Response to Reviewers' Comments

Dear reviewer,

We are grateful to receive your valuable and constructive comments in helping us improve this manuscript. According to your comments and suggestions, we have revised the manuscript seriously, including data, algorithm, discussion and conclusion. Please find the point-to-point responses as follows (Reviewer's comments in black and responses in blue). Thank you very much!

Reviewer: 1

Review on "Estimating snow depth on Arctic sea ice based on reanalysis reconstruction and particle filter assimilation" by Li et al.

The author provides a new method for estimating snow depth, and gives a detailed evaluation of data accuracy. Snow thickness is an important parameter in the cryosphere, which is of great significance to the mass balance of Arctic sea ice, the radiation balance of ocean and the retrieval of sea ice thickness using satellite altimeter data. Therefore, it is a paper suitable for publication in TC. However, at present, there are still many issues that need to be improved or corrected in the method and expression of this paper. Therefore, I recommend that the publication of the paper be considered after major revision.

General comments

The data used for validation is the focus of evaluating the product quality of the estimated snow thickness data. Therefore, it is necessary to evaluate the quality of the validation data itself and the characteristics of the data source in detail. For example, the data of buoys get the snow thickness on flat ice, which is generally low. A negative value does not indicate error, but indicates that the sea ice surface has melted, etc.

Response: Thank you for this thought-provoking suggestion. In the revised manuscript, we have added detailed information about the quality of the validation data and the characteristics of the data source.

(1) For the IMB data, the added contents are as follows:

The quality control of snow depth is applied and snow depth within 0–2 m is retained (Perovich et al., 2021). The IMB, equipped with an acoustic sounder, can measure the positions of the snow surface. The errors of IMB snow depth are within ±1 cm (Blanchard-wrigglesworth et al., 2018).

References:

Perovich, D., Richter-Menge, J., and Polashenski, C.: Observing and understanding climate change: Monitoring the mass balance motion, and thickness of Arctic sea ice, CRREL-Dartmouth Mass Balance Buoy Program, http://imb-crrel-dartmouth.org/, last access: 20 November 2021.

Blanchard-Wrigglesworth, E., Webster, M.A., Farrell, S.L., and Bitz, C.M.: Reconstruction of Snow on Arctic Sea Ice. J. Geophys. Res. Oceans, 123(5), 3588-3602, https://doi.org/10.1002/2017JC013364, 2018.

(2) For the OIB data, we have added two additional OIB products and the added contents are as follows:

The Operation IceBridge (OIB) mission is proposed for filling the data gap between ICESat and ICESat-2, providing snow depth on sea ice, sea ice thickness, and sea ice type information in the Arctic. These data are widely applied to evaluate satellite-derived or simulated snow depth values. In this study, three OIB products are used which are available to the public: (i) the IceBridge Sea Ice Freeboard, Snow Depth, and Thickness Quick Look, Version 1 (hereafter referred to as OIB_{QL}), covering the period 2012-2019; (ii) the IceBridge L4 Sea Ice Freeboard, Snow Depth, and Thickness, Version 1 (IDCSI4, hereafter referred to as OIB_{IDCSI4}), covering the period 2009-2013; and (iii) the Snow Depth on Arctic Sea Ice Data Set (Newman et al., 2014) which is provided by the NOAA (hereafter referred to as OIB_{NOAA}), covering the periods 2009-2012 and 2014-2015. OIB_{QL} has a mean bias of about -5 cm, underestimating snow depth (Kwok et al., 2017). OIB_{IDCSI4} product tends to underestimate snow depth (mean bias is about -1 cm) and OIB_{NOAA} tends to overestimate snow depth (mean bias is about 2 cm).

References:

Newman, T., Farrell, S. L., Richter-Menge, J., Elder, B., Connor, L., Kurtz, N., and McAdoo, D.: Assessment of radar-derived snow depth measurements over Arctic sea ice. J. Geophys. Res.: Oceans, 119, 8578-8602, https://doi.org/10.1002/2014JC010284, 2014.

Kwok, R., Kurtz, N. T., Brucker, L., Ivanoff, A., Newman, T., Farrell, S. L., King, J., Howell, S., Webster, M. A., Paden, J., Leuschen, C., MacGregor, J. A., Richter-Menge, J., Harbeck, J., and Tschudi, M.: Intercomparison of snow depth retrievals over Arctic sea ice from radar data acquired by Operation IceBridge. The Cryosphere, 11(6), 2571-2593. https://doi.org/10.5194/tc-11-2571-2017, 2017.

(3) For the MOSAiC data, the added contents are as follows:

Snow buoys include four independent sonar measurements. A negative value does not indicate the error, but indicates that the sea ice surface has melted (Nicolaus et al., 2021).

Reference:

Nicolaus, M., Hoppmann, M., Lei, R., Belter, H. J., Fang, Ying-Chih., Rohde, J.: Snow height on sea ice, meteorological conditions and drift of sea ice from autonomous Snow Buoys

during MOSAiC 2019/20. PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.933742 (dataset in review), 2021.

This is a paper that introduces new methods and new data. The access path of new data should be given in the data availability section.

Response: According to the suggestion, we have uploaded the data to the National Tibetan Plateau Data Center. The data is now available at http://data.tpdc.ac.cn/en/disallow/5f33769e-8cd9-400e-ab2b-1b75657bec9f/.

Specific comments

Line 30: "limits solar radiation absorption" changes to "limits solar radiation absorption by the ocean".

Response: According to the suggestion, we have changed "limits solar radiation absorption" to "limits solar radiation absorption by the ocean".

Line 33: "Meltwater originating from thin snow" not just from thin snow, so, changes to "snow and ice surface"

Response: According to the suggestion, we have changed "Meltwater originating from thin snow" to "Meltwater originating from thin snow and ice surface".

2 Data: Instead of just listing data, we should give application purposes of different data at the beginning, which will make readers more understand the research ideas.

Response: Thank you for this thought-provoking suggestion. In the revised manuscript, we have given application purposes of different data at the beginning of each data introduction.

3 Line 100 "Data pertaining to the ten subregions covering the period from 2012–2020 are selected" --This sentence has been repeated several times.

Response: Thank you for this thought-provoking suggestion. In the revised manuscript, we have deleted the repeated sentences in sections 2.2 and 2.3.

4 Ice mass balance buoy (IMB) data are retrieved from the Cold Regions Research and Engineering Laboratory (CRREL)-Mass Balance Buoy Program-- This data base is initiated by the CRREL, but is jointly maintenanced by the CRREL and University of Dartmouth.

Response: Thank you for this thought-provoking suggestion. In the revised manuscript, we have changed "Ice mass balance buoy (IMB) data are retrieved from the Cold Regions Research and Engineering Laboratory (CRREL)-Mass Balance Buoy Program" to "IMB data base is initiated by the Cold Regions Research and Engineering Laboratory (CRREL), but is jointly maintenanced by the CRREL and University of Dartmouth".

5 Line 125 "This dataset is developed to monitor the sea ice volume": The IMB cannot monitor the ice volume because it is not the point measurement.

Response: We extremely agree with this suggestion. In the revised manuscript, we have changed "This dataset is developed to monitor the sea ice volume and mass balance to better understand climate change" to "This dataset is developed to monitor the mass balance of the sea ice cover to better understand climate change".

6 Line 170: Blowing snow lost to leads: wind forcing causes any snow lost from the new snow layer to lead/open water: When the sea ice is relatively compact, the destination of wind blown snow may not be in the waterway or open water, but also in the downwind direction of the ice ridge. Therefore, the snow depth of level ice is generally smaller than that over the ridge.

Refer to:

Wagner, DN, Shupe, MD, Persson, OG, Uttal, T, Frey, MM, Kirchgaessner, A, Schneebeli, M, Jaggi, M, Macfarlane, AR, Itkin, P, Arndt, S, Hendricks, S, Krampe, D, Ricker, R, Regnery, J, Kolabutin, N, Shimanshuck, E, Oggier, M, Raphael, I, Lehning, M. 2021. Snowfall and snow accumulation processes during the MOSAiC winter and spring season. The Cryosphere Discussions: 1-48. DOI: https://doi.org/10.5194/tc-2021-126.

Lei R*, Tian-Kunze X, Li B, Heil P, Wang J, Zeng J, Tian Z. 2017. Characterization of summer Arctic sea ice morphology in the 135°-175°W sector using multi-scale methods, Cold Regions Science and Technology, 133, 108–120.

Response: Thank you for this thought-provoking suggestion. We agree that the destination of wind-blown snow may not only be in the lead/open water, but also in the downwind direction of the ice ridge. The roughness of the ice ridge is large, and the wind-blown snow is hindered by the ice ridge and distributed around the ice ridge. Therefore, the snow depth of level ice is generally smaller than that over the ridge. Ice ridges are mainly distributed in multi-year ice areas, and they have an impact on the distribution of snow depth in local areas. Parametric processes considered in this paper will affect the snow depth in the whole Arctic, so the influence is greater than that of the ice ridge. Although the blowing snow lost to ice ridge is not considered in the parameterization process of the model at present, the final snow depth estimates assimilate the satellite-derived snow depth and can capture the high snow depths over the ice ridge, which weakens the impact caused by the lack of consideration of ice ridge in NESOSIM_M model. In the future, we can deeply study the influence of ice ridge over snow depth and try to parameterize the process of blowing snow lost to ice ridge and introduce it into the numerical model, so as to improve the model. In the revised manuscript, we have added the limitations of the parameterization process in section 5 and proved that the assimilated snow depth obtained in this paper had captured the high snow depth over the ice ridge, indicating the advantages of the model after the assimilation of satellite-derived snow depth.

(1) In section 2.5, we added the introduction of Landsat 8:

Landsat 8 was launched on February 11, 2013, and was equipped with the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS). OLI includes nine bands. Except for the panchromatic band with a spatial resolution of 15 m, the remaining eight bands have a spatial resolution of 30 m. Due to its high resolution, it can find finer details on sea ice. Therefore, Landsat 8 Level 1 Terrain Corrected (L1T) product is downloaded to distinguish the ice ridges.

(2) In section 5.2, we added the related content of ice ridges according to the Landsat 8:

Based on Landsat 8 images, it was found that ice ridges were distributed in the Beaufort Sea on March 22, 2020, while there were no ridges in the same area on March 6 (Fig. 11(a) and (b)), indicating that ice ridges were generated from March 6 to March 22. NESOSIM_M snow depth on March 22 was greater than on March 6, but NESOSIM_M snow depth decreased from March 15 to March 22 (Fig. 11(c)). The existence of an ice ridge will promote snow accumulation, and the snow depth over the ice ridge is higher than that of level ice (Lei et al., 2017; Wagner et al., 2021). The NESOSIM_M ignored the influence of the existence of ice ridge on snow depth. Meanwhile, the change of NESOSIM_M-PF snow depth well reflected the increase of snow depth over the ice ridge (Fig. 11(c)). Point A represented the NESOSIM_M-PF snow depth on March 6 (i.e., 11.3 cm), and point B represented the NESOSIM_M-PF snow depth on March 22 (i.e., 16.0 cm), with an increase of 4.7 cm. From March 6 to March 22, NESOSIM_M-PF snow depth increased. The snow depth increased rapidly from March 17 and reached the local maximum on March 22. It proves that the NESOSIM_M-PF can capture the high snow depths over the ice ridge and weaken the impact caused by the lack of consideration of ice ridge in the NESOSIM_M. In the future, we will try to parameterize the process of blowing snow lost to ice ridge and introduce it into the numerical model to improve the NESOSIM_M.

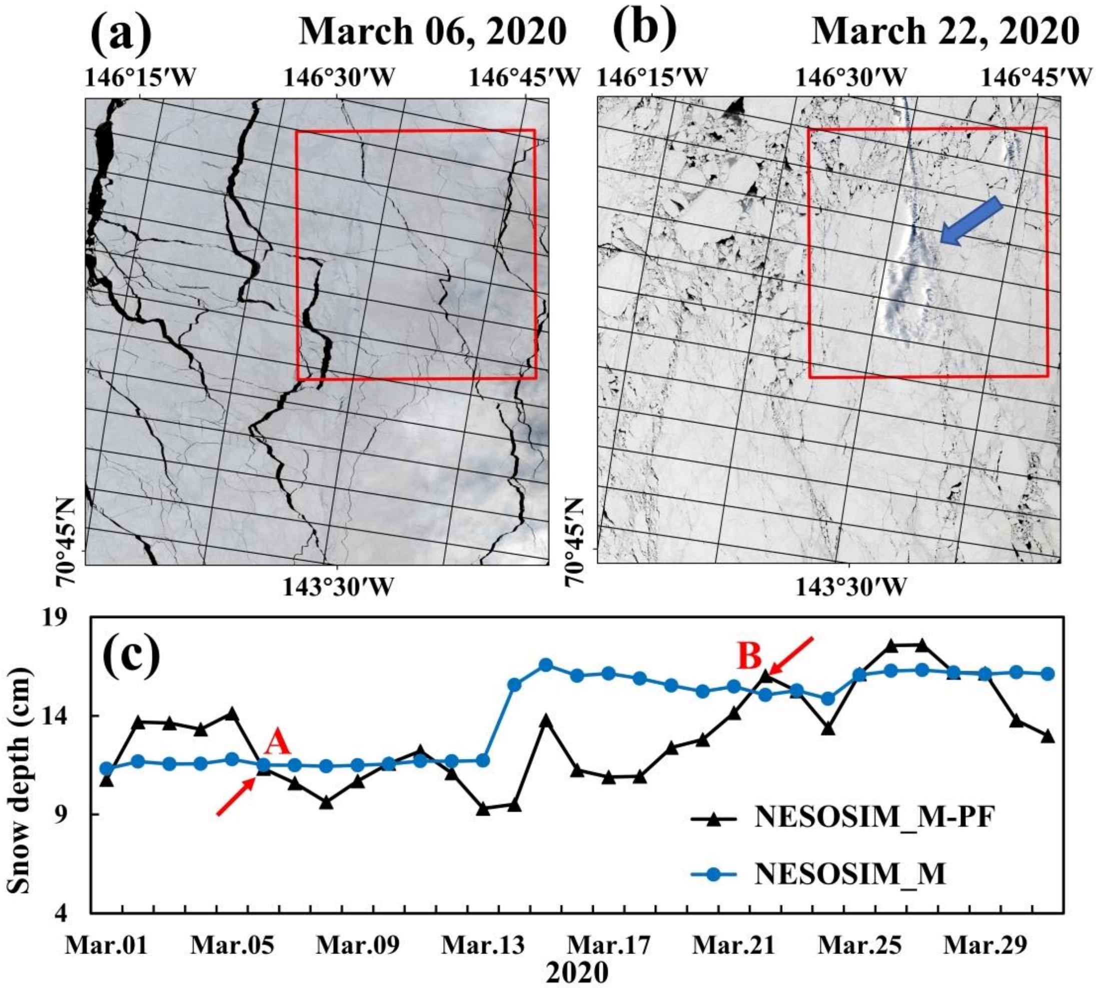

Fig 11. Distribution of the ice ridge in the Beaufort Sea on (a) March 6, 2020, and (b) March 22, 2020. (c) Variations in NESOSIM_M-PF and NESOSIM_M snow depth in the red box (the box is shown in (a) and (b)) in March 2020. Note that the blue arrow of (b) shows the location of ice ridges, point A and B in (c) represent the NESOSIM_M-PF snow depth on March 6 and March 22, respectively.

References:

Lei, R., Tian-Kunze, X., Li, B., Heil, P., Wang, J., Zeng, J., Tian, Z.: Characterization of summer Arctic sea ice morphology in the 135°-175°W sector using multi-scale methods, Cold Reg. SCI. Technol., 133, 108-120, https://doi.org/10.1016/j.coldregions.2016.10.009, 2017.

Wagner, D. N., Shupe, M. D., Persson, O. G., Uttal, T., Frey, M.M., Kirchgaessner, A., Schneebeli, M., Jaggi, M., Macfarlane, A. R., Itkin, P., Arndt, S., Hendricks, S., Krampe, D., Ricker, R., Regnery, J., Kolabutin, N., Shimanshuck, E., Oggier, M., Raphael, I., Lehning, M.: Snowfall and snow accumulation processes during the MOSAiC winter and spring season. The Cryosphere Discussions: 1-48, DOI: https://doi.org/10.5194/tc-2021-126, 2021.

7 Line 195 “the 2-m temperature (Tair) is higher than 0 °C”: Snow may also melt below 0 degrees Celsius, mainly due to solar radiation.

Refer to:

Bliss, A. C., & Anderson, M. R. (2018). Arctic Sea Ice Melt Onset Timing From Passive Microwave-Based and Surface Air Temperature-Based Methods. Journal of Geophysical Research: Atmospheres, 123(17), 9063-9080.

Response: Thank you for this thought-provoking suggestion. We agree that snow may also melt below 0 °C, mainly due to solar radiation. Different studies have adopted different thresholds to determine the melt onset (MO). Bliss and Anderson (2018) compared the MO obtained by three different thresholds. They found that MO using 0 °C or thresholds from Rigor et al. (2000) was later than that using the threshold of -1 °C. There are also studies using -0.5 °C (Lindsay, 1998) and -1.9 °C (Andreas and Ackley, 1982) as thresholds. Under different circumstances, such as changes in salinity will change the melting point of snow. We use 0 °C as the threshold to judge the existence of the melting term, which will inevitably underestimate the snow loss caused by snow melting. The model starts running in mid-August because there is heavy snowfall in the central Arctic in August, and great snow melting events in June and July have been avoided (Petty et al., 2018). In mid-August, sea ice is mainly distributed in the central Arctic, and snow melting events also mainly occur in the central Arctic. Stroeve et al. (2006) revealed that the MO determined by the threshold closer to 0 °C would agree more closely with passive microwave (PMW)-based MO dates for the sea ice within the central Arctic. Therefore, we choose 0 °C as the threshold, assuming that when the air temperature is less than 0 °C, the snow melting term is negligible. According to the suggestion, we have added references to explain why we chose 0 °C as the threshold and discussed limitations for the current snow melting process.

(1) In section 3.2.2, we added reasons for selecting the threshold of 0 °C as follows:

The mid-August is selected because there is heavy snowfall in the central Arctic, and great snow melting events in June and July have been avoided (Petty et al., 2018). In mid-August, sea ice is mainly distributed in the central Arctic, and snow melting events also mainly occur in the central Arctic. For the sea ice within the central Arctic, Stroeve et al. (2006) revealed that the melt onset (MO) determined by the threshold closer to 0 °C would agree more closely with passive microwave (PMW)-based MO dates. Therefore, we choose 0 °C as the threshold. When the 2-m temperature (T_{air}) is higher than 0 °C, we consider that there occurs a snow melting process on sea ice.

(2) In section 5.2, we added limitations for selecting the threshold of 0 °C as follows:

Moreover, snow may also melt below 0 °C, mainly due to solar radiation. Different studies have adopted different thresholds to determine the MO. Bliss and Anderson (2018) compared the MO obtained by three different thresholds, and found that MO using 0 °C or thresholds from Rigor et al. (2000) was later than that using the threshold of -1 °C. There are also studies using -0.5 °C (Lindsay, 1998) and -1.9 °C (Andreas and Ackley, 1982) as thresholds. Under different circumstances, the melting point of snow is not fixed. We use 0 °C as the threshold to judge the existence of the melting term, which will inevitably underestimate the snow loss caused by snow melting.

References:
Andreas, E. L., and Ackley, S. F.: On the differences in ablation seasons of Arctic and Antarctic Sea ice. J. Atmos. Sci., 39(2), 440-447, https://doi.org/10.1175/1520-0469(1982)039<0440:OTDIAS>2.0.CO;2, 1982.
Bliss, A. C., and Anderson, M. R.: Arctic Sea Ice Melt Onset Timing From Passive Microwave-Based and Surface Air Temperature-Based Methods. J. Geophys. Res.: Atmospheres, 123(17), 9063-9080, https://doi.org/10.1029/2018JD028676, 2018.
Lindsay, R. W.: Temporal variability of the energy balance of thick arctic pack ice. J. Climate, 11(3), 313-333, https://doi.org/10.1175/1520-0442(1998)011<0313:TVOTEB>2.0.CO;2, 1998.
Rigor, I. G., Colony, R. L., and Martin, S.: Variations in surface air temperature observations in the Arctic. J. Climate, 13(5), 896-914, https://doi.org/10.1175/1520-0442(2000)013<0896:VISATO>2.0.CO;2, 2000.
Stroeve, J., Markus, T., Meier, W. N., and Miller, J.: Recent changes in the Arctic melt season. Ann. Glaciol., 44, 367-374, https://doi.org/10.3189/172756406781811583, 2006.

8 Line 200 “wind transports snow into the atmosphere” Most of the snow due to the Blowing snow will fall back to the ice, but there is a spatial redistribution. Main mechanism to transport snow into the atmosphere is evaporation.

Response: Thank you for this thought-provoking suggestion. Indeed, most of the snow due to the Blowing snow will fall back to the ice. The main mechanism to transport snow into the atmosphere is evaporation. However, for a grid cell, the wind will bring snow to the atmosphere, causing the redistribution of snow and changing the snow depth of the grid cell. In 2020, Petty (2020) proposed that the snow lost to the atmosphere process when wind speed exceeds the threshold should be considered in NESOSIM. In this study, we do not consider the snow loss to the atmosphere caused by evaporation, but only the blowing snow loss to the atmosphere by the wind. In the revised manuscript, we have added this limitation of the proposed method in the discussion.

The added contents are as follows:

Furthermore, the NESOSIM_M-PF only considers the simple melting process and does not involve the snow loss caused by evaporation. More complex thermodynamics processes need to be further considered in the future.

9 Line 243 “OIB-measured snow depth is 10.79 cm”: Whether the two digits after the decimal point are meaningful? also in other similar places. According to my understanding, the observation accuracy of snow depth can hardly be better than 1cm.

Response: Thank you for this thought-provoking suggestion. Some studies use values that include two digits after the decimal point (e.g., Rostosky et al., 2018; Kwok et al., 2017) to describe snow depth. Some studies use one digit after the decimal point (e.g., Kilic et al., 2019; Zhou et al., 2021; Stroeve et al., 2020), and some studies do not retain the number after the decimal point (Petty et al., 2018). In this paper, NESOSIM_M-PF snow depth was obtained, and the errors of different snow depths were compared. When the improvement of accuracy is small, the improvement of accuracy will be ignored if we use no digits after the decimal. For example, if we use no digits after the decimal, the RMSE of the two snow depth estimates (NESOSIM v1.0 and NESOSIM_M snow depths) is 7 cm (Based on the OIB_{QL} data). However, the RMSE of NESOSIM_M is less than 7 cm, and the RMSE of NESOSIM v1.0 is greater than 7 cm. Keeping one and two decimal places will have less impact on the results of this study. According to the suggestion and references, we chose the commonly used strategies to describe snow depth (i.e., one digit after the decimal point). Referring to Kwok et al. (2017) and Stroeve et al. (2020), we changed the description in the manuscript to use one digit after the decimal point and the values in the table and figures still retained two decimal places.

10 Line 283 “the IMB-measured snow depth are much smaller than 0, indicating great snow depth underestimation”: it is not underestimation, but means the melt of ice surface.

Response: We are sorry that this sentence caused a misunderstanding. This sentence means the biases between three estimated snow depths (F1, F2 and F3 snow depth) and the IMB-measured snow depths are less than 0, rather than the IMB-measured snow depth are smaller than 0. In the revised manuscript, we have changed “The biases between the F1, F2 and F3 snow depths and the IMB-measured snow depth are much smaller than 0, indicating great snow depth underestimation” to “The negative biases indicate these three schemes (i.e., FI, F2 and F3) underestimate the snow depth (Table 1)”.

Table 1. Accuracy of NESOSIM_M with different atmospheric loss coefficient values (γ) based on the IMB-measured snow depth (number of same matching points (Ns), RMSE (cm), bias (cm), MAE (cm) and r).

γ	0.015 (F1)	0.020 (F2)	0.025 (F3)
Ns	443	443	443
RMSE (cm)	16.58	16.85	17.11
Bias (cm)	-6.67	-7.36	-7.97
MAE (cm)	11.06	11.28	11.51
r	0.12	0.12	0.11

11 Figure 8: what the meaning fro the increased jump at the end of September?

Response: Thank you for this thought-provoking suggestion. Except for August and September, the satellite-derived snow depth has been used for assimilation. There is no satellite-derived snow depth in August and September. Therefore, the estimated snow depth in August and September is the NESOSIM_M snow depth, resulting in the increased jump at the end of

September.

We are sorry we ignored this increased jump earlier. To solve the increased jump at the end of September, we use the NESOSIM_M-PF snow depth and NESOSIM_M snow depth at the same time and location in October to establish the linear regression equation as follows:

$$h_{NESOSIM\_M\text{-}PF}=1.2138\times h_{NESOSIM\_M}+0.9214 \quad (21)$$

We use Eq. (21) to obtain NESOSIM_M-PF snow depths in August and September. The results show that the increased jump at the end of September disappears and variation in snow depth from September to May is more reasonable (Fig. AA).

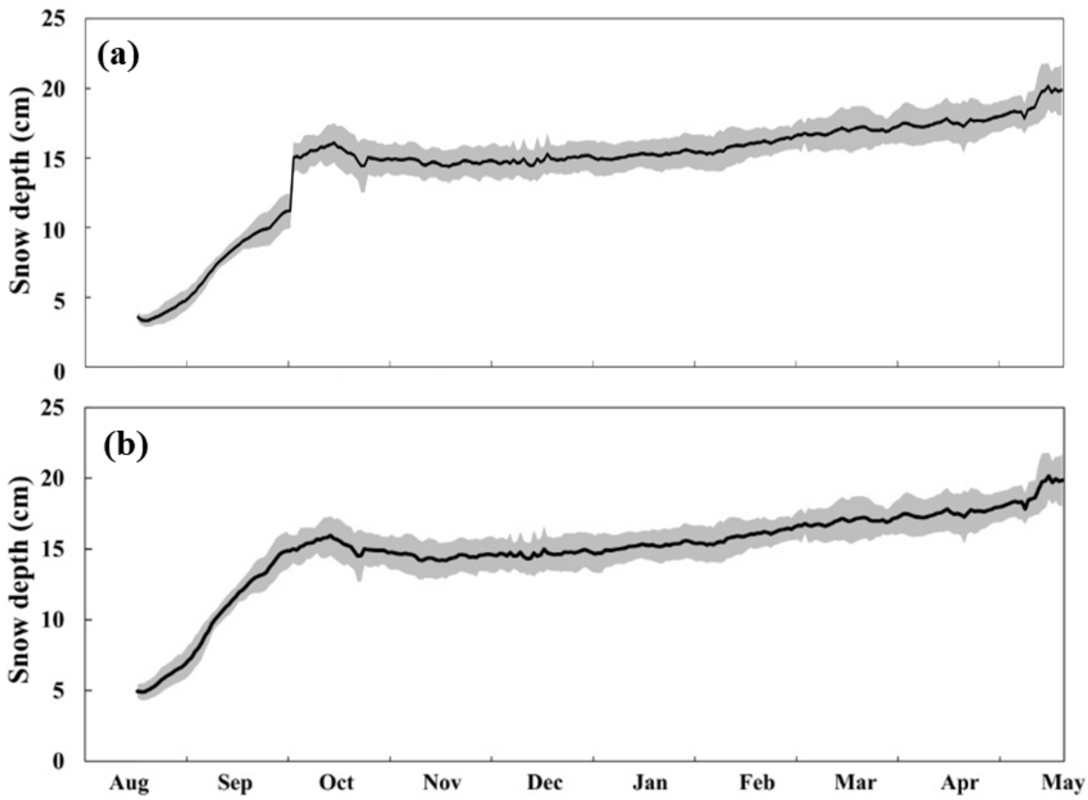

Figure AA. (a) Variations in the daily average Arctic default snow depth (no post-processing). (b) Variations in the daily average Arctic default snow depth (with post-processing).

In the revised manuscript, we have added the additional processing for eliminating the increased jump at the end of September. The revisions are as follows:

Except for August and September, the satellite-derived snow depth has been used for assimilation. There is no satellite-derived snow depth in August and September. Therefore, the estimated snow depth in August and September is the NESOSIM_M snow depth, resulting in the increased jump at the end of September. To solve this problem, we use the NESOSIM_M-PF snow depth and NESOSIM_M snow depth at the same time and location in October to establish the linear regression equation as follows:

$$h_{NESOSIM\_M\text{-}PF}=1.2138\times h_{NESOSIM\_M}+0.9214 \quad (21)$$

We use Eq. (21) to obtain NESOSIM_M-PF snow depths in August and September.