Interactive comment on “Snow depth on Arctic sea ice from historical in situ data” by Elena V. Shalina and Stein Sandven

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The authors would like to thank the reviewer for his time and valuable comments. The corresponding changes and refinements have been made in the revised paper and are also summarized in our reply below. Authors’ responses are in blue. Reviewer’s comments are in black. When our manuscript is cited, it is shown in italics.

The study "Snow depth on Arctic sea ice from historical in situ data" evaluates observations of snow and sea ice surface properties from the Sever aircraft landings on Artic sea ice from the 60th through 80th of the 20st century. The data contains snow depth from surfaces representative of the area near the landing site as well as some information on the snow depth distribution, from which the authors deduce average snow depth. This information is used to construct a climatological snow depth map based on significantly improved observational density in the Russian part of the Arctic compared to the Warren climatology. However, this climatology is only valid for the month between March and May due to visibility constraints for the landings.

The necessity and value to document and utilize these extensive observational datasets from the past cannot be understated and the paper constitutes a valuable contribution to this effort. The paper is generally well written and adds a thorough analysis to the documentation of the methodology. There are however a few general minor points and specific comments where the analysis and the presentation of the results could be improved before publication:

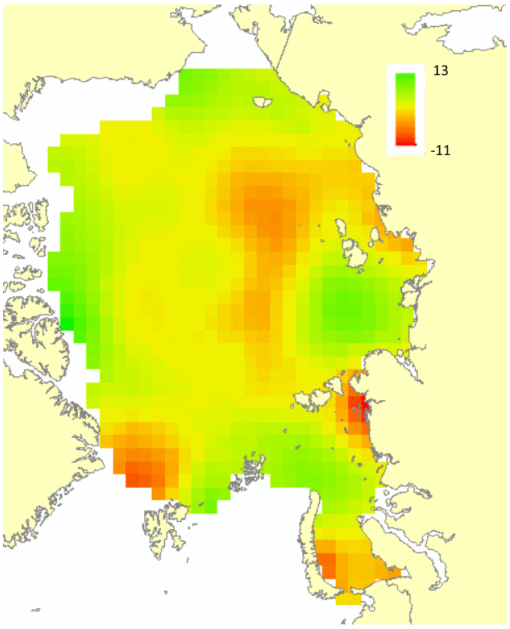
1) The authors provide a detailed climatology of average snow conditions but without a magnitude of the snow depth variability. It would be important to have this information as a measure the uncertainty of the climatology. Of course, variability can only be estimated in areas with repeated observations, but might be possible with pooling data on the Russian shelves.

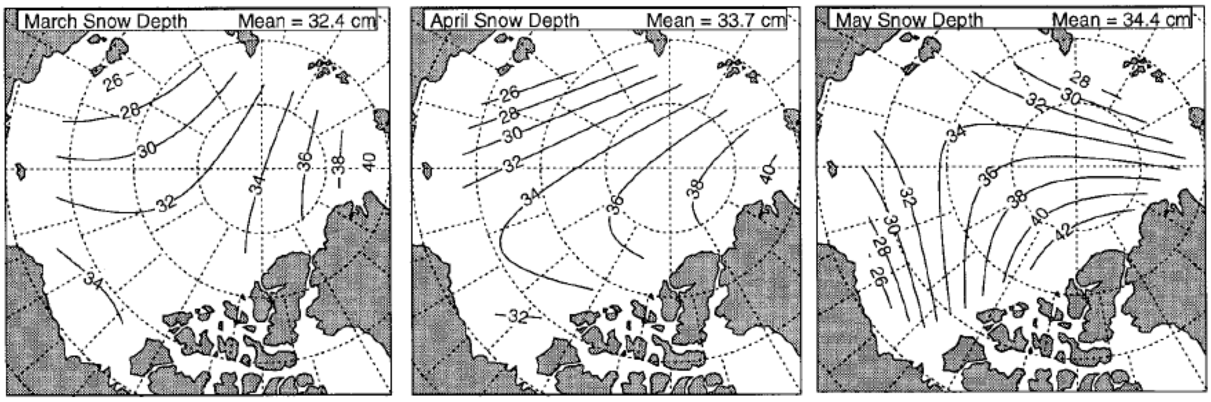
We calculated standard deviation of the data used for producing the new climatology. It is calculated as a weighted standard deviation from variances of the snow depth and the height of sastrugi with a weight of 0.35, which is an average portion of sastrugi area in the Arctic. It is included in the updated Fig. 11 (see figure below, on the 3-rd page). Certainly, it is only a part of the uncertainty of the new climatology, however it is difficult to evaluate errors from other sources. The height of snow attached to ice ridges was not included in the calculations because 1) the Sever measurements in the Western part of the Arctic Ocean are too scarce, and 2) there are no estimations of the area covered by such features from the Sever expeditions. The effect of not including that data results in some underestimation of the average snow depth. The underestimation is most important in the western Arctic, especially north of the Canadian Archipelago, where the highest concentration of the ridged ice is expected.

2) The authors also did not show the difference to the Warren climatology. The improvements on the Russian shelves are obvious, but it would be valuable to assess the impact of the localized nature of the NP observations compared to the regional coverage of the Sever program on the generation of climatologies in regions where the observations should be comparable.

Below you will find the difference between Warren climatology and the new one. It demonstrates the deficiencies of both approaches. On the one hand, it reveals artificiality of the smoothness of Warren's climatology - it is a consequence of estimating parameters through polynomial fitting in the areas where the values of those parameters change considerably. On the other hand, it shows that Sever expeditions did not provide enough data to get a smooth distribution in the central Arctic and to describe adequately areas near the Canadian coast. Thus we have unphysical smoothness of W99's data and unevenness of Sever data (caused by lack of data).

It is also worth to keep in mind that Warren's monthly climatology depends on the distribution of the available for that months NP measurements. Luck of measurements in some cases causes strange results: for example, according to W99 the snow depth in the area to the east of Greenland changed from 40 cm in March and April to 34 cm in May and in June it increased up to about 46 cm (!).





We included the averaged for the MAM months Warren's snow depth map in Fig. 11, together with our result. We hope it's enough to assess the difference. Please see below the updated Fig. 11.

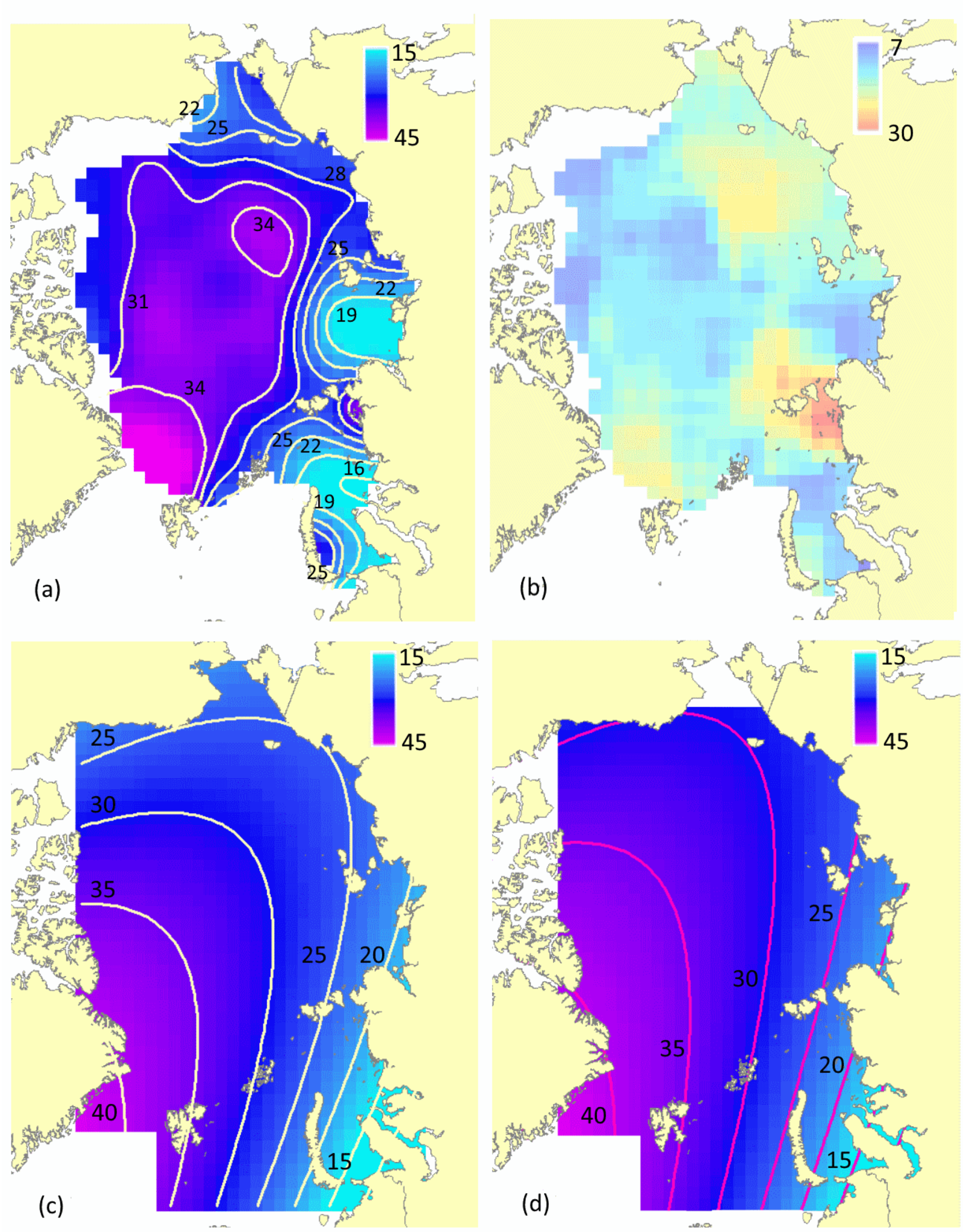


Figure 11. *Map of snow cover depth (in cm) on the sea ice in the MAM months in 1959-1988: a) gridded data with the grid cell 100x100 km and contour lines overlaid on it, b) standard deviation of the data used for gridding, c) map produced from the same data as (a), but using two-dimensional quadratic fit, d) Warren climatology averaged for the MAM months.*

3) As the authors state themselves, the comparison with modern data is difficult due to different methodology of point measurements and the surveys at landing sites. Therefore, the result are not very insightful, especially without a magnitude of interannual variability in the timeframe of the Sever program. I would therefore suggest reducing the space allocated in the manuscript for this comparison.

The authors think it is a valuable part of the paper because the measurements described have been taken in the central Arctic. (The field campaigns that we mention in the paper usually were carried out in the Beaufort Sea or close to Canada or Greenland - in the limited area that is not well presented in the Sever data.) Though buoy measurements do not cover long period of time, they nevertheless show the range of temporal variability of snow depth and even the range of spatial variability (in the case of AWI buoys). As to space used to describe and analyze buoy data, the authors cannot see how it can be reduced.

Specific comments:
- replace 'fastice' with 'fast ice' throughout the document
Done.

- P10L16: Specify section number that you mean with "later"
The rewritten sentence is:
The snow in the form of sastrugi, attached to hummocks and ice ridges is not described here, the relevant analysis will be presented in Sect. 4.2 and 4.3.

- P12L6ff: Did the authors exclude MY thicknesses in this regression, because these would not be "undeformed"?
We have included MY ice thickness in the updated version of the paper. It was not included in the discussed version because of differences in the process of snow accumulation on the FY and MY ice. In the case of FY ice it is more ... straightforward and the relation is supported by more data.

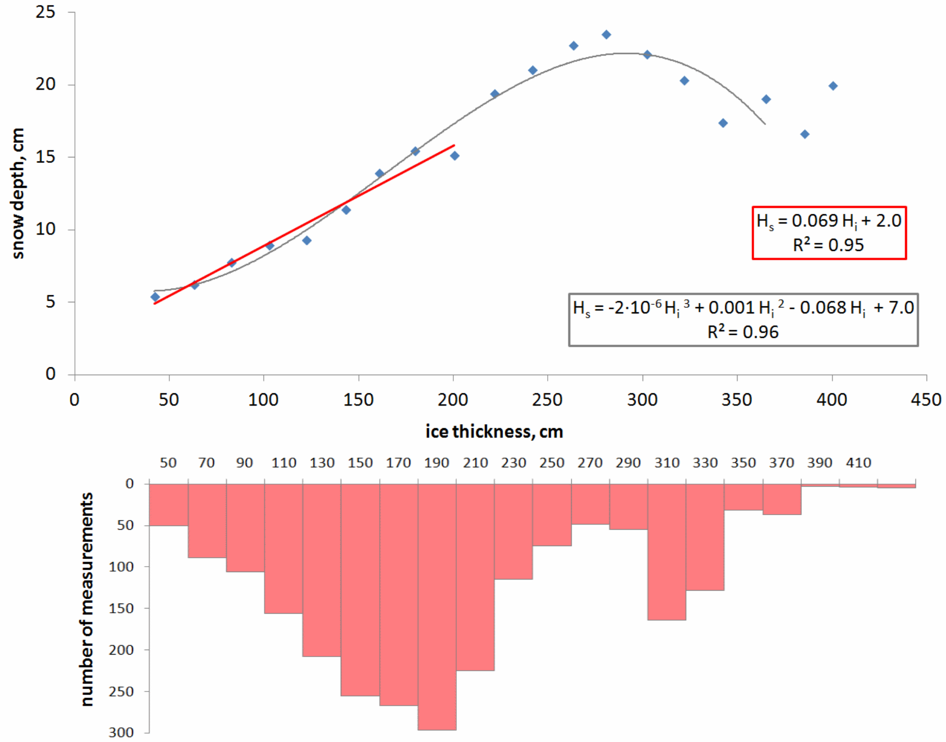


Figure 7. *The relation between the thickness of the undeformed ice and the depth of accumulated snow in the end of winter.*

- P16L23: Rephrase sentence: "In the Kara Sea, there was the second (?) after ..."
The rewritten sentence is the following:
In the Kara Sea, there was the highest number of measurements comparing to other seas that probably allowed to observe most cases of snow dune layouts and states.

- P20L6: Please provide the formula
The formula is provided and described:
In order to produce an integrated map that describe the average state of snow cover in the MAM months, the Sever and NP measurements have been combined by gridding all Sever data on snow depth on the level ice together with NP data. The height of sastrugi weighted in proportion to the sastrugi area was added for each Sever grid cell snow depth using the formula

$$H_{sev} = H_s + P_{sas}^{reg} \cdot H_{sas} ,$$

where H_s is the depth of snow measured on the level ice (described by data providers as the snow depth on the prevailing ice in the landing area), H_{sas} is the height of sastrugi, and P_{sas}^{reg} is the average portion of the ice surface covered by sastrugi in the regions of the snow measurement (see Table 3). In the *central Arctic, where the ice was mainly perennial at the time of measurements, only observations made on the MY ice during Sever expeditions have been included as was explained in Sect. 3. The height of snow attached to ice ridges was not included in the calculations because 1) the Sever measurements in the Western part of the Arctic Ocean are too scarce, and 2) there are no estimations of the area covered by such features from the Sever expeditions. The effect of not including that data results in some underestimation of the average snow depth. The SHEBA observations indicated that in April and May 1998 about 3.9% of the examined area was covered by deep snow (>80cm) associated with ice ridges (Sturm et al., 2002). The underestimation is most important in the western Arctic, especially north of the Canadian Archipelago, where the highest concentration of the ridged ice is expected (Bourke and McLaren, 1992, Makshtas et al., 2003, Shoutilin et al., 2005).*

- P20L6: Would it not be necessary to include the snow dunes in the estimation of average snow depth? Is there not information (ridge density) to do this?

We mention that we do not include snow dunes in the averaging in the undated text. We also give reasoning (which is absence of the ridge density in the area, as the referee rightly stated). It is a part of the paragraph shown above:

The height of snow attached to ice ridges was not included in the calculations because 1) the Sever measurements in the Western part of the Arctic Ocean are too scarce, and 2) there are no estimations of the area covered by such features from the Sever expeditions. The effect of not including that data results in some underestimation of the average snow depth.

- P20L15: Please provide coefficients of the quadratic fit

Coeff	value
H_0	35.05
1	-4.96E-06
2	-1.46E-06
3	-2.27E-12
4	2.91E-12
5	-1.16E-12

1-5: coefficients in the regression equation. Snow depth: $H_s = H_0 + C_1*x + C_2*y + C_3*x^2 + C_4*xy + C_5*y^2$.
Coordinates are in meters. Projection is North Pole Stereographic, datum WGS_1984, latitude of origin = 90.0, central meridian = 20.0.
In the text of the updated paper:

The two-dimensional quadratic fit has been calculated as
$H_s = H_0 + C_1 \cdot x + C_2 \cdot y + C_3 \cdot x^2 + C_4 \cdot xy + C_5 \cdot y^2$,
where $H_0 = 35.05$ *cm,* $C_1 = -4.69 \cdot 10^{-6}$, $C_2 = -1.46 \cdot 10^{-6}$, $C_3 = -2.27 \cdot 10^{-12}$, $C_4 = 2.91 \cdot 10^{-12}$, $C_5 = -1.16 \cdot 10^{-12}$, *and x and y are coordinates in the North-Pole Stereographic projection. Units of x and y are meters.*

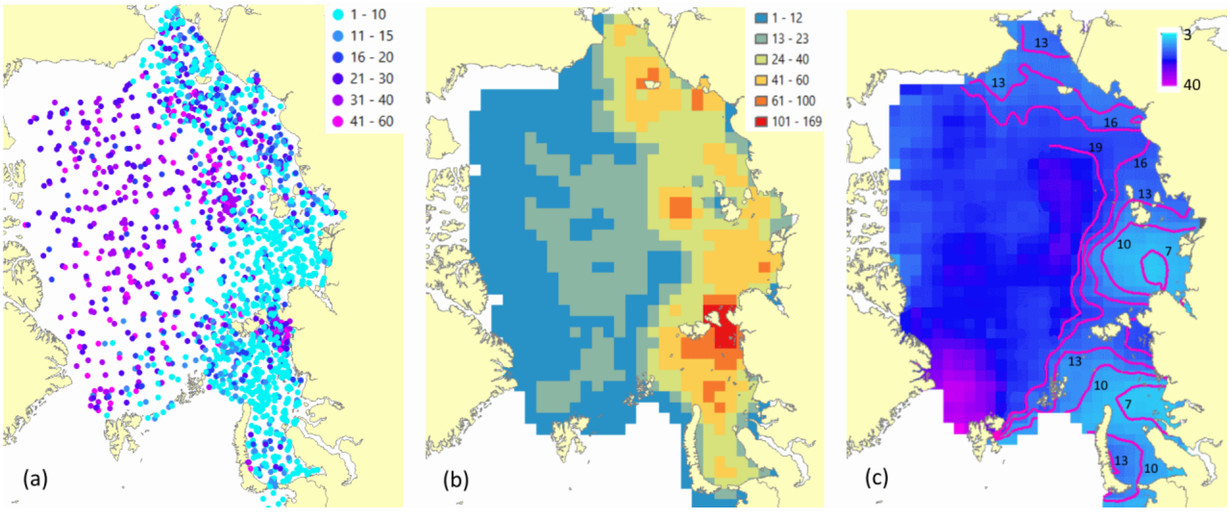
- P22L17: The authors correctly state that it is difficult to draw any conclusions from a direct comparison of modern buoy data and historical in-situ data. Consider to shorten section 4.6 and move the main message to the discussion/conclusions section.

In our view the section 4.6 is very short (it was much longer in one of our earlier versions), we do not see how it can be shorten.

Figures:

- Figure 5: Consider to replace the contour plot with a colour-coded plot in Figure 11

Please see the new Figure 5 below.



- Figure 10: Consider adding histograms for the three month. It is very difficult to make out any changes other than seemingly random snow redistribution.

Please see the updated Figure 10 below.

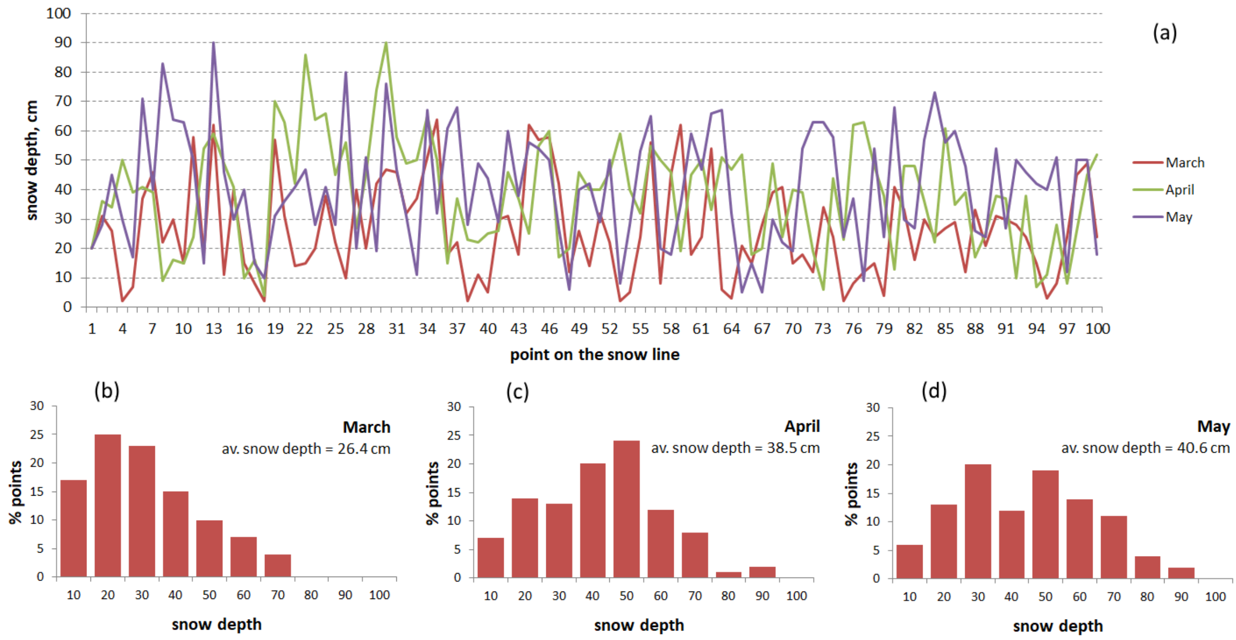


Figure 10. *(a) Snow line measurements made in 1969 in the MAM months during the work of NP16 drifting station. The length of snow line was 1 km. (b) - (d) Distributions of measured snow depths in March, April and May 1969.*

- Figure 11: Panels b and d are quite redundant. Consider showing W99 or difference to W99 instead

The updated Figure 11 is shown above. It was assembled differently, in accordance with the referee comments.

- Figure 11: The scale of the colorbars in panels c and d are slightly and unnecessary different

Now all color bars for the snow maps are the same (see Fig. 11 above).

- Figure 14: Should the standard deviation (std) not be shown in both directions from the different snow depth values

Figure 14 has been redone:

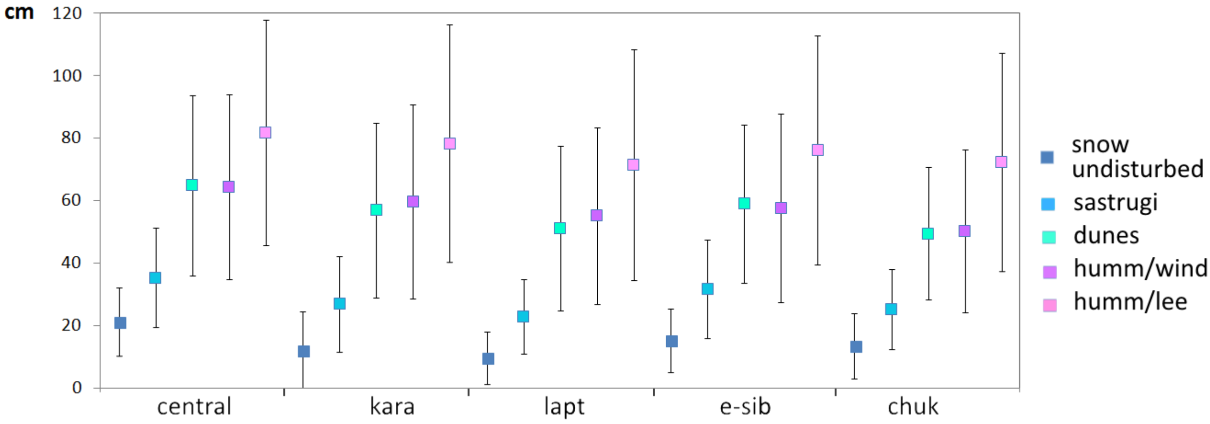


Figure *14. Sever snow depth observation statistics in the MAM months: depth of undisturbed snow on the level ice, snow depth of sastrugi, snow depth of dunes extending out from ice ridges, depth of snow on windward and leeward sides of the hummock and corresponding standard deviations. ...*

- Figure 14: Consider spelling out level ice snow depth (SD) as the acronym is ambiguous with standard deviation (std)

SD is replaced by "snow undisturbed" in the caption to this figure and throughout the paper it is replaced by H_s.

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2017-278, 2017.