Dear Editor and reviewers,

We thank you very much for your efforts in reviewing our manuscript and providing us with constructive comments. We have revised this manuscript accordingly, and the point-to-point responses to your comments are listed below. We have quoted the text from the paper and displayed in bold the changes/additions.

Qinghua Yang and Bo Han,

On behalf of all the authors

Reviewer 2

General comments

This paper used the single-column sea ice model ICEPACK forced by the ERA5 atmospheric reanalysis and by atmospheric in situ observations to simulate snow depth and sea ice thickness at Zhongshan Station, Antarctic. Through some sensitivity experiments, the authors tried to find which variables from atmospheric forcing affected the simulations largely. Overall, the manuscript has a potential value for publishing. However there are some major issues need to be clarify firstly.

Response:

We thank you for the constructive comments which are greatly helpful to improve the manuscript. We have modified the article accordingly below and responded to them one by one.

When assessing the importance of the forcing variables, it is not fair to compare their absolute values. Relative values should be considered.

Response:

We have used bias ratio instead of the absolute value in Table 3. The bias ratio is defined as the ratio between the bias and the observation value in this study.

Table 3 Bias of ice thickness, snow depth and of each forcing variable derived from SEN1. ‘All’ means using the full set of ERA5 atmospheric forcing

Variable	Bias		Bias ratio (%)
	Ice (cm)	**Snow (cm)**	**Forcing**
R_{sd} (W m^{-2})	-0,044	-0.130	**9.031**
R_{ld} (W m^{-2})	3.050	2.243	**-9.672**
T_a (K)	0.001	0.029	**-0.453**
Q_a (10^{-4} kg kg^{-1})	1.099	-1.299	**-9.326**
P (mm day^{-1})	14.519	17.312	**303.509**
Θ_a (K)	-0.483	0.407	**0.112**
ρ_a (kg m^{-3})	0.119	-0.071	**-1.592**
U_a (m s^{-1})	-0.311	-3.421	**50.735**
All	16.824	17.882	/

Some results may be close related to the threshold values in the model parameterization, for example, 1 mm/day in the Figure 7. If yes, please discuss the possible results to use another threshold value. If no, explain the reason why it is 1 mm/day.

Response:

The threshold value is related to sea ice thickness, snow depth and model parameterization. Snow-ice process is based on Archimedes' Principle. The base of the snow is at sea level when

$$\rho_i h_i + \rho_s h_s = \rho_w h_i$$

Where ρ_i=917 kg/m^3, ρ_s=330 kg/m^3 and ρ_w represent the density of ice, snow and sea water respectively. h_i and h_s indicate sea ice thickness and snow depth respectively.

Thus the snow base lies below sea level when

$$h_s > \frac{(\rho_w - \rho_i)h_i}{\rho_s}$$

We have revised the text in response to this concern:

'The simulation bias of the sea ice thickness is quite small before the precipitation increases by about 1 mm per day (Figure 7). In fact, the simulated sea ice thickness even decreases at a rate of -3.4 cm per 1 mm increase in precipitation. It is because the snow-ice formation is small (Figure 6c) and the stronger isolation of the snow layer (Figure 6d) hampers the sea ice growths. If precipitation is larger than 1 mm day^{-1}, the simulated sea ice thickness quickly increases at a rate of 22 cm/(mm day^{-1}). In contrast, the simulated snow depth deepens rapidly at a rate of 23.9 cm/(mm day^{-1}) when the enforced precipitation remains small, and at a rate of 6.5 cm when the added precipitation is large. This is because more snow is converted into flooding ice, and the snow-ice formation process strongly overrules the effect of the larger isolation of the thicker snow layer, which promotes the sea ice growth. **The snow-ice process is based on Archimedes' Principle. Therefore, the threshold value (1 mm/day^{-1}) is related to the density value of ice, snow and water in model parameterization, and also related to the sea ice thickness and snow depth. If sea ice and snow density, initial snow depth decrease, or sea water density and initial ice thickness increase, the threshold will increase, and vice versa.'**

The discussion is not sufficient. The biases caused by precipitation may come from flooding ice (direct thickness contribution) and thermodynamic insulate effect (indirect). The quantitative contributions from those two aspects should be fully studied and clearly presented. Some oceanic heat flux experiments on OML depth should be considered.

Response:

Thank you for your constructive suggestions. We have revised Figure 6 and quantitatively analyzed the effects of precipitation on flooding ice and thermodynamic insulate effect. We used net surface heat flux to represent the insulate effect of snow layer, but we don't know how much the net surface heat flux will change the sea ice thickness. We have only used the snow-ice formation process and insulate effect to analyze the sensitivity of precipitation on sea ice thickness and snow depth in the text.

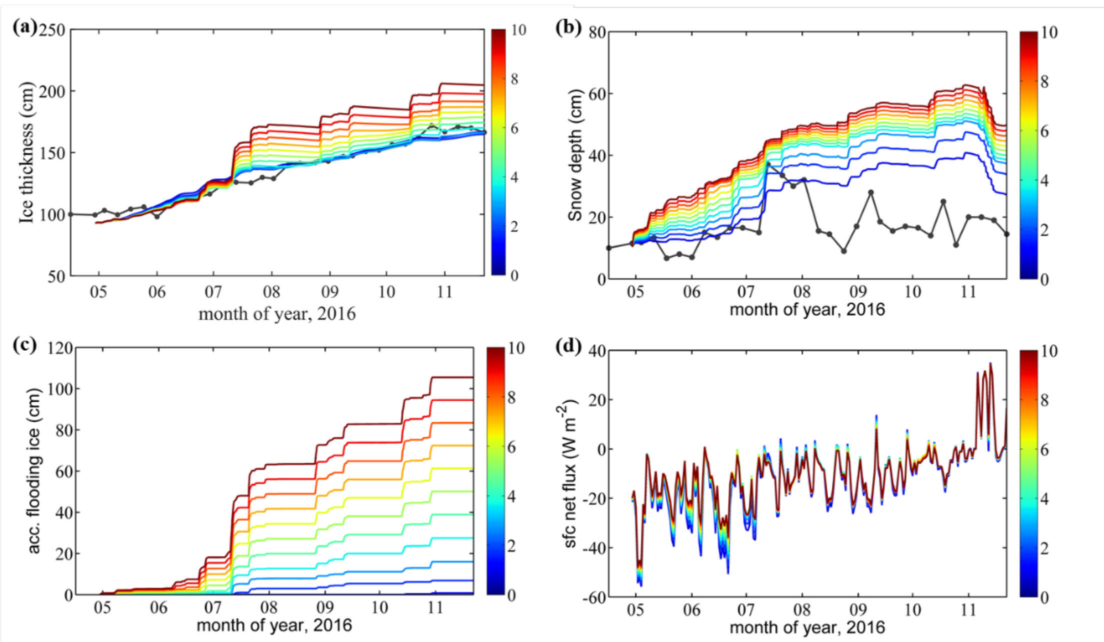

Figure 6 Time series of the simulated (a) sea ice thickness, (b) snow depth, **(c) accumulated flooding ice and (d) net surface heat flux** in the n experiments of SEN2. The black solid line with black points show the *in situ* observations (Obs). The 11 colored lines denote the 11 sensitivity experiments. When n = 0, precipitation is from the *in situ* observation. When n = 10, precipitation is from ERA5.

'The simulation bias of the sea ice thickness is quite small before the precipitation increases by about 1 mm per day (Figure 7). In fact, the simulated sea ice thickness even decreases at a rate of -3.4 cm per 1 mm increase in precipitation. **It is because the snow-ice formation is small (Figure 6c) and the stronger isolation of the snow layer (Figure 6d) hampers the sea ice growths.** If precipitation is larger than 1 mm day^{-1}, the simulated sea ice thickness quickly increases at a rate of 22 cm/(mm day^{-1}). In contrast, the simulated snow depth deepens rapidly at a rate of 23.9 cm/(mm day^{-1}) when the enforced precipitation remains small, and at a rate of 6.5 cm when the added precipitation is large. **This is because more snow is converted into flooding ice, and the snow-ice formation process strongly overrules the effect of the larger isolation of the thicker snow layer, which promotes the sea ice growth.** The snow-ice process is based on Archimedes' Principle. Therefore, the threshold value (1 mm/day^{-1}) is related to the density value of ice, snow and water in model parameterization, and also related to the sea ice thickness and snow depth. If sea ice and snow density, initial snow depth decrease, or sea water density and initial ice thickness increase, the threshold will increase, and vice versa.'

We find that water depth of sea ice observation site is about 10 m in precious study (Zhao et al., 2019). We have changed the MLD to 10 m in the text. Also we find that the change in MLD has little impact on simulation of sea ice thickness in our study. We have done the sensitivity experiments with different oceanic mixed layers, including 10 m and 20 m, and we find the simulation of sea ice thickness and snow depth is not sensitive to this value.

The oceanic mixed layer can modify the oceanic forcing through changing the sea surface temperature. The ocean forcing also plays an important role on sea ice evolution. We admit that there is a lack of sufficient analysis in oceanic forcing. In our future research, sensitivity of the oceanic forcing and their impact on the sea ice simulation will be addressed.

Reference

Zhao, J., Cheng, B., Vihma, T., Yang, Q., Hui, F., Zhao, B., Hao, G., Shen, H., and Zhang, L.:

Observation and thermodynamic modeling of the influence of snow cover on landfast sea ice thickness in Prydz Bay, East Antarctica, Cold Reg. Sci. Technol., 168, 102869, 2019.

The writing have a lot of typo errors. For example, the citing of the subplots are wrong for many figures.

Response:

We have revised the text in response to this concern and have checked all the figure references

Specific comments

Lines 163: how about the water depth of the sea ice observation site? Should the real water depth was considered when you set the MLD to 20 m?

Response:

Thank you for your advice. We find that water depth of sea ice observation site is about 10 m in precious study (Zhao et al., 2019). We have changed the MLD to 10 m in the text. Also we find that the change in MLD has little impact on simulation of sea ice thickness in our study.

'The oceanic forcing includes sea surface temperature, sea surface salinity, and oceanic mixed layer depth. The period concerned in this study is from 22 April, when observed sea ice generally starts to grow, to 22 November in 2016. **Since there are no observations of the ocean mixed-layer depth, we set it to 10 m based on a previously published study (Zhao et al., 2019).'**

Reference

Zhao, J., Cheng, B., Vihma, T., Yang, Q., Hui, F., Zhao, B., Hao, G., Shen, H., and Zhang, L.: Observation and thermodynamic modeling of the influence of snow cover on landfast sea ice thickness in Prydz Bay, East Antarctica, Cold Reg. Sci. Technol., 168, 102869, 2019.

Lines 206-208: what is the role of wind on precipitation comparisons? The strong wind caused snow blowing events and the precipitation observation bin could not collect all the snow fall. Do the larger biases occurred during the strong wind events? This should be assessed here.

Response:

Thank you for your advice, and we have revised the text in response to this concern:

'Nevertheless, using precipitation from Progress II for Zhongshan Station may be questioned as well because of the distance of about 1 km to Zhongshan Station. **Moreover, strong wind causes snow drift events and the precipitation observation might not collect all snowfall correctly. This may cause larger bias between ERA5 and observations during strong events**.'

Lines 232: a space missed between the number and the unit, and the same errors should be checked through the paper.

Response:

Thank you for this critical suggestion and we have checked all the number and the unit throughout our revised manuscript.

Lines 251-253: As figure 3b shown, both blue lines and red lines were different compared to black lines. However, in figure 3a, no obvious ice thickness differences occurred for red lines, but the large difference occurred for blue lines. Does this indicated that the ice thickness simulation became more sensitive when the snow biases exceeded some values? What kind of parameterizations in the model caused this phenomena?

Response:

Yes, we have done a sensitivity experiment in section 3.5 and found that the ice thickness simulation is sensitive to the snow simulation bias. When the snow deviation between Sim_Obs and Obs is greater than 24 cm (Figure 7b), the simulated ice thickness will increase rapidly due to the snow-ice transformation in ICEPACK. We added a discussion in response to this concern:

'The simulation bias of the sea ice thickness is quite small before the precipitation increases by about 1 mm per day (Figure 7). In fact, the simulated sea ice thickness even decreases at a rate of -3.4 cm per 1 mm increase in precipitation. It is because the snow-ice formation is small (Figure 6c) and the stronger isolation of the snow layer (Figure 6d) hampers the sea ice growths. If precipitation is larger than 1 mm day^{-1}, the simulated sea ice thickness quickly increases at a rate of 22 cm/(mm day^{-1}). In contrast, the simulated snow depth deepens rapidly at a rate of 23.9 cm/(mm day^{-1}) when the enforced precipitation remains small, and at a rate of 6.5 cm when the added precipitation is large. This is because more snow is converted into flooding ice, and the snow-ice formation process strongly overrules the effect of the larger isolation of the thicker snow layer, which promotes the sea ice growth. **The snow-ice process is based on Archimedes' Principle. Therefore, the threshold value (1 mm/day^{-1}) is related to the density value of ice, snow and water in model parameterization, and also related to the sea ice thickness and snow depth.** If sea ice and snow density, initial snow depth decrease, or sea water density and initial ice thickness increase, the threshold will increase, and vice versa.'

Lines 290: the influences of Qa on ice was 1.009, not comparable to the other two variables, therefore its contribution was not that strong.

Response:

We have deleted Qa in the sentence.

Lines 292-293: this sentence is not clear. As Table 3 shown, P should be the largest factor for snow and ice simulations.

Response:

We have deleted this sentence in response to this concern:

'Comparing the individual biases, it turns out that *P* and R_{ld} from ERA5 contribute to the bias in sea ice thickness most strongly. For snow depth *P*, U_a and R_{ld} contribute largest.'

Lines 292: "Ua … the largest …" you cannot compare the absolute value here, you should use the relative percentage. Also the column value "Forcing" in the table.

Response:

This relates to the comment above. We have used bias ratio instead of the absolute value in Table 3. The bias ratio is defined as the ratio between the bias and the observation value in this study.

Table 3 Bias of ice thickness, snow depth and of each forcing variable derived from SEN1. 'All' means using the full set of ERA5 atmospheric forcing

Variable	Bias		Bias ratio (%)
	Ice (cm)	Snow (cm)	Forcing
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R_{ld} (W m^{-2})	3.050	2.243	**-9.672**

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U_a (m s^{-1})	-0.311	-3.421	**50.735**
All	16.824	17.882	/

Lines 295-297: it is not reasonable to say P caused the major overestimation, based on the current experiment design. Only one sensitivity experiment was run for every single variable, this is not enough. You should design multi-sensitivity experiments for every single variable. If we say the variable P, the additional experiments like 0.5*P, 2.0*P, 3.0*P … should be considered.

Response:

Thank you for your advice. We did not discuss the sensitivity of each variable to the simulation of sea ice thickness and snow depth in this section. We only study the influence of the deviation between the reanalysis and observations on the simulation of sea ice thickness and snow depth. Also we have added sensitivity experiments in section 3.5 and quantitatively analyzed the impact of precipitation on the simulation of sea ice thickness:

'The precipitation from ERA5 not only shows the largest deviation compared to the *in situ* observation, but also contributes largest to the bias in the sea ice and snow simulation. **To find out how sensitive sea ice and snow are on precipitation, 10 sensitivity experiments are set up, named SEN2 (Figure 6). In the *n*-th experiment, *n*×10% of the daily difference between *P* from ERA5 and the *in situ* observation is added to the *in situ* observation on that day.** This procedure increases the magnitude of the precipitation gradually in the experiments, while the timing of the daily precipitation events remains almost unchanged.'

Line 299: not figure 4b, snow is in figure 4d. It is not usual to place (a) (b) (c) vertically in the figure.

Response:

We have renumbered the Figure 4 and have checked all the figure references throughout our revised manuscript.

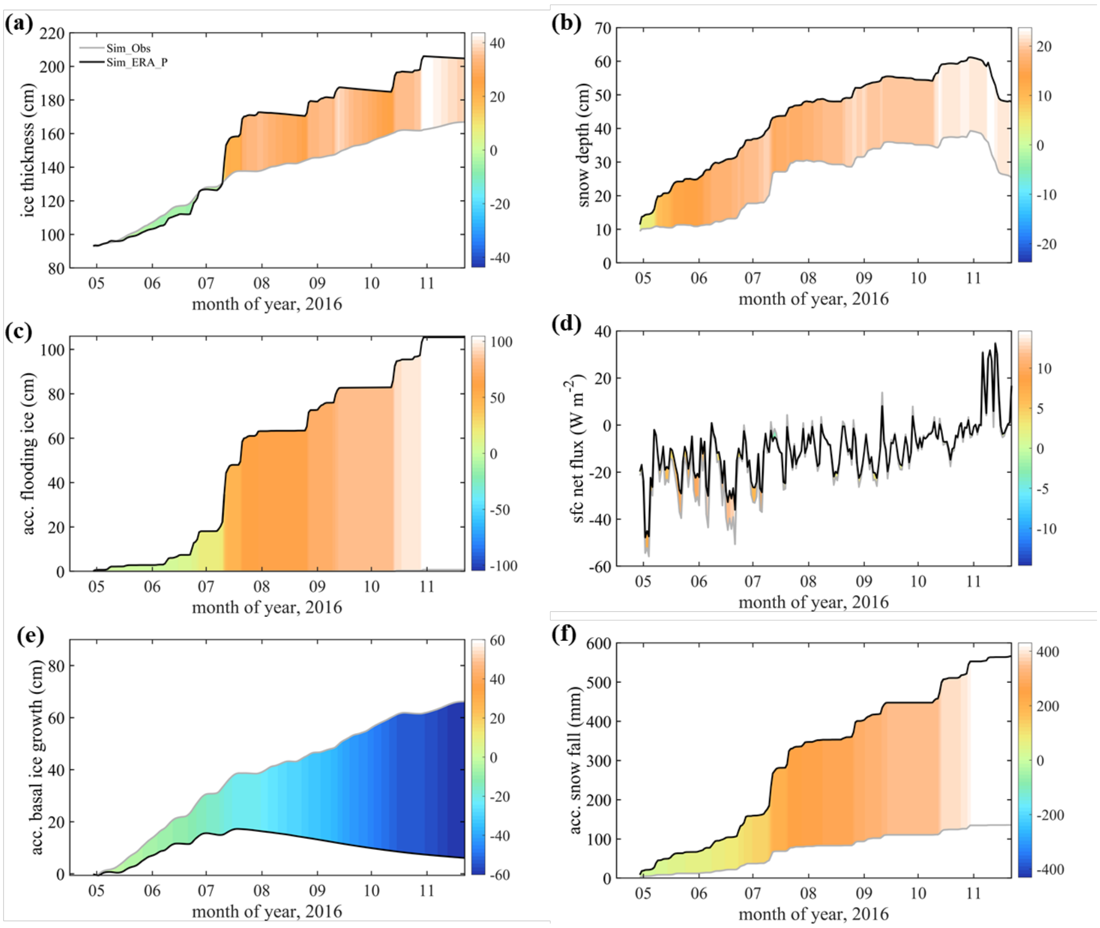

Figure 4: Times series of (a) sea ice thickness, (b) snow depth, (c) accumulated flooding ice, (d) net surface heat flux, (e) accumulated basal ice growth and (f) accumulated snow fall. The gray line represents the simulation using precipitation from observation (Sim_Obs). The black line represents the simulation using precipitation from ERA5 (Sim_ERA_P). The color bar represents their difference (Sim_ERA_P – Sim_Obs).

Figure 4c: the accumulated ice growth decreased since middle July. Why? Does that mean ice started to melt in the bottom?

Response:

Yes, we have pointed out the reason in the text:

‘The reason for this difference might be that as the snow-ice process occurs, the increase in sea ice thickness will reduce the heat transfer between the ocean and the atmosphere, and inhibit the basal growth of sea ice in winter.’

Lines 318-319: check the subplot label (a) (b) (c) (d), and make sure they were cited correctly.

Response:

As with the problems pointed out above, we have checked all the figure references throughout our revised manuscript.

Lines 320-325: The flooding ice was parameterized to total ice thickness in the model? When water flooded into ice surface layer, snow-ice will formed if snow existed, however we didn't see snow thickness change a lot when accumulated flooding ice rapidly increased in July, why?

Response:

Yes, the total ice thickness contains flooding ice in ICEPACK. When the snow-ice process occurs, the snow depth decreases and the ice thickness increases. We have mentioned in the text why the snow depth changes less when the snow-ice process occurs in July:

'The snowfall (Figure 4f) is calculated by precipitation (Figure 2b) and is converted to new snow depth at the top surface using snow density of 330 kg m-3 in ICEPACK (Hunke et al., 2019). **Comparing Figure 4b with Figure 4f, we find that the change in snow depth (11 cm) is much lower than the accumulated snow fall (57 cm) because of flooding during precipitation event in July.'**

Lines 325-326: Accumulated snow fall was about 400 mm (40 cm) in July, similar to snow thickness (40 cm), I didn't see "much lower" you mentioned here. How the model deal with the relationship between snow fall, snow thickness, flooding ice, snow-ice thickness and total ice thickness should be explained clear in this section.

Response:

We have revised the text in response to this concern:

'When there is heavy snow fall, which happens frequently after July 11, the snow load subpresses the sea ice surface below sea level and sea water is flooding onto the sea ice surface causing the overlaying snow to freeze. **This snow-ice formation process will form flooding ice (snow-ice thickness) at the sea ice surface and increase the total sea ice thickness rapidly (Figure 4a).** The difference (~100 cm) in accumulated flooding ice (Figure 4c) between Sim_Obs (0.8 cm) and Sim_ERA_P (105.5 cm) is greater than the difference (~40 cm) in simulated sea ice thickness

(Figure 4a), while the net surface heat flux compares well after July 11 (Figure 4d). The reason for this difference might be that as the snow-ice process occurs, the increase in sea ice thickness will reduce the heat transfer between the ocean and the atmosphere, and inhibit the basal growth of sea ice in winter (Figure 4e). The flooding induced snow-ice formation happens with a rate larger than 0.5 cm per hour after July 11. **The snowfall (Figure 4f) is calculated by precipitation (Figure 2b) and is converted to new snow depth at the top surface using snow density of 330 kg m^{-3} in ICEPACK (Hunke et al., 2019). Comparing Figure 4b with Figure 4f, we find that the change in snow depth (11 cm) is much lower than the accumulated snow fall (57 cm) because of flooding during precipitation event in July.'**

Reference

Hunke, E., Allard, R., Bailey, D. A., Blain, P., Craig, T., Dupont, F., DuVivier, A., Grumbine, R., Hebert, D., Holland, M., Jeffery, N., Lemieux, J., Rasmussen, T., Ribergaard, M., Roberts, A., Turner, M., and Winton, M.: CICE-Consortium/Icepack: Icepack1.1.1, doi:10.5281/zenodo.3251032, 2019.

Line 321: You proposed a guess here. This could be confirmed by calculating the conductive heat flux and bottom heat flux balance.

Response:

Thank you for your advice. We have checked that basal ice growth is calculated by the conduction heat flux and bottom heat flux in ICEPACK. We have deleted the 'guess' in the text:

'The reason for this difference might be that as the snow-ice process occurs, the increase in sea ice thickness will reduce the heat transfer between the ocean and the atmosphere, and inhibit the basal growth of sea ice in winter.'

Lines 340-341: If wind-blowing was not considered by the model, therefore snow thickness was the accumulation of total snow fall? Or any other processes were included? What caused the differences of snow thickness simulations? Why the surface heat fluxes can affect the snow thickness?

Response:

The simulation of snow depth in the ICEPACK is not only affected by total snowfall, but also includes snow-ice formation process, snow melting because of temperature rising, and snow condensation or sublimation due to surface heat fluxes. Ua can affect the snow depth through modifying the surface heat fluxes in the bulk formulations. We have revised the text in response to this concern:

'Although the snow-drift process is currently not implemented in ICEPACK, U_a still affects the snow depth through modifying the surface heat fluxes in the bulk formulations (Fairall et al., 2003). **Latent heat changes the snow depth through snow condensation or sublimation process.** Compared with Sim_Obs, Sim_ERA_W simulates in the mean a -2.5 × 104 W m^{-2} lower accumulated latent heat (Figure 5b), i.e., a larger sublimation (Figure 5c), and a reduction of about -3.4 cm of the snow depth (Figure 5a). Therefore, when ERA5 is forcing ICEPACK, the overestimation in U_a partly neutralizes the effect of overestimation in P at Zhongshan Station.'

Line 369: it should be the bias of sea ice thickness and snow depth

Response:

We have added 'bias' in the text.

Lines 370: why to calculate from 27 July, not the initial day of experiments in April?

Response:

We have tried to calculate the bias from initial day of experiments in April. However, the statistical data is scattered and box plot have many outliers, so we start calculating from 27 July. Different start or end dates of this period do not change this result.

Lines 375-377: what control the threshold value to be 1 mm/day. Was it related to the value in the model parameterization?

Response:

This relates to the comment above. The threshold value is related to sea ice thickness, snow depth and model parameterization. Snow-ice process is based on Archimedes' Principle. The base of the snow is at sea level when

$$\rho_i h_i + \rho_s h_s = \rho_w h_i$$

Where ρ_i=917 kg/m^3, ρ_s=330 kg/m^3 and ρ_w represent the density of ice, snow and sea water respectively. h_i and h_s indicate sea ice thickness and snow depth respectively.

Thus the snow base lies below sea level when

$$h_s > \frac{(\rho_w - \rho_i)h_i}{\rho_s}$$

We have revised the text in response to this concern:

'The simulation bias of the sea ice thickness is quite small before the precipitation increases by about 1 mm per day (Figure 7). In fact, the simulated sea ice thickness even decreases at a rate of -3.4 cm per 1 mm increase in precipitation. It is because the snow-ice formation is small (Figure 6c) and the stronger isolation of the snow layer (Figure 6d) hampers the sea ice growths. If precipitation is larger than 1 mm day^{-1}, the simulated sea ice thickness quickly increases at a rate of 22 cm/(mm day^{-1}). In contrast, the simulated snow depth deepens rapidly at a rate of 23.9 cm/(mm day^{-1}) when the enforced precipitation remains small, and at a rate of 6.5 cm when the added precipitation is large. This is because more snow is converted into flooding ice, and the snow-ice formation process strongly overrules the effect of the larger isolation of the thicker snow layer, which promotes the sea ice growth. **The snow-ice process is based on Archimedes' Principle. Therefore, the threshold value (1 mm/day^{-1}) is related to the density value of ice, snow and water in model parameterization, and also related to the sea ice thickness and snow depth. If sea ice and snow density, initial snow depth decrease, or sea water density and initial ice thickness increase, the threshold will increase, and vice versa.'**

Lines 380: I notice snow had a rapid melt in November (Figure 6). How about the superimposed ice formation in summer, which is caused by snow melt and refreeze? Is it considered in this model?

Response:

Due to the increase in temperature in November (Figure 2a), the snow melts quickly, which may produce superimposed ice. The superimposed ice which is implemented in ICEPACK with melt ponds parametrization is not run in this study. We have discussed the superimposed ice in discussion section:

'Sim_obs is underestimating compared to Obs in November3a). The reason might be that superimposed ice was not considered in this study. Superimposed ice usually corresponds to liquid precipitation or melted snow permeate downward form the ice surface to form a fresh slush layer that refreezes Superimposed ice is present in early autumn when snow starts to melt (Kawamura et al., 1997) and contributes significantly to sea ice growth (up to 20% of mass) (Granskog et al., 2004).

The superimposed ice is implemented in ICEPACK via the melt ponds parametrization but that is not used in this study because it would need deformation forcing which is not available at the study area. Therefore, the simulation may underestimate sea ice thickness and overestimate snow depth and we will apply the melt ponds in the follow-up research work.'

Lines 408-409: what will happen if we used a different oceanic mixed layer, for example 10 m? Are the results sensitive to this value?

Response:

Thank you for your advice. The same as the comment above, we find that water depth of sea ice observation site is about 10 m in precious study (Zhao et al., 2019). We have changed the MLD to 10 m in the text. Also we find that the change in MLD has little impact on simulation of sea ice thickness in our study. We have done the sensitivity experiments with different oceanic mixed layers, including 10 m and 20 m, and we find the simulation of sea ice thickness and snow depth is not sensitive to this value.

The oceanic mixed layer can modify the oceanic forcing through changing the sea surface temperature. The ocean forcing also plays an important role on sea ice evolution. We admit that there is a lack of sufficient analysis in oceanic forcing. In our future research, sensitivity of the oceanic forcing and their impact on the sea ice simulation will be addressed.

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Zhao, J., Cheng, B., Vihma, T., Yang, Q., Hui, F., Zhao, B., Hao, G., Shen, H., and Zhang, L.: Observation and thermodynamic modeling of the influence of snow cover on landfast sea ice thickness in Prydz Bay, East Antarctica, Cold Reg. Sci. Technol., 168, 102869, 2019.