Is incoming shortwave radiation the same as surface irradiance?

Answer: The "incoming shortwave radiation" in this study is observed from the AWS near the sampling site. It is not the same as "surface irradiance".

-
- Page 8 line 1: How is "solar shortwave insolation" different from "incoming shortwave radiation"?

Answer: They are the same, in the main text, we have revised.

- Page 8 line 8: Is the observed snow depth based on previous studies? If so reference them here.

Answer: Yes. We have added the reference in the main text (Page 8, Line 14).

- Page 8 lines 6-9: Include units in parentheses for all variables in the text where they are described.

Answer: We have added the units in the main text. (Page 8, Line 12-14)

- Page 8 line 32: Have higher OC/EC ratios than what? Fossil fuels?

Answer: Have higher OC/EC ratios than that from fossil fuels combustion. We have changed this sentence in the main text (Page 9, Line 9).

- Page 9 line 20: "for half of the BC deposition" How was "half" determined, quantitatively? Same with 30% on line 22 and 70% on line 26.

Answer: Here in the study means about 50 %. We have changed the sentence in the main text (Page 9, Line 30).

- Page 10 line 11: What is the upper boundary and how does it compare to your grain size measurements?

Answer: In this study, the upper boundary (10 μm) is referred to the **dust size** in the SNICAR model (Fig. R2). It is not referred to the snow grain size.

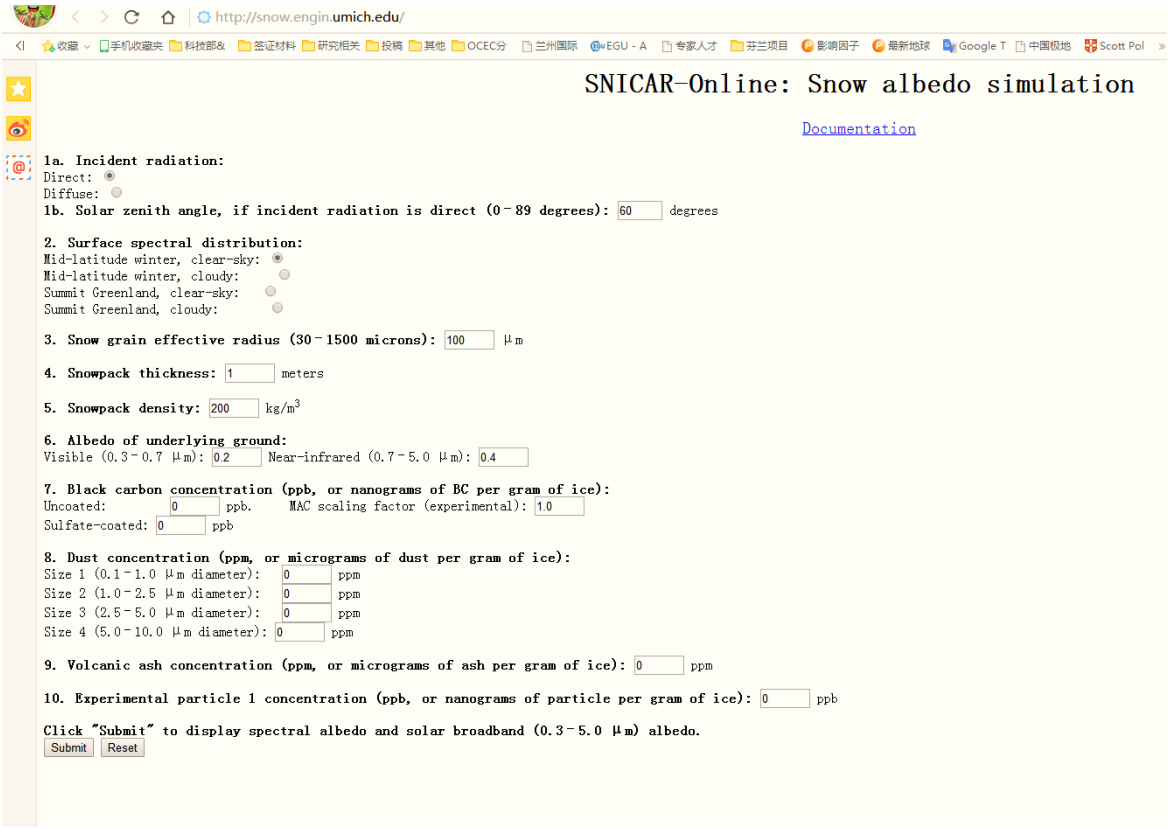

Fig. R2 The input parameters of SNICAR model online. (Flanner et al., 2007)

References:

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.

- Page 10 line 7: insert to be more explicit what these numbers are referring to.

Answer: from wavelength of 350 to 800 nm. We have added information in the main text (Page 10, Line 16).

- Page 10 line 22: What do you mean by "radiative flux"? Can you express in terms of previously used variables, such as RF or albedo?

Answer: Here it means the "radiative forcing".

RF represents the "radiative forcing" in this study. It means the difference between insolation (sunlight) absorbed by the snow surface and energy radiated back to space in this study.

In IPCC AR5 (Myhre et al., 2013), RF means the change in net downward radiative flux at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding surface and tropospheric temperatures and state variables fixed at the unperturbed values.

In this study, snow albedo is defined as the ratio of irradiance reflected to the irradiance received by snow surface. Snow albedo is highly variable, ranging from as high as 0.9 for freshly fallen snow, to about 0.4 for melting snow, and as low as 0.2 for dirty snow.

References:

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. *In*: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

- Page 11 line 15: What is shortwave radiation "input data"? Is it surface irradiance? You need to be consistent in your defined terms throughout the manuscript.

Answer: Here is the shortwave radiation.

- Page 12 line 18: What are Koch snowflakes?

Answer: Koch snowflakes is one of snow grain types (Fig. R3b) (Liou et al., 2014; von Koch, 1904).
A Koch snowflake, which has the fractal dimension of 1.262, takes place only on side planes. However, the two basal planes are flat. Thus, a 3-D Koch snowflake contains two flat basal planes and $3 \times 4n$ highly irregular side planes (with six-side symmetry) associated with n fractal iterations (see Figure 1b, where n = 4) (Liou et al., 2014).

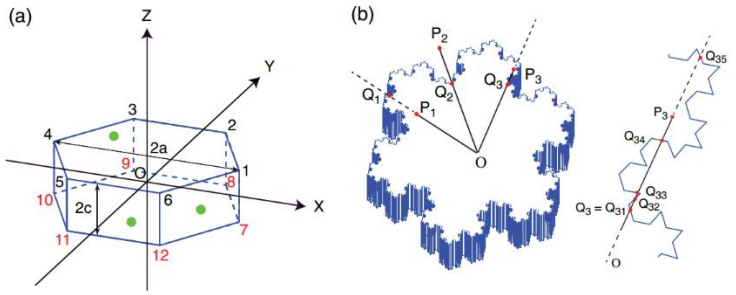

Figure 1. (a) Geometry for the internal inclusion of BC/dust particles inside a hexagonal plate (a convex-shaped particle) in the *xyz* coordinates where the numbers (1–12) denote the corner position of the hexagon defined by the diameter 2*a* in basal planes and the length 2*c* in the *c* axis. (b) A schematic diagram for a basal plane of a Koch snowflake of the order 4 in which the points P_i, (i = 1, 2, and 3) are determined by random numbers, and Q_i are points on the boundary of the snowflake, and Q_{ij} denotes subset points of Q_i to represent the concave condition of a Koch snowflake such that selected random points (BC/dust) are within it.

Fig. R3 Snow gain type of Koch snowflake cited from (Liou et al., 2014).

- Page 13 line 11: "Snow cover durations were shortened during the melt season from X-Y days…" Insert numbers for X and Y.

Answer: Snow cover durations were shortened during the melt season from 1.26−9.4 days…
We have added the number of days in the main text (Page 13, Line 27).

- Page 13 line 13: "annual mass budget" Is this a loss of mass? "mass budget" does not necessarily imply a loss.

Answer: Yes, it is "annual mass loss". We have changed in the main text (Page 13, Line 29).

- Page 14 line 2: Wasn't this study a survey of LAP, and not snow cover?

Answer: It is a survey of LAP in snow cover. We have changed in the main text (Page 14, Line 18).

- Page 14 line 13: What is radiation input data? Is this observed surface irradiance?

Answer: It is shortwave radiation. We have deleted "input data".

Although the grammar and wording are somewhat improved, there are still some issues. Some specific suggestions on word changes are below which should help to clarify the manuscript.

Answer: Thank you very much for all the suggestions and comments. We have carefully changed in the main text.

- Page 1 line 20: insert "relative" before "biomass burning"

Done

- Page 1 line 21: insert "relative" before "contribution"

Done

- Page 1 line 23: delete "changes of"

Done

- Page 2 line 10: change “by” to “of”

Done

- Page 2 line 16: replace “the simulation showed” with “suggested”

Done

- Page 2 line 17: deposited ***to*** land snow, not in Page 2 line 17: put a comma after W m^{-2}

Done

- Page 2 line 17: replace “or as large as” with “contributing as much as”

Done

- Page 2 line 19: replace “in” with “for the”

Done

- Page 2 line 20: insert “also” between “can” and “change”

Done

- Page 2 line 23: replace “in particular, from” with “especially = “

Done

- Page 2 line 24: replace “on Claridenfirn of” with “in”

Done

- Page 2 line 26: remove comma after “region” Page 2 line 27: what is “disturbed” desert dust?

Done

- Page 2 line 29: remove “even”

Done

- Page 3 line 22: replace “seldom” with “sparse”

Done

- Page 3 line 26: remove “cover” after “snow”

Done

- Page 3 line 27: change first comma to a period to end the sentence. Then start the next sentence with “We further…”

Done

- Page 3 line 28: insert “observed” before LAPs.

Done

- Page 3 line 28-29: should read “We use back trajectory analysis coupled with BC fire emission inventories to approximate natural/anthropogenic contributions”

Done

- Page 3 line 29: increase *our* understanding

Done

- Page 3 line 30: insert comma after TP and remove the next word “and”

Done

- Page 3 line 30: replace “this is also helpful for” with “inform”

Done

- Page 4 line 5: remove “in the earth system”

Done

- Page 4 line 17: remove “on”

Done

- Page 4 line 27: replace “contains” with “includes”

Done

- Page 5 line 23: remove “special”

Done

- Page 5 line 25: Should read “The sample is reheated further in a stepwise fashion to near 900…”

Done

- Page 5 line 26: Should read “burn out all remaining BC”

Done

- Page 5 lines 27-30: Move this sentence up to after “…of the OC in the sample.” Change “modified .. arranged” to “limited the initial temperature plateau”

Done

- Page 6 line 6: Should read: “…used approach for determining source regions of various atmospheric species.”

Done

- Page 6 line 7: remove “that”

Done

- Page 6 line 7: can be *qualitatively* attributed

Done

- Page 6 line 19: Remove “Then,”

Done

- Page 6 line 23: Should read “FINN used satellite” (remove “the”)

Done

- Page 6 line 25: Remove “Then,”

Done

- Page 6 lines 29-30: Should read: “Note that this analysis is qualitative and does not take into account loss from wet and dry deposition”

Done

- Page 6 lines 31-32: Remove sentence beginning “Thus,”

Done

- Page 6 line 32: Should read “Despite these uncertainties, the relative differences between the BC contributions are used to…”

Done

- Page 7 line 2: remove second comma

Done

- Page 7 line 25: Should read “will lead to discrepancies between”

Done

- Page 8 line 6: insert “and” before “for”

Done

- Page 8 line 7: should read “clean snow due to changing snow grain sizes with show age”

Done

- Page 8 line 28: replace “values” with “concentrations”

Done

- Page 8 line 29: replace “by the soil” with “from the soil”

Done

- Page 8 line 30: replace “represent” with “examine”

Done

- Page 9 line 3: replace “little” with “slightly”

Done

- Page 9 line 13: remove “arrived at”

Done

- Page 10 line 2: replace “simulate” with “estimate the”

Done

- Page 10 line 13: Should read “albedo differences between measurements and simulations is less”

Done

- Page 10 line 20: remove “when testing regional to global scale models”

Done

- Page 11 line 5: Replace “validation” with “assessment”. It is impossible to “validate” a model (although I realize this term is frequently used in the literature)

Done

- Page 11 line 11: Should read “Thus, this does doesn’t include the effect of OC on estimates of”

Done

- Page 11 line 14: Changes *in* snow cover

Done

- Page 11 line 24: low *SD* scenarios

Done

- Page 12 line 19: A lack of OC *consideration* due to

Done

- Page 12 line 25: Remove "We also have to pay attention to the fact that". Replace "their" with "dust"

Done

- Page 12 line 26: replace designed with "assumed".

Done

- Page 12 line 27: efficient *at* light scattering

Done

- Page 12 line 28: replace "materials that" with "and"

Done

- Page 13 line 8: replace "the estimation" with "estimates"

Done

- Page 13 line 30-31: "would have been marginal" depends on assumed concentrations. Maybe say "uncertain" instead of "marginal"

Done

- Page 14 line 14: reduced *snow cover* from several

Done

- Page 14 line 19-20: "total mass balance" should read "mass lost" if I'm understanding this correctly

Yes, it is "mass lost"