Responses to the reviews, including relevant changes made in the manuscript, and a marked-up manuscript version

The authors would like to thank all referees for the review of the manuscript, valuable comments and the discussion involved in the process. 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 (black). When other papers are cites, they are in green.

Response to S. Hendricks (Referee)

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.

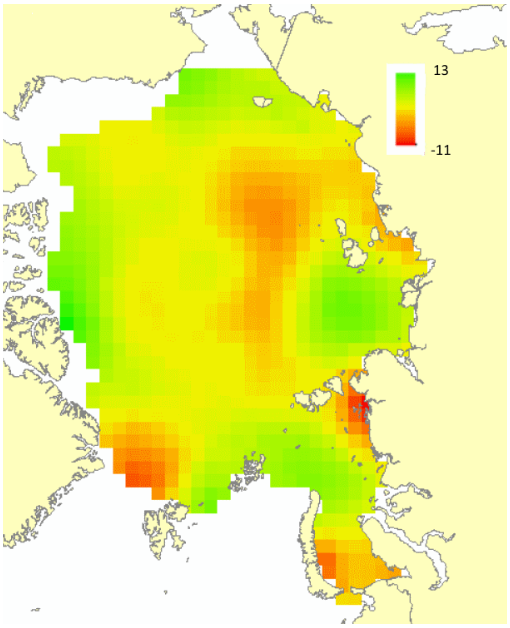
The necessity and value to document and utilize these extensive observational datasets from the past cannot be understated and the paper constitutes a valuable contribution to this effort. The paper is generally well written and adds a thorough analysis to the documentation of the methodology.
We thank the reviewer for his overall positive evaluation of our work and constructive comments, which were of great help in revising the manuscript. The point by point response to the comments is listed below.

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. First of all, the Sever data provided by NSIDC does not have any description of errors or uncertainty. Referring to our calculation, we have to note that the height of snow attached to ice ridges was not included in the calculation because the Sever measurements in the Western part of the Arctic Ocean are too scarce, and 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.

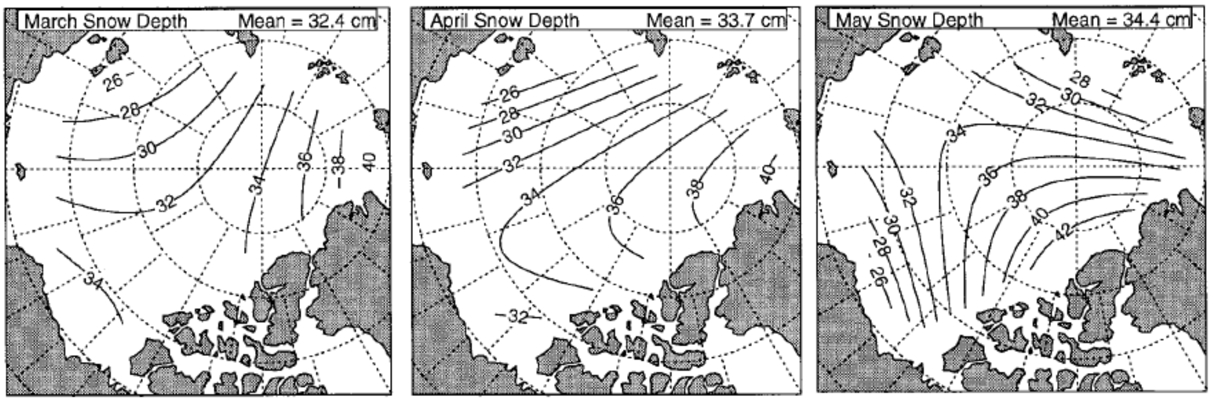
2) The authors also did not show the difference to the Warren climatology. The improvements on the Russian shelves are obvious, but it would be valuable to assess the impact of the localized nature of the NP observations compared to the regional coverage of the Sever program on the generation of climatologies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

Below please see the mapped difference between the Warren climatology (W99) 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 snow depth in the area near the Canadian coast. Thus we have unphysical smoothness of W99's data and unevenness of the Sever data in some regions.
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.



The difference between the Warren's snow depth and the new climatology based on Sever observations. The units are cm.

Below are W99 maps of snow depth for the MAM months.



Change: We included the averaged for the MAM months Warren's snow depth map in Fig. 11, together with our results: gridded map and quadratic feet. We hope it's enough to assess the difference. Please see the updated Fig. 11 below.

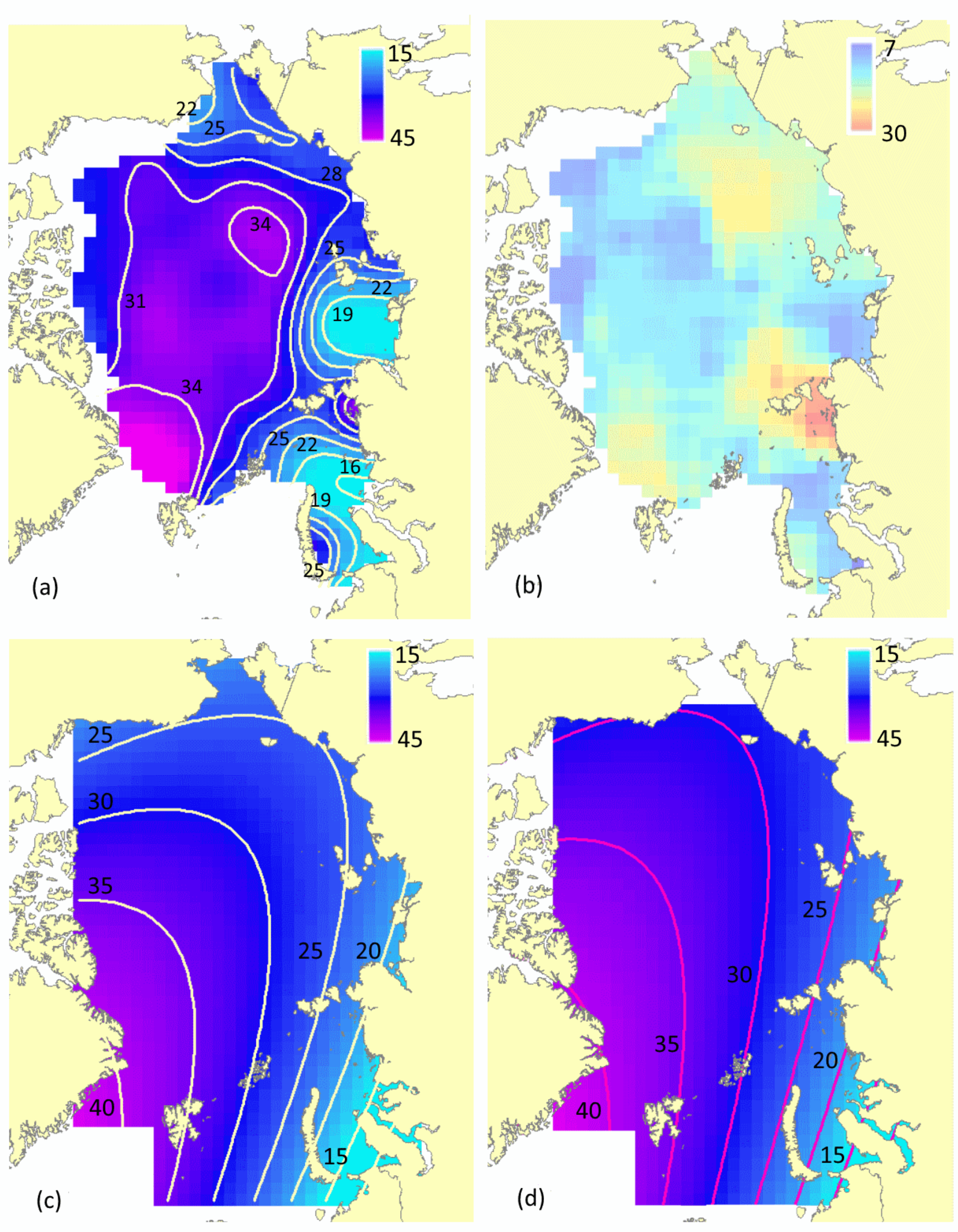


Figure 11. *Map of snow cover depth (in cm) on the sea ice in the MAM months in 1959-1988: a) gridded data with the grid cell 100x100 km and contour lines overlaid on it, b) standard deviation of the data used for gridding, c) map produced from the same data as (a), but using two-dimensional quadratic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

We think it is a valuable part of the paper because the measurements described have been taken in the central Arctic. (The field campaigns, where snow measurements were collected, that we mention in the paper usually were conducted in the Beaufort Sea or close to Canada or Greenland - in the limited area that is not well represented in 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 deployed in the same year and traveled through different paths in the central Arctic). 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
Changed.

- P10L16: Specify section number that you mean with "later"
We have clarified this sentence as follows:
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.

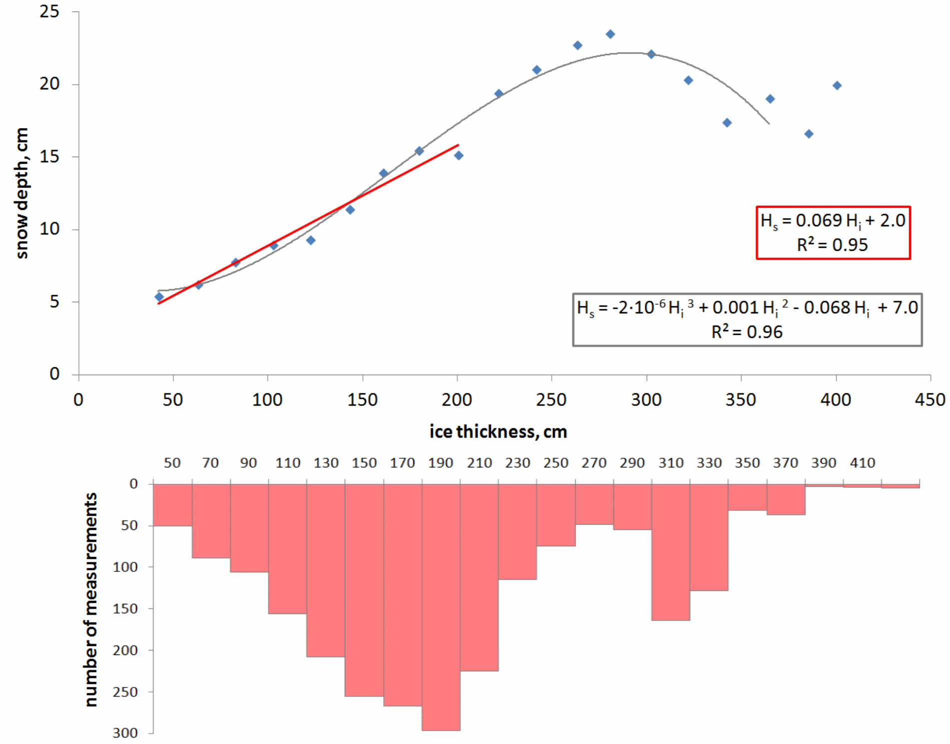


***Figure 7**. The relation between the thickness of the undeformed ice and the depth of accumulated snow in the end of winter.*

- P16L23: Rephrase sentence: "In the Kara Sea, there was the second (?) after ..."
We have clarified the sentence as follows:
In the Kara Sea, there was the highest number of measurements comparing to other seas that probably allowed observing 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 updated version of the paper. We also give reasoning (which is absence of information about 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

The coefficients have been calculated and provided 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.*

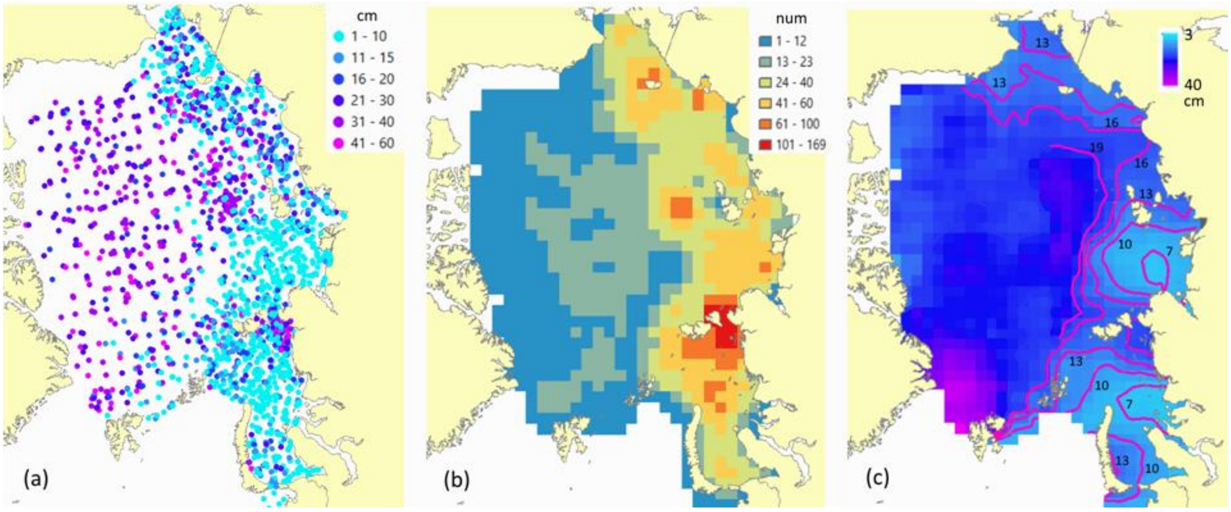
- P22L17: The authors correctly state that it is difficult to draw any conclusions from a direct comparison of modern buoy data and historical in-situ data. Consider to shorten section 4.6 and move the main message to the discussion/conclusions section.

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

The Figure has been changed. Please see the updated 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.

Thank you for this suggestion. Please see the updated Figure 10 below.

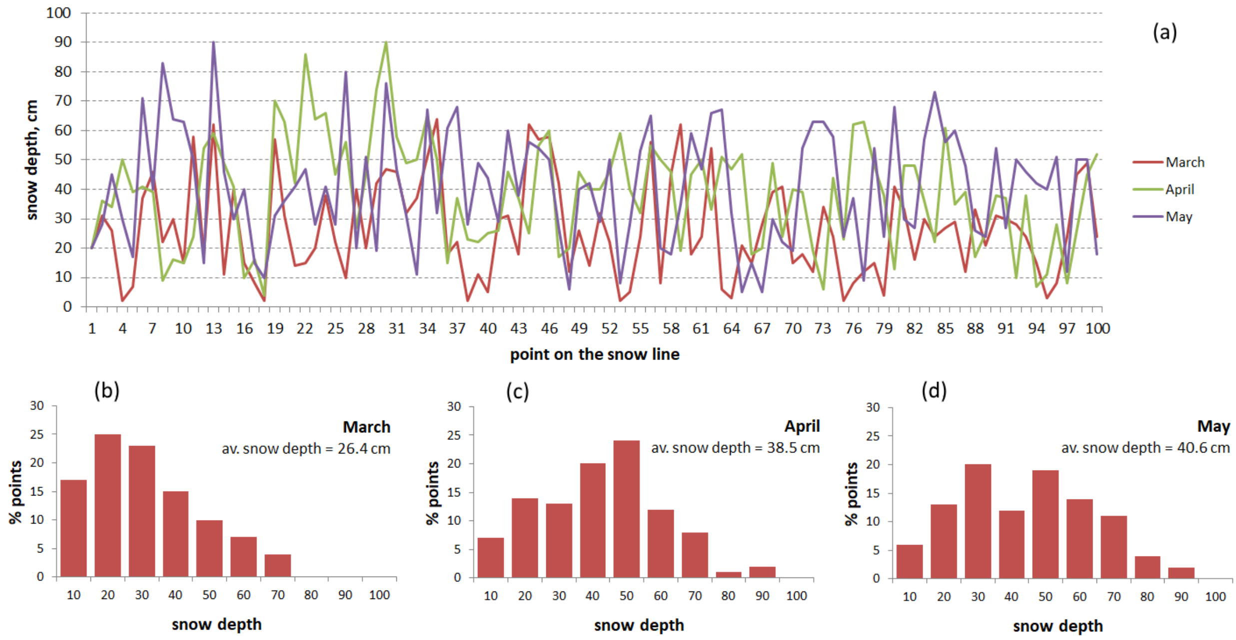


Figure 10. *(a) Snow line measurements made in 1969 in the MAM months during the work of NP16 drifting station. The length of snow line was 1 km. (b) - (d) Distributions of measured snow depths in March, April and May 1969.*

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

The updated Figure 11 is shown above (on the 3rd page of this document). 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 shown above).

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

Figure 14 has been changed:

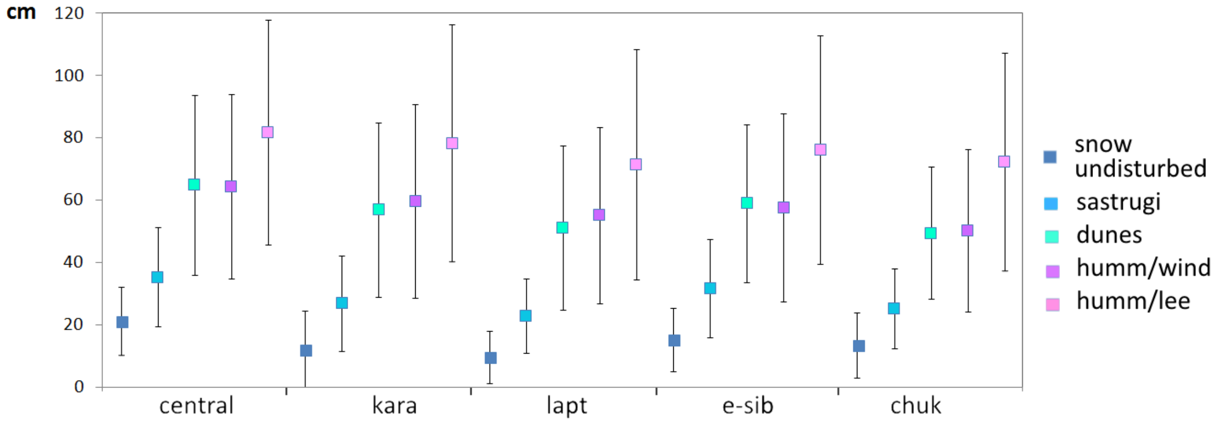


***Figure** 14. Sever snow depth observation statistics in the MAM months: depth of undisturbed snow on the level ice, snow depth of sastrugi, snow depth of dunes extending out from ice ridges, depth of snow on windward and leeward sides of the hummock and corresponding standard deviations. ...*

- 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 legend to this figure and throughout the paper it is replaced by H_s.

Response to Anonymous Referee #2

This paper incorporates a wealth of data measured from the Russian Sever expeditions to improve our historical knowledge of snow depth on sea ice, in particular in the marginal seas. The data used represent a massive effort spanning several decades and I am happy to see such a study done. The paper is thorough and generally well written, though I do have a few points I would like to see addressed.
Thank you for the kind feedback. The comments are addressed in the revised manuscript and the point by point response to comments is listed below.

An updated climatology to that produced by Warren et al., 1999 is one of the main results of the paper. However, in the Warren paper the Sever data were examined but not used for these reasons quoted in the paper:
"It is puzzling that the snow should be so much deeper around hummocks (45 cm) than behind ridges. The geographical patterns are also puzzling. Because some of the variation in average snow depth across the Arctic seen in Fig. 9 is probably due to different areal coverages of sastrugi, ridges, and hummocks, one would expect the geographical gradients of snow within these classifications to be smaller than those of Fig. 9. However, this is not the case. The snow depth behind ridges appears to decrease toward Canada, while the height of snow around hummocks increases. These strange patterns cause us to question the representativeness of the measurements made at the aircraft landing sites. We favor the measurements made at the NP stations that were conducted more systematically."
I believe these points need to be addressed directly by the authors prior to publication. In addition to the points raised in the Warren paper, I would like to see a better explanation for why the new climatology was produced using only the sastrugi and landing snow depth. The Warren climatology used data from snow lines which contains a mixture of snow depth from level ice as well as deformed ice, I'm not sure the snow depths produced from the Sever data would be equivalent. Perhaps a statistical analysis could be done to better relate data from the snow lines to that sampled in the Sever data.

In the Warren et al., 1999 (W99) paper the authors mention only data from Sever expeditions collected in April. However there were also quite sufficient number of measurements collected in March and May. In our study we have processed observations collected in March, April and May (the MAM months) that indicates enlarging the amount of processed data in our case. It is difficult to say in what proportion the amount of data has been enlarged in our case since in W99 there is no information about the number of processed Sever observations. The Sever data set from NSIDC (the one that we use) contains snow depth measurements distributed over the MAM months in the following proportion: 46% of all measurements were done in April, 27% in March and 27% in May. Thus, March and May observations make a substantial addition to data collected in April. It is stated in W99 that geographical sampling of landings was very uneven, however the distribution of sampling sites used in the analysis is not shown and it is not possible to compare it with what was available for the analysis in our case. The suspect that we and W99 have processed different data sets is confirmed by comparing W99's estimates of the average snow depths behind pressure ridges and near hummocks. W99 indicates the puzzling fact (cited above by the referee) that the estimates of the mentioned parameters are very different. In our case the parameters are comparable (see Table 4 and Fig. 9 of our paper) and their estimations are different from W99's: for instance, the average depth of snow in the dunes extending out from ice ridges from our calculations is 56.3 cm, which is much higher than shown in W99 22 cm. Decreasing snow depth behind ridges towards Canada mentioned by W99 (page 1826) is most probably caused by the deficiency of data in Sever dataset collected in the region north of the Canadian Archipelago (again: we don't know the distribution of the Sever observations processed by W99).

NP measurements were conducted on the MY ice and on the same floe throughout the life of the NP station. Snow line measurements catch very well natural variability of snow conditions on the spot, however, taking into account limited number of NP expeditions and unevenness of the distribution of their measurements in the Arctic, one may choose to find additional sources of data. Furthermore, one could also find strange geographical patterns in the W99 climatology: 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 to about 46 cm.

As to comparability of NP data and Sever data used in new climatology, there is no information about ice conditions, corresponded to NP snow line measurements, that complicates building a valid imitation. Ice conditions were not observed and did not described, so we do not know how much deformed ice affected the average snow depth measured along the lines. We see in W99: " The deep snow at about one-third of the way along the line in March **is probably** in a snow dune or in a drift near a pressure ridge" (Page 1817), which shows that there were no certainty about causes of snow depth variations among the authors. We built the new climatology basing on the snow depth measured in the vicinity of landing site + the height of sastrugi, weighted in proportion to the sastrugi area. The height of snow attached to ice ridges was not included into calculations because we do not have estimations of the area covered by such features from Sever expeditions. The effect of not including that data in the computation results in some underestimation of the average snow depth.

Change: In the updated paper the text related to including sastrugi and not including snow behind ice ridges has been rewritten :

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).

Specific comments

P1 L23-24: In comparing to the Warren climatology it is necessary to state what is being compared: level ice snow or does it mix in snow from deformed ice too?

This recommendation is about improving the text in the Abstract. We updated that text:

The main result of the study is a new snow depth climatology for the late winter using data from both the Sever expeditions and the North Pole drifting stations. The snow load on the ice observed by Sever expeditions has been described as a combination of the depth of undisturbed snow on the level ice and snow depth of sastrugi weighted in proportion to the sastrugi area. The height of snow accumulated near the ice ridges was not included in the calculations because there are no estimates of the area covered by those features from the Sever expeditions. The effect of not including that data can lead to some underestimation of the average snow depth.

All details are discussed in the paper.

P3 L1-2: The Warren climatology gives a representation of the mean error in the form of the interannual variability, so I don't think this statement is correct here. The climatology did not have adequate sampling to provide information on the errors due to spatial variability, so I suggest this statement be revised to reflect this aspect.

Thank you for correction. The text has been changed:

Though the interannual variability is estimated in W99, the spatial variability cannot be adequately described because of insufficient sampling.

P6 L20-34: In the W99 paper there is significant discussion about the representativeness of the sampling. While this section describes the sampling method, this important point has not been addressed. I note particular the analysis done with random samplings of the same population to see how the error for a given set of measurements changes with sample size and snow depth.

We have done the analysis of sampling statistics. It has been done on the measurements of the snow depth on the level ice. For every sea and for the central Arctic random samplings from all available observations have been generated. The subsets contained 50, 100, 150, 200, and more (where possible) observations with the increment 50. 100 subsets were generated for every number of subset population in every region. Average snow depth was calculated for every subset population. Variability between averages was estimated by standard deviation. (The central Arctic is the region with the highest mean snow depth; the Kara Sea is the region with the largest variability of the measured snow depth values).

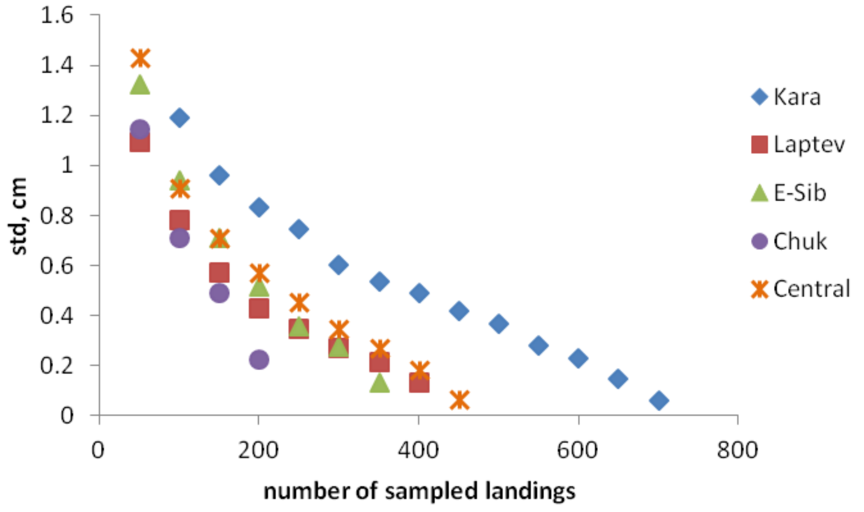


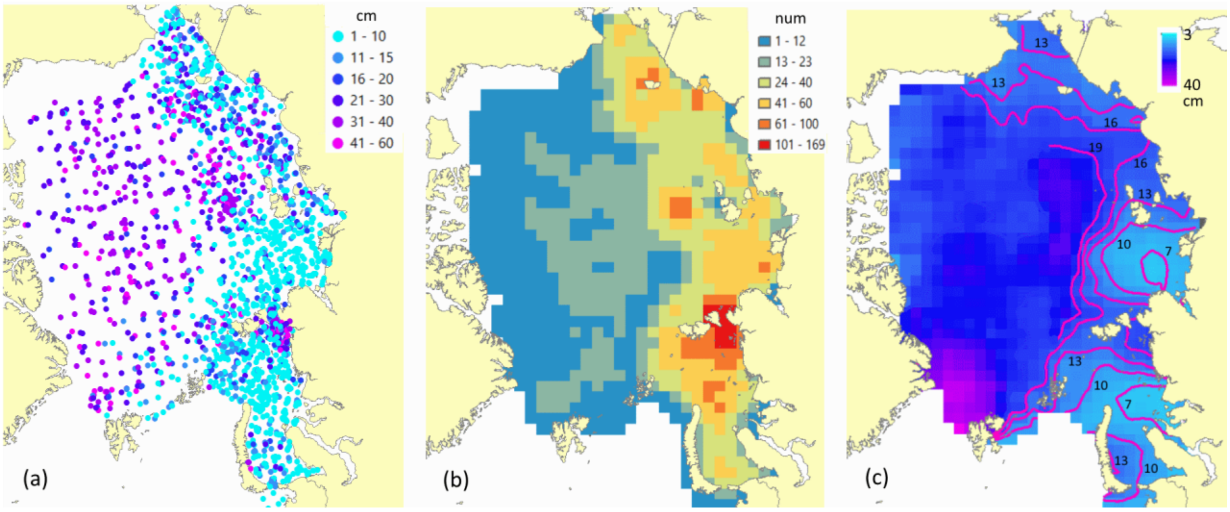
Figure caption: Standard deviation of the average of a set of snow depth measurements as a function of the number of landings used in the average computation. Measurements were randomly selected from the whole set of data for every region. The amount of randomly generated subsets was 100 for every number of sampled landings.

P7 L15-16: This statement seems like it belongs more in the caption for Figure 4.

This text describes what is shown in Fig.4. It is not the caption, just the text of the paper. The format that we have to follow does not differentiate between the text of the figure caption and the text of the paper.

Figure 5: It would be easier to read if the figure panel with snow depth had the units labeled.

We have changed the figure. We tried to take into account all comments regarding it. The revised figure is as follows:



P9 L19: I don't understand the last sentence, particularly with regard to the word "implying". Were all snow measurements used or was the MY subset used?

All measurements collected in the marginal seas were used:

"*By using the same ice thickness threshold in the marginal seas, the fraction of data coming from MY ice was 9% in the Kara Sea, 11% in the Laptev Sea, 34% in the East-Siberian Sea and 23% in the Chukchi Sea. These fractions of MY ice seem reliable, thus all snow observations in the marginal seas were used in the subsequent analysis*" (This section has been rewritten.)

P10 and throughout: "fastice" should be "fast ice"

Changed.

P13 L4-8: I'm confused by this section as the regression equation implies the sastrugi height is simply a constant 15.5 cm higher than the undisturbed snow.

This result is a surprise for us too. Please keep in mind that it's an average over the whole dataset.

P20 L5-8: Why were only the snow on the landing area and sastrugi data used and not any of the others described?

Snow attached to ice ridges and hummocks is not included into calculation because there is no data describing their density. The section has been changed in order to increase transparency:

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 region, to which snow measurement belongs (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).*

P20 L15-18: Although the detail of the data is lost in the quadratic fit, an advantage of the W99 climatology is that the fit coefficients were provided such that others could easily reproduce the climatology values. I suggest the authors put the fit coefficients in here.
The coefficients have been calculated and provided.
We have added the following text in 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.*
Projection (North Pole Stereographic, datum WGS_1984, latitude of origin = 90.0, central meridian = 20.0) is described in the text before this formula.

P25 L34-35: Petty et al., 2016 (The Cryosphere) found FY feature heights of around 1 m which might be a more thorough comparison to the Sever data.
In Petty et al., 2016, the authors derive information regarding the heights of the sea ice topographic features using the elevation threshold of 20 cm. Though the snow elevations including sastrugi have to be captured by methodology, it is difficult to identify them and separate from the ice features.

Response to Anonymous Referee #3

The manuscript presents an analysis on the snow data collected during the Sever expeditions with the objective of producing an improved climatology over the historical climatology by Warren et al., 1999. The analysis provides useful statistics on the sampling scheme from the Sever expedition, and demonstrates relationships between snow depth and morphological features. However, there are critical limitations to the Sever snow data set, as addressed in Warren et al., 1999 (pages 1825-1827). These limitations were considered too biased to incorporate into the historical climatology.
The manuscript's main conclusions overlook these limitations and over-interpret how representative the Sever data set is.

In the Warren et al., 1999 (W99) paper the authors mention data from Sever expeditions collected in April. However there were also quite sufficient number of measurements collected in March and May. In our paper we have processed observations collected in March, April and May (the MAM months) that already indicates enlarging the amount of processed data in our case. It is difficult to say in what proportion the amount of data has been enlarged in our case since in W99 there is no information about the number of processed observations. The Sever data set from NSIDC (that we use) contains snow depth measurements distributed over the MAM months in the following proportion: 46% of all measurements were done in April, 27% in March and 27% in May. Thus, March and May observations make a substantial addition to the data collected in April. It is stated in W99 that geographical sampling was very uneven, however the distribution of sampling sites used in the analysis is not shown and it is not possible to compare it with what was available for the analysis in our case. Contrarily to W99, we openly show the distribution of sampling sites and the number of processed observations. The suspect that we and W99 have processed different data sets is confirmed by comparing W99's estimates of the average snow depths behind pressure ridges and near hummocks. W99 indicates the "puzzling" (page 1826) fact that the estimates of the mentioned parameters are very different. In our case the parameters are comparable (see Table 4 and Fig. 9 of the paper) and their estimations are different from W99's. Decreasing snow depth behind ridges towards Canada mentioned by W99 (page 1826) is very probably caused by the deficiency of data in the region close to Canada coast that prevented adequate analysis and interpretation of the results.

Sever measurements were dependent on the availability of a landing spot. Landings were conducted in the areas where a proper runway was available. It might make an impression that the measurements were heavily biased to the level FY ice, however it was not so. As mentioned in the paper, the difference between the thickness of the runway ice and the ice of the area where landing measurements were conducted was in some cases about 300 cm and on the whole 46% of the measurements were conducted on the ice with the ice thickness larger than the ice thickness of the runway. In April about 50% of all measurements were made on the ice with the thickness greater than 200 cm. Collected measurements of snow related to ice ridges and hummocks confirm that deformed ice was visited and surveyed, Fig. 3 shows the density of corresponded observations.

Comparing Sever data with NP data we would like to mention the following points. Snow observations in the MAM months available from the Sever expeditions were done at more than 2330 landings (P7, L30). The number of monthly averaged snow depths from NP stations for the same months was 143 and all data were collected on the MY ice. ("Only 499 snow lines were measured over the whole period of NP expeditions" - W99, page 1820). Sever expeditions collected data on both types of ice (FY and MY). Data collected in the marginal seas is certainly the main benefit that we can gain from Sever expeditions observations. In the central Arctic the measurements were less dense comparing to other regions and since visited ice in the central

Arctic was quite diverse (at least from the point of view of its thickness) those measurements provide inhomogeneous picture of the snow depth that is reflected in the final map (P.23, Fig.11). NP measurements being "conducted more systematically" (Page 1826, W99) are obviously biased to the thick ice and to the specific ice conditions that were to be met when the station was established. Additionally, snow depth observations on every NP station were conducted over the same line on the same floe during the station lifetime that also limits representativeness of NP measurements. Thus, we think that Sever measurements bring us one step closer to better understanding the distribution of snow on the sea ice in the Arctic. Combining NP and Sever observations in the central Arctic, we believe that we merge data that complement each other and therefore we build the best possible picture of the snow on the Arctic sea ice in 1970-80s.

More descriptions are needed on the assumptions made in the methodology and approach in the statistical analyses in consideration of these limitations. Please find specific comments below that I hope the authors will find useful:

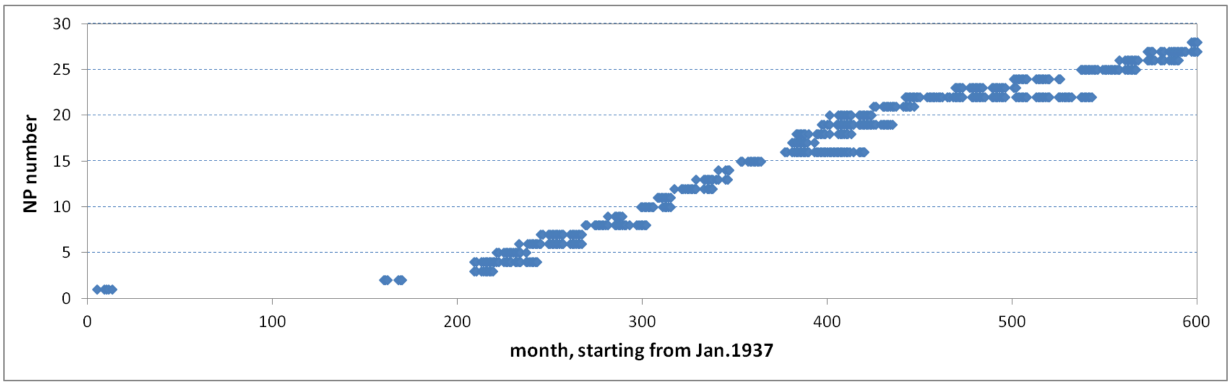
- In general, there's a lack of references throughout the manuscript; more references would help bolster the explanations of snow processes and interpretation of the results.
Which specific references does the referee have in mind? Please give us concrete references and we will happily mention them.

Page 2, Lines 15-30+. There have been numerous campaigns that have sampled snow on sea ice outside of the list presented here.
We have change the section including more references :
Valuable data on snow properties has also been collected from other expeditions, buoy measurements, ice camps and validation experiments in specific areas of the Arctic. In situ snow depth measurements has been carried out in spring time in the Beaufort Sea, Elson Lagoon and Chukchi Sea (Sturm et al., 2002, Sturm et al., 2006, Markus et al., 2006, Newman et al., 2012, Nghiem et al, 2013, Webster et al, 2014), in the Canadian waters between islands (Iacozza and Barber, 1999, King et al., 2015) and near the coast of northern Greenland (Farrel et al., 2012, King et al., 2015). With the aim to describe spatial distribution of snow on sea ice as a function of ice type, field experiments SIMMS'95 and C-ICE'96 in the Canadian Arctic have been conducted (Iacozza and Barber, 1999). Observations were made at the sites covered with only one sea ice type and snow topography on a given type of ice was described using variogram modelling. In 1997-98, extensive snow depth measurements have been made during SHEBA (Sturm et al., 2002). One of the objectives was to record temporal evolution of snow depth over the year, to evaluate its spatial variability (as broad as conditions of the experiment allowed), and to estimate the freshwater amount contained in the snow cover. Changes of snow depth connected with ice type and the level of deformation were also studied under SHEBA. Another expedition, the AMSR-Ice03 validation campaign carried out in March 2003 offshore of Barrow collected snow data for comparison with satellite products and also for analysis of snow depth on the sea ice of different age and different roughness (Sturm et al., 2006, Markus et al, 2006). During the Norwegian Young Sea ICE (N- ICE2015) campaign, snow depth was measured on the sea ice north of Svalbard (Gallet et al., 2017, Merkouriadi et al., 2017). In recent years a series of IceBridge validation/calibration campaigns have been conducted including in situ snow measurements on several ice types: undeformed level first-year (FY) ice, multiyear (MY) ice, and heavily deformed pressure ridges. Results have been published from studies near Greenland in April 2009 where measurements collected at the Danish GreenArc sea ice camp (Farrell et al., 2012), from surveys in the Beaufort Sea in March 2011 (Gardner et al., 2012; Newman et al.,

2014), from measurements taken in March 2012 during BROMEX field campaign (Webster et al., 2014) and in March-April 2014 in the Canadian Arctic Archipelago waters close to Eureka and in the Lincoln Sea near the northern coast of Greenland (King et al., 2015). Assessment of five snow depth retrieval algorithms that differently process IceBridge snow radar data has been made through comparison with field measurements from two ground-based campaigns, 2012 BROMEX near Barrow, Alaska, and 2014 Eureka, near the research base with the same name in Canada (Kwok et al., 2017).

Please give us concrete references to add if something important is missing.

Page 3, Line 1. Figure 1 in Warren et al., 1999 shows that more than two stations were regularly present in a given year.
In W99, Page 1814, in the Abstract, then on the Page 1820 (thrice), it is mentioned that "typically (usually) only two stations were operating at any time/ in any particular year". The next figure, produced by co-authors confirms that. Points on the graph correspond to months when snow line measurements were conducted in 1937-1987. The data used here are the NP measurements provided by V.Radionov.



In the period from Nov.1968 to Dec.1971 there were 3 and even 4 stations conducting snow measurements in the Arctic, but that was a very short period.

Page 3, Line 2. The instrumental errors were likely quite small. What do the authors mean here exactly?
The authors did not mean instrumental errors. We rephrased the sentence as following:
Though the interannual variability is estimated in W99, the spatial variability cannot be adequately described because of insufficient sampling

Page 6, Lines 6-7. Snow lines were selected on a flat ice surface is contradictory to the description in Radionov et al., 1997 and Warren et al., 1999.
"*The snow line was selected on a flat ice surface with no human objects or ice hummocks that could influence the snow depth (Colony et al, 1998*)."
Selection of snow lines is not described in Radionov et al., 1997 and Warren et al., 1999 explicitly. Only Colony et al., 1998 describes the ice surface where the line was selected (see citations).
It is also worth to notice that in W99 it is written that " this dataset is described by Colony et al. (1998)".
Colony et al., 1998: " Snow-line measurements of the snow-cover characteristics have been carried out since 1954. As a rule, the investigations were conducted once per month and sometimes once per 10-day period. The sites of the snow-line measurements were chosen away from the ice station. **Sites were selected on a flat ice surface and located clear of any**

constructions and ice hummocks. The same snow line was used for these measurements during the entire period of station operations."

<u>Warren et al., 1999</u>: " The direction of the **snow line was chosen randomly** when a station was established, but once chosen, subsequent measurements were made along that same line for the lifetime of the station. (Page 1816) ... *Later in the text*: When available, we use measurements on the snow lines in preference to those at the stakes, for two reasons: 1) The snow lines cover a long enough track to obtain a representative distribution of snow depths, passing through sastrugi, snow dunes, and pressure ridges as well as level snow." (Page 1817) *and* "The deep snow at about one-third of the way along the line in March **is probably** in a snow dune or in a drift near a pressure ridge." (Page 1817)

The remark "probably" shows that ice conditions corresponded to measured snow depths were not known. In our paper we mention that point (P.20, L.22)

<u>Radionov et al., 1997</u>: "To determine the snow depth and density as well as the water equivalent of the snow in the areas adjacent to the station, snow measurements were carried out along lines 1000 m in length established outside the boundaries of the station. **The orientation of a line could be set as desired relative to the structures at the station**, but once established, the lines were not changed during the operation period of the station. " (Page 2-1).

We interpreted both Colony and Warren as following: the line was chosen on a flat ice surface, but later due to several natural processes ridges appeared.

Page 6, Line 20. Please provide information on the spatial domain in which the 10-20 random snow thickness measurements were made.

There is no information about that in the description of data.

Data description (from http://nsidc.org/data/g02140#title8) :

Before an ice landing, a characteristic site of ice- and snow-parameter variation was selected. Ice thickness and snow depth were evaluated at different locations on first-year, as well as multiyear ice...

Representative areas for measuring snow parameters were chosen from the air. After landing, snow depth was measured at 10-20 random points and on characteristic forms of ice surface terrain (including level ice, frozen melt ponds, and ridges). Snow depth on level first-year and, whenever possible, on multiyear ice was measured at 3-5 points on the runway. For snow cover more than 10 cm deep, at least 10 measurements were made over the entire ice floe, as well as on adjacent floes. Snow depth in 2-3 snow-covered ridges was measured on both windward and lee sides using a measuring pole at 10-20 points. The area covered by sastrugi was estimated from the air. After landing, the airborne observation data were checked, and other measurements made. Lengths and depths (at their mid-lengths) of snow dunes stretching from ice ridges at various angles were measured at 3-5 sites during every landing (Romanov 1995).

Page 6, Lines 23-24. This indicates that the sampling was biased towards level first year sea ice, which is one reason to question how representative the Sever data set is.

The next sentence (next to the sentence mentioned by referee) in the paper just says that the conditions around the landing place could be quite different from the conditions that characterize the runway: " *the difference between the ice thickness of the runway and of the area where other measurements were conducted was in some cases about 300 cm*"

We can add that, for example, in April about 50% of all measurements were done on the ice with the thickness greater than 200 cm; 46% of all measurements were conducted on the ice with the ice thickness different (larger) than the ice thickness of the runway.

Page 6, Lines 27-28. Does the 10 cm threshold for sample size introduce an additional bias to the data set?

In the Sever data description (see the data description above) the situation when snow thickness was more than 10 cm is specifically mentioned, however it does not mean they did not measure smaller snow depths during Sever expeditions. In the data set there are a lot of measurements showing snow thickness smaller than 10 cm (see Fig. 4).

In order to make the matter more clear we have added some clarifications in the description of data:
The runway was chosen on flat ice that was most probably first year ice, but could also be multiyear ice. Meanwhile, the ice conditions around landing track were usually different from that on the runway: the difference between the ice thickness of the runway and of the area where other 25 measurements were conducted was in some cases about 300 cm. In the description of data the ice in the area around runway is called "prevailing ice of the landing area ". Later in the paper we use definition "undeformed ice" as a substitute for "prevailing ice of landing area", since snow cover associated with ice features caused by ice deformation like ice ridges and hummocks is described separately. After landing, snow depth was measured at 10-20 random points on prevailing ice of the landing area and on ice surface with distinctive features. For snow depth of more than 10 cm, at least 10 measurements were conducted over the entire ice floe, as well as on adjacent floes. How many measurements were made in case when snow depth was lower than 10 cm is not indicated in the description of data. The depth of snow dunes stretching from ice ridges and depth of snow on hummocks were measured using the following steps. The snow depth on 2 or 3 snow-covered hummocks was measured on both windward and lee sides at 10-20 points. The depth of snow dunes stretching from ice ridges were measured at 3-5 sites at their mid-length. The height of sastrugi on the undeformed ice was measured at several points. Note that all types of snow dunes formed on a flat ice surface by wind were referred to as sastrugi in Sever expeditions' data set. The averaged measurements of the mentioned parameters were reported in the documents from each expedition.

Figure 4. What is meant by the prevailing landing area ice? Are these measurements from the runway or surrounding sea ice? Do these data also include sastrugi and ridge measurements?
The combination of words "prevailing landing area ice" was used in the description of data (by data providers). That's why we use it too. It is surrounding undeformed ice, not the runway. In the paper, we use definition "undeformed ice" as a substitute. In cases when there were ice features like ridges and hummocks around, snow measurements were made too and depth of snow associated with those features was reported separately. Sastrugi (formed on the flat ice surface due to wind action) were measured and reported separately. See updated text *in Italic* above.
In the discussed version of the paper Figure 4 is mentioned in the sentence (P.7, L.14-15):
Data on the depth of <u>undisturbed snow</u> measured on the prevailing type of ice in the landing area from all Sever expeditions landings over the period from 1959 to 1988 is presented in Fig. 4.

Page 9, Lines 8-9. How was the 2.0 m threshold chosen, and how sensitive are the results to this threshold?
In the "WMO Sea-Ice Nomenclature. WMO - No.259. Volume 1 – Terminology and Codes" FY ice is described as "Sea ice of not more than one winter's growth, developing from *young ice*; thickness 30 cm - 2 m. May be subdivided into *thin first-year ice/white ice, medium first-year ice* and *thick first-year ice*."
In order to make the matter more clear we rewrote the paragraph on P.9, L. 8-14:
In the analysis it was useful to discriminate observations from FY and MY ice because MY ice as a platform to accumulate snow is different from FY ice. Firstly, MY ice exists from the very beginning of the fall and thus is able to catch the earliest falling snow. Secondly, the topography of MY ice is different from that of FY ice, being more irregular, that influences redistribution of

snow. We separate observations from FY and MY ice by using an ice thickness threshold, since ice thickness was measured at every landing. The threshold was chosen to 2.0 m, implying that ice thinner than 2 m is defined as FY ice and ice thicker than 2 m is defined as MY ice (WMO Sea-Ice Nomenclature). In the decades of the Sever expeditions, MY ice dominated in the central Arctic, the fraction of MY ice being close to 100% in 60s-80s. Using the 2 m threshold, it was found that 78% of Sever observations from the central Arctic were conducted on the MY ice and 22% on the FY ice. The sampling made by the Sever expeditions was probably biased towards level ice. In order to derive maximally representative data set for the central Arctic, we decided to use only MY-based measurements for that area. Supposing that NP and Sever observations complement each other we merged Sever snow depth observations from MY ice with NP data to produce snow depth climatology for the central Arctic.
We understand that the threshold 2 m does not work in all cases, however we think its use will separate most of FY and MY ice correctly.

Page 9, Lines 13-14. It's not clear why only multiyear sea ice observations were included in the analysis here. Please provide more explanation on this decision, and whether it is a valid assumption for creating an historical climatology for the Sever region.
The text has been changed (it is also shown above) with the intention to clarify the raised issue :
In the analysis it was useful to discriminate observations from FY and MY ice because MY ice as a platform to accumulate snow is different from FY ice. Firstly, MY ice exists from the very beginning of the fall and thus is able to catch the earliest falling snow. Secondly, the topography of MY ice is different from that of FY ice, being more irregular. We separate observations from FY and MY ice by using an ice thickness threshold, since ice thickness was measured at every landing. The threshold was chosen to 2.0 m, implying that ice thinner than 2 m is defined as FY ice and ice thicker than 2 m is defined as MY ice (WMO Sea-Ice Nomenclature). In the decades of the Sever expeditions, MY ice dominated in the central Arctic, the fraction of MY ice being close to 100% in 60s-80s. Using the 2 m threshold, it was found that 78% of Sever observations from the central Arctic were conducted on the MY ice and 22% on the FY ice. The sampling made by the Sever expeditions was probably biased towards level ice. In order to derive maximally representative data set for the central Arctic, we decided to use only MY-based measurements for that area. Supposing that NP and Sever observations complement each other we merged Sever snow depth observations from MY ice with NP data to produce snow depth climatology for the central Arctic.

Page 11, Line 3. Which measurements (ridge, sastrugi) are included in the average snow depth?
The average snow depth discussed here is the average snow depth shown in Table 2 (P.10, just before the text). In the Table header the parameters is described: "*Snow depth (H_s) of undisturbed snow cover on level ice in the landing areas in different parts of the Arctic Ocean for the months March, April and May*."
Snow attached to the ice ridges and sastrugi are not included in these measurements. Those observations are described later in the paper.

Page 11, Lines 16-17. This statement needs support (quantitative results) from a statistical analysis.
We removed the mentioned statement from the place where it was.

Page 12, Lines 6-8. It would be helpful to state that this relationship is dependent on the season, spatial domain, and sea ice type.
The part of the paper related to the mentioned relationship has been changed:
The start time of snow accumulation is one of the major factors determining the snow depth by the end of snow accumulation season (Radionov et al., 1997; Hezel et al., 2012). In the case of FY ice, snow accumulation can only start after the sea ice freezing is stable. A delayed sea ice

freeze-up will lead to a delayed start of snow accumulation and thereby have impact on the snow depth evolution during the winter (Webster et al., 2014). MY ice begins to accumulate snow earlier in the fall; additionally, in some regions the snow can survive through the summer season. The ice thickness generally increases throughout the cold season, and though the sea ice growth rate is known to be inversely proportional to its thickness (e.g., L'Heveder and Houssais 2001, Bitz and Roe, 2004) we would expect the ice thickness to be related to the depth of snow accumulated during the winter. Figure 7 plots the depth of snow versus the ice thickness. The data are averages corresponded to ice thicknesses divided into 20 cm-ice-thickness intervals. All measurements used here were conducted throughout the Arctic (see Fig. 5a) in the MAM months on the undeformed ice. The number of measurements is shown by the histogram.
An empirical linear relation between ice thickness and snow depth can be derived for the FY ice, using least square regression, as shown in Fig. 7 by red line. The derived relation is the following:

$H_s = 0.069 * H_i + 2.0.$

In the equation H_s is the snow depth of the undisturbed snow on the undeformed ice and H_i is the ice thickness (both in cm). The FY ice has been separated using a threshold of 200 cm. The linear regression was carried out using averaged snow depth and mean ice thickness for each 20 cm-ice-thickness group of data. The coefficient of determination (R^2) is 0.95. The relation between snow depth and sea ice thickness for the whole data set can be described by the polynomial function (see Fig. 7). The highest values of ice thickness from the lowest number of measurements were rejected from the polynomial calculation.

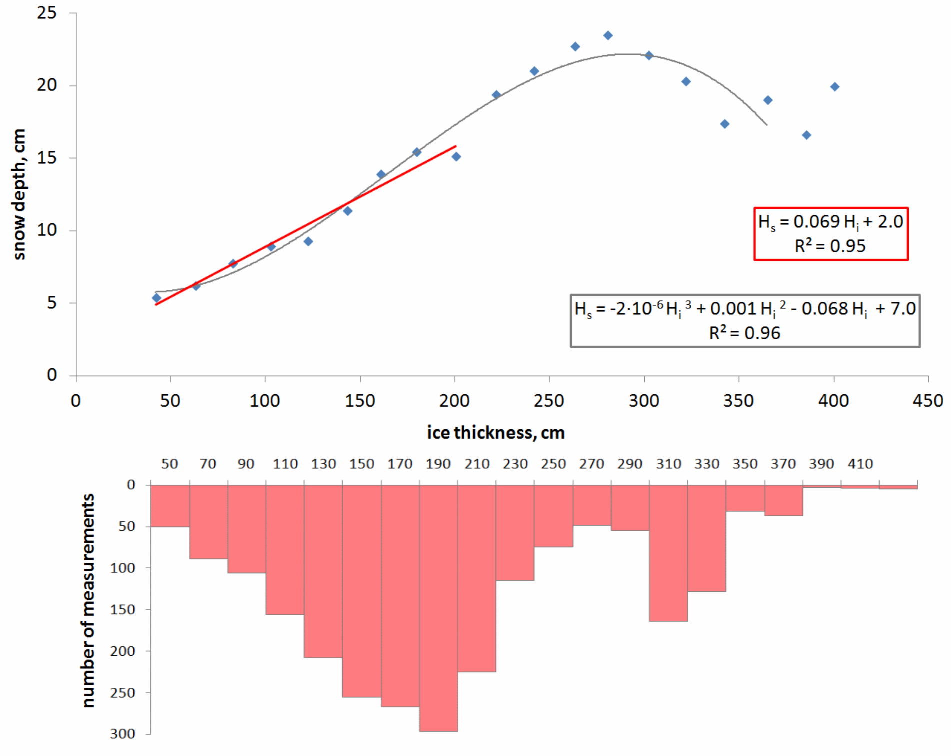


***Figure 7**. The relation between the thickness of the undeformed ice and the depth of accumulated snow in the end of winter.*

Figure 8. This figure doesn't show new information from Figure 16 in Warren et al., 1999.

We disagree. As we explained earlier (in the very beginning of the Reply to referee#3) we process data from March, April and May, which is already new information with respect to Figure 16 in W99. Besides, we show distribution and amount of measurements (together with measured values). We think it all is different from isopleths based on April measurements shown in W99.

Page 14, Lines 6-7. How much did spatial variation between landing sites affect the difference between the March and May values, rather than the conclusion that it's an increase? Were there equal sample sizes between the months of March, April, and May at the same sites?

Measurements were never done at the same sites, at least there was no such task. The decision about landing had been taken basing on what the researches saw during the flight. " *By comparing monthly mean values for the MAM months, the height of sastrugi on the MY ice had increased from 31 cm in March to about 38 cm in May.* " - That's a statistical conclusion based on all data collected on the MY ice.

Page 15, Lines 12-13. Is this a representative statistic if the landings were biased towards level first year sea ice?

The landings were biased towards the level FY sea ice, but the MEASUREMENTS were NOT.

Page 15, Lines 20-22. This is not correct. Multiyear ice has more variable surface relief, which acts to create more variability in snow depth distributions than level first year sea ice. Wind speed is not a valid explanation for the difference considering the observed frequency of blowing snow events.

" *Winds in the central Arctic are weaker than in the Siberian seas and wind speed is less variable (Frolov et al., 2005, Martin et al., 2014), which gave a smoother snow depth histogram for the central Arctic in comparison to marginal seas (Fig. 9).*" We believe that wind has its influence. We added to that text in the paper the following text:

Additionally, greater roughness of the MY ice surface exhibits more barriers to blowing snow.

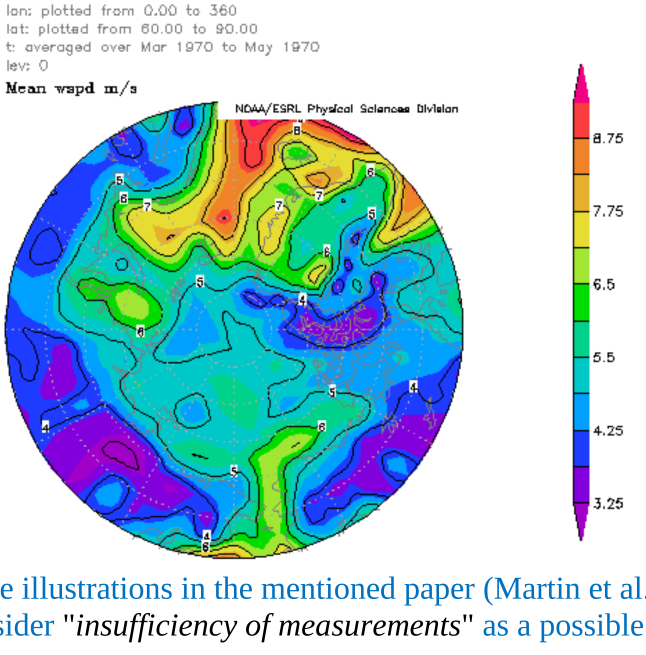
Page 16, Lines 23-24. This finding is unclear.

The text has been changed:

In the Kara Sea, there was the highest number of measurements comparing to other seas that probably allowed to observe most cases of snow dunes layouts and states.

Page 17, Line 1. The wind speed needs to be at least 5 m/s in order for snow to drift and redistribute. Wind speed is not a valid explanation for the difference.

Analysis of NCEP Reanalysis Wind Product shows that in the MAM month in the Chukchi Sea the wind speed is higher on the average than 5 m/s and higher than in other Siberian seas and in the central Arctic. Please see the example.



It is also supported by the illustrations in the mentioned paper (Martin et al., 2014). Note, that in the text of paper we consider "*insufficiency of measurements*" as a possible cause as well.

Page 17, Lines 12-15. Where did these results come from if fast ice observations were not made during the Sever expeditions?

In order to make the matter more clear we changed the sentence slightly:

In these cases the ice can become highly deformed with shear ridges or stamukhi (Barry et al., 1979). The areas of stamukhi were not observed by Sever expeditions because landing was not possible.

Page 20, Lines 5-9. Why were these adjustments made?

The text (Page 19, from Line 12 onwards) has been changed in order to make it more clear:

NP drifting station snow observations were not accompanied by any ice observations. Therefore the variability in NP snow depth measurements cannot be explained from different ice characteristics. That complicates processing Sever data with the aim to make them similar to NP data. The only information about NP snow measurements is that the NP data were collected from a solid MY floe. Figure 10 represents snow line observations made by NP16 drifting station personnel in 1969 in the MAM months. It shows that spatial variability of measured values was very high. The range of values over the same line was from 2 to 64 cm in March, from 4 to 90 cm in April and from 5 to 90 cm in May. The low correlation between repeated measurement lines (0.18 between March and April and 0.04 between April and March) suggests that the variations were primarily caused by wind.

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 to each Sever snow depth in a grid cell 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 region, to which snow measurement belongs (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 into computation 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 in the computation results in a slight underestimation of the average snow depth.*

Figure 12. The buoy data need to be quality checked. Buoy 2013F does not show a realistic snowfall event.

That buoy worked another year and it produced reasonable results after the period shown in the paper (that raised doubts from the referee). Ref. : http://imb-crrel-dartmouth.org/imb.crrel/irid_data/2013F_thick.png We believe that buoy's steady work in the later (following) year confirms its normal functionality in the MAM months 2013.

Snow depth on Arctic sea ice from historical in situ data

Elena V. Shalina[1,2], Stein Sandven[3]

[1]Nansen International Environmental and Remote Sensing Centre, St.Petersburg, 199034, Russia
[2]St. Petersburg State University. Institute of Earth Sciences, St.Petersburg, 199034, Russia
[3]Nansen Environmental and Remote Sensing Center, 5006 Bergen, Norway

Correspondence to: Elena Shalina (elena.shalina@niersc.spb.ru)

Abstract. ~~In this paper we analyze~~The snow data from the Soviet airborne expeditions Sever ~~that was collected~~ in the Arctic ~~around places of landings~~collected over several decades in March, April and May ~~and cover~~ have been analyzed in this study. The Sever data included more measurements and covered a much wider area ~~than the region of observations of Soviet North Pole drifting stations. Particularly, there were a lot of Sever observations~~, particularly in the Eurasian marginal seas~~.~~ ~~We investigate~~ (Kara Sea, Laptev Sea, East-Siberian Sea and Chukchi Sea), compared to the Soviet North Pole drifting stations. The latter collected data mainly in the central part of the Arctic Basin. The following snow parameters have been analyzed: average snow depth on the level ice~~,~~ (undisturbed snow) height and area of sastrugi, depth of snow dunes attached to ice ridges and depth of snow on hummocks. ~~We have built new snow depth climatology for the late winter that was calculated using both Sever expedition and North Pole drifting station observations. Our result refines the description of snow depth in the central Arctic and provides detailed information on snow depth in the marginal seas. In the~~ In the 1970s-80s ~~the snow cover~~ in the central Arctic ~~had~~ the ~~following characteristics: the snow~~average depth of ~~the~~ undisturbed snow was 21.2 cm, the depth of sastrugi (that occupied about ~~36~~30% of the ice surface) was 36.2 cm and the average depth of snow ~~assembled~~ near ~~the~~ hummocks and ridges was about 65 cm. For the marginal seas ~~Sever observations revealed that~~ the average depth of undisturbed snow on the level ice ~~changed~~varied from 9.8 cm in the Laptev Sea to 15.3 cm in the East Siberian Sea, ~~the topmost value in the East Siberian Sea is explained by the highest proportion~~ which had a larger fraction of multiyear ice ~~there. Observations demonstrated a very high~~ . In the marginal seas the spatial variability of snow depth ~~in the marginal seas~~ was characterized by standard deviation ~~changing from~~varying between 66 ~~to~~and 100%. ~~Average~~The average height of sastrugi ~~in the Eurasian seas~~ varied from 23 cm to about 32 cm with standard deviation ~~from~~between 50 ~~to~~and 56%. ~~Average~~The average area covered by sastrugi in the marginal seas was estimated ~~as~~to be 36.5% of the total ice area ~~of the ice floe~~ where ~~those features have been~~ sastrugi were observed. The ~~snow map introduced here as~~main result of the study is a new ~~climatology is built from Sever and North Pole data, with the latter amounted to 6.1%~~snow depth climatology for the late winter using data from both the Sever expeditions and the North Pole drifting stations. The snow load on the ice observed by Sever expeditions has been described as a combination of the depth of undisturbed snow on the level ice and snow depth of sastrugi weighted in proportion to the sastrugi area. The height of snow accumulated near the ice ridges was not included in the calculations because there are no estimates of the ~~whole data set. On the whole, our~~area covered by those features from the Sever expeditions. The effect of not including that data can lead to some underestimation of the average

snow depth~~ map reveals lower values~~. The new climatology refines the description of snow depth in the central Arctic compared to the results by Warren et al. (1999) and provides additional detailed data in the marginal seas. The snow depth climatology is based on 94 % Sever data and 6 % North Pole data. The new climatology shows lower snow depth in the central Arctic comparing to Warren climatology ~~in the central Arctic and shows refined information for~~and more detailed data in the Eurasian seas.

1 Introduction

Most of the Arctic sea ice is covered with the snow year round except in the melt season when meltponds are present. Snow cover plays an important role in the thermodynamic processes of sea ice. In winter the snow ensures high sea ice surface albedo of about 0.9 associated with low energy absorption. On the other hand, snow insulates the sea ice from the influence of cold air and reduces the rate of ice growth. After snow begins to melt in summer producing melt ponds, reduction of the surface albedo and higher energy absorption results in a more rapid ice melt. Thus data on snow depth and surface albedo is important for quantification of the thermodynamical processes. Besides, information on snow depth is also very important for ice thickness retrieval from satellite altimeter measurements of sea ice freeboard and their conversion to thickness using hydrostatic equation (Laxon et al., 2013~~;~~, Kwok et al., 2017, Kern et al., 2015~~; Kwok et al., 2017~~).

Changes of the arctic ice cover over the last decades are well documented in data from different satellite, aircraft, submarine, buoy and in situ measurements. There is clear evidence of a decline in sea ice area and thickness (~~Comiso and Nishio, 2008;~~ Kwok and Rothrock, 2009; ~~Kwok et al., 2009~~Comiso and Nishio, 2008; Wadhams, 2012; Stroeve et al., 2012; Lindsay and Schweiger, 2015). This implies that the Arctic sea ice changes from predominantly multiyear ice to increased fraction of seasonal ice (Maslanik et al., 2007; Tschudi et al., 2010~~;~~, Maslanik et al., 2011; Comiso, 2012; Tschudi et al., 2016). As a result the whole ice pack becomes more vulnerable to strong atmospheric impacts (Parkinson and Comiso, 2013). Sea ice retreat leads to larger areas of open ocean, which absorbs more solar energy and consequently enhances the warming of the upper layer of the Arctic Ocean. This warming also contributes to melting of the sea ice underside (Perovich et al., 2007). Reduction of the sea ice cover also amplifies warming of the atmospheric boundary layer in the high latitudes (Screen and Simmonds, 2010). This process may accelerate the sea ice decline and diminish the proportion of precipitation in form of snow (Screen and Simmonds, 2012).

In situ observations of the snow cover of the Arctic sea ice are presently very scarce, especially year-round measurements which are needed to document the seasonal variability of the snow cover. The most extensive data set in the past was collected during the Soviet North Pole (NP) drifting stations in 1937 and 1954-1991. Data from these expeditions have been used to establish the Warren snow climatology data set (Warren et al., 1999), hereafter denoted W99, providing distribution of the snow depth and density for each month of the year. Valuable data on snow properties has also been collected from other expeditions, buoy measurements, ice camps and validation experiments in specific areas of the Arctic. ~~For example, snow depth has been measured during SHEBA (Sturm et al.,~~In situ snow depth measurements has been carried out in spring time in the Beaufort Sea, Elson Lagoon and Chukchi Sea (Sturm et al., 2002, Sturm et al., 2006, Markus et al., 2006, Newman et al., 2012, Nghiem et al, 2013, Webster et al, 2014), in the Canadian Arctic between the islands (Iacozza and Barber, 1999, King et al., 2015) and near the coast of northern Greenland (Farrel et al., 2012, King et al., 2015). With the aim to describe spatial distribution of snow on sea ice as a function of ice type, field experiments SIMMS'95 and C-ICE'96 in the Canadian Arctic have been conducted (Iacozza and Barber, 1999). Observations were made at the sites covered with only one sea ice type and snow topography on a given type of ice was described using variogram modelling. In 1997-98, extensive snow depth measurements have been made during SHEBA (Sturm et al., 2002). One of the objectives was to record temporal evolution of snow depth over the year, to evaluate its spatial variability (as broad as conditions of the experiment allowed), and to estimate the freshwater amount contained in the snow cover. Changes of snow depth connected with ice type and the level of deformation were also studied under SHEBA. Another expedition, the AMSR-Ice03 validation campaign carried out in March 2003 offshore of Barrow collected snow data for comparison with satellite products and also for analysis of snow depth on the sea ice of different age and different roughness (Sturm et al., 2006~~).~~, Markus et al, 2006). During the Norwegian Young Sea ICE (N-ICE2015) campaign, snow depth was measured on the sea ice north of Svalbard (Gallet et al., 2017, Merkouriadi et al., 2017). In recent years a series of IceBridge validation/calibration campaigns have been conducted including in situ snow measurements on several ice types: undeformed level first-year (FY) ice, multiyear (MY) ice, and heavily deformed pressure ridges. Results have been published from studies near Greenland in April 2009 where measurements collected at the Danish GreenArc sea ice camp (Farrell et al., 2012~~) and~~), from surveys in the Beaufort Sea in March 2011 (Gardner et al., 2012; Newman et al., 2014~~).~~), from measurements taken in March 2012 during BROMEX field campaign (Webster et al., 2014) and in March-April 2014 in the Canadian Arctic Archipelago waters close to Eureka and in the Lincoln Sea near the northern coast of Greenland (King et al., 2015). Assessment of five snow depth retrieval algorithms that differently process IceBridge snow radar data has been made through comparison with field measurements from two ground-based campaigns, 2012 BROMEX near Barrow, Alaska, and 2014 Eureka, near ~~Eureka, Nunavut,~~the research base with the same name in Canada (Kwok et al., 2017).

The W99 snow climatology provides monthly averaged gridded snow depth maps for the whole Arctic, representing the means over the whole period of the North Pole (NP) drifting station observations. However, the averages are based on measurements from usually not more than two stations established in the Arctic in any given year. Though the interannual variability is estimated in W99, the spatial variability cannot be adequately described because of insufficient sampling. ~~Due to the high spatial and temporal variability of the snow depth it is difficult to estimate the errors of the mean values of the W99 climatology~~. Another serious limitation of W99 climatology is the fact that the NP drifting stations were established on the MY ice, which means that climatology does not include snow on FY ice and is therefore heavily biased towards MY ice.

In this paper, we analyze snow data from Soviet airborne expeditions Sever that was collected through 28 years in the middle of the NP time period and cover much wider area than NP stations. The Sever expedition landings were made not only on the MY ice in the central Arctic but also on the FY ice in the Eurasian seas, especially on the Siberian shelf where practically no NP data was collected. The main goal of this study is to produce improved data set of snow depth for the whole Arctic for the late winter season (March-April-May) by combining Sever and NP data sets. Both data sets were collected mainly in the 1960s, 70s and 80s. The combined snow distribution data set and obtained dependencies will be useful for validating sea ice and climate models and also as input into the algorithms retrieving ice thickness from satellite altimeter data. The data set will be important for comparison with snow observations in the present sea ice conditions.

The snow depth varies significantly within the Arctic region. It varies in time (both seasonally and interannualy) and space (over large distances and locally within a single ice floe). Ice age and intensity of precipitation are the main factors to determine the snow depth. The older the ice is the more snow can accumulate depending on the amount of precipitation. Furthermore wind and ice roughness play a role in determining the distribution of the snow depth. Fresh snow on an ice floe can easily be blown away from the smooth ice into the rough ice areas. On the rough ice the blowing snow is trapped and consequently snow depth is larger in the areas of ice ridges and hummocks in comparison with the smooth ice area. Another manifestation of snow depth deviation caused by wind is sastrugi, irregular ridges and grooves of snow formed on the ice surface. When the snow is light, snow dunes are easily moved by the wind, however they consolidate by the end of winter due to compression and crystallization. All mentioned aspects of snow depth variations in the end of winter season are described in this paper basing on Sever expeditions measurements.

This paper is organized as follows: in Sect. 2 we describe the data collected during Sever expeditions and compare it briefly with NP data. In Sect. 3 we describe methods used for data processing. Description of the depth of snow cover atop Arctic sea ice of different roughness is given in Sect. 4. That section also contains separate description of snow on ~~fastice~~fast ice, results on combination of Sever and NP data and analysis of ~~available~~ contemporary ~~in situ~~buoy snow depth measurements. Discussion of the new results presented in the paper is provided in Sect. 5.

2 Data Description

The airborne Sever expeditions took place in 1937, 1941, 1948-1952, and 1954-1993. The first expedition was organized to support the Soviet drifting station North Pole-1 (NP-1). The personnel, goods and equipment were transported by the Sever expedition airplanes to the ice floe at 89° 25′ N, 78° 40′ W where NP-1 was deployed. The NP-1 expedition collected different oceanographic, meteorological and gravimetric measurements during its 9 month successful operation. The valuable experience of landing an aircraft on sea ice laid the foundation for further Arctic airborne expeditions. It was decided that oceanographic, meteorological, snow and ice measurements in the Arctic should be done by ice researchers throughout a series of short landings of specially equipped airplanes. The advantage of such observations was that a wide area of the Arctic could be covered by landings and the sites to visit could be chosen in accordance with the goal of the study.

Most of the landings took place from mid-March to early May, when there was enough daylight to operate and before melting started and aircraft could not land on the ice. In some years landings occurred also before March and after May

(Table 1). In contrast to the NP data, which covers only MY ice, the Sever data were collected on both MY and FY ice, as long as the ice could provide a runway for the aircraft.

Table 1. The number of landings of Sever expeditions by decade and month.

	January	**February**	**March**	**April**	**May**	**June**	**July**
1930s				2	5		
1940s				21	24		
1950s		2	21	286	147	4	1
1960s	3	13	107	282	290	46	
1970s			438	679	148		
1980s		3	380	526	339		

The Sever data used in this study were obtained from the US National Snow and Ice Data Center (NSIDC) (http://nsidc.org/data/g02140). The dataset contains sea ice and snow measurements of 23 parameters, in particular, including ice thickness and snow depth and density on the runway and surrounding area, as well as dimensions and snow coverage of ridges, hummocks, and sastrugi. Not all parameters were measured at every landing. Only ice thickness measurements were conducted over the whole period of Sever expeditions. Observations of snow started in 1959 and were conducted up to 1988 with small time gaps. The present study is concentrated on analysis of data from March, April and May (the MAM months further in the text) when most of the data was collected.

The monthly mean positions of the NP drifting stations in 1954-1991 for the MAM months and landing sites of Sever expeditions where snow measurements were conducted in 1959 -1986 in the same months are shown in Fig. 1. The NP data covers mainly the central part of the Arctic while the Sever data covers much larger areas with most of the data collected along the Siberian shelf seas between Novaya Zemlya and the Bering Strait. The selection of sites for the NP station deployment depended on requirements for sufficient ice thickness, floe size, possibilities for cargo aircraft landings and other factors.

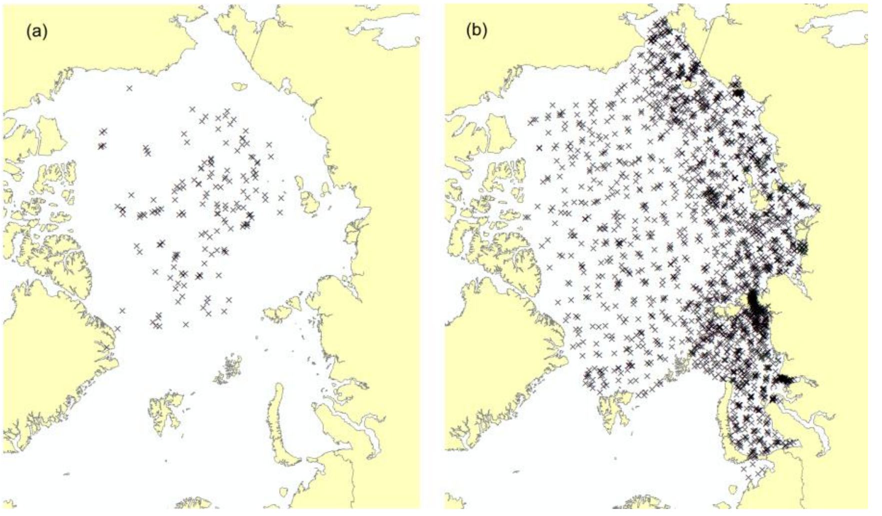


Figure 1. Monthly mean positions of NP drifting stations in 1954-1991 (a) and Sever expedition landings where snow measurements were conducted in 1959-1986 (b). Only observations in the MAM months are shown for both sets of measurements.

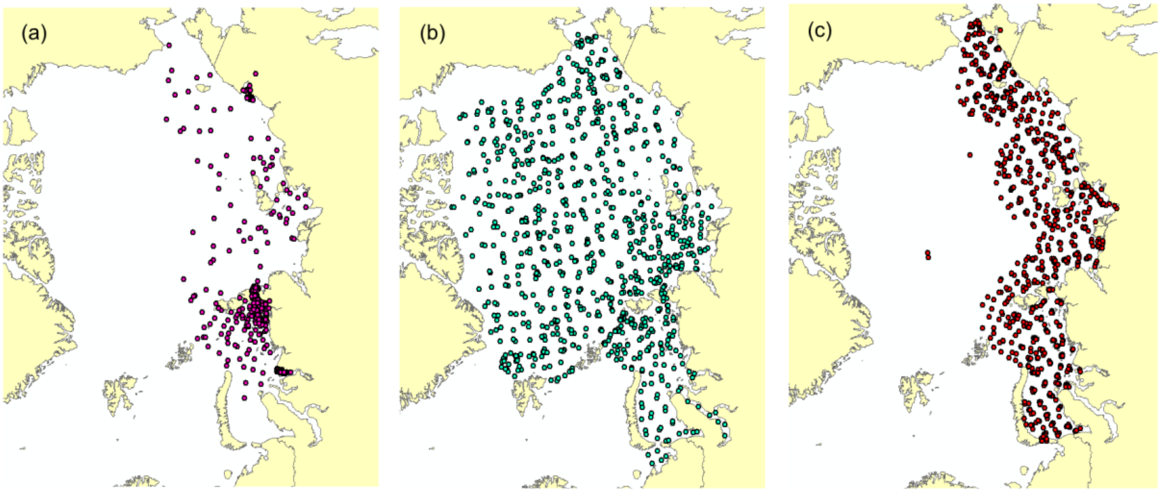


Figure 2. Sever expedition landings where snow measurements were conducted in the MAM months: 60s (a), 70s (b) and 80s (c).

The geographical distribution of the Sever landings for each of the three decades when most of the snow data was collected is shown in Fig. 2. In the 60s (including 1959) the landings were focused in the Russian part of the Arctic Ocean with most frequent observations in the northern Kara Sea where 69 % of all landings took place. In the 70s the landings were distributed over most of the Arctic Ocean, while in the 80s observations were concentrated in the Siberian shelf seas, supporting the Northern Sea Route.

The Sever and NP expeditions had different data collection strategy not only regarding spatial and temporal sampling, but also in the way snow observations were collected.

At the NP stations three types of snow measurements have been provided: snow line measurements, snow gauge precipitation measurements and snow stake measurements at the meteorological station site (Radionov et al. 1997; Colony et al, 1998). Snow line measurements were repeated once per month and sometimes once per 10-day period along the same lines of 500 m or 1 km length. The distance between each measurement (along the line) was 10 meters. The snow line was selected on a flat ice surface with no human objects or ice hummocks that could influence the snow depth (Colony et al, 1998). The snow line surveys were carried out and documented if the average snow depth along the line was at least 5 cm. Snow cover and the ice under it changed during the station lifetime and line measurements allowed "to obtain a representative distribution of snow depths, passing through sastrugi, snow dunes, and pressure ridges as well as level snow" (Warren et al., 1999). The advantage of the NP line measurements is that natural local variability on the same ice is captured as well as the time evolution over the year. Other measurements of snow depth were carried out daily using three permanent snow stakes installed at the meteorological station site. These sites were generally located close to the station camp, implying that observations could be influenced by camp structures. Consequently, the measurements of snow cover depth from snow stakes in many cases did not agree with the line measurements (Radionov et al., 1997). Also snow gauge measurements did not always agree with the line measurements. W99 used mainly snow line measurements to produce their snow climatology data set considering those measurements most reliable.

The benefit of the Sever expeditions was that data were collected over much larger geographical area compared to NP data. During Sever landings various snow depth measurements were carried out in different locations on and around the runway. The measured parameters included runway snow depth, snow depth on the prevailing ice in the landing area, snow depth at mid-length of snow dunes extending out from ice ridges, depth of snow on hummocks, on both windward and lee sides, and height of sastrugi on the dominant type of ice in the landing area. Representative areas for measuring snow parameters were chosen from the air before landing, including estimation of sastrugi areas. The runway was chosen on flat ice that was most probably first year ice, but could also be multiyear ice. Meanwhile, the ice conditions around landing track were usually different from that on the runway: the difference between the ice thickness of the runway and of the area where other 25 measurements were conducted was in some cases about 300 cm. In the description of data the ice in the area around runway is called "prevailing ice of the landing area". Later in the paper we use definition "undeformed ice" as a substitute for "prevailing ice of landing area", since snow cover associated with ice features caused by ice deformation like ice ridges and hummocks is described separately. After landing, snow depth was measured at 10-20 random points on prevailing ice of the landing area and on ice surface with distinctive features. For snow depth of more than 10 cm, at least 10 measurements were ~~made~~conducted over the entire ice floe, as well as on adjacent floes. How many measurements were made in case when snow depth was lower than 10 cm is not indicated in the description of data. The depth of snow dunes stretching from ice ridges and depth of snow on hummocks were measured using the following steps. The snow depth on 2 or 3 snow-covered hummocks was measured on both windward and lee sides at 10-20 points. The depth of snow dunes stretching from ice ridges were measured at 3-5 sites at their mid-length. The height of sastrugi on the undeformed ice was measured at several points. Note that all types of snow dunes formed on a flat ice surface by wind were referred to as sastrugi in Sever expeditions' data set. The averaged measurements of the mentioned parameters were reported in the documents from each expedition.

In addition to the description of Sever data measurements, it is important to mention that in all cases observations were conducted by highly experienced personnel who selected typical objects for measurements in order to produce a representative picture of the landing area. Estimating value of Sever observations, we can mention that data on distribution of sastrugi area over the Arctic has not been found in other studies. Data on sastrugi height and on snow attached to hummocks and ridges are very few.

Some statistics about the snow measurements of the Sever expeditions are shown in Figure 3. From 1959 to 1989 a total of 3234 landings were conducted, of which 2331 landings provided snow depth measurements. The number of landings increased significantly during the 1970s, associated with expanding the surveys to cover the whole Arctic Ocean (Fig. 2). Towards the end of the 1980s the Sever programme came to an end, with the last expedition in 1989. Altogether, most intense and broad snow measurements have been carried out in the period 1977-1986. In the paper we analyze all parameters shown in Fig. 3 except for one – area of hummocks that was measured only 555 times.

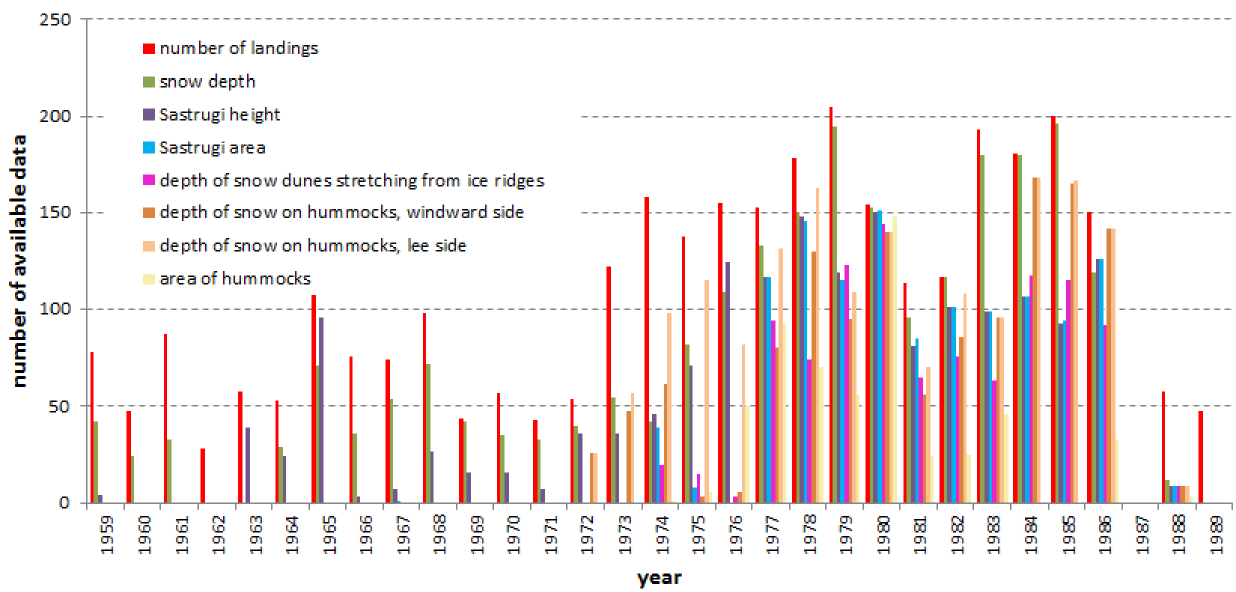


Figure 3. The number of landings and the number of different snow observations per year carried out in the MAM months.

Data on the depth of undisturbed snow measured on the prevailing type of ice in the landing area from all Sever expeditions landings over the period from 1959 to 1988 is presented in Fig. 4. Since ~~most~~a substantial portion of measurements ~~were~~was conducted on the FY ice the snow depth is below 20 cm for 79 % of all samples.

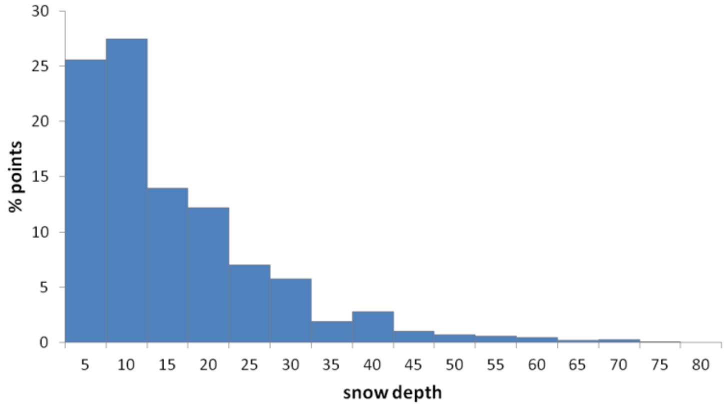


Figure 4. Observations of snow depth on prevailing landing area ice from Sever expeditions made in the MAM months, 1959-1988. Observations are grouped in 5 cm intervals.

3 Methods

The Sever data contains the following snow parameters: average snow depth of the undisturbed landing site, height and area of sastrugi (on the dominant type of ice in the landing sites), depth of snow dunes attached to ice ridges (at mid-distance between ridge and undisturbed snow area), and depth of snow on hummocks (on windward and lee sides). These snow parameters are interconnected, and a statistical description of each of them can be useful in order to characterize snow cover ~~in~~on sea ice. The analysis also included preparation of a data set that can be compared and integrated with the NP data and thereby improve W99 the snow cover climatology.

The spatial variability of snow parameters in the MAM months is one of the important characteristics that can be elucidated using the Sever data. Snow depth variations on local scale are caused by wind forcing, resulting in sastrugi formation~~ and~~, increased snow depth near ice ridges and hummocks and reduced snow depth on level ice. On larger scale snow depth variations are synoptic in origin (Sturm et al., 2006) or caused by different age of ice where snow cover has been built up. Local and large scale variations are further discussed in Sect. 4.

The large scale spatial variability of snow depth is quantified by averaging observations from the landing sites in 100 by 100 km grid cells, as shown in Fig 5. To produce regular grids we averaged all points within the 3x3 cell neighborhood around every grid cell. The number of measurement sites used in the gridding operation varied from 1 to 23 in the Central Arctic and from 25 to 76 in the Siberian marginal seas (Kara Sea, Laptev Sea, East Siberian Sea and Chukchi Sea). The area with the highest density of measurements (around 160) lies in the north-eastern part of the Kara Sea and in the Vilkitsky Strait, which was the priority area for the Sever expeditions in the 1960s (Fig. 2a and 5b).

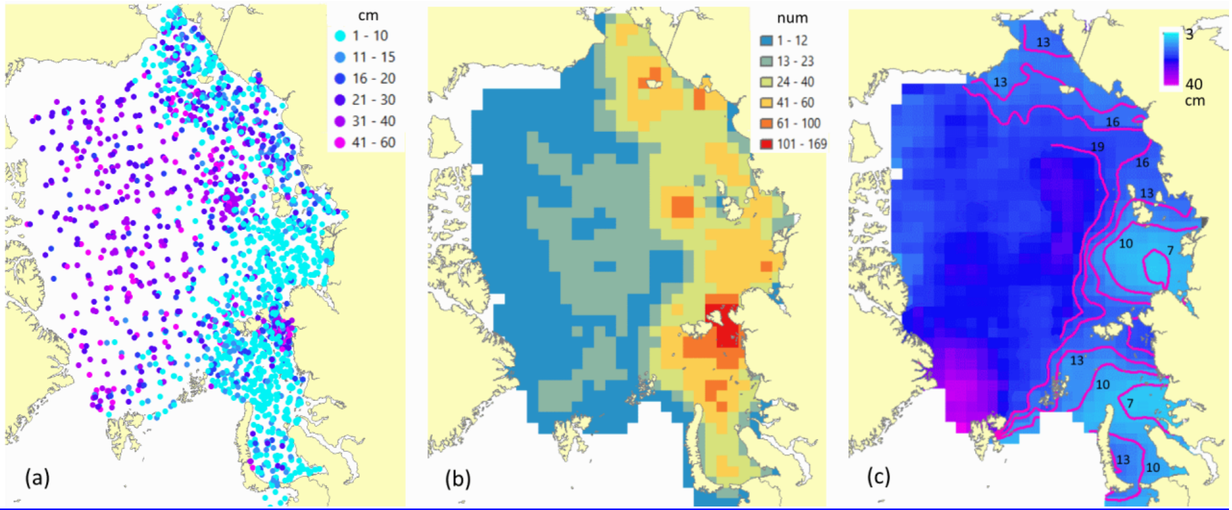
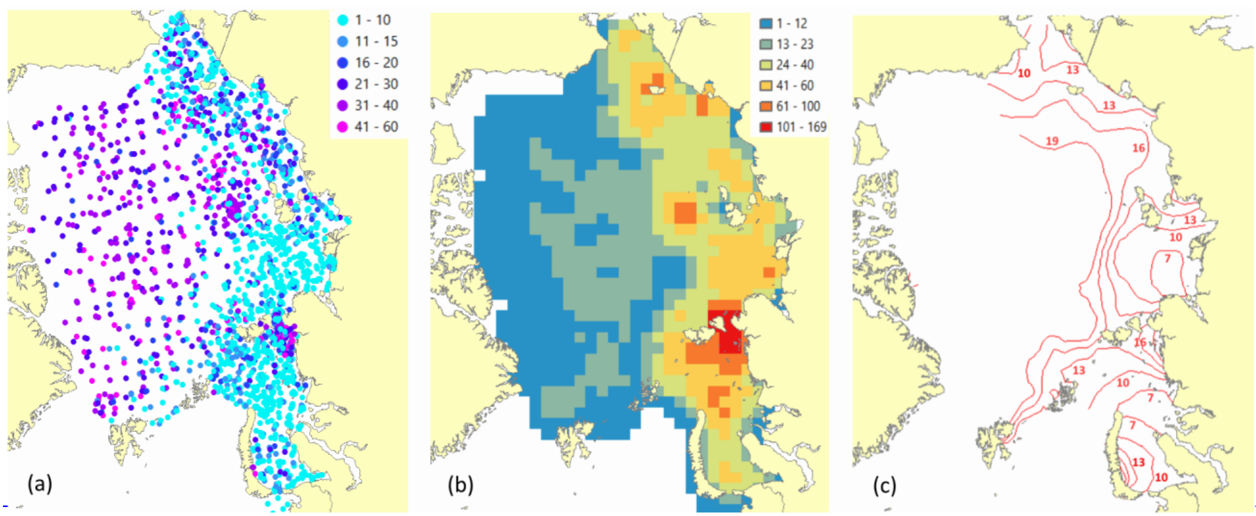


Figure 5. Spatial distribution of measured snow depth on the level ice around Sever landing sites, MAM months, 1959-1988 (a). Number of point measurements used in gridding, grid cell is 100x100 km (b). Contour lines of the snow depth in the marginal seas produced using observations shown on the left panel (c). Snow depth is in cm.



~~**Figure 5**. Spatial distribution of measured snow depth around landing sites from Sever expeditions, MAM months, 1959-1988 (a). Number of points measurements used in gridding, grid cell is 100x100 km (b). Contour lines of the snow depth in the marginal seas produced using observations shown on the left panel (c). Snow depth is in cm.~~

The Siberian marginal seas are poorly represented in the W99 climatology but quite well represented in the Sever data. Hence, the Sever data can provide a significant contribution to improved snow climatology in these areas as well as in the ~~Central~~central part of the Arctic Ocean. The depth of undisturbed snow is typically less than 10 cm in the Kara and Laptev seas and less than 20 cm in other areas (Fig.5c). With included sastrugi, snow dunes and snow on hummocks, the ~~in~~ average snow depth estimates become larger, as discussed in Sect. 4 and 5.

In the analysis it was useful to discriminate observations from FY and MY ice because MY ice as a platform to accumulate snow is different from FY ice. Firstly, MY ice exists from the very beginning of the fall and thus is able to catch the earliest falling snow. Secondly, the topography of MY ice is different from that of FY ice, being more irregular, that influences redistribution of snow. Furthermore, there are melt ponds on the MY ice in summer that become local depressions during winter, accumulating snow and forming deeper than average snow patterns (Perovich et al., 2003). We separate ~~In the analysis it was useful to separate the~~ observations from FY and MY ice by using an ice thickness threshold, since ice thickness was measured at every landing. The threshold was chosen to 2.0 m, implying that ice thinner than 2 m is defined as FY ice and ice thicker than 2 m is defined as MY ice~~.~~ (WMO Sea-Ice Nomenclature). In the decades of the Sever expeditions, MY ice dominated in the ~~Central~~central Arctic, ~~while in the marginal seas both FY and~~the fraction of MY ice ~~were present~~being close to 100% in 60s-80s. Using the 2 m threshold, it was found that 78% of Sever observations from the central Arctic were conducted on the MY ice and 22% on the FY ice. The sampling made by the Sever expeditions was probably biased towards level ice~~, because the real fraction of MY ice in~~ . In order to derive maximally representative data set for the central Arctic~~ was close to 100% in 60s-80s. Therefore, it was~~, we decided to use only MY-based measurements for ~~merging~~ that area. Supposing that NP and Sever observations complement each other we merged Sever snow depth observations from MY ice with NP data to produce ~~a~~ snow depth climatology for the central Arctic.

By using the same ice thickness threshold in the marginal seas, the fraction of data coming from MY ice was 9% in the Kara Sea, 11% in the Laptev Sea, 34% in the East-Siberian Sea and 23% in the Chukchi Sea. These fractions of MY ice seem reliable, ~~implying that~~thus all snow observations in the marginal seas (both FY- and MY-based) were used in the subsequent analysis.

Snow data collected on the FY and MY ice were analyzed to find an empirical relation between snow depth and sea ice thickness. The relation is estimated from a regression analysis and is presented in Sect. 4. Such relation can be expected because both ice thickness and snow depth grow through the freezing season from September to May, although the relation is not straight forward as snow cover acts as an insulator reducing the freezing rate of the ice.

In processing of the sastrugi data, average height and areas covered by sastrugi were estimated. Furthermore, attempts were made to find relation between sastrugi height and snow depth in the surrounding areas. Spatial changes of sastrugi height were identified through estimating averages for different Arctic regions. In addition to height, the spatial variability of the area of sastrugi was analyzed because it contributes to the estimation of the average depth of snow cover. Snow depth associated with ridges and hummocks was also estimated; but the effect of this part of the snow cover on the averaged snow depth could not be evaluated because the areas covered by these features were not sufficiently observed.

The fraction of snow data collected on ~~fastice~~fast ice could be extracted using sea ice climatology data GO2172 available from NSIDC, covering the period 1975 - 1984. After delineation of ~~fastice~~fast ice areas it was possible to provide snow and sastrugi depth estimates on that type of ice.

Finally, attempts were made to look at contemporary snow depth data in order to compare with results from the Sever expeditions~~, but the different methodologies made it difficult to compare contemporary and historical data~~. We analyzed buoy snow depth data since those data has been collected in the area that overlaps with the space observed during Sever expeditions. It is difficult to compare contemporary and historical data because of the different methodologies in collecting data. However, it was important for us that besides providing in situ snow depth observations, buoy measurements demonstrate the range of temporal and spatial variability of snow depth in the end of winter.

4 Results

4.1 Depth of undisturbed snow cover

The spatial analysis of snow depth changes from the Sever data is based on the observations made on the prevailing ice types in the landing areas, consisting of level FY or MY ice. Since the landing sites were irregularly distributed, the basic statistical characteristics were calculated in two ways: (1) from point measurements and (2) from gridded data as shown in Fig 5b. The statistics for the two methods is presented in Table 2. The ~~effect~~snow in the form of sastrugi, attached to hummocks and ~~snow dunes~~ice ridges is not ~~taken into account~~described here~~, but~~; the relevant analysis will be ~~included later~~presented in Sect. 4.2 and 4.3. Data from the Barents Sea is not included because of very few measurements in that region.

Table 2. Snow depth (~~SD~~H_s) of undisturbed snow cover on level ice in the landing areas in different parts of the Arctic Ocean for the months March, April and May.

Snow depth (cm)	Central Arctic*)	Kara Sea	Laptev Sea	East-Siberian Sea	Chukchi Sea
		Statistics based on the gridded data			
Average	21.0	10.3	9.8	15.3	13.3
Std	5.5	3.6	3.1	3.4	3.1
Number of measurements	460	641	442	368	227
		Statistics based on the point data			
Average	21.2	12.2	9.6	15.2	13.5
Std	10.9	12.2	8.4	10.1	10.5
Median	20	8	7	15	10
Min	2	1	1	1	2
Max	70	97	65	60	60

*) All data including the number of measurements correspond to observations carried out on the MY ice (ice with the thickness >200 cm).

Average snow depth estimated from point measurements and gridded data is similar in all regions except in the Kara Sea. The difference of about 2 cm in this region can be explained by very selective sampling in 1960s, when most of measurements were carried out in the north-eastern part of the Kara Sea near the coast and in the Vilkitsky Strait. The reason for this biased sampling is not known. The maximum average snow depth of about 21 cm was observed in the central Arctic. Among the marginal seas, the East-Siberian Sea showed the largest fraction of snow depths above 15 cm, as shown in distributions (Fig 6).

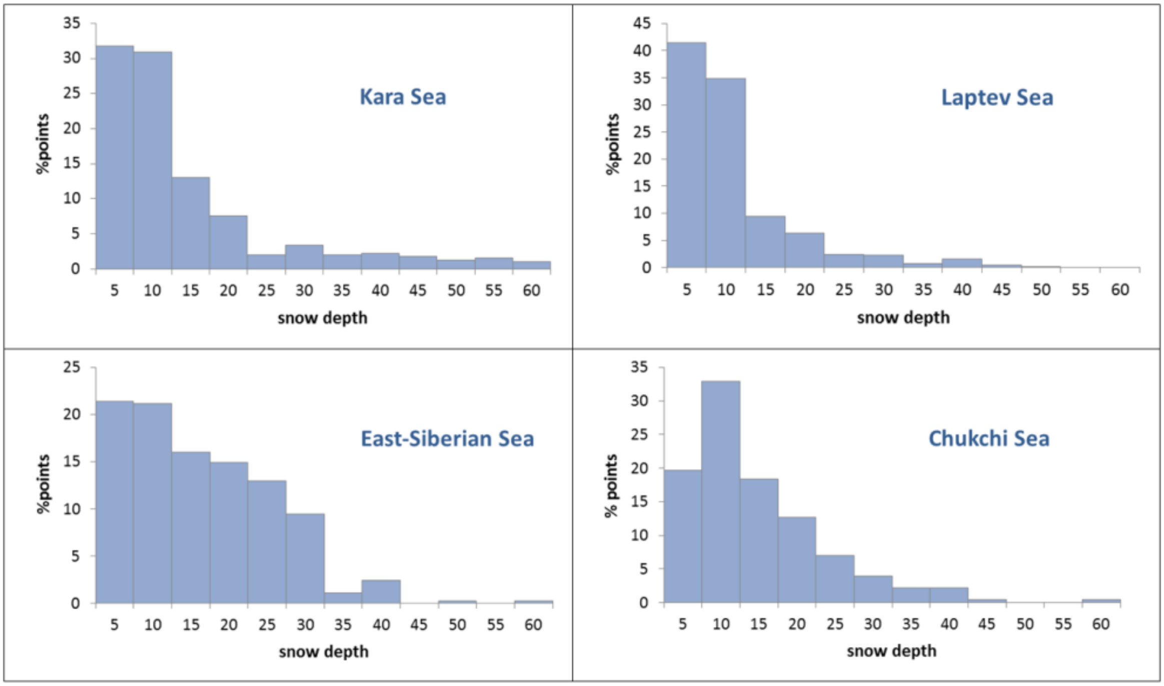


Figure 6. Distribution of snow depth on the level ice in the marginal seas.

The snow depth in the Kara and Laptev seas is dominated by snow depth up to 10 cm, indicating prevalence of FY ice. The Kara Sea also has cases of very thick snow cover, which can be explained by high density of data in the north-eastern part of the Kara Sea as shown in Fig 5. Snow conditions observed in that area were highly variable, which ~~can be~~is explained by very ~~dense~~condensed observations that captured a wide variety of ice and snow characteristics in that region. On average, the East-Siberian and Chukchi seas had more observations of thicker snow cover, which agrees with the higher proportion of MY ice in these regions. ~~Although the data in Fig. 6 represent level ice in the landing areas excluding local variations like sastrugi, the results are in agreement with other studies of in situ data (Sturm et al., 2006; Farrell et al., 2012; Newman et al., 2014) and data from IceBridge airborne surveys (Kurtz and Farrel, 2011; Kwok, 2017). It is noteworthy that the snow depth distribution in the Chukchi Sea agrees very well with the data collected during the AMSR-Ice03 validation campaign, covering a smaller part of that sea (Sturm et al., 2006).~~

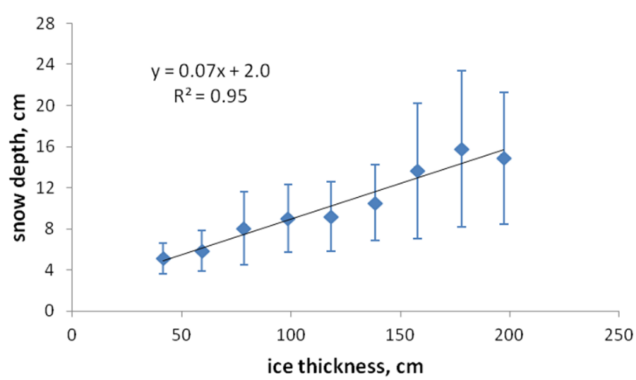
The start time of snow accumulation is one of the major factors determining the snow depth by the end of snow accumulation season (Radionov et al., 1997; Hezel et al., 2012). In the case of FY ice, snow accumulation can only start after the sea ice freezing is stable. ~~-~~A delayed sea ice freeze-up will lead to a delayed start of snow accumulation and thereby have impact on the snow depth evolution during the winter (Webster et al., 2014). ~~From the Sever data an empirical relation between ice thickness and snow depth can be derived for FY ice, using least square regression, resulting in the equation:~~MY ice begins to accumulate snow earlier in the fall; additionally, in some regions the snow can survive through the summer season. The ice thickness generally increases throughout the cold season, and though the sea ice growth rate is known to be inversely proportional to its thickness (e.g., L'Heveder and Houssais 2001, Bitz and Roe, 2004) we would expect the ice thickness to be related to the depth of snow accumulated during the winter. Figure 7 plots the depth of snow versus the ice thickness. The data are averages corresponded to ice thicknesses divided into 20 cm-ice-thickness intervals. All measurements used here were conducted throughout the Arctic (see Fig. 5a) in the MAM months on the undeformed ice. The number of measurements is shown by the histogram.

~~$SD = 0.069 * Ice_{th} + 2.0$~~

~~where SD is~~An empirical linear relation between ice thickness and snow depth can be derived for the FY ice, using least square regression, as shown in Fig. 7 by the red line. The derived relation is the following:

$$H_s = 0.069 * H_i + 2.0. \quad (1)$$

In the equation (1) H_s is the snow depth of the undisturbed snow on the undeformed ice and ~~Ice_th is ice thickness of the FY ice (in cm), using a threshold of 200 cm, as shown in Fig. 7. The equation~~ H_i is ~~based on all data collected on the undeformed ice with~~ the ice thickness ~~less than 200~~(both in cm~~, and it~~). The FY ice has been ~~calculated~~separated using ~~data divided into 20~~a threshold of 200 cm ~~ice-thickness intervals~~. The linear regression was carried out using averaged snow depth and mean ice thickness for each 20 cm-ice-thickness group of data. The coefficient of determination (R^2) is 0.95. The relation between snow depth and sea ice thickness for the whole data set can be described by the polynomial function (see Fig. 7). The highest values of the ice thickness from the lowest number of measurements were rejected from the polynomial calculation.



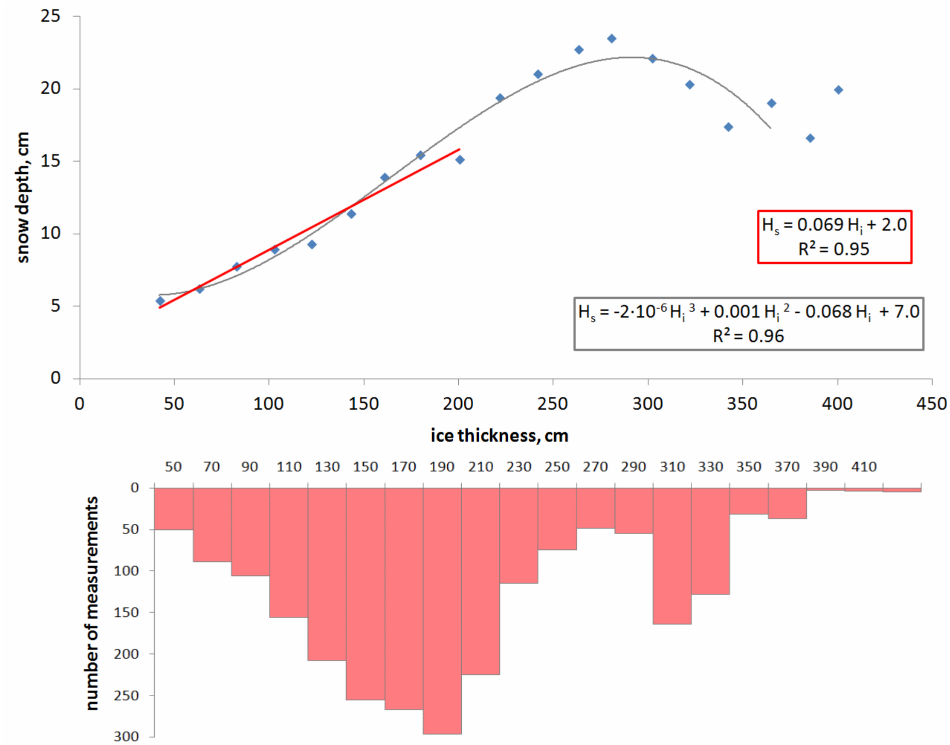


Figure 7. The ~~least squares regression~~relation between ~~FY ice~~the thickness of the undeformed ice and the depth of accumulated snow ~~depth~~in the end of winter.

The next step in the analysis of the Sever data was focused on the local variations of snow depth caused by wind action and ice deformation, leading to formation of sastrugi, hummocks and snow dunes. As described in Sect. 2, measurements of snow depth of sastrugi (sastrugi height), snow depth on hummocks and depth of snow dunes connected to ice ridges have been done at a significant number of landings (Fig. 3). That data allows us to evaluate local variations of snow depth on single floes and to analyze spatial variability of snow irregularities over larger areas.

4.2 Snow depth of sastrugi

Observations of sastrugi height started in 1963, resulting in measurements from 1748 landings. Sastrugi area observations started in 1974, providing data from 1217 landings. A map of measured sastrugi heights is shown in Fig. 8a. Similar to the case of snow depth measurements, the highest density of observations was in the marginal seas.

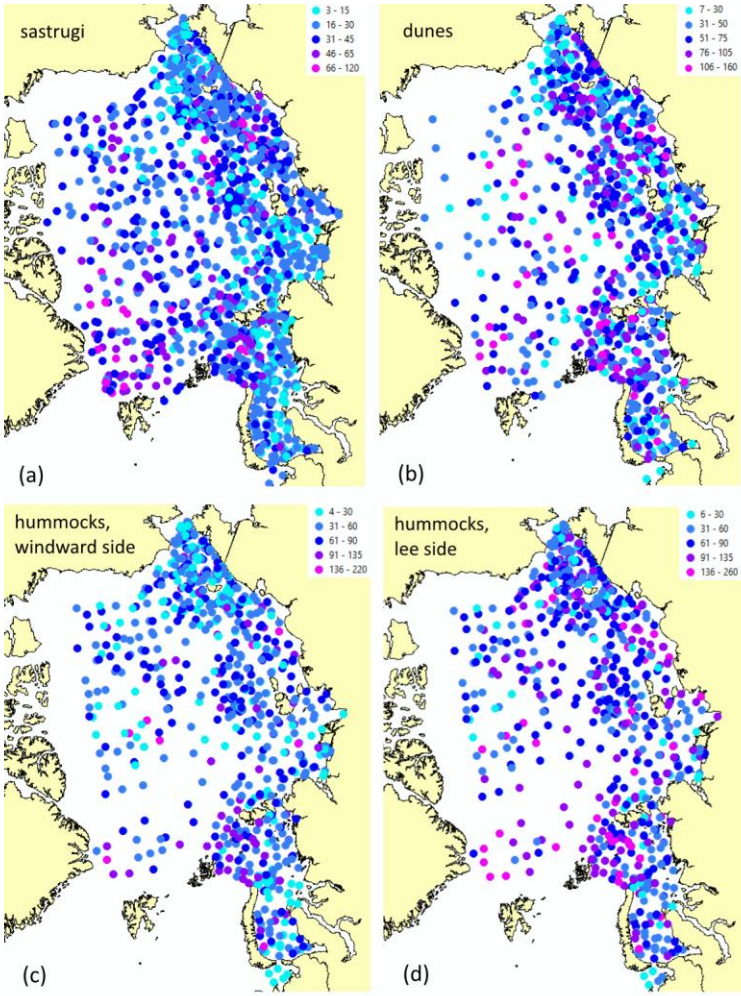


Figure 8. Height of sastrugi (a), depth of snow dunes extending out from ice ridges measured at a mid-length of a dune (b), snow depth on hummocks measured on the windward side (c) and snow depth on hummocks measured on the lee side (d), in cm. All observations were made in the MAM months.

It is reasonable to assume that the sastrugi height (~~SasH~~H_{sas}) is related to the depth of undisturbed snow (~~SD~~H_s) because both parameters were obtained from the same landing areas. To calculate such empirical relation snow data collected in the MAM months were grouped into 5 cm-snow-depth intervals, and the regression between averages in each interval were computed resulting in the following equation: ~~SasH = SD~~$H_{sas} = H_s$ +15.5 with the coefficient of determination (R^2) of 0.99, where ~~SasH~~H_{sas} and ~~SD~~H_s are in cm. The average sastrugi height variation of 10 cm is nearly constant over the full range of measured ~~SD~~H_s and ~~SasH~~H_{sas} values. This implies that in the case of small snow depth the height of sastrugi can be ten or even more times higher than the surrounding snow depth.

The relation between level snow depth and sastrugi height is used later in the study to estimate average snow depth on the ice surface in order to make Sever expeditions data compatible with NP stations data. Since area covered by sastrugi is only a part of the ice surface, it is important to assess the extent of sastrugi areas, which started to be observed from 1974.

Sastrugi height and area of FY and MY ice has been analyzed separately to get statistics for the two different ice types. The average sastrugi height on the MY ice was 35.4±16.0 cm and the average sastrugi area was 29.3±18.1% of the ice surface observed during the Sever expeditions. By comparing monthly mean values for the MAM months, the height of sastrugi on the MY ice had increased from 31 cm in March to about 38 cm in May. The average sastrugi height on the FY ice varied from about 18 cm on the thinnest visited ice to about 28 cm on the thickest FY ice (with the ice thickness from 190 to 200 cm). It is important to note that there was relatively ~~few~~little number of measurements on the thin ice. The sastrugi area changed from about 31% on the thin ice to about 47% on the thick ice. The monthly averaged sastrugi height on the FY ice increased from about 22 cm in March to about 31 cm in May.

Table 3. Summary statistics of the height and area of sastrugi on the prevailing type of ice in the landing area in the marginal seas of the Arctic Ocean.

Statistics	Central Arctic	Kara Sea	Laptev Sea	East-Siberian Sea	Chukchi Sea
			Sastrugi, cm		
Average	36.2	27.0	23.0	31.8	25.4
Std	15.8	15.3	11.9	15.8	12.8
Median	35.0	25	20	30	25
Min	5	4	3	5	3
Max	120	93	85	100	90
Number of measurements	489	458	293	290	218
			Area of sastrugi, percent of the ice area		
Average	29.3	34.9	38.1	40.7	32.2
Std	18.1	20.3	24.6	20.6	20.8
Median	20.0	30	30	40	30
Min	2	3	4	2	3
Max	85	100	100	90	90
Number of measurements	285	293	226	242	171

The sastrugi height in the marginal seas is the result of the length of snow accumulation period, wind activity, type of ice surface and some other factors. The summary statistics of the height and area of sastrugi for the marginal seas are presented in Table 3, showing that the sastrugi properties follow the level snow depth in different seas (shown in Table 2). For example, the largest sastrugi height is found in the East Siberian Sea which also has the largest level snow depth. In the Kara Sea relatively high value of the average sastrugi height is followed by high standard deviation. This may be explained by the high number of measurements in that region. Variability of the estimated sastrugi area is from 50 to 64% of the reported value that is predominantly governed by the natural diversity of the parameter.

Attempts to derive a relation between sastrugi area and sastrugi height did not provide any result in the case of MY ice. Generally, there is an increase of sastrugi area with increasing height; however the variability of the area values is very high. In the case of FY ice, the regression between ~~SasH~~H_{sas} averages in 5 cm intervals and corresponding sastrugi area values results in a sigmoid curve (an "S"-shaped curve) with the minimum value of about 25 cm, maximum of about 45 cm. The variability of the area was as large as 88% at the lower ~~SasH~~H_{sas} values end and 35% at the highest ~~SasH~~H_{sas} values end.

4.3 Depth of snow on hummocks and depth of snow dunes

Snow depth on hummocks was measured at more than 1300 landings in the period from 1972-1986 (Fig. 8, c and d). The estimated area covered by hummocks was 24% of the observed ice surface where hummocks existed. The snow depth measured on the windward surface of a hummock was typically 23 % smaller than magnitude observed on the leeward side, however in 25% cases equal depths of snow were measured on both sides of the hummock. The average snow depth was 58.8 ± 35.3 cm on the windward side of the hummock and 76.6 ± 36.5 cm on the lee side. The maximum snow depth observed on hummocks was found in the East-Siberian Sea in 1982 when 220 cm was measured on the windward side and 260 cm on the lee side. Average values of the hummock snow depth are highest in the central Arctic (Table 4) that can be expected. Differences in average snow depths on hummocks in the Siberian seas can be the result of selectiveness of measurements. Winds in the central Arctic are weaker than in the Siberian seas and wind speed is less variable (Frolov et al., 2005, Martin et al., 2014), which gave a smoother snow depth histogram for the central Arctic in comparison to marginal seas (Fig. 9). Asymmetry in distributions of the snow depth on hummocks in the seas is the result of stronger and changeable winds and also perhaps a consequence of the movement of the floes. For example, rotation of the floes can swap windward and leeward sides of the hummock.

Depth of snow dunes extending out from ice ridges has been measured at mid-length at 1012 landings from 1974 – 1986 (Fig. 8b). The average observed value was 57.1 ± 27.0 cm and the maximum was 160 cm. Values obtained in the central Arctic were 16% higher than in the marginal seas (Table 4). Difference in the average values for marginal seas is perhaps the result of the selectiveness of measurements.

From the Sever observations, the snow depth of the dunes behind ice ridges could be estimated in relation to surrounding snow cover. Note that this characteristic cannot be obtained through comparison of average values of snow depth on the level ice (Table 2) and depth of the dunes behind ice ridges (Table 4) because the depth of snow dunes was not measured at every landing. The average (over the whole Arctic) snow depth on the level ice in the neighborhood of ice ridges was 13.8 cm with the median of 10 cm, being lower than average from all landings. It means probably that if there is a trap for blowing snow like an ice ridge, snow is relocated there from the level ice into considerable accumulations. Comparison of the depth of snow dunes extending out from ice ridges and snow depth on the surrounded ice measured during the same landing showed that in the central Arctic the depth of dunes measured on their mid-length was 4.5 times greater than the level snow cover. In the marginal seas the dunes in the midpoint of their length were 4.5 - 8 times higher than the surrounded snow cover.

The depth of snow dunes that stretch out from ice ridges depends on the height of the ridges. Sea ice ridges are elevated structures that form when ice floes are moved by wind, ocean currents, or other forces relative to each other that results in colliding and producing a lot of ice fragments that are piled up along a line, with the steep-sloped edge. The height of the ridge above sea level depends on several factors, the thickness of the compressed ice being one of them. Hibler et al. (1972) provided the value of about 1.3 m as an average sail (a part of the ridge that is above the water surface) height basing on data collected in the Baffin Bay in 1970 on the ice of 1.2 m and 0.6 m average thickness. During Sever expeditions a parameter called "prevailing height of ridge hummocks" was observed. In the description of the ice measurements during a landing it is indicated that "the heights of several typical ridges were measured, with 5-10 measurements on each ridge", thus we can use the mentioned parameter as a reasonable representation of the average sail height. The data have been collected over the whole Arctic area and the average sail height measured on the ice with the thickness less than 2 m (1504 landings) was about 1.5 m and the same average on the thicker ice (818 landings) was about 2 m. We can assume that the most heavily ridged ice was inaccessible for airborne expeditions and reported values most probably underestimate the real height of ridges.

The distribution of depth of snow dunes extending out from ice ridges (Fig. 9) reflects differences in morphology of sea ice in different parts of the Arctic, and partly, probably, is the results of bias in the sampling of measurements. In the central Arctic the highest values were observed in connection to the largest ice ridges (Table 4). MY ice is exposed to various deformations in different years and structure of a ridge undergoes continuous evolution due to new ridging, freezing, melting and erosion. MY ice ridges therefore become smoother with time; along with that fresh ridges emerge and are present among the old ones.

In the Kara Sea, there was the ~~second after central Arctic~~highest number of measurements comparing to other seas that probably allowed ~~covering~~observing most cases of snow ~~dunes~~dune layouts and states. The ice where measurements were conducted in that sea was quite thin, with the average thickness of about 110 cm; however the prevailing height of ridges averaged over all landings was 153 cm, being close to the same parameter in the East-Siberian and Chukchi seas (159 cm) where presence of MY ice implies existence of higher ridges. Availability of high snow dune depths (see the tail in the histogram, Fig. 9) that were observed near large ice ridges provides a high average snow dune depth of 57.0 cm. In the Kara Sea the difference between the depth of snow dunes and the depth of snow cover in the landing area was the highest, being 48.7 cm on the average. In the Laptev Sea, the prevailing height of ice ridges was estimated at 140 cm and averaged depth of snow dunes attached to ridges was 51.2 cm. The smoothness of the histogram (Fig. 9) is perhaps a result of equal representation of all heights of ridges that happened to exist on the landing spots. More irregular histograms for the East-Siberian and Chukchi seas (Fig. 9) is caused by presence a substantial fraction of the MY ice there. Average depth of snow dunes in the East-Siberian Sea was the highest among all marginal seas, being 59.0 cm on the average. Lack of the highest values of the snow dune depth in the Chukchi Sea can be explained by strong winds that are typical for that area (Martin et al., 2014) or perhaps by insufficiency of measurements. Collected observations resulted in 49.5 cm average snow depth of the dunes attached to ice ridges in the Chukchi Sea, with the lowest difference between the depth of dunes and the depth of snow cover in the landing area (36.1 cm).

Table 4. Depth of snow in dunes extending out from ice ridges and on the hummocks in different parts of the Arctic.

Region	snow dunes		snow on hummocks	
	average depth, cm	number of measurements	average depth windward/lee side, cm	number of measurements
Central Arctic	64.9±28.9	241	64.4±29.7 / 81.8±36.3	171
Kara	57.0±28.0	222	59.8±31.2 / 78.3±38.2	136
Laptev	51.2±26.4	157	55.2±28.2 / 71.5±36.9	95
East Siberian	59.0±25.3	215	57.6±30.1 / 76.2±36.6	142
Chukchi	49.5±21.2	161	50.4±26.1 / 72.3±34.9	172

4.4 Snow depth on ~~fastice~~fast ice

~~Fastice~~Fast ice is the part of sea ice that stays relatively immobile because it is attached to the coastline or to the shallow sea floor. The most extensive fast ice cover is formed in the Laptev, East-Siberian and Kara seas; the East-Siberian Sea is characterized by the largest fast ice area in the Arctic and the greatest interannual variability (~~Yu et al., 2013;~~ Johannessen et al., 2007, Yu et al., 2013). Since ~~fastice~~fast ice in general does not move, it provides conditions where snow can accumulate from the beginning of winter being relocate only by the wind. ~~Fastice~~Fast ice is smooth when it forms but can be deformed during wind events or when drifting ice is pushed against the seaward boundary of the ~~fastice~~fast ice. In these cases the ice can become highly deformed with shear ridges or stamukhi (Barry et al., 1979). ~~Such~~The areas of stamukhi were not observed by Sever expeditions because landing was not possible.

The average snow depth on the prevailing ice of landing area on the fast ice was 15 ± 13 cm with the average ice thickness where landings occurred being 169 ± 48 cm. The average sastrugi height was 29 ± 16 cm. How average snow depth and sastrugi height change from one area to another is illustrated by Table 5. There is also indication of the proportion of measurements carried out on the ~~fastice~~fast ice in comparison to all measurements performed in the sea.

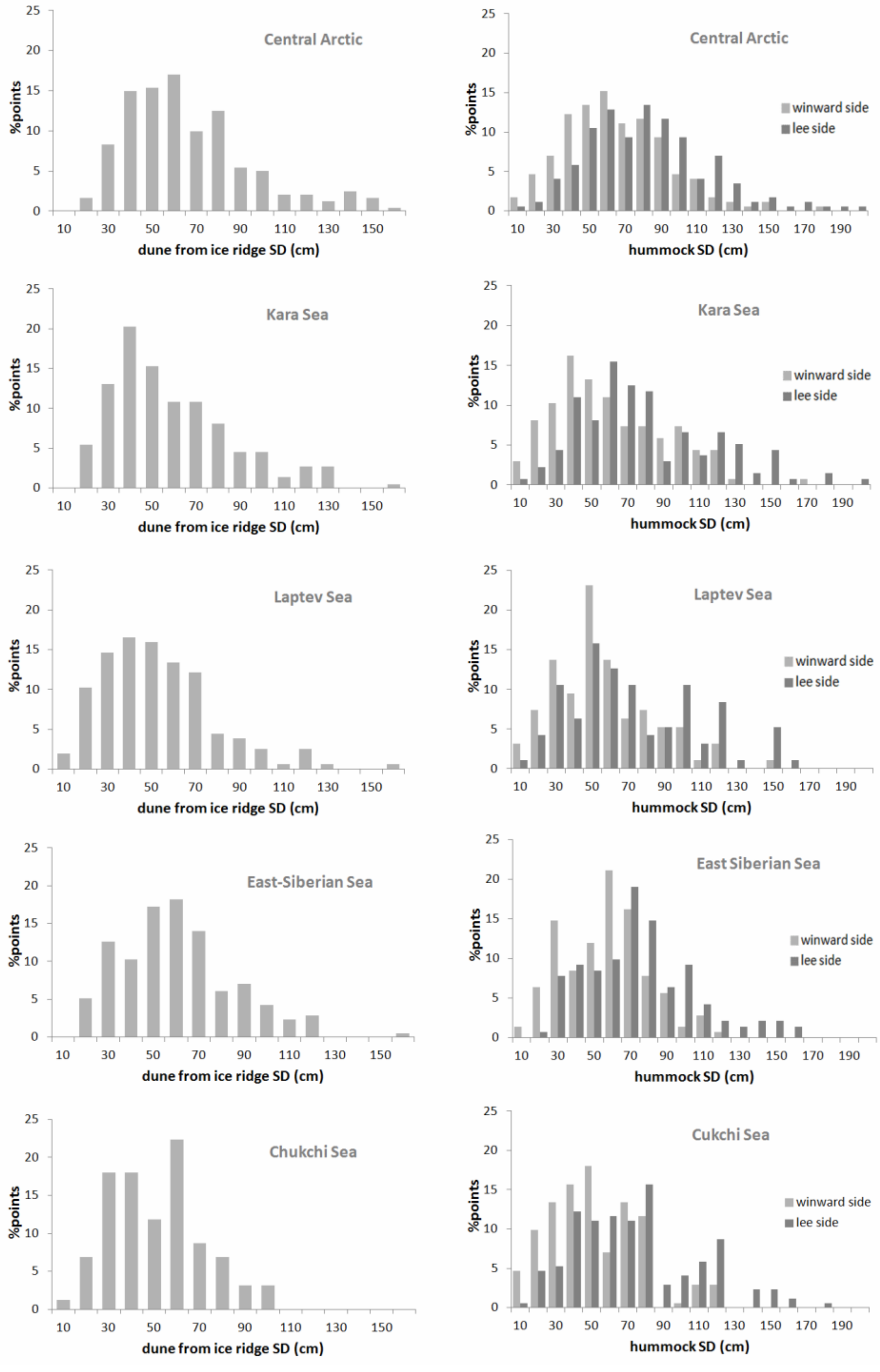


Figure 9. Distribution functions of snow depth in the dunes and around hummocks (on the windward and on the lee side) in different parts of the Arctic.

The small number of measurements in the Chukchi Sea was caused by limited possibilities of taking such observations because the ~~fastice~~fast ice in this region is formed in a narrow zone near the coast. The other marginal seas had much more landings on ~~fastice~~the fast ice. The analyzed data can be biased due to sampling, for example in the Kara Sea in the north-eastern part of the sea and in the Vilkitsky Strait, where sampling in the 1960s was much denser than in any of the other areas. There is lack of other studies that makes it difficult to assess the values shown in Table 5. The deepest snow covering fast ice was observed in the Kara Sea with the highest variability; the same is valid for sastrugi. That perhaps is (at least partly) a result of combined effect of the intensity of precipitation and air masses movement, which has specific characteristics because of existence of relatively sheltered areas. The lowest values of snow depth have been recorded in the Laptev Sea, which is characterized by comparatively low level of ridging (Eicken et al., 2005) allowing the snow to be blown off the ice surface.

Table 5. Average snow depth on the level ice and height of sastrugi in the ~~fastice~~fast ice area.

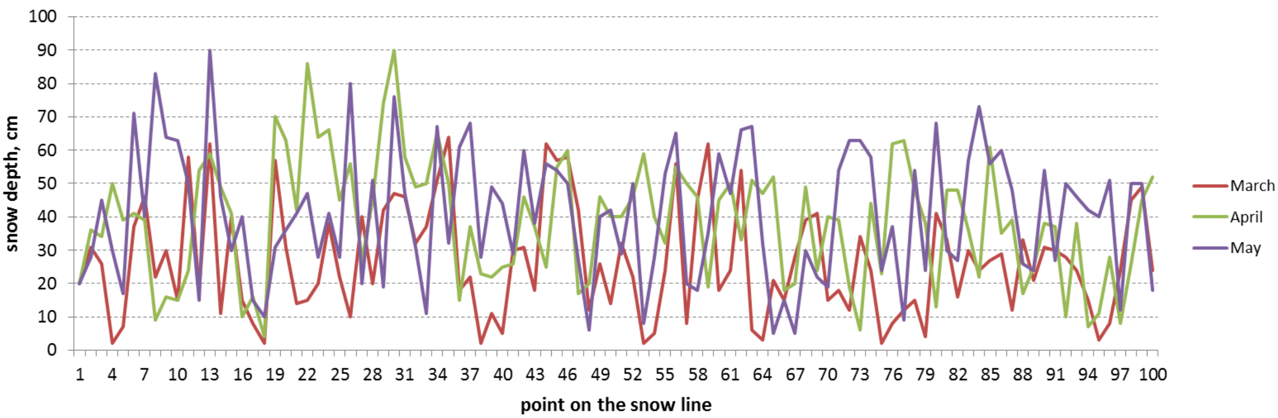
	Snow depth on prevailing ice			Sastrugi		
Region	Average depth, cm	Number of measure-ments	Percent of all ~~measure-ments~~measurements, %	Average height, cm	Number of measure-ments	Percent of all measurements, %
Kara	17.0 ± 16.0	243	38	34.2 ± 18.4	181	39
Laptev	11.6 ± 9.1	204	46	22.2 ± 11.7	147	50
East Siberian	14.2 ± 8.4	151	41	32.9 ± 13.9	90	31
Chukchi	15.9 ± 13.5	15	7	23.3 ± 10.7	11	5

In the Kara and Laptev seas the average snow depth measured on the level ~~fastice~~fast ice (see Table 5) is higher than the snow depth on the level ice averaged for the whole sea (see Table 2). That can be explained by longer (on the average) period of ice existence in the case of ~~fastice~~fast ice. The standard deviation is also proportionally higher. In the East Siberian Sea the average snow depth on the ~~fastice~~fast ice is lower than the same parameter of the whole sea, probably because the relatively high proportion of MY ice outweighed ~~fastice~~fast ice in benefits for snow accumulation. In the Chukchi Sea the similar comparison is hardly have meaning because the number of measurements on the fast ice was too small.

4.5~~–~~ Combining NP and Sever data for the MAM months

When merging NP and Sever data it is important to treat the data in such a way that comparison makes sense and a combined product is meaningful.

~~With the present data it is difficult to process the Sever data to make them similar to NP~~ NP drifting station ~~data because~~ snow ~~depth~~ observations ~~from the NP data~~ were not accompanied by any ice observations. Therefore the variability in NP snow depth measurements cannot be explained from different ice characteristics. That complicates processing Sever data with the aim to make them similar to NP data. The only information about NP snow measurements is that the NP data were collected from a solid MY floe. Figure 10 represents snow line observations made by NP16 drifting station personnel in 1969 in the MAM months. It shows that spatial variability of measured values was very high. The range of values over the same line was from 2 to 64 cm in March, from 4 to 90 cm in April and from 5 to 90 cm in May. The low correlation between repeated measurement lines (0.18 between March and April and 0.04 between April and March) suggests that the variations ~~are caused by wind.~~ were primarily caused by wind. Average snow depth increased from 26.4 cm in March to 40.6 cm in May and the number of high snow depths has increased correspondingly (Fig. 10 b-d).



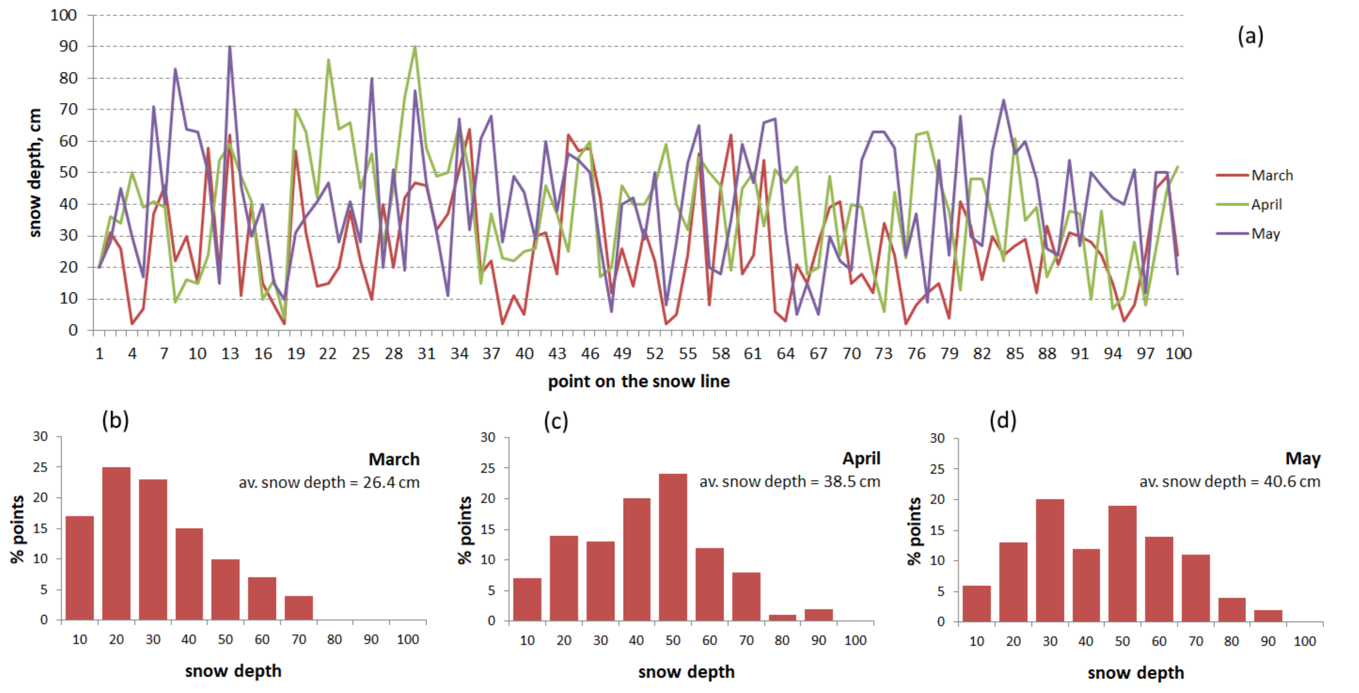


Figure 10. (a) Snow line measurements made in 1969 in the MAM months during the work of NP16 drifting station. The length of snow line was 1 km. (b) - (d) Distributions of measured snow depths in March, April and May 1969.

~~Thus, in~~In order to produce an integrated map ~~of snow depth on the sea ice~~ that describe the average state of snow cover in the MAM months, the Sever ~~data~~ and ~~the~~ NP ~~observations~~measurements have been combined ~~in the following way. From~~by gridding all Sever ~~observations only~~ data on snow depth on the ~~prevailing~~level ice ~~of the landing area were used, adjusted by adding the~~together with NP data. The height of sastrugi weighted in proportion to the sastrugi area~~. Sastrugi height has been~~ was added to each Sever snow depth ~~on the level ice~~in a grid cell using the ~~relation between SasH and SD and average proportion of the area covered by them for different parts of the Arctic Ocean~~ formula

$$H_{sev} = H_s + P_{sas}^{reg} \cdot H_{sas}, \quad (2)$$

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 region of snow measurements (see Table 3). In the central Arctic, where the ice was mainly perennial ~~only~~ at the time of measurements, only observations made on the MY ice during Sever expeditions have been included into computation 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

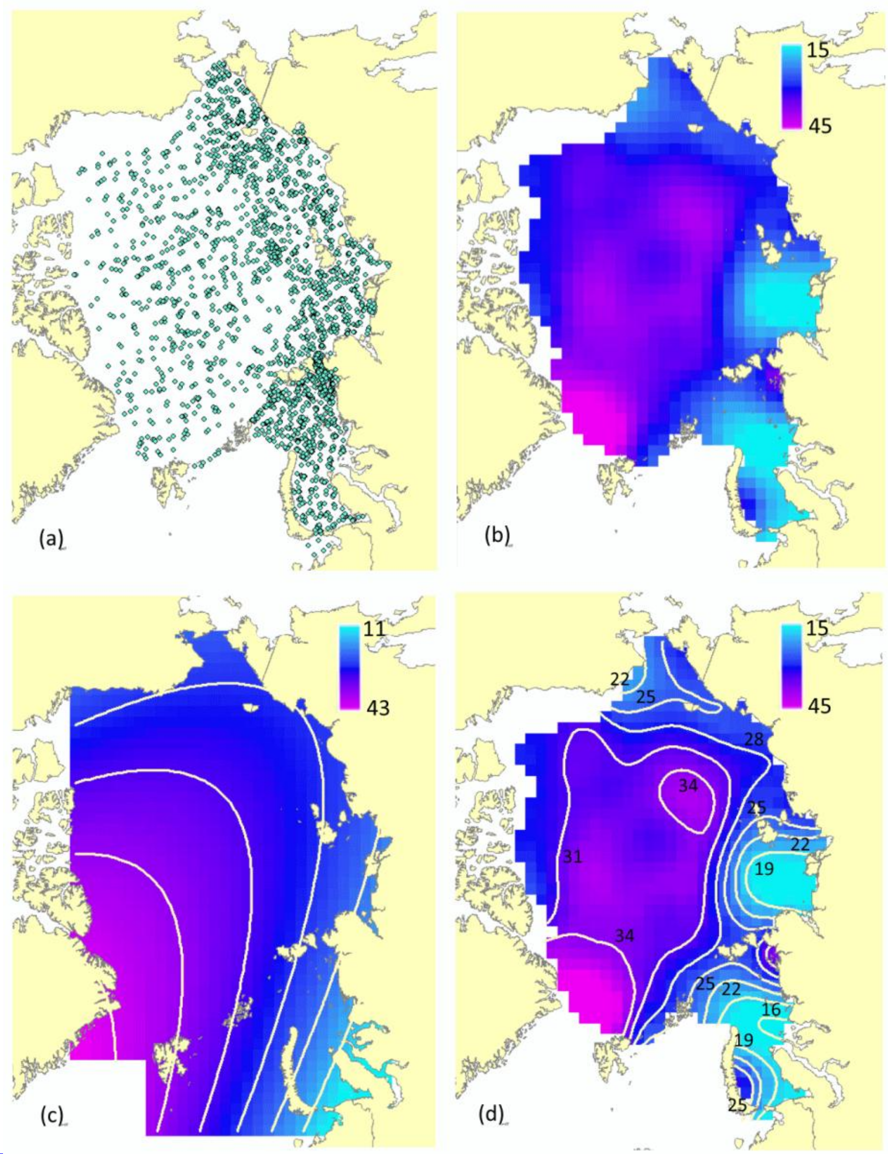
Arctic, especially north of the Canadian Archipelago, where the highest concentration of the ridged ice is expected (Bourke and McLaren, 1992, Makshtas et al., 2003, Shoutilin et al., 2005).

The snow depth distribution on the sea ice in the MAM months in 1960-80s has been generated using ~~2331~~2302 points, 143 of which were monthly averaged NP data~~. The distribution of these points is presented in Fig. 11a.~~ and others were Sever snow depths calculated as described in the previous paragraph. Two approaches have been used to produce a new snow depth map for the MAM months in the Arctic. The first approach was based on gridding as described in Sect. 3 with a grid resolution of 100x100 km. The result is presented in ~~Figure 11b~~Fig. 11a. The projection is North-Pole Stereographic with the central meridian 20° E and the ~~latitue~~latitude of origin 90°. Standard deviation of the data shown in Fig. 11a is represented by Fig. 11b. It is calculated as a weighted standard deviation from variances of H_s and H_{sas} and a weight of 0.35, which is an average portion of sastrugi area in the Arctic (see Table 3). The second approach was similar to the one used by W99. The two-dimensional quadratic fit has been calculated using the combined data set of ~~2331~~2302 points. The result is shown in Fig. 11c. It is a much smoother data set compared to map in Fig. ~~11b~~11a. The detailed mapping of the snow depth in the marginal seas is lost~~ in this data set. ~~. The two-dimensional quadratic fit has been calculated as

$$H_s = H_0 + C_1 \cdot x + C_2 \cdot y + C_3 \cdot x^2 + C_4 \cdot xy + C_5 \cdot y^2 , \quad (3)$$

where H_0 = 35.05 cm, $C_1 = -4.69\cdot10^{-6}$, $C_2 = -1.46\cdot10^{-6}$, $C_3 = -2.27\cdot10^{-12}$, $C_4 = 2.91\cdot10^{-12}$, $C_5 = -1.16 \cdot 10^{-12}$, x and y are coordinates in the North-Pole Stereographic projection. Units of x and y are meters. To support the comparison between the new and the W99 climatologies, Fig. 11d shows W99 climatology for the MAM months, which is an average of the mean snow depths for March, April and May.

The contour lines generated from the gridded data are shown in Fig. ~~11d~~11a where the spatial variability in the marginal seas is well captured. The lowest snow depth is found in the middle of Kara and Laptev seas where the sea ice was absent in the summer for most of the years. Increased values of snow depth near Novaya Zemlya, Severnaya Zemlya and in the Yana Bay is associated with the ice massifs in these areas consisting of thick rough ice. Relatively high values of snow depth in the East-Siberian Sea are connected to large amount of MY ice in the area. In the Chukchi Sea, there were less MY ice than in the adjacent East-Siberian Sea but more than in Laptev and Kara seas. In the central Arctic, there is much less data available for each grid cell, leading to larger uncertainty compared to the marginal seas. In the Canadian sector there is very little observation data and the map in Fig. ~~11b~~11a shows too little snow depth in an area where ice thickness is known to be largest.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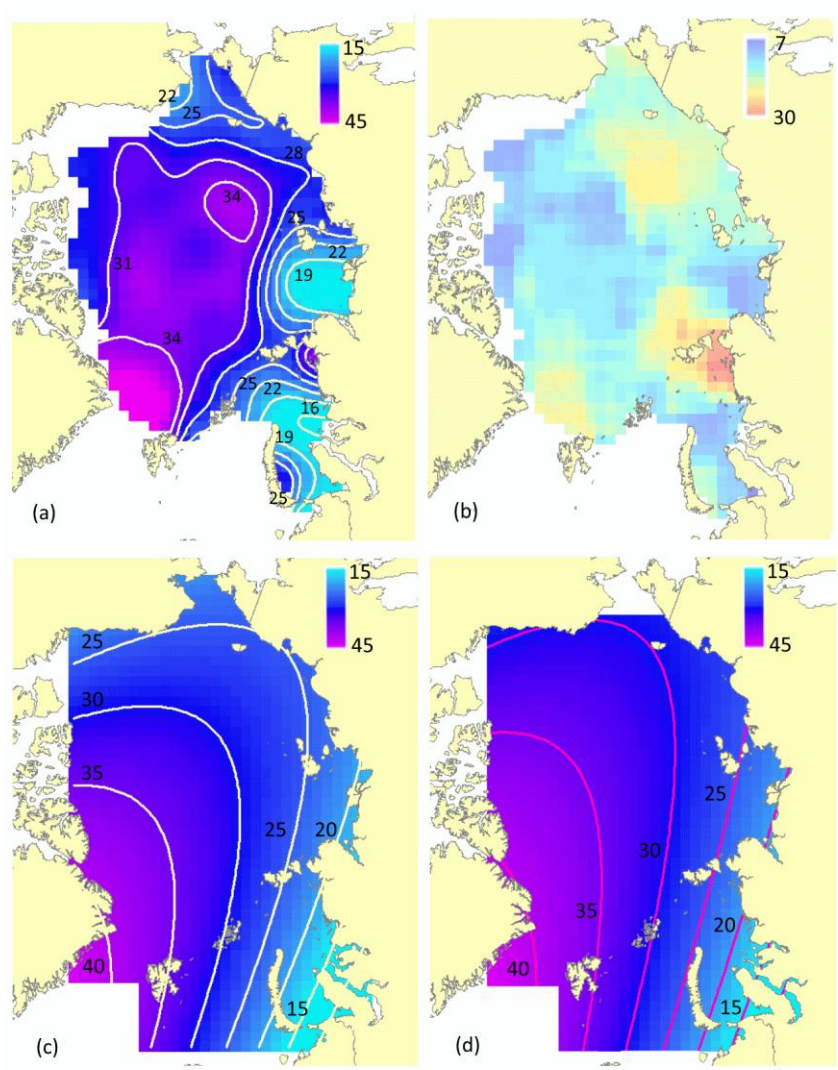


Figure 11. Map of snow cover depth (in cm) on the sea ice in the MAM months in 1959-1988: a) ~~positions of local measurements from Sever and NP expeditions – the base for gridding, b)~~ gridded data with the grid cell 100x100 km~~, c) map produced in a way similar to the one used in Warren et al. (1999), d) gridded data with~~ 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 shown by formula (3), d) Warren climatology averaged for the MAM months.

4.6 Contemporary in situ snow depth measurements

In the changing Arctic climate it is important to have contemporary data on snow parameters that can be compared to historical data such as the Sever data. After 1989 no extensive observations like those from the Sever expeditions have been collected. So there is no similar data from present years that can be compared with historical data to assess changes in snow cover on sea ice. In the last two decades in situ measurements of snow depth from various automated buoys have been collected, in particular from Ice Mass Balance buoys (IMB), see (Richter-Menge et al~~.;~~., 2006, Polashenski et al., 2011~~;~~, Perovich et al., 2013.). Buoy measurements provide time series of the snow depth gained from the same position on an floe, providing good data on time evolution of snow depth, but very limited data on spatial variability. The Sever data were opposite providing good spatial coverage, but very limited temporal coverage. The NP data were more similar to IMB data, but allowed spatial sampling inside a 1 km grid. Attempts were made to compare the Sever/NP estimates with contemporary IMB estimates in order to detect possible trends in snow depth over the last five – six decades.

Snow depth data from selected IMB buoys that were deployed on sea ice and operated through the winter season from 2011 to 2015 have been analyzed for the MAM months. The buoys, which were provided by CRREL, were placed on the level ice, measuring snow depths at specific sites of MY ice floes. Changes in snow depth were therefore caused by precipitation and wind action. Time series of snow depth from buoys in different parts of the Arctic are presented in Fig. 12. The snow depth variations over the three month period are small, except for a few buoys which registered significant changes due to some abrupt snow events. The average snow depth from all the buoys in the MAM months is 27 cm while the median depth is 24 cm. The time-averaged snow depth for each buoy varies from less than 10 cm (2011J) to more than 50 cm (2013F). The spatial variability in snow depth from the 10 buoys seems to be random. The average IMB snow depth of 27 cm compares well with the average Sever snow depth of 21 cm in the central Arctic, but different sampling schemes makes it difficult to draw any conclusion from these measurements.

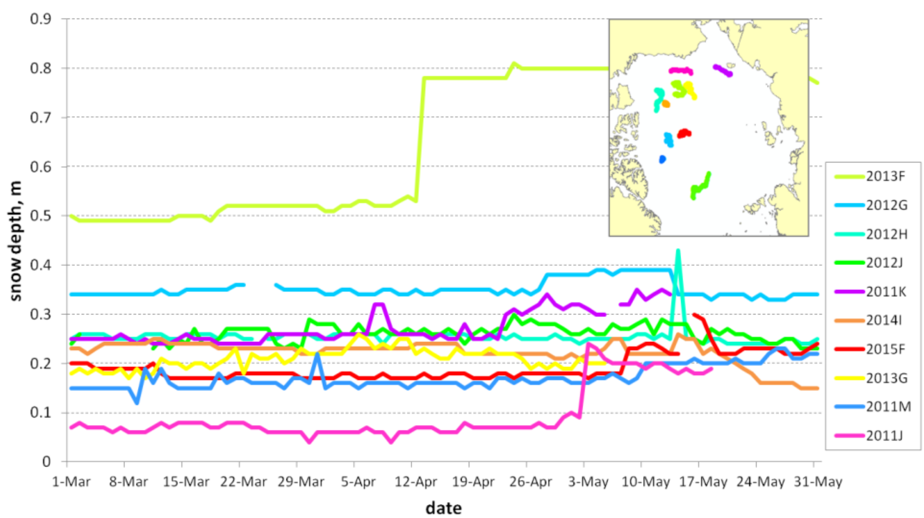


Figure 12. IMB observations of snow depth in the MAM months, 2012-2016, provided by CRREL. The number before a letter in the buoy's name indicates the year when the buoy has been deployed. Tracks of the buoys in the MAM months are shown on the map.

Another snow depth data set is provided by AWI (Nicolaus et al., 2016), which deployed snow buoys on FY ice floes in the central Arctic in 2015. The FY floes became second-year ice in the following winter. The buoys drifted towards the Fram Strait as shown in Fig. 13. The average snow depth in the MAM months of 2016 was 21±9 cm, which is very similar to the Sever data in the central Arctic. Although the buoys were located quite close to each other they measured rather different snow depths, varying in the range from 10 to 40 cm. This is another example of large spatial variability in the snow depth within a relatively limited area, illustrating the challenge of sampling snow depth on Arctic sea ice.

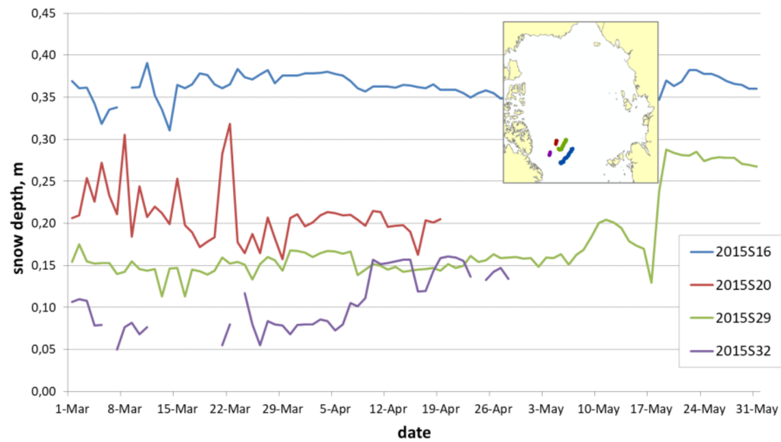


Figure 13. Snow depth AWI buoy in the MAM months of 2016. All buoys measured snow depth on the second-year ice. The plots show daily averages of snow depth from four buoys.

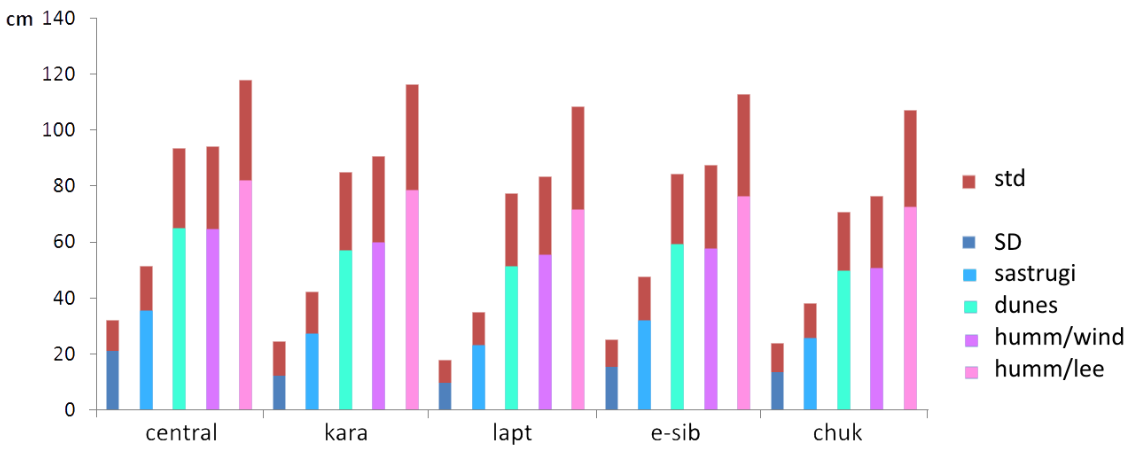
5 Discussion and Conclusions

This paper presents an analysis of ~~data from the high-latitude airborne expeditions Sever collecting~~ snow depth and other ~~parameters on~~ Arctic sea ice data from the Sever expeditions and the North Pole drifting stations in the period 1959-1989. By merging snow depth data from the ~~Sever expeditions with the NP drifting station observations, a~~ two extensive observing programmes, a new snow depth climate data set has been provided for the end of winter ~~months~~season (March, April and May). This ~~is the main result which~~data set is an important extension ~~to~~of the previous snow depth climatology provided by W99. The ~~result~~data set is also important as a reference data set for comparison with contemporary and future observations of snow cover in the Arctic.

The Sever measurements were obtained over large parts of the Arctic sea ice mainly during March, April and May when the aircraft could land on sea ice. Snow and sea ice data were collected both from the runway and the surroundings of the runway, called “prevailing ice of the landing area”. A total of 3234 landings were conducted, of which 2331 provided snow depth measurements. The landing areas were chosen in order to collect representative data in different parts of the Arctic Ocean. Analysis of the Sever ~~expeditions~~ data for the whole Arctic shows that the average ~~of all~~ snow depth ~~measurements on the~~ of level ice was 14.3 cm with the standard deviation ~~(std)~~ 11.9 cm~~,~~. The average depth of sastrugi was 30.1±15.7 cm,

~~for~~of snow dunes attached to ice ridges ~~it was~~ 57.1±27.0 cm, and ~~for~~of snow on hummocks ~~it was~~ 58.8±35.3 cm ~~on the~~ (windward side) and 76.6±36.5 cm ~~on the~~ (lee side ~~of the hummock.~~).

The ~~analysis~~results for ~~each of the~~different Arctic regions ~~is~~are presented in Tables 2, 3, and 4 and summarized in Fig. 14~~, which is a graphical presentation of the numbers in Tables 2-4. Average~~. The Central Arctic has an average snow depth ~~on the~~of level ice ~~in the Siberian seas changed~~of 21 cm, while it varies from 9.6 to 15.2 cm ~~and was about 21 cm in the Central Arctic. It had the highest spatial variability (among other snow depth measurements) that ranged from 51% in the Central Arctic to 100% in the Kara Sea. In the seas,~~in the marginal seas. The average sastrugi depth ~~was in the range~~varied from 23.0 to ~~31.8 cm, being the highest in the East-Siberian Sea. In the Central Arctic the average sastrugi depth gained~~ 35.4 cm.~~ The variability of sastrugi depth was lower than variability of depth of undisturbed snow with standard deviation (std) ranging from 45% in the Central Arctic to 56% in the Kara Sea.~~ The average depth of snow attached to ice ridges was in the range from 49.5 cm in the Chukchi Sea to 64.9 cm in the Central Arctic~~ and it showed variability from 43 - 52%.~~. On a windward side of the hummock the ~~highest~~ average snow depth ~~was observed~~ varied from 64.4 cm in the Central Arctic ~~being 64~~to 50.4 cm ~~and the lowest~~ in the Chukchi Sea~~, 50.4 cm, with std about 52% and on~~. On the lee side the average snow depth was in the range from 71.5 cm (Laptev Sea) to 81.8 cm (Central Arctic~~) with std about 48.~~). The average snow load on the ice in the Arctic can be described as a combination of the depth of undisturbed snow on the level ice and snow depth of sastrugi that covered about 35% of the ice surface. Furthermore, the average snow depth should include a contribution from snow connected to hummocks and ridges. But since there was no adequate data on the area covered by hummocks and ridges from Sever expeditions, this factor could not be included in the snow depth climatology, implying that it is probably underestimated.



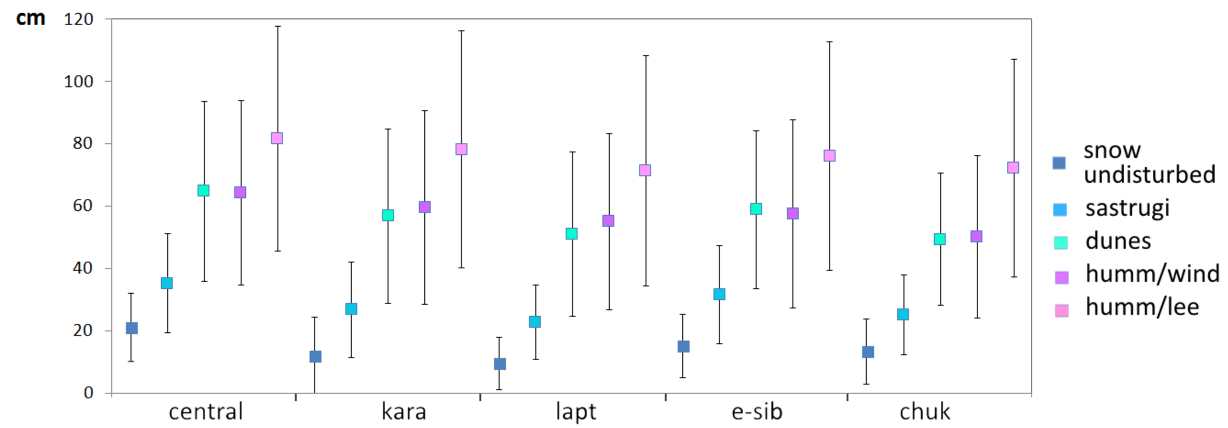


Figure 14. Sever snow depth observation statistics in the MAM months: ~~snow~~ depth of undisturbed snow on the level ice ~~(SD),~~, snow depth of sastrugi, snow depth of dunes extending out from ice ridges, depth of snow on windward and leeward sides of the hummock and corresponding standard deviations. Data shown are averages for the central Arctic and for the four seas: Kara, Laptev, East-Siberian and Chukchi.

The snow depth data set by W99 ~~has been~~was obtained ~~from~~by gridding of relatively limited data from the North Pole Drifting Stations using a quadratic fit. The present ~~result~~data set, which has been obtained by averaging a much larger ~~data set~~ number of observations from the Sever expeditions ~~into a 100 by 100 km grid for the MAM months. This is because the Sever data were only collected in these months when aircraft landings on sea ice were possible.~~ ~~Comparison of the new snow depth data with W99 shows that the new map is based on much more observations~~ , especially in the marginal seas, ~~and~~ is therefore more ~~realistic~~representative than the W99 data~~.~~ for the MAM period. Furthermore, the new data set ~~has~~shows a lower average snow depth in the central Arctic compared to W99. That can be explained by the fact that the NP data was collected on one MY ice floe per year, while the Sever data ~~added~~aggregated observations ~~collected on~~from a large number ice floes ~~representing more~~ , providing a better representation of the spatial variability. The NP data ~~allow also estimation of~~ , on the other hand, provided information on the seasonal evolution of the snow depth on a single MY-floe. The NP data could therefore be used to estimate the temporal standard deviation ~~over time in~~for the MAM ~~months~~period, which was 2.1 cm ~~using all available NP data. The same characteristic can~~. A similar temporal standard deviation could be derived from contemporary buoy measurements, ~~resulting in~~which was 3.7 cm for the 10 CRREL buoys and 3.1 cm for the four AWI buoys.

~~The average snow load on the ice can be described as a combination of 21.2±10.9 cm depth of undisturbed snow on the level ice and 36.2± cm snow depth of sastrugi that covered about 36% of the ice surface. Furthermore, the average snow depth should include a contribution from snow connected to hummocks and ridges. The average snow depth around that features is about 65 cm (82 cm on the leeward side of the hummock). But since the area covered by hummocks and ridges is unknown, this factor is not included. On the other hand, the present average snow depth is probably underestimated because data from the largest hummocks and ridges are not included due to the fact that the Sever landings could not sample these areas.~~

The W99 climatology is based on data collected on the MY ice mainly in the central Arctic and is therefore only valid for snow on MY ice. In the marginal seas, there is a mixture of MY and FY ice, which have very different history of snow accumulation. All the marginal seas ~~were~~are completely covered by ice in winter (with the exception of the south-western part of the Barents Sea). FY ice ~~is~~was dominant in most seas, ~~fastice is~~fast ice was present along the coasts and MY ice ~~is~~was present in various degrees. The ~~integrated~~current snow depth ~~map from the present study~~climatology is based on ~~1678~~1699 landings in the marginal seas~~ and~~, 460 Sever landings in the central Arctic Ocean and 143 NP averages for the MAM months. The snow depth climatology from this study should therefore be well representative for the three decades when data were collected.

In the last decades, the Arctic sea ice has changed significantly~~. One~~, in particular due to the reduction of the ~~characteristic trends is the reduced amount of ice that survives summer melt (Comiso, 2012; Stroeve et al., 2012; Parkinson and Comiso, 2013; Kwok and Cunningham, 2015; Wang et al., 2016). This is closely connected with the~~MY ice, increased fraction of FY ice, with a corresponding thinning of the ~~sea ice (Kwok and Rothrock, 2009; Kwok and Cunningham, 2015;~~total ice cover (e.g. Wadhams, 2012~~) and the change in the ice age distribution with less MY ice and more FY ice (~~, Kwok and Cunningham, 2015, Tschudi et al., 2016). ~~-~~Later onset of freeze~~ (Stroeve et al., 2014)~~ and correspondingly later start of snow accumulation is the last but not the least factor that determine snow depth distribution in present time (Wang et al., 2013~~;~~, Stroeve et al., 2014, Webster et al., 2014).

The~~ new~~ snow depth climatology from the Sever data ~~represents~~from the period 1959 – 1989 and is therefore not necessarily valid for the present situation in the Arctic. But results of the study can enlighten several aspects of the snow on ice problem which is important today. The difference between MY and FY regarding snow cover~~,~~ has impact on estimation of energy fluxes from ocean to atmosphere in coupled models, ~~the impact on snow cover on~~ on satellite altimeter retrievals of ice thickness and passive microwave retrievals of thin ice thickness (Tian-Kunze et al~~.;~~., 2014, Key et al., 2016).

~~Snow on MY ice may completely melt during summer; however it does not melt completely in some areas (Radionov, 1997). The most important aspects in gaining snow depth on the MY ice are meteorological conditions and ice roughness. Observations from the AWI snow buoys are few, but give an indication of how MY snow depth varies with meteorological conditions. Average MAM snow depth on the MY ice in the central Arctic in recent years is 24.3±0.7 cm according to IMB buoy measurements from CRREL and 21.2±9.4 cm according to AWI snow buoy measurements. These values are in agreement with the statistics obtained for snow on MY ice in our study. Therefore, we suggest using climatological snow depth for MY ice in current ice conditions.~~

Most in situ snow measurements that were taken during validation campaigns in the last 20 years were collected in the Western Arctic covering near-shore regions of the Chukchi Sea, Elson Lagoon, some areas in the Beaufort Sea, some places in the Canadian Arctic among the islands and in a near-shore area close to Greenland. Those regions are poorly represented in the Sever data collection or not represented at all. Besides, the mentioned observations describe snow conditions in a particular year when the measurements were conducted that can differ from the average. However, it can be noted that the mean snow depth of 33.7 ± 19.3 cm measured at SHEBA during April and May (Sturm et al., 2002) is comparable with the snow depth for that area in the present gridded data. In our case the value is a bit lower and it is most probably a consequence of not including snow attached to ice ridges into calculation together with low density of available Sever measurements in that area. Average snow depth reported from Navy Ice Camp located at 72°55’ N, 147°34’ W, closer to the coast in comparison to SHEBA, was 20.6 ± 18.8 cm (Sturm et al., 2006), which is also in a good agreement with the gridded Sever data. Observations in an area north of the Greenland coast describe average snow depth as 25.7 ± 26.3 cm on the combinations of FY and MY ice near the coast (Farrel et al., 2012) and as 41.5 ± 19.6 cm on the MY ice 50 km off the coast (King et al., 2015) and that range of values agrees with the new climatology. Snow depth measured during the N-ICE2015 campaign in the area north of Svalbard in the end of winter was 52±12 cm over second-year ice and 33±14 cm over FY ice (Gallet et al., 2017). It is higher than the average climatology suggests, however, along with that, it is within the range of observed snow depth and sastrugi height values in that region. The average snow depth on the MY ice in the central Arctic for the MAM period is 24.3±0.7 cm according to recent IMB buoy measurements from CRREL and 21.2±9.4 cm according to AWI snow buoy measurements. These values are in agreement with the measurement of snow depth on MY ice in our study.

The existence of ice ridges and hummocks has significant impact on the snow distribution on sea ice. The Sever expeditions provide useful data to quantify properties of snow accumulated around these features. But ridges and hummocks are also changing over last decades due to less MY ice and more FY ice. According to Wadhams (2012), the reduction in ice thickness has been accompanied by loss of ice in ridges, particularly in the MY ice. ~~One may speculate what the effect is on the snow accumulation.~~ For FY ice the average sail height has been reported to be about 0.7 m (Strub-Klein and Sudom, 2012) for some parts of the Arctic using data collected in the period from 1976 to 2011. This estimate can be compared with similar data ~~form~~from the Sever expeditions, showing an average sail height of 1.5 m. This suggests that snow dunes attached to FY ice ridges have been reduced significantly.

The Sever expeditions represented a unique observing programme in the Arctic, which is not likely to be repeated anytime in the future. Present and future observations of snow and sea ice will rely on satellites, aircraft and automated buoys, as described in Sect. 4.6. Satellite observations from altimeters, Synthetic Aperture Radar and optical /Infrared sensors will be the backbone of a monitoring system for the polar regions, especially for sea ice and snow measurements. In addition, a network of ice buoys to observe temporal changes and regular aircraft/UAV surveys to observe spatial variability will be essential to monitor snow and other sea ice properties as supplement to and validation of the satellite measurements.

Data availability.

The data generated within the research is openly available as a Supplement

Author contribution. E Shalina performed the data analysis and interpretation of the results. S Sandven critically revised the work and gave important feedback for improvement. Both co-authors participated in writing the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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