The Cryosphere Discuss., 8, C2896–C2904, 2015
www.the-cryosphere-discuss.net/8/C2896/2015/

Interactive comment on "Black carbon in snow in the upper Himalayan Khumbu Valley, Nepal: observations and modeling of the impact on snow albedo, melting, and radiative forcing" *by* H.-W. Jacobi et al.

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Received and published: 16 January 2015

Reply to referee 1 (Referee's comments in italic)

This manuscript presents the observations and modeling the impact of black carbon in snowmelt processes at Khumbu region of Nepal Himalaya. The content of the manuscript is of weighted significance in snow modeling community as this paper discusses about the upgrade and evaluation of the physics based snow model (Crocus) with the effect of black carbon against field observations. This is a well written manuscript; however some points should be clarified and revised and then the manuscript shall be considered for publication in TC.

We thank Referee 1 for the thorough and insightful review. We have responded to each comment below.

1. Page 5046, line 14-16, Pokhrel et al, 2014 had not corrected the precipitation at Pyramid station, thus the corrected annual value in this paper cannot be compared with Pokhrel et al., 2014.

We agree that it remains unclear in the article by Pokhrel et al. if and how the observations were corrected. We will remove this reference in a revised manuscript. In contrast, Salerno et al. (Salerno et al., Weak precipitation, warm winters and springs impact glaciers of south slopes of Mt. Everest (central Himalaya) in the last two decades (1994-2013), Cryosphere Discuss. 8, 5911-5959, 2014) obtained an annual mean for the precipitation at PYRAMID of the order of 449 mm for the period 1994 to 2013. We will instead compare our values to this multiyear mean.

2. Page 5052, line 2-6; in this paper evaluation of the model is presented for point scale then why the point scale measurements show error for point scale validation. I would agree authors view if they simulate the impact on basin scale.

The referee is right that in general local simulations and observations should agree. However, in the case of snow the spatial variability can be huge. This is well documented in the scientific literature and to cite just one example, we refer to one of our previous publications in The Cryosphere (Jacobi et al., Simulation of the specific surface area of snow using a one-dimensional physical snowpack model: Implementation and evaluation for subarctic snow in Alaska, The Cryosphere 4, 35-51, 2010), where we presented in Figure 1 multiple snow height measurements from the same site in the Arctic. Even at such a homogeneous site, snow height measurements can differ considerably especially during the melting period. This high variability of the snow is well documented in many further publications. Furthermore, in the rugged terrain of the

Himalayas also the atmospheric observations may only represent very localized conditions. As a result, we believe that the non-ideal conditions at the field site introduce additional variability that can not be represented by the simulations. We will re-phrase this paragraph to underline this point in the revised manuscript.

3. Provide the table for the model parameters of the standard and upgraded Crocus model for the simulation of albedo.

The parameters used in the simulations with the standard Crocus model correspond to those described in Vionnet et al. (2012) and summarized in their Table 4. Therefore, we believe it is not necessary to repeat the same numbers here. The upgraded Crocus model does not rely on a prescribed set of parameters, but calculates for each snow layer the optical properties according to the theory described by Warren and Wiscombe (1980) and Wiscombe and Warren (1980) using as input snow grain size, SWE, soil albedo, BC, dust, and the solar zenith angle (only for the top layer). To apply the equations of Warren and Wiscombe (1980) and Wiscombe and Warren (1980) the optical properties of the three materials ice, BC, and dust need to be calculated. They are based on fixed parameters and like in previous applications of the same module (Krinner et al., 2006; Ménégoz et al., 2013b), we used published optical properties for ice and assumed log-normal size distributions for BC and dust. All characteristic numbers for the properties of BC and dust are summarized on page 5045, but they represent completely different properties and are, thus, not comparable to the parameters presented by Vionnet et al. (2012). We prefer to keep this information in the text, but if requested by the editor this information can also be presented in a table.

4. How the decay of the albedo is accounted in standard Crocus model. The large bias/overestimation in snow albedo is due to its poor representation of the decay of the albedo. Employment of more physically based scheme for decay of albedo is undershadowed by the implementation of upgraded version of the model for black carbon and dust. Many albedo parameterization schemes were adopted for various land surface schemes. Please clarify the parameterization of old scheme vs. implementation

of upgraded version.

In the standard Crocus model, the albedo of the snow only depends on the properties of the top snow layer. The parameterization relies on the age of the snow and the optical diameter, which depends on the grain size, sphericity, and dendricity. In general, with increasing grain size the optical diameter increases reducing the albedo. The albedo further decreases according to the age of the snow. As a result, the decay of the albedo is not prescribed but depends via the optical diameter on the simulated metamorphism of the snow. This is described in more detail in Vionnet et al. (2012). As described above, in the upgraded Crocus model the albedo is calculated based on the optical properties of the entire snowpack. Since the snow grains change over time according to the implemented metamorphism scheme in Crocus, the albedo changes. There is no prescribed decay of the albedo as a function of snow age or similar, since the albedo relies only on the simulated properties of the snowpack. We will stress this point in the revised manuscript. Since the albedo in both model versions depends on the simulated properties a simple and straightforward comparison of the parameterizations is not possible. A reasonable direct comparison of the albedo is only possible for the derived albedo in the different model versions as done in Fig. 4. However, it must be noted that differences in the simulated albedo can only be directly linked to the parameterizations if the snowpack is the same in the model runs. As demonstrated for the period in Fig. 4, modeled snowpack properties quickly deviate and cause additional differences in the albedo as described in chapter 3.3 of the manuscript.

5. The biases in albedo and snow depth is critical in the melting season. Please perform the analysis in the melting season similar to the analysis presented for 22-31 Jan 2005 (fig.4).

Like noted above the comparison of the albedo is complicated because the entire snowpack properties are taken into account. Therefore, a direct comparison of the albedo is only useful for periods when the snowpack properties are comparable like in the example shown in Figure 4 when the precipitation event in January 2005 led to a similar built up of the snowpack in all simulations. To do a same comparison for the melting season for example the albedo of the last days before the complete melting of the snowpack would needed to be compared. However, these melting periods occurred during different periods with different environmental conditions hampering a direct comparison of the simulated albedo. The simulated albedo may be regarded as a value that integrates the entire or a large part of the history of the seasonal snowpack. Since the snowpack develops differently in different model runs and also different to the observations a comparison delivers limited information. This could be improved if the simulations were forced closer to the observations using assimilated data. However, we believe that for such an approach more comprehensive data including regular measurements in snow pits like done at other more accessible sites (e.g. Morin et al., An 18-yr long (1993-2011) snow and meteorological dataset from a mid-altitude mountain site (Col de Porte, France, 1325m alt.) for driving and evaluating snowpack models, Earth Syst.Sci.Data 4, 13-21, 2012) would be needed. Nevertheless, we compared the average differences in the albedo for BC = 0, 100 ppb, and 300 ppb for mid-April 2004 and derived albedo differences that correspond to the maximum differences described on page 5054 (around 0.03 and 0.08). This indicates that during the winter season the differences in the albedo further increases and reach maximum values before the melting of the snowpack as long as fresh snow does not increase the albedo values.

6. What is the reason for the large discrepancy of albedo decay even for the upgraded model as presented in Fig.5.

The large discrepancy is mainly linked to the overestimation of the duration with snow on the ground and the snow height. While the maximum observed snow height remained below 40 cm, the simulated maximum heights were in most runs higher. As a result, the simulated snow remained much longer on the ground compared to the observations causing the large differences in the albedo later in the winter season. The overestimation of the snow height and duration can be due to many different reasons, the most important may be an overestimation of the precipitation and/or an overestimation of the fraction of solid precipitation. Other factors may also contribute like the spatial variability as mentioned in the manuscript, the ground heat flux as raised by the referee, or a bias in the simulations of the turbulent fluxes. Further modifications and applications of the Crocus model are certainly needed before it can be considered as a fully validated model for the Himalayas. However, these tests are beyond the scope of this manuscript.

7. Please present the analysis of simulated vs observed soil temperature as soil temperature has larger effect on shallow snowpack, mainly in the melting season. How the initial condition for soil parameters were provided, please clarify.

The simulation were performed with the stand-alone version of the Crocus model where the ground heat flux was imposed depending on the geographic location, the elevation, and the season (Brun et al., 1989; 1992). Therefore, soil temperatures are not simulated and can not be compared to observations. We checked the simulated ground heat fluxes and found average values between 2 and 6 W m2 warming the snow depending on the different seasons and model runs. These fluxes are small compared to the net solar, net IR and sensible heat fluxes between the atmosphere and the snow. Albeit not negligible, the ground heat fluxes are, thus, small terms in the overall energy budget of the snowpack. Preliminary uncorrected data on soil heat fluxes (E. Vuillermoz, Ev-K2-CNR Committee, Bergamo, Italy, personal communication) indicate monthly averages between 0.5 and 5.4 W m2 for the months between November and March. These numbers are comparable to the simulated fluxes indicating that the simulated ground heat fluxes play only a small role in the overestimation of the snow height. Nevertheless, the differences between simulations and observations can be larger early and late in the winter season and for specific snowfall events. Simulations with a coupled snow-soil model would help to address this issue. We will modify the revised manuscript accordingly stressing the possible importance of the ground heat fluxes.

8. Are threshold air temperature parameter (for separation of precipitation into rainfall and snowfall) and fresh snow density parameters sensitive? If so, it is better to show *quantitative analysis of their effect on snowpack simulation as these parameters are the drivers for the correction of snowfall.*

The threshold air temperatures are certainly of great impact for the simulations since it determines the amount of solid precipitation especially in fall and spring when average temperatures swap from positive to negative values and vice versa. However, the use of the fixed thresholds to determine solid and liquid precipitation is a very simplified approach and more sophisticated methods can be found in the literature (see for example Y. Lejeune et al., Melting of snow cover in a tropical mountain environment in Bolivia: Processes and modeling, J.Hydromet. 8, 922-937, 2007 and references therein). We believe instead of testing the sensitivity of the simulations versus the threshold temperatures it would be more important to derive a more reliable time series of precipitation based on observation for the studied site. However, this is beyond the scope of the current manuscript. Nevertheless, the overestimation of the snowpack in the simulations may be caused by the selection of threshold temperatures. For example, Lejuene et al. used -1°C instead of 0°C to determine solid precipitation, which would lead to a reduction of the amount of solid precipitation in our simulations and obviously also of the simulated snow heights and duration of snow on the ground.

9. Please discuss a little about the future strategies for improving the simulation of albedo besides enhanced field observations.

The major open point for the simulation of the albedo is the deposition of the absorbers to the snow and their post-depositional behavior. So far, the simulations were performed with constant and homogeneous BC and/or dust concentrations without dealing with the deposition processes. These simulations can only represent test cases with likely upper and lower limits of the absorbers. The simulations do not capture all processes inside the natural snowpack. For example, the layers will exhibit different concentrations of absorbers, which depend on wet and dry deposition. Sublimation, melting, and refreezing of the snow will modify the concentrations. These modifications especially in the case of the formation of liquid water will further depend on the

solubility of the absorbers. It must be noted that BC particles undergo a chemical transformation in the atmosphere from more hydrophobic to hydrophilic. It is presently unknown if a further modification of the chemical properties of the BC particles in the snow occurs. It has been shown that BC tends to increase in the melting snowpack (H. Conway et al., Albedo of dirty snow during conditions of melt, Water Resour.Res. 32, 1713-1718, 1996.; S.J. Doherty et al., Observed vertical redistribution of black carbon and other insoluble light-absorbing particles in melting snow, J.Geophys.Res. 118, 5553–5569, 2013). Unfortunately, currently exists no snowpack model that can treat the behavior of impurities in the snow. This will be a major challenge for future developments. Another important issue is the accelerating effect of multiple absorbers like BC and dust on the melting of the snow. This is opposite to the impact on the albedo because further addition of absorbers has a smaller impact on the albedo of dirty snow compared to clean snow. However, the decreasing impact on albedo has been used to deduce that the impact on the radiative forcing also decreases for the dirty snow. According to our simulations this is not correct. This also points to the need to know all absorbing compounds (e.g. brown carbon, organic compounds, . . .) in the snow before the impact of a single absorber like BC can be determined. This will also be an issue for future observations and modeling of the snowpack.

10. Corrections in citation: a. Line 25-27; Kaab et al, 2012 and Menegoz et al 13a do not discuss about black carbon. b. Page 5039, line 9; Immerzeel et al, 2010 also does not discuss about BC, please reorganize the sentence.

The two sentences do not claim that BC is the topic of the three cited papers. They give background information regarding the extent of the cryosphere in the Himalayas in general (page 8) and the role of the hydrological cycle in the Himalayas (page 9). In our opinion, there is no need to rewrite the two sentences.

c. Shresta should be replaced by Shrestha throughout the manuscript

This will be corrected in the revised manuscript.

Interactive comment on The Cryosphere Discuss., 8, 5035, 2014.