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Interactive comment on "Boreal snow cover variations induced by aerosol emissions in the middle of the 21st century" *by* M. Ménégoz et al.

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We would like to thank Referee #2 for its useful and thorough reviews. Our replies to its comments follow below. Note that our reply to comment 9/ appears in the supplementary material. Moreover, a revised version for our manuscript can be found in the supplementary material associated to our answers to Referee #1.

1. First major point:

The second referee is partially true when saying that our nudged experiments do not cancel completely the effects of the aerosols when they are in the atmosphere. Applying nudging to wind fields also partially nudge temperature, as these variables are physically linked in a hydrostatic model (e.g. Holton, 2004). This point explains that we

found small temperature differences between our nudged experiments (checked but not shown). However, as pointed out by Referee #2, such protocol does not avoid the aerosol diming induced by the aerosols when they are in the atmosphere. It does not cancel either a part of the warming induced by absorbing aerosols when they are in the atmosphere. Consequently it is not only the "snow darkening effect" associated to an increase of the ships traffic in the Arctic which does not impact the snow cover. It is the set of "snow darkening effect", "aerosol diming" and "atmospheric warming associated to absorbing aerosols" which does not impact directly the snow cover. This point does not change significantly our conclusion. However, we suggest to modify some statements in section 3 (Results, 4745, 4746) and in Section 5 (Conclusion, 4752,10-12 and 4753,1), as described below:

Section 3: "Considering an increase in aerosol emissions from Arctic ships or from biomass burning in our 2050-2060 nudged experiment induce MNDWS variations quasi equal to zero (see Figure 3c and 3d, showing respectively MNDWS differences S3_N-S2_N and S4_N-S2_N). It clearly means that the snow albedo changes associated with this possible increase in aerosol emission is negligible in comparison with the snow albedo changes induced today by the current aerosol emissions in the Northern Hemisphere. We have to keep in mind that these future sensitivity experiments were nudged, a process that limits atmospheric feedbacks: these experiments allow to quantify the changes of snow cover duration induced by the aerosol effects on snow albedo, strongly minimizing both the effect of aerosols when they are in the atmosphere and the temperature changes induced by the snow cover variations. The nudging was applied only to the horizontal wind, but temperature is also indirectly nudged as these two variables are quite dependent in a hydrostatic approximation model (e.g. Holton, 2004). Hence, the variations of temperature induced by atmospheric aerosols changes are partially cancelled in these nudged simulations. Nevertheless, the effect of atmospheric aerosol was not completely inactivated in these nudged simulations, as it induces also a modification of the radiative flux reaching the surface and a residual atmospheric warming."

Section 5: “We have to keep in mind that applying nudging techniques in these sensitivity experiments strongly limits all the possible atmospheric feedbacks, but does not cancel completely the diming happening in surface and the atmospheric warming due to atmospheric aerosols. As a consequence, atmospheric BC aerosols associated to these Arctic ships traffic have also no direct impact on the snow cover.” “This demonstrates that our biomass burning emission scenario does not induce a significant reduction of the snow cover, either via “snow darkening effects”, either via “aerosol diming”, and either via “atmospheric warming due to absorbing aerosols”.

2. Second major point:

The second referee pointed out the maybe most delicate issue in our paper asking for a physical explanation of the MNDWS change modelled in Quebec and Siberia without nudging in our 2050 scenarios with additional emissions. Two main points have to be considered in such analysis: * Firstly, the reduction of the MNDWS in some regions of Quebec and Northern Siberia is clearly explained by the ending of the snow season which occurs earlier during the spring. This has yet been explained in our paper (4746, 26 to 4747, 12). To certify that the MNDWS changes are small during the rest of the year, we checked the snow cover variables during the other seasons. In the text of our manuscript, we added in the beginning of the discussion the following statement: “(Note that the MNDWS changes are very low in our simulation during the other seasons, not shown)”. * Secondly, it is clear that the MNDWS change is more explained by atmospheric feedbacks, even if the aerosol – in the atmosphere or in the snow – trigger the process. In consequences, we added the following statement in our conclusion: “It appears very challenging to estimate accurately the snow cover changes induced by the possible changes in aerosol emissions in the Arctic and in the boreal region because of the complex processes linking aerosol forcing, atmosphere response and snow cover dynamics. Thanks to the comparison between our nudged and free-running simulations, we can assert that the decrease of MNDWS that we simulated in our scenario with increased ships traffic or enhanced fire emissions is

more explained by the atmospheric feedbacks than by the forcing directly generated by these aerosols, either in the atmosphere, either deposited on the snow. The aerosol forcing is the initiator of the modelled changes, but several feedbacks can be involved: As an example, a warming induced by absorbing aerosols located in the snow or in the atmosphere will imply a decrease of the snow cover duration. This one will then induce a decrease of the surface albedo, therefore an increase of the solar energy absorbed by the surface, and finally an increase of the surface temperature, itself impacting the atmospheric circulation and the precipitation pattern and phase. In particular, we found in our simulation a decrease of both snowfall and SWE in the area where we modelled a decrease of MNDWS. Such variations are associated to a warming of the low layers of the atmosphere in these regions (not shown). Further simulations could be performed to diagnose accurately the aerosol direct and indirect effects generated by the aerosol emissions scenarios that we suggest in this paper. Such protocol has yet been applied to estimate the radiative forcing of the present-day aerosol emissions (IPCC, 2007). However, if it is quite easy to diagnose the aerosols direct effect (e.g. Balkanski et al., 2010), it appears to be more challenging to analyze the indirect effects (e.g. Déandreis et al., 2012), as they are linked with clouds feedbacks in some complex way (Lohmann, 2005), and highly difficult to simulate with current climate models (Quaas et al., 2009). Anyway, we predict that the likely future aerosol emissions from ships traffic over the Arctic region or an increase in biomass burning will play a minor role in the reduction of continental snow cover area trough snow darkening direct effects at high Northern latitudes.”

Finally, we are in agreement with Referee #2 that it would be passionate to understand exactly which process drive the change of MNDWS in our simulation. As explained previously, this point is particularly delicate, and would necessitate including new developments in our model (in particular the diagnosis of the radiative forcing of the absorbing aerosols which are deposited into the snow), and to follow complex simulations protocol to diagnose all the direct and indirect aerosol effects (see Quaas et al., 2009, Déndréis et al., 2012). Such topics could be the purpose of further study. Nevertheless, we found relevant to analyze the aerosol - snow albedo interactions discussing the MNDWS changes. This method appeared particularly useful to reach the main conclusions of our paper.

3. First minor pointÂă: As recommended, we suggest explaining both in the abstract and in Section 2.2 the limits existing when using prescribed SST in the simulations: Abstract: These experiments do not take into account the climate response induced by the interactions between ocean and atmosphere as they were conducted with prescribed sea surface temperatures. Section 2.2: As for the two present-day simulations, using prescribed SST for these experiments cancel completely all possible feedbacks involving atmosphere-ocean interactions.

4. 4734,29: We corrected the sentence in the abstract:Âă"They are induced both by radiative forcings of the aerosols when they are in the snow and in the atmosphere, and by all the atmospheric feedbacks."

5. 4737,8: Radiative -> Representative

6. 4739, 21: As recommended by the two first referees, we completed the explanation dealing with the aerosol content in the snow. However, we did not want to describe this scheme in detail, as it was already done by Krinner et al. (2006), but we added in the new version of our manuscript the following statement: "If snowfall brings less than the maximum height of the surface layer, the new aerosol concentration of the surface layer is computed with the proportional contributions of the old aerosol concentration of the surface layer and those of the snowfall which reaches the surface layer (wet deposition). During melt or sublimation, snow mass is supposed to be lost from the surface layer. This one is therefore extended downwards to attain 8 mm SWE (if enough snow remains in the bottom layer). The aerosol mass corresponding to the lost snow height is added to those of the new surface layer. The timestep used to compute the snow aerosol content is the same as those applied to all the surface scheme, i.e. 30 min. More details about this snow scheme can be found in Krinner et al. (2006)."

7. 4740, 9: We add in the revised manuscript: “Snow grain size evolves pronostically as a function of snow age and temperature (Marshall and Oglesby, 1994), but unlike the aerosol content, it takes the same value in both snow layers.”

8. 4740, 14: As suggested, we added the following statement: "In future model developments, we hope to include a more accurate representation of the interaction between aerosols and snow grain. Flanner et al. (2012) showed that accounting for the internal mixing of BC within snow grains increases its radiative forcing by 40 to 85% compared with treatments of externally-mixed BC in snow. Therefore, the simplification applied in our study may potentially underestimate the BC effect on snow albedo."

9. The answer to this point can be found in the first supplement material

10. 4742, 9: This aspect has yet been pointed out by Referee #1. As explained in the response to this first referee, we suggest to include a more complete statement describing the fire scenario, saying that both the intensity of the fire and the length of the season are increased (inducing a total increase of more than 50% of the annual emissions): "Following Flannigan (2009a; 2009b), we consider an increase of 50% of BC and other aerosols emitted by fire during all the year. In addition, we consider also a 1-month extension of the fire season in the Northern hemisphere (starting 15 days prior and extending 15 days after the fire season of the present-day) : From January to June (resp. from August to December), monthly emissions are computed as the average between the emission of the current month and those of the following (resp. previous) month."

11. 4742,13: As explained in our paper (P. 4741), the present simulations were conducted with the same observed SST, and the 6 future simulations were performed with the same SST issued from a previous run using a coupled ocean-atmosphere model. In the revised manuscript, we suggest to explain more in detail the consequences using such a protocol: “S2, S3 and S4 experiments consist of a pair of 11-yr simulations, with initial conditions slightly modified in one of them, to be able to analyze 20 yr of

model output. Note that 10 yr would clearly be insufficient to make comparisons statistically robust, as the signal that we try to detect is quite small in comparison with the high natural variability of the atmosphere. We have also to keep in mind that the pairs of 11-yr simulations are not fully independent, as they were performed with the same SSTs. The variability simulated with ocean-atmosphere coupled models would clearly be higher, necessitating longer periods of simulations to characterize signals relatively lows."

12. 4743,7: Two reasons explain that the aerosol emissions integrated north of 30°N are slightly increased even if there is a deviation of the ships traffic in the Arctic: First, we integrated the emissions not over the whole planet, but only North of 30°N. Therefore, there is a decrease of the emissions occurring at lower latitudes than 30°N which is not taken into account in this sum of emissions. Second, our ships traffic scenario in the Arctic does not only consider the traffic increase associated to deviated routes, but also those induced by local transport, which is expected to take place in new industrialized areas. As pointed in the paper, Referee #2 can find all the details of such ships scenarios in the study of Corbett et al. (2010).

13. 4743, 17: We suggest adding in the paper the following statement: "We considered the surface to be snow covered when the snow mass averaged over one day exceeds 0.01 kg.m-^{2} (i.e. 0.01 mm. snow water equivalent)."

14. 4743, 17: As recommended, we changed the statement: "We computed the mean number of days per year with snow at the surface (MNDWS) in all of our simulations as an indicator of the effects of aerosols emissions on snow cover."

15. 4745, 15: "all of" has been removed.

16. 4747, 7: See response to second major point.

17. 4747, 12: We defined explicitly the spring season as "April-May-June".

18. 4748, 18: Statement grammatically corrected: "Considering BC deposition on

snow in present-day conditions (S1B-S1) induces only a small SWE decrease over large parts of Eurasia and Northern America ranging from 0 to 10 mm (Fig. 6b)."

19. 4749,19: "no changes in aerosol deposition" -> "no changes in spring aerosol deposition"

20. 4750, 8: Corrected (S1 instead of S1B).

21. 4752, 25: "2 weeks earlier" -> "2 weeks earlier and later".

22. Table 1: We specified that the nudging was only applied to horizontal wind in the description column.

23. Fig. 1: We chose to let the units in month-1 instead of year-1, in order to put the same units in Figure 1 and Figure 5. This way, it is easier for the reader to see that emissions and deposition have the same order of magnitude. We could not apply units in year-1, as deposition is only described for the spring season (tree months). Finally, it appears more coherent to let all the units in month-1, even if the total emissions are given in year-1 in the text.

24. Caption of Figure 2 corrected (it is S1 and not S1B simulations which has been used)

25. Fig 3a: Thanks a lot for this remark! We corrected in several places this error, replacing S1B-S1 with S1-S1B.

26. Graphs: We tried to apply the graphical method of the IPCC to represent more accurately on the same graphs the anomalies and the significance. This method is very useful, but is not so appropriate when a signal is significant over very small regions (ex. Fig. 4). We decided to keep the first method used in our submitted manuscript. However, in the revised version, when the signal is statistically significant over the whole snow covered areas, we indicated it in the Figure caption. As suggested we also ensure that the figure will appear as large as possible in the final version.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/6/C2960/2013/tcd-6-C2960-2013-supplement.pdf

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Interactive comment on The Cryosphere Discuss., 6, 4733, 2012.