Cover letter

Dear Editor:

We thank you and two reviewers very much for the constructive comments and suggestions for the paper ‘The sensitivity of landfast sea ice to atmospheric forcing in single-column model simulations: a case study at Zhongshan Station, Antarctica’ submitted to *the Cryosphere*. They are very valuable and very helpful for improving our manuscript. We have made a substantial revision according to the comments and suggestions from the editor and the two reviewers, and replied to them one by one 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

Responses to Editor

Editor

Comments to the author:
Dear Authors,

Thank you for your improved manuscript. As acknowledged by both referees you have great material including a set of useful model experiments and meaningful figures, but your conclusions do currently not summaries your findings adequately. Please use the comments and questions from both reviews to improve your Discussion and Conclusion sections and the last 2 sentences of the Abstract. My message from your analysis is that ERA-5 overestimates snowfall for your selected location resulting in too much snow and ice. If applying observed precipitation, snow depth is still overestimated due to missing snow drift in model, but ice thickness is accurate. Further sensitivity experiments reveal that this is due to compensating factors from snow: isolation reduces ice growth and snow-ice formation.

Please respond to the points made by both referees and provide an updated manuscript.

Response:
Thank you for your constructive comments. We have revised the texts based on the specific comments below and responded to them point-to-point.
We have changed the last 2 sentences of the Abstract to 'Shortcomings of this simulation study are also discussed'.

Responses to referee #1

Reviewer 1

Review of second revision of: “The sensitivity of landfast sea ice to atmospheric forcing in singlecolumn model simulations: a case study at Zhongshan Station, Antarctica”, by Fengguan Gu et al.

General comments

Thank you for the updated version of your manuscript, and for responding to my previous comments.

While the discussion and conclusions are improved (and it is good to see the ‘shortcomings’ section), I had hoped to see the discussion or conclusions linked more closely to the key results shown in Figure 3, with a summary of the main features of this figure (ie a recap of when and how the model and the observations agree and differ), and a clearer attribution or plausible cause for each difference. I feel this information is all there in the paper but there is still some work for the reader to do to extract and piece together the findings. I have made some specific suggestions below.

Response:

We thank you for your encouragement and pertinent comments. Your constructive comments have indeed greatly improved the manuscript. We have revised the article based on the specific comments below and responded to them point-to-point.

The new set of sensitivity experiments are interesting but are focussed towards answering a rather different question than the original set of experiments, and so are complementary. I would suggest retaining the original table 3 and some of the text as well, especially as some of these experiments are still discussed in the text.

Specific comments

P12 Section 3.4 As mentioned above, I would suggest including the original set of sensitivity experiments here as well, with the original table 3, as these experiments are now discussed later in the text without much explanation.

Response:

Thanks for your advice. We have revised the text in response to this concern:

‘To determine which atmospheric variables, including T_a , P and U_a , are the most

crucial in the sea ice simulation, we designed a set of sensitivity simulation experiments named SEN1. The simulation under the forcing from the *in situ* observed atmospheric variables is the control experiment and named Sim_Obs. In each experiment of SEN1, one atmospheric variable is replaced by the corresponding variable from ERA5, while all others are identical to those of the control experiment. In Table 3, the averaged bias between the simulation and the observation of the outputs (ice thickness and snow depth), and the bias ratio of forcing atmospheric variables are listed separately.

Table 3 Bias of ice thickness, snow depth and bias ratio for each forcing variable come from Table 2. '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	/

To determine the sensitivity of sea ice and snow depth near Zhongshan station on atmospheric forcing, we designed a set of numerical experiments named SEN2. In the control run, the forcing of the simulation directly used the means of observed atmospheric variables (Mean_Obs in Table 4). For a specific atmospheric variable, we build a set of sensitive runs. The focused atmospheric variable changed from its mean (Range in Table 4), and other variables are the same as the control run. Considering the actual range in each observed variable, we set the maximum change in T_a, Θ_a, and ρ_a to 2%, and other atmospheric variables to 50%. Then, we concluded the sensitivity of sea ice and snow to each atmospheric forcing from its corresponding sensitive runs.

Because sea ice and snow depth show a quasi-linear response to the change in each specific atmospheric forcing (not shown), the choice of the variable's range will not alter the sensitivity results.

Table 4 The atmospheric forcing (Mean_obs for the control run and range for the sensitive run), sensitivity, and potential bias from SEN2.

Variable	**Mean_Obs (Control)**	**Range (%)**	**Sensitivity**	
			Ice (cm/%)	**Snow (cm/%)**
R_{sd} (W m^{-2})	67.714	±50	-0.033	-0.008
R_{ld} (W m^{-2})	198.023	±50	-0.368	-0.201
T_a (K)	257.809	±2	-1.247	-0.526
Q_a (10^{-4} kg kg^{-1})	8.247	±50	-0.025	0.029
P (mm day^{-1})	0.660	±50	-0.032	0.135
Θ_a (K)	259.437	±2	-1.297	-0.491
ρ_a (kg m^{-3})	1.322	±2	-0.054	0.021
U_a (m s^{-1})	4.228	±50	-0.054	-0.022

Comparing the individual biases in Table 3, 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 the largest. In Table 4, the sensitivity of ice thickness and snow depth to each atmospheric variable are listed. Comparing the individual sensitivity, it turns out that the sea ice thickness and snow depth are most sensitive to T_a and Θ_a. However, T_a from ERA5 is close to the *in situ* observation, so the simulated sea ice thickness and snow depth are hardly impacted (Table 3). The results from SEN1 reveal that the overestimation in P in ERA5 is the major source for the overestimation of sea ice thickness and snow depth, even with less sensitivity to precipitation (Table 4).'

P12 L282 onwards How was the design of the new sensitivity experiments chosen? What were the reasons behind the values of 50% or 2% for the maximum change? Was this choice based on any previous work?

Response:

We chose this maximum range based on the range of variation in each observed atmospheric forcing on an interannual scale. We have revised the text in response to this concern:

'The focused atmospheric variable changed from its mean (Range in Table 4), and other variables are the same as the control run. **Considering the actual range of each observed variable on an interannual scale (Van Den Broeke et al., 2004; Jakobs et al., 2020; Roussel et al., 2020),** we set the maximum change in T_a, $\Theta_{a,}$ and ρ_a to 2%, and other atmospheric variables to 50%'.

Jakobs, C. L., Reijmer, C. H., Smeets, C. P., Trusel, L. D., Van De Berg, W. J., Van Den Broeke, M. R., and Van Wessem, J. M.: A benchmark dataset of in situ Antarctic surface melt rates and energy balance, J. Glaciol., 66, 291-302, 2020.

Roussel, M., Lemonnier, F., Genthon, C., and Krinner, G.: Brief communication: Evaluating Antarctic precipitation in ERA5 and CMIP6 against CloudSat observations, The Cryosphere, 14, 2715-2727, 2020.

Van Den Broeke, M., Reijmer, C., and Van De Wal, R.: Surface radiation balance in Antarctica as measured with automatic weather stations, Journal of Geophysical Research: Atmospheres, 109, 2004.

P15 L348 This result is no longer shown (as the original table 3 has gone).

Response:

We have added the original table 3 in section 3.4.

P17 Section 4 A sentence or two introducing this section would be good. Is it intended to be a comprehensive list of short comings that could affect the simulation? It would be good to be clear about that, as the lack of modelled snowdrift is not mentioned here. Maybe it is 'other shortcomings' which are not mentioned elsewhere.

Response:

Thanks for your advice. We have added introducing and put the snowdrift in this section:

'**The simulated ice thickness and snow depth deviate from the observations in this study (Figure 3). We list the shortcomings that could affect the simulation: 1) Superimposed ice is not considered in this study; 2) The snow-ice formation might**

be overestimated on the landfast sea ice in ICEPACK; 3) Snowdrift process has not been involved in the version of ICEPACK used here.

Superimposed ice is present in early autumn when the snow starts to melt (Kawamura et al., 1997) and contributes significantly to sea ice growth (up to 20% of mass) (Granskog et al., 2004). Superimposed ice usually corresponds to liquid precipitation or melted snow that permeates downward to form a fresh slush layer and refreezes. The superimposed ice is implemented in ICEPACK via the melt ponds parametrization but has not been considered in this study. Therefore, the simulation may underestimate sea ice thickness and overestimate snow depth compared to observation in November (Figure 3a). We will apply the melt ponds scheme in the follow-up research work.

Flooding-induced snow-ice formation is common in the Antarctic ocean because of the thin ice and heavy snowfall (Kawamura et al., 1997). It can contribute to considerable ice mass (12%-36%) and reduce the snow depth by up to 42-70%, depending on the season and location (Jeffries et al., 2001). The parameterization of the flooding process in the ICEPACK is based on Archimedes' Principle for the pack ice, which might be problematic for the coastal landfast sea ice. With a much larger volume and shallower seawater around than the pack sea ice, part of the coastal landfast sea ice might contact the sea bed rather than float in the sea. Thus, the flooding should be much weaker even with weighted snow cover. Besides, the change in density of ice due to the flooding process is significant (Saloranta, 2000) but not well considered in ICEPACK. For example, a slushy layer of 10 cm depth would refreeze within three days from observation (Provost et al., 2017), while the process only needs one day in ICEPACK. Hence, the landfast sea ice growth due to snow-ice formation needs improvement in ICEPACK, especially when the input precipitation is significantly exaggerated, e.g., the ERA5 forcing.

Surface drifting snow particles play an essential role in the surface mass balance (Van den Broeke et al., 2004). Figure 3b shows that the observed snow depth has quickly decreased from 32 cm on August 2 to 15.5cm on August 10, which should be attributed to the snowdrift because the surface wind is > 8 m s^{-1} in most of this period (Figure 2c). Friction velocity becomes sufficiently high to overcome the gravity and bonds between snow particles in this strong wind and raise the snow particles from the surface (van den Broeke et al., 2006; Thiery et al., 2012; Tanji et al., 2021). However, the mean surface wind in ERA5 is convergent around the observation site during the intense wind period (Figure 8), which might not be expected for snow depth decrease due to snowdrift. The coarse resolution of the atmospheric reanalysis might not produce a realistic surface wind field, which is primarily determined by the topography (Van Den Broeke et al., 1999; Frezzotti et al., 2005). In addition, surface sublimation of drifting snow particles, which is most significant in warm, dry, and windy weather (Thiery et al., 2012), plays an important role in surface mass balance (Van den Broeke et al., 2004) but has not been involved in ICEPACK yet.

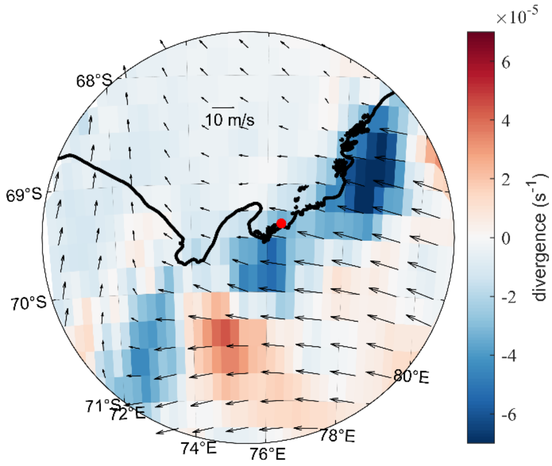

Figure 8 The mean ERA5 surface wind and divergence from August 2 to 10. The black line represents the coastline, and the red point represents the observation site’.

P18 L404-405 This says the simulation potentially underestimates the ice thickness due to the lack of the melt pond scheme, but actually the simulation over estimates the ice thickness (Figure 3a) , so perhaps some acknowledgement of that here and rewording.

Response:

Sim_Obs underestimate sea ice thickness in November compared to observation (Figure 3a). The reason may be that superimposed ice has not been considered in this study.

P18 L422 onwards I did not understand the first part of the discussion. I thought the suggestion was that the simulated snow depth did not decrease in the same way as the observations because the snow drift parametrisation was not included in the simulations?

Is the point that this is unlikely because ERA5 suggests that the wind field is convergent? Or is the point that EAR5 is probably wrong here?

Response:

Yes, we believe that the snowdrift process is the main reason for the rapid decrease in snow depth in August. When the wind field of ERA5 is convergent, we consider that there are two reasons for the rapid reduction of snow depth: 1) the wind of ERA5 may be uncertain, 2) the snowdrift process can promote the sublimation of snow particles.

P21 Conclusions If I have understood things correctly, the suggestion is that for Sim_obs, the snow depth does not decrease after the 11th July precipitation event because the model does not include the effect of snow drift.

For Sim_ERA5 this is also the case, but in addition the snow gets even thicker because there is too much precipitation. Following the 11th July precipitation event the snow gets so thick in Sim_ERA5 that too much snow-ice is formed, causing the discrepancy in ice thickness seen in Figure 3b. Apologies if I have misunderstood this, but if that is broadly correct, I would suggest stating that chain of events more explicitly in this section.

Response:

Thanks for your advice. We have revised the Conclusions section in response to this concern.

‘This work uses the single-column sea ice model ICEPACK forced by the ERA5 atmospheric reanalysis and atmospheric *in situ* observations to simulate snow depth and sea ice thickness at Zhongshan Station, Antarctic. **We find that forced by atmospheric variables from in situ observations. The ICEPACK can reasonably simulate the sea ice thickness evolution but significantly overestimates the snow depth after the heavy snowfall on July 11. When using atmospheric forcing from ERA5, sea ice thickness simulation is close to observation before July 11 but suddenly increases after the snowfall event.**

From the sensitivity experiments, we find that the significant deviation in the precipitation of ERA5 contribute to the largest bias in both sea ice thickness and snow depth even though the precipitation is moderately sensitive to sea ice thickness (-0.032 cm/%) and snow depth (0.135 cm/%). On average, about 2 mm

day^{-1} more precipitation in ERA5 is found during the observation period, which produces about 14.5 cm excess in sea ice thickness and 17.3 cm more snow depth.

We further explore the physical mechanism of the effect of precipitation on ice thickness. Snow-ice formation can be triggered by a heavy snowfall episode, like on July 11. It efficiently produces ice at the sea ice surface, decelerates the snow accumulation, and inhibits sea ice's basal growth. When the snowfall is weak, the snow layer thickens quickly and hampers the sea ice growth through its insulation effect. When the snowfall increases to a certain degree (~1 mm day^{-1}), it will trigger a continuous flooding process, accelerating the sea ice growth and slowing down the snow layer thickening.'

Technical corrections

The figure numbers are now incorrect – there is no figure 5, and there are two figure 8s.

Response:

Revised as suggested.

Responses to referee #2

Reviewer 2

Review on “The sensitivity of landfast sea ice to atmospheric forcing in single-column model simulations: a case study at Zhongshan Station, Antarctica” by Gu et al.,

The sensitivity of landfast sea ice to atmospheric forcing using a case study at Zhongshan Station, Antarctica is a very interesting study and is of great significance for the large-scale simulation of landfast ice in Antarctica, because the atmospheric reanalysis data in Antarctica are uncertain, and how these uncertainties affect the results of sea ice simulation is not very clear.

Based on the comments and suggestions of the previous round, the author has made appropriate modifications to the paper, because I recommend that the paper can be considered for publication after some minor revisions. The following are some comments:

Response:

We thank you for your encouragement and pertinent comments. Your constructive comments have indeed greatly improved the manuscript. We have revised the article based on the comments below and responded to them point-to-point.

General comments:

The parameterization scheme of the model has not been reasonably described, especially the parameterization of the oceanic heat treatment. Readers do not know how to set some parameters and parameterization schemes of processes. In addition, it is not that the simulation result is consistent with the measurement that the simulation is reasonable. When one parameter causes the simulation result to be too large and another causes the result to be too small, the result is also close to the measurements.

Response:

Thanks for your advice. We have added the parameterization of the oceanic heat in Table 1.

Table 1 Detailed options of physical parameterizations and model settings for the ICEPACK.

ICEPACK	**Value**
time step	3600 s
Number of layers in the ice	7
Number of layers in the snow	1
Ice thickness categories	5 (Bitz et al., 2001)
Initial ice thickness	99.5 cm (observed)
Initial snow depth	11.5 cm (observed)
Albedo scheme	CCSM3 (Collins et al., 2006)
Ice thermodynamic	Mushy-layer (Turner et al., 2013)
Shortwave radiation	Delta-Eddington (Briegleb and Light, 2007)
Snowdrift	Not implemented in ICEPACK 1.1.1
Melt ponds (superimposed ice)	Not used in this study
Ocean heat transfer coefficient	**0.006 (Maykut and McPhee, 1995)**
SST restoring time scale (days)	**0 (use observed SST as oceanic forcing)**
Ocean friction velocity minimum (m/s)	**0.0005 (Tsamados et al., 2013)**

Maykut, G. A., and McPhee, M. G.: Solar heating of the Arctic mixed layer, Journal of Geophysical Research: Oceans, 100, 24691-24703, 1995.

Tsamados, M., Feltham, D. L., and Wilchinsky, A. V.: Impact of a new anisotropic rheology on simulations of Arctic sea ice, Journal of Geophysical Research: Oceans, 118, 91-107, 2013.

Specific comments:

Line 118 “the measurement accuracy is better than ±0.5 °C”-- the accuracy of this type of sensor is ±0.1 °C.

Response:

Revised as suggested.

Table 1 “Snowdrift” is not implemented in the model. Thus, the modelled result will be underestimated compared with the observed value because the snow in this area will accumulate around small islands or icebergs under the action of wind-driven snow blowing.

Response:

Thanks for your advice. Topography can affect the snowdrift process but it is hard to be represented in single-column model. The snowdrift process means that wind speed becomes sufficiently high to raise the snow particles from surface. Part of the drifting snow particles will sublimate in the air or be lost in leads. The rest will be redistribution to the snow surface (Thiery et al., 2012; Lecomte et al., 2015).

Lecomte, O., Fichefet, T., Flocco, D., Schroeder, D., and Vancoppenolle, M.: Interactions between wind-blown snow redistribution and melt ponds in a coupled ocean–sea ice model, Ocean Model., 87, 67-80, 2015.
Thiery, W., Gorodetskaya, I. V., Bintanja, R., Van Lipzig, N., Van den Broeke, M. R., Reijmer, C. H., and Kuipers Munneke, P.: Surface and snowdrift sublimation at Princess Elisabeth station, East Antarctica, The Cryosphere, 6, 841-857, 2012.

Line 191 "ERA5 was 1.168 °C lower than the in situ observation" --Truncation of one decimal place is sufficient.

Response:

Revised as suggested.

Line 258 ". In other words, the enormous bias in snow depth seems to have little effect on the sea ice thickness in the simulation. This counter-intuitive finding is of great interest to us because it disobeys the general realization that the snow layer significantly modifies the energy exchange on top of the sea ice."

We can't say that if the simulation results of sea ice thickness are good, it can show that the effect of snow is small. This may be due to two reasons: 1) the thermal insulation of snow itself and the formation of snow ice counteract each other, as your later analysis; 2) the unreasonable description of other processes and contributions leads to the opposite contribution against snow, which counteracts each other. Therefore, you can further compare the conductive heat flux or temperature gradient through the ice, especially at the top layer. In this way, we can see the impact of snow.

Response:

Thanks for your constructive suggestions. We have calculated the changes in the temperature gradient at the top layer of ice during the 20 days (The observed snow depth has a 20-day peak in Figure 3b) before and after the July precipitation event by observation (TY thermistor-chain) and simulation (ICEPACK), respectively.

Observation and simulation show the mean temperature gradient at the top layer of ice is 2.5 ± 1.6°C, 1.8 ± 0.6°C(mean ± standard deviation) before the event and 0.6 ± 0.3°C, 0.8 ± 0.2°Cafter the event, respectively. The results show that after a precipitation event, an increasing snow depth reduces the sea ice temperature gradient, leading to a decrease in conductive heat flux, which affects the increase in sea ice thickness.

Figure 3: In fact, all simulation experiments can not reasonably describe the accumulation process of snow, so the process of snow blowing is very important, which is also the future development direction of the model, and some discussions can be added.

Response:

We have added the snowdrift process in the Shortcomings section.

‘Surface drifting snow particles play an essential role in the surface mass balance (Van den Broeke et al., 2004). Figure 3b shows that the observed snow depth has quickly decreased from 32 cm on August 2 to 15.5cm on August 10, which should be attributed to the snowdrift because the surface wind is > 8 m s^{-1} in most of this period (Figure 2c). Friction velocity becomes sufficiently high to overcome the gravity and bonds between snow particles in this strong wind and raise the snow particles from the surface (van den Broeke et al., 2006; Thiery et al., 2012; Tanji et al., 2021). However, the mean surface wind in ERA5 is convergent around the observation site during the intense wind period (Figure 8), which might not be expected for snow depth decrease due to snowdrift. The coarse resolution of the atmospheric reanalysis might not produce a realistic surface wind field, which is primarily determined by the local topography (Van Den Broeke et al., 1999; Frezzotti et al., 2005). In addition, surface sublimation of drifting snow particles, which is most significant in warm, dry, and windy weather (Thiery et al., 2012), plays an important role in surface mass balance (Van den Broeke et al., 2004) but has not been involved in ICEPACK yet.

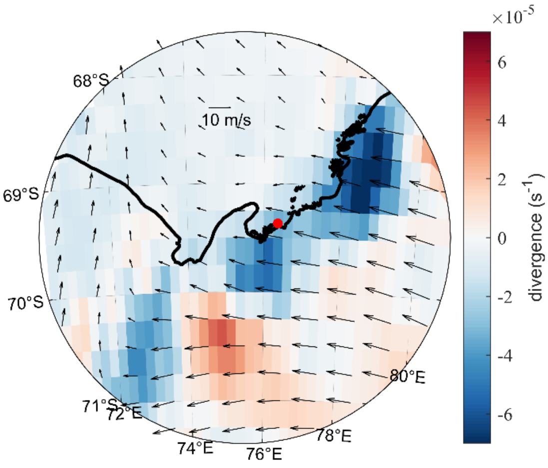

Figure 8 The mean ERA5 surface wind and divergence from August 2 to 10. The black line represents the coastline, and the red point represents the observation site.’.

Line 311: into the ice surface HN: It is snow surface or ice surface?

Response:

We have changed ‘ice surface’ to ‘snow surface’.

Line 331: “the increase in sea ice thickness will reduce the heat transfer between the ocean and the atmosphere” change to “the increase in sea ice thickness will reduce the heat loss from the ice cover”

Response:

Thanks. We have revised this sentence to ‘This difference may be because as the snow-ice process occurs, **the increase in sea ice thickness will reduce the heat loss from the ice cover** and inhibit the basal growth of sea ice in winter’.

Line 378 “ the simulated snow depth deepens ” change to “ the simulated snow depth increases”

Response:

Revised as suggested.

Line 402 “The superimposed ice is implemented in ICEPACK via the melt ponds parametrization but has not been considered in this study because the deformation information of sea ice is not available”

Neither melt pond nor superimposed ice formation process can be directly related to sea ice deformation. Superimposed ice is formed by the refreezing of melt water penetrating into the ice surface. The distribution of melt pond can be related to the roughness of ice surface.

Response:

Thanks for your advice. We have deleted the sentence about sea ice deformation.

‘Superimposed ice usually corresponds to liquid precipitation or melted snow that permeates downward to form a fresh slush layer and refreezes. The superimposed ice is implemented in ICEPACK via the melt ponds parametrization but has not been considered in this study.’