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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Open fires in Greenland: an unusual event and its impact on the albedo of the Greenland Ice Sheet" *by* Nikolaos Evangeliou et al.

Nikolaos Evangeliou et al.

nikolaos.evangeliou@nilu.no

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Anonymous Referee #2

General comments : This work investigates the quantification of emissions of black carbon (BC) from intense fires on peat lands in Western Greenland during summer 2017 and their impacts on albedo reduction and radiative forcing. The authors conclude that those impacts of BC deposition of the Greenland Ice Sheet are almost negligible, which turns out to be a scientific result for the community. This study is interesting and sound for ACP. I have nevertheless several criticisms requiring a careful and revision and in-depth improvements both in the methodology, often unclear, and in the discussion of

the results before the paper is suitable for publication in ACP.

–Response: We acknowledge the reviewer's comments and his effort to improve this manuscript. We have tried to follow his suggestions to correct the manuscript and have basically re-written parts of the manuscript (please see manuscript with Track Changes).

Specific comments : L1-2 : The title seems to indicate that the main focus of the paper is the quantification of the reduction in albedo due to open fires in Greenland. Only ten lines in the paper really focus on the modification of the albedo due to BC deposition. The title should reflect the main findings of the paper : quantification of BC emissions of this unusual event, transport of the plume, deposition.

–Response: We agree; we have changed the title to "Open fires in Greenland in summer 2017: transport and deposition of BC and impact on the Greenland Ice Sheet"

L41-44 and L496-500 : I find a bit strange to conclude both abstract and conclusion by something purely speculative and that does not match the main results of the paper.

–Response: We admit that this is probably an extreme formulation and we have changed it to a weaker statement. We would like to draw attention that this statement is not a conclusion, but a logical hypothesis. To further show that it's not a conclusion, we now support the paragraph with references (see last paragraph in conclusions).

L83-84 : "the largest fires". Give maybe statistics or cite a climatological study to support this assertion.

–Response: We have plotted the annual number of active fires from NASA's MODIS product in supplements' Figure S1 (or Fig.R1) starting from first year that satellite data were available (2001).

L111 : The authors should give more details about the procedure applied on the data. "Additional classification" is too vague.

–Response: The statement has been removed!

L130 : “assuming a 6h persistence”. How is this hypothesis justified ? Is it confirmed b observations or by other studies ?

–Response: Well, this is confirmed by previous studies (Kaiser et al., 2012 – reference in the paper). We chose a persistence model similar to what is done in Kaiser et al. (2012) and used a time of the same order of magnitude with the mean return time of MODIS in the afternoon (peak time of fire) $\sim$ 4h. For a description of the persistence model that was used, please see line 8 - page 9852 of Paugam et al. (2015).

L161 : Say clearly that the only variable computed in this study from measurements is the burned area A. The other factors are based on assumptions or provided by previous studies.

–Response: Corrected. This is now explicitly mentioned in Line 184.

L181 : Those values suggest that aerosols are not only composed of BC (which is a reasonable assumption). How do the authors justify this size distribution ? It has indeed a huge influence on the deposition efficiencies (both sedimentation and wet removal) and on the calculation of aerosol optical properties. Both the radiative forcings and reduction of albedo on snow surfaces will be sensitive to this assumption on the size distribution. I suggest that the authors perform a sensitivity study on the influence of those parameters.

–Response: After rapid coagulation, more than 90% of the mass of BC after fires is present in sizes between 0.1 – 1 μm in the atmosphere. This has been highlighted by many experiments/measurements and is now well justified in section 3.2. However, we have followed the suggestion of the current reviewer and performed a sensitivity study using different size distribution of the BC particles produced from the 2017 fires in Greenland and we calculated the uncertainty on the deposited mass of BC due to different size distribution. We present and discuss the results at the end of section 3.2.

The effect of different size distribution on residence times has been already studied by Grythe et al. (2017) [reference in the manuscript] and the different deposition coefficients in Evangeliou et al. (2018) [reference under editorial check in ACP Discussions]. The calculated uncertainty from this sensitivity test ranges from 10%–30% in 86% of the Sheet’s surface to up to 50% in the rest of the Sheet’s surface.

L200 : “a simple emission scheme”. What does it mean? Why don’t the authors use the same methodology for all fires ?

–Response: We appreciate reviewer’s comment here. This was a typo error and we have updated this part of the methodology.

L200-201 : Those emission factors should depend on the type of soil and vegetation. Which maps have been used here ? Which values for emission factors have been finally chosen ? The reader should be able to reproduce the results of this study ; without such assumptions, it is impossible.

–Response: Corrected; See previous comment.

Sect. 2.4 : Do the authors calculate radiative forcing assuming refractive index of BC only? The choice of the refractive index should be done in accordance with the size distribution (L181), which probably reflects an internal mixture of aerosols.

–Response: The radiative forcing was calculated using the refractive index of BC only. We agree with the reviewer that BC was likely present as an internal mixture with other aerosol components (especially OC). However, we did not simulate OC and therefore used only the refractive index of BC. This will lead to an underestimation of the atmospheric effects of BC, since internal mixing with OC will likely enhance the BC absorption, and there may also be other absorbing components in the aerosol. However, we think that as an order of magnitude estimation of the atmospheric effects, our assumption should be sufficient. Furthermore, the more important impact of BC on the albedo is less (or not) sensitive to the mixing state of the aerosols.

L226 : “we display” : where ?

–Response: We substituted ‘display’ with ‘used’.

L292 : “a small portion of the emitted BC”. Please quantify it.

–Response: We have quantified the portion that lifted up in this particular day (≈516 kg).

L334 : “due to the generally dry weather when the fires were burning”. It can be also ascribed to the fact that dry deposition mostly occurs in the quasi-laminar sublayer close to the surface. Aerosols are quickly deposited close to the sources before being injected at higher altitudes and being transported away from sources.

–Response: Thanks for this comment. We have included it in the manuscript.

L365 : “the anthropogenic contribution is larger”. For the sake of clarity, the authors might write that the anthropogenic is relatively larger in Southern Greenland in contrast to Northern Greenland but remains lower than the biomass burning contribution.

–Response: Comment was added to the manuscript.

L367 : “the BC concentrations that are calculated here for the studied fire period are relatively high compared to those reported previously”. I am not sure this is always true. The authors should also quote more recent studies, e.g. Polashenski et al. (2015), Legrand et al. (2016) or Thomas et al. (2017), who have reported higher events of biomass burning BC deposition over Greenland. If the BC deposited on snow/ice surfaces is much larger in those studies, it also suggests higher surface BC concentrations.

–Response: We thank the reviewer for providing the references and have added them to the previous section. Please see Line 425-426 for Polashenski et al (2015) and Legrand et al. papers. However, the Thomas et al. paper is using another unit (g/m2) and without knowing the density of the samples no conversion to ng/g (units used in

the present) can be applied.

L378 and L389 : “dosages”. Do you mean concentrations / mixing ratios ?

–Response: They are dosages of concentrations. It is now explained in the last paragraph of section 3.3 and in the caption of the respective Figure.

L397-398 : BC particles are probably not the main contributors to AOD in this region for two reasons : the BC loadings are rather low in comparison to other aerosol compounds and the diameter of BC-containing particles is much smaller than the wavelength (0.5 um). A better proxy of the temporal evolution of the integrated BC would be the absorbing AOD (AAOD), which is also often provided at AERONET stations. The AAOD/AOD would be also a good indicator of the contribution of BC to the total AOD (even if BC is not the only absorbing component). This should be shown on Fig. 5.

–Response: The reviewer has a very good point here and we tried to retrieve AAOD data as he suggested. Though in Kangerlussuaq and Thule no AAOD Level 2 data are available for July-September 2017, while in Narsarsuaq AAOD Level 2 data are available for 2 September 2017 (when the fires had been already extinguished). In Andrews et al. (2017) paper is stated that “One obvious limitation of the AERONET inversion retrievals is that the uncertainty of the derived SSA becomes very large at low values of AOD (Dubovik et al., 2000). To minimize the effects of this uncertainty, the AERONET Level 2 data invalidate all absorption-related values if the AOD at wavelength 440 nm (AOD440) is below 0.4 (Dubovik et al., 2000, 2002; Holben et al., 2006).” In page 6043 of the same paper it is stated that “It should be noted that AERONET does not recommend the use of absorption-related parameters (e.g., SSA, AAOD and complex index of refraction) at AOD440 below 0.4.” In our case, except for the characteristic peak of AOD that is attributed to the N. American fires, all the other AOD values were below 0.4. Sometimes researchers use AAOD LEV 1.5 data, but these get high uncertainty (see Andrews et al, 2017). In page 6051 of the Andrews et al. (2017) paper is also stated that “Using the sum-of-squares propagation of errors to calculate the uncertainty in AAOD for both high and low AAOD cases results in an AAOD uncertainty of approximately 0.015 for both high- and low-AOD cases . . . An AAOD uncertainty value of 0.015 suggests an uncertainty of about 60% in AAOD for AOD440 D0.5 and more than 140% uncertainty in AAOD for AOD440 < 0.2." Therefore, we do not think that these uncertain LEV1.5 AAOD measurements should be plotted instead of AOD here. However, if the reviewer or the editor disagree, we have retrieved them and we could use them in a next step. Besides, we only used AOD as an indicator for the presence of the plume, and for that purpose it should be sufficient.

L401-407 : How do the authors explain the significant AOD enhancement at the beginning of September observed at Narsarsuaq station ?

–Response: As the reviewer can see, in the attached Fig.R2 we present the biomass burning BC from GFAS (upper panel) in the beginning of September and the footprint emission sensitivity from the Narsarsuaq station (bottom panel) on September 3rd. We observe that the highest footprint emission sensitivity is located exactly at the place where GFAS emissions are the highest (Canada). Therefore, we have a clear indication that the increase that the reviewer mentioned is due to the Canadian wildfires.

L422 : "was not studied". Does it mean that the transport of those North American fire plumes was not correctly captured by FLEXPART ? It is indeed impossible to see on Fig. 6d as the vertical scale is not appropriate.

–Response: Here, we wanted to state that the existence of the N. American fires in the attenuated backscatter measurements that we get from CALIOP was not further studied. The study of the N. American fires is beyond the scope of this paper. We have used a better formulation in the manuscript now.

Sect. 4.2 : The authors should remind that they calculated only the forcing due to the Greenland fires, which is itself small compared to the North American or Eurasian fires. It should also be said explicitly that the calculated radiative forcing values does not include semi-direct nor indirect effects, which may be dominant here.

–Response: We have rewritten the first part of the section to include the information requested by the referee.

L436 : "cloudless conditions". I do not understand the purpose of this. It is only an ideal simulation, which is not commented in the paper afterwards. What does it bring to the discussion ?

–Response: The IRF for cloudless conditions is compared against IRF including clouds in the subsequent lines. IRF for cloudless conditions was included, as they show the potential maximum effect of the forcing. The results presented show that the clouds reduce both the TOA and BOA IRF.

L440-442 : It is not clear if the given values refer to the total radiative forcing of BC. What are the relative contributions of the direct radiative forcing of BC and of the radiative forcing of BC deposited on snow surfaces ? The authors also give the values without any uncertainty, but a lot of assumptions have been done to retrieve the BC emissions, the BC size distribution, the BC optical properties. Each of those hypothesis would lead to a range of values of IRF.

–Response: The given values refer to the total instantaneous radiative forcing, that is including both the effect of atmospheric BC and BC deposited on the snow. The latter dominates the IRF contributing between 85 to 99 % depending on BC amount. This has been clarified in the manuscript. The composition of the BC from the fire is not known. Hence average BC optical properties were adopted. We have subsequently performed an uncertainty analysis using realistic variations in BC optical properties. This uncertainty analysis is included in the supplementary material and referred to in the manuscript. We have also performed a sensitivity study and estimated the uncertainty of the BC deposition over Greenland due to the use of different size distribution of BC particles (see answer to previous comments).

L 442: "Fig 7c depicts the temporal behaviour..." Does it represent calculations in cloudy conditions ?

–Response: It is the cloudy conditions that are shown. This information has been added both in the text and the figure caption. The temporal behaviour is shown in Fig 7d. This typo has been corrected as well.

L443-444 : I don't see how this information (blue line) can be useful. The location of the pixel where the maximum IRF is found likely varies with time. Besides the analysis of this figure is not done in text. I recommend to remove it.

–Response: We have removed the blue line from the plot. The idea of plotting the TOA max IRF was to show that the single pixel maximum and area averaged RFs peak at different times. However, we agree with the reviewer that this information was perhaps not so useful.

L448-455 : If the authors want to be able to compare their results to global studies, as it is done here, they need to multiply the value of RF by the area of the simulation domain to obtain a forcing value in watts, and then divide it by the surface area of the Earth to obtain an equivalent global radiative effect in mW/m2 that could be compared to results for global studies.

–Response: The cited value from Skeie et al. (2011) is not a global value, but a value representative for the Greenland ice sheet (Fig 17 of Skeie et al., 2011). It is this value we are comparing against. The values from Myhre et al (2013) are included in order to give the reader a global value to compare against. This has been clarified in the text. It is clear that, on a global scale, the obtained RF values are negligible.

L453-455 : What about the impact of North American and Eurasian fires, whose plumes reach Greenland during the studied period ?

–Response: These plumes are not the focus of the present study. Similar plumes have been studied before, so we don't think focusing on these plumes would provide a lot of new information beyond what has been published before. More technically, we only estimate the impact of these plumes using backward calculations, whereas

RF calculations would require forward calculations. We think this is out of scope of the present paper. What we have done, instead, is to calculate the impact of the N. American fires in the surface concentrations of BC over Greenland (see section 3.3). This proved that the BC concentrations from the N. American fires in August 2017 are more than 1 order of magnitude higher compared with those produced from the Greenland fires of August 2017 (see updated Figure 4).

L456-457 : What is the albedo reduction due to BC deposition that can be ascribed to Greenland fires / to fires outside Greenland / to anthropogenic sources ? If the goal of the paper is indeed to focus on the impact of the Greenland fires, quantifying this effect and comparing it to the relative contribution of the different sources would be really valuable for the paper. The authors should also compare their albedo reduction values to previous studies, e.g. Polashenski et al. (2015).

–Response: We now compare our results to those of Polashenski et al. (2015) in section 4.2. The detailed study of the fires outside Greenland and from anthropogenic sources is beyond the scope of this paper. Notice that the albedo effects can't be done on the basis of the backward calculations done for the other sources and would require totally new forward simulations. However, giving the range of surface BC concentrations over Greenland (section 3.3 and Figure 4) is already enough to conclude that the event that we studied in the current paper has minor effects on the albedo or RF compared to BC from the N. American fires or from anthropogenic sources simply because of the different magnitude and duration of these fires.

Sect. 5 : The conclusions may be more quantitative. For example : L478-479 : the ratio of BC deposition from the different sources can be given

–Response: We have not quantified how big the deposition from anthropogenic and biomass burning sources is, and we have removed this sentence from the manuscript.

L481-483 : the AOD enhancement can be precised

–Response: Corrected.

L488 : "albedo change due to the BC deposition". Which sources have been considered ?

–Response: Corrected. It is the albedo change due to BC deposition from the Greenland fire of 2017.

L496-500 : Remove this purely speculative sentence. The opposite could also be said, given the findings of the paper.

–Response: These lines state that "The very large fraction of the BC emissions deposited on the Greenland Ice Sheet (30% of the emissions) makes these fires very efficient climate forcers on a per unit emission basis. If the expected future warming of the Arctic (IPCC, 2013) produces more fires in Greenland in the future (Keegan et al., 2014), this could indeed cause substantial albedo changes and thus contribute to accelerated melting of the Greenland Ice Sheet." We do not understand why this is speculative. A fraction of 30% deposition on the Greenland ice sheet is substantial, much higher than from any other source type and source region, so – on a per unit mass basis – the forcing due to albedo change is efficient, even if it is small overall. The second sentence can perhaps be considered somewhat speculative, but we have now reformulated it and, moreover, we support it with references. Furthermore, it is not presented as a conclusion, so it should be very clear to the reader to what extent this sentence is speculative. We nevertheless consider it important enough to keep it.

The choice of the figures kept in the manuscript is rather strange. Most useful figures relevant for the discussion have been displaced to the Supplementary Material. I recommend to move them to the main paper.

–Response: We have moved the figure with the calculated dosages to the manuscript (Fig. 4), as the dosages are discussed more in the text. We have now placed back to the supplements (Fig. S5) the figure of the footprint emission sensitivities that are

not the main focus of the paper. We are willing to put more figures in the manuscript in a next step, if the reviewer point into this direction. The only reason for using limited number of figures was that this paper was intended to be short.

Fig. 2a: Are those values averaged over the simulation domain ? over Greenland ? I had hard time to figure out how those values could be realistic. I think there is either a issue with the unit or a mistake in the calculation. Shouldn't it be ng/m3 or ng/kg instead of ug/m3 ? The total concentrations of BC in the domain should be calculated as the volume average of the grid cell concentrations, not the sum over all grid cells in the domain...

–Response: We thank the reviewer for this comment that we have now corrected. We now present the average vertical concentrations over Greenland from the 2017 fires in pg/m3 in the updated Figure 2.

Fig 2b : Here again, there is an issue with the unit. The color bar indicates ug/m2 (which is probably right), but the caption says ng/m2. Which one is correct ?

–Response: We also appreciate reviewer's help to correct this mistake. The error was in the legend and it has now been updated.

Fig. 4 : It is extremely difficult to see the colored grid cells an read their values. Please improve the quality of this figure.

–Response: Quality of the figures has been set to 300 dpi. This should solve the problem.

Fig. 5 : Does the altitude represent agl or amsl ? The orography in Greenland is not flat. Response: It is agl altitude and we now clarify it in the legend.

Fig 5 : Why do you keep the contribution of fires burning outside Greenland but exclude the BC contribution of anthropogenic sources ? According to Fig. 4, their contribution is absolutely not negligible and they might modify the time series of column-integrated BC in Greenland.

–Response: We thank the reviewer for this comment. We tried to put also anthropogenic BC in these time-series. Column-ntegrated anthropogenic BC is very low and a stacked line does not show anything in the time-series and that's the reason that we decided not to present it. We have added a small comment in the legend.

Fig. 6 : it would be better to use the same scale for longitude and altitude on panels (b) and (d).

–Response: The reason that we did not use the same scale for longitude and altitude in these two figures is due to the small aerosol structure at high altitudes seen in the CALIOP data. We thought that this is likely due to the N. American fires that were burning at the same time with the Greenland ones. This is visible from the AOD measurements at many of the Greenland stations where large increases in AOD were observed. In a previous comment for the AOD increase in the Narsarsuaq station at the beginning of September, we provided relevant footprint emission sensitivities and biomass burning emissions from CAMS_GFAS (see Figure R2). They explicitly show that the largest footprint was found in Canada in areas with large biomass burning emissions. However, since we do not study the impact of the N. American fires in detail, the sentences about the presence of N. American fire plumes at high altitudes in section 4.1 are rather speculative and we have removed them. We have also corrected Figure 6, as the reviewer suggested and for this, we acknowledge him.

Fig. 7c : Is the snow albedo reduction plotted for 31 August or for the full period ?

–Response: The snow albedo reduction due to BC deposition from the beginning of the fires until 31 August is plotted in Figure 7c (please see last paragraph of section 4). Legend has also been updated.

Table 1 : This table is not commented nor anlyzed in text. We can notice changes in the sources of RS data at different periods, which should be detailed in the methodology section.

–Response: In line 105 we state that we used different RS data to better delineate fire perimeters and define burn severity. Which day each RS tool was used is shown by pointing to Table 1. In addition, discussion of the results presented in Table 1 is presented in section 3.1 and 3.2.

Legrand, M., et al. (2016), Boreal ïnËĞA Ìĺre records in Northern Hemisphere ice cores: A review, Clim. Past, 12(10), 2033–2059. Polashenski, C. M., J. E. Dibb, M. G. Flanner, J. Y. Chen, Z. R. Courville, A. M. Lai, J. J. Schauer, M. M. Shafer, and M. Bergin (2015), Neither dust nor black carbon causing apparent albedo decline in Greenland's dry snow zone: Implications for MODIS C5 sur-facereïnËĞC ÌĄectance,Geophys.Res.Lett.,42,9319–9327,doi:10.1002/2015GL065912. Thomas, J. L., et al. (2017), Quantifying black carbon deposition over the Green- land ice sheet from forest fires in Canada, Geophys. Res. Lett., 44, 7965–7974, doi:10.1002/2017GL073701.

Technical comments : L350 : "adopted". Do you mean "adapted" ?

–Response: In this sentence we think that "adopted" fits better. We just used active fires from MODIS; we did not adapt anything.

L394 : Replace "for validating" by "to validate".

–Response: Corrected.

L485 : Replace "attenuation" by "attenuated"

–Response: Corrected.

L512 : Please write "Brent Holben" in two words.

–Response: Corrected.

REFERENCES

Holben, B. N., Eck, T. F., Slutsker, I., Smirnov, A., Sinyuk, A.,Schafer, J., Giles, D., and Dubovik O.: AERONET's Version 2.0 quality assurance criteria, http://aeronet.gsfc.nasa.gov/new_web/Documents/AERONETcriteria_final1.pdf, 2006.

Andrews, E., Ogren, J. A., Kinne, S., and Samset, B.: Comparison of AOD, AAOD and column single scattering albedo from AERONET retrievals and in situ profiling measurements, Atmos. Chem. Phys., 17, 6041-6072, https://doi.org/10.5194/acp-17-6041-2017, 2017.

Dubovik, O., Smirnov, A., Holben, B. N., King, M. D., Kaufman, Y. J., Eck, T. F., and Slutsker, I.: Accuracy assessment of aerosol optical properties retrieval from AERONET sun and sky radiance measurements, J. Geophys. Res., 105, 9791–9806, 2000.

Paugam, R., Wooster, M., Atherton, J., Freitas, S. R., Schultz, M. G., and Kaiser, J. W.: Development and optimization of a wildfire plume rise model based on remote sensing data inputs – Part 2, Atmos. Chem. Phys. Discuss., 15, 9815-9895, https://doi.org/10.5194/acpd-15-9815-2015, 2015.

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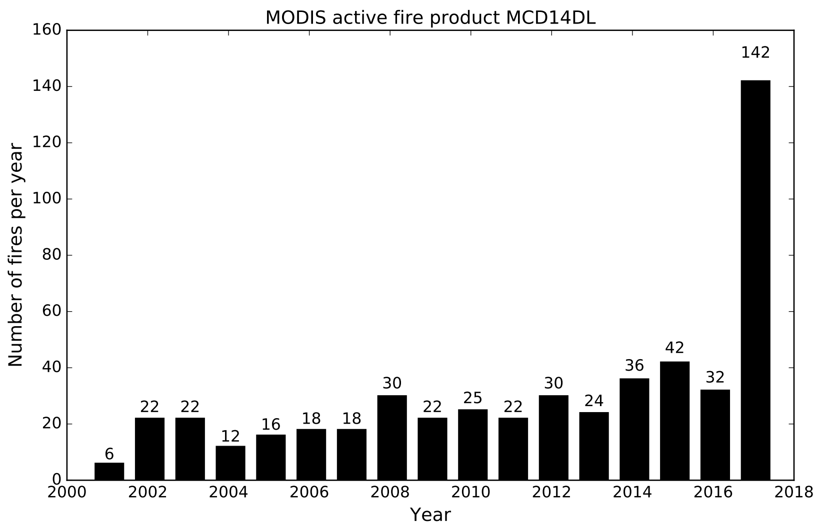

Fig. 1. Annual number of active fires over Greenland during the last 17 years as seen from NASA's MODIS satellite (product MSC14DL).

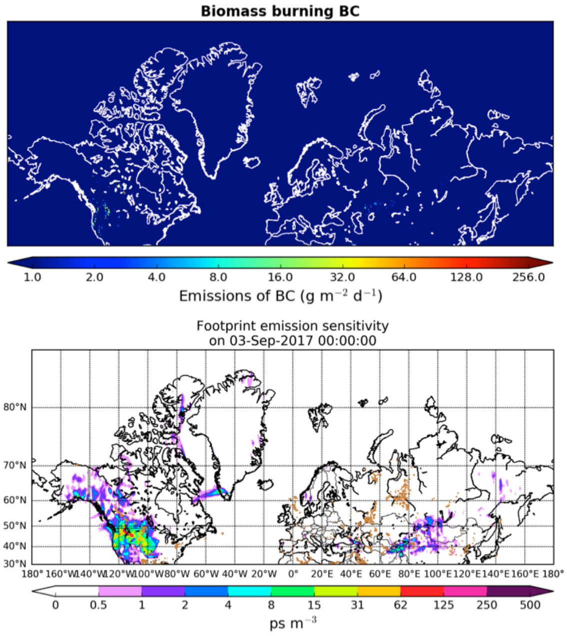

Fig. 2. Biomass burning emissions of BC from GFAS (upper panel) in the beginning of September and the footprint emission sensitivity from the Narsarsuaq station (bottom panel)