We thank you for your extensive and constructive comments that are helpful to improve our manuscript. We agree with your comments and have worked diligently to address these and revised the manuscript and hopefully have improved it significantly.

Main changes are:
i. Intervals referred to in the manuscript are defined in terms of Ka with arrows added to the inset of Figure 1A to clarify glacial terminations and glaciations.
ii. The insets of Figure 1 has been modified to use a more data-based record of the glaciation transition.
iii. The text has been revised to clarify the point that sea ice feedback mechanisms are one of many. However, what we are trying to propose in this manuscript is that negative sea ice feedbacks can play a critical role at bifurcation points and in this way regulate the pace of the glaciation.

Our point-to-point responses to each comment are below:

Referee #1

Received and published: 22 April 2019

Overall:

This paper proposes two possible feedbacks due to Arctic sea ice that could influence Northern Hemispheric glacial-interglacial variations, in particular the sawtooth asymmetry long noted in 100,000 year cycles. Sea-ice feedbacks could well play a role in aspects of glacial-interglacial cycles, whether as primary feedbacks or as secondary influences among others. However, in my view the description of the mechanisms here is confusing, and I have several concerns that question their viability relating to the asymmetry. Given the main concerns (#1 to 4 described below), I think that the mechanisms in the paper are not organized in a physically coherent way, and the proposed sequence is not sufficiently developed and plausible for an ESD Ideas paper.

Authors

We are grateful to you for reading and letting us know your concerns with the manuscript. We appreciate the details in your comments, and it has served us well in helping us improve our understanding of some concepts and it is appreciated, thanks.

Referee #1
Specific points:
1. The text and Fig. 1 are confusing regarding the sequence of processes, mechanisms, and stages, and how they relate to the "inception" and "termination" periods of the title. The text should define the intervals (in years before present, ka) the intervals of "inception" (and also termination, presumably ~20 to 10 ka), and the text and red arrows in the insets should specify more precisely to what parts of the long-term record the proposed mechanisms and stages apply. The time periods for each stage in the panels in Fig. 1 should be specified explicitly, either by giving ka values or with time bars in the insets relating to the long-term record.

Authors

You raise a good point, we have revised the manuscript to reflect this by defining glacial inception, termination, intermediate stage and the full transition to glacial conditions in terms of ka for the last termination and glaciation. In doing this, we realized the term ‘glacial inception’ may not be the best words to describe what we meant and have replaced it with ‘glaciation’.

Authors changes in manuscript

Therefore, the title of the paper now reads “Why are glaciations slower than deglaciations?”

Referee #1

In particular the time period referred to as "inception" is unclear. "Inception" is often taken to mean the first rapid buildup of ice following the last interglacial, around ∼120 to 110 ka. Given that, the long-term record in Fig. 1. insets does not have a pronounced difference in the slope (rate of growth), compared to the rate of retreat during the last termination ∼20 to 10 ka. By eye at least, they both look equally steep. In that case the whole premise of the paper is on shaky ground. But perhaps "inception" here refers to the later more gradual buildup over a longer part of the cycle, averaged over several orbital variations, even as long as ∼100 to 20 ka, which does give rise to the long-noted sawtooth asymmetry. This may be the case, as suggested by the phrase "changeover to a glacial period takes tens of thousands of years" (line 23).

Authors

Thank you, we have now clarified this point by defining the intervals; glacial inception and the glaciation process which includes both the glacial inception and intermediate stages. By pointing this out perhaps you have helped us to significantly improve this manuscript.

Authors changes in manuscript

From benthic $\delta^{18}O$ (‰) records from ODP Site 983 from Raymo et al., (2004) the duration of the last termination is ~ 10ka while the glaciation process including the inception and intermediate stage had a duration of ~ 77ka.

Referee #1

Other sources of confusion are: (i) none of the arrows in Fig. 1, or the intervals referred to in the text, lie in the interval roughly ∼20 to 10 ka usually referred to as "termination", i.e., the last deglacial retreat since LGM, and (ii) it does not seem to matter whether the red arrows in the insets fall in a zenith or nadir of faster orbital/millennial fluctuations of the long-term record.

Authors

To show the difference in the rates between glacial terminations and the glaciation process, gray arrows are used to indicate these in the inset of Figure 1A.

Referee #1

The long-term record in the insets of Fig. 1 is presumably from Fig. 1b of Bintanja et al. (2008), which is a model-dependent reconstruction. It would be better to use a purely data-based record, with ice-core, deep-sea-core d18O, or sea-level proxies.

Authors

We have revised the insets of Figure 1 using benthic $\delta^{18}O$ (‰) records from ODP Site 983 in the North Atlantic by Raymo et al., (2004).

Referee #1

2. Several aspects of the mechanisms discussed in the middle paragraphs (lines 38-89) are confusing and/or questionable. The first of the two feedbacks, "sea ice- precipitation", is reasonable and has been involved in previous studies, i.e., greater Arctic sea ice cover reduces evaporation and hence high-latitude precipitation, reducing the surface budget of Northern Hemispheric ice sheets. The second feedback, "sea ice-insulation", involves the sea-ice "lid" insulating the Arctic Ocean thermally from the atmosphere, but it is not clear in what sense this is a feedback, positive or negative, and how it influences ice-sheet growth or retreat. (It must have an effect on the latter, given the premise of the paper). Various processes are mentioned in lines 66-89 including buildup of geothermal heat flux, but how they are negative feedbacks on terrestrial ice sheet volume variations is absent or unclear.

Authors

The second feedback aids sea ice ablation and a return to decreased albedo and warmer temperatures and in this way serves as a negative feedback. We had adjusted a few lines in paragraph 4 to make this clear.

Authors changes in manuscript

"Sea ice disintegration decreases albedo resulting in a return to higher temperatures and the development of the intermediary stage of almost interglacial conditions depicted in Figure 1C. The intermediary stage of reduced albedo and warmer conditions may have a wider influence by affecting other climate variables such as land-based ice-sheets which can in turn impact the behavior of other dominant players in this climate transition."

Referee #1

3. Arctic sea ice, up to a few meters thick, is a "fast" component of the climate system, coming into quasi-equilibrium with the regional atmospheric and oceanic climate within a few decades, i.e, it has only decadal-scale inertia, and its mass turns over every few years to ~decade. As such it can influence climate sensitivity to external changes (like water-vapor feedback for instance), or influence tipping points between multiple stable states. But it is not itself a long-term component of the climate system with inertial time scales of hundreds to many thousands of years (such as ice-sheet size, deep-ocean temperatures, bedrock deformation state, CO2 level). This important distinction seems to be blurred in places, and sea ice is implied to have inertia of thousands of years, e.g., lines 85-86 ("since not all first-stage ice was lost") seem to require that the same sea-ice mass persists between the stages discussed here (Stage A to D, or perhaps C to D), tens of thousands of years apart. This contributes to the confusion regarding the sequence of mechanisms and processes in the middle paragraphs.

Authors

We agree that these feedbacks are only temporarily dominant and their influence changes depending on how close to bifurcation points the system may be. The text has been revised to increase its clarity.

Authors changes in manuscript

This stage remains dominant temporarily with sea ice cover formation increasing and ablation processes following until gradually sturdier sea ice forms as overall, temperatures cooler than interglacial temperatures prevail as shown in Figure 1D.

Referee #1

4. In places, the text neglects associated processes that are likely to dominate the process under discussion. For instance, in line 51, less summer melting of sea ice could well dominate over less precipitation, favoring and not hindering sea-ice growth. (A related point: the dominant control of Northern Hemispheric ice-sheet variations on orbital time scales is generally considered to be not snowfall, but ice melt in southern ablation zones, i.e., summer atmospheric temperatures, not precipitation rates, as recognized by Milankovitch and many subsequent studies by choosing summer-season insolation at ~60 or 70 N as the orbital metric). Sea ice-precipitation feedback may still function, but why it is not dominated by changes in summer air temperatures and ablation-zone melt should be justified if possible.

Authors

Gradual changes in a forcing can result in little change in a dynamic system until some critical threshold has been surpassed when a sudden large shift may be seen in the system (Scheffer et al., 2012). We think that may be the case here, the sea ice-precipitation feedback though still functional throughout the glaciation is most effective in assisting large change at critical points.

Referee #1

Another example is in lines 69-70 discussing the buildup of geothermal heat flux. The effect of this on Arctic ocean temperatures would likely be minor compared to changes in ocean circulation exchange between the deep Arctic and the North Atlantic.

Authors

A previous model study (Rial and Saha, 2011) has shown that sea ice cover can cause buildup of geothermal heat flux in the deep ocean increasing temperature so it is higher than surface temperatures resulting in increased buoyancy of the deep ocean and eventually increased vertical turbulence which enhances the break up of the sea ice. While this may be minor, we think it provides enough change at the tipping point to facilitate the development of an intermediate stage and may explain why this mechanism is not dominant throughout the glacial stage.

Referee #1

5. Tziperman and Gildor (2003) referenced here and their related papers involve many of the same mechanisms as here: sea-ice switches, deep ocean temperatures, and the sea ice-precipitation feedback on ice sheets. How are the feedbacks and the sequences here different from theirs?

Authors

Gildor and Tziperman, (2000) proposed a sea ice switch mechanism which says the sea ice acts as a control of the atmospheric moisture fluxes and precipitation through its albedo and insulating effects switching it between two modes: growing land ice and retreating land ice.

In the current proposed mechanism, the sea ice is also thought to control atmospheric moisture and precipitation. However, the mechanism presented here differs in that it considers the effect of insulation on the temperature and stability of the deep ocean instead of land ice sheets. Here sea ice cover is considered as a control on deep ocean temperature in the Arctic which in turn can control the extent of sea ice cover by vertical turbulence.

Authors changes in manuscript

Gildor and Tziperman, (2000) proposed a sea ice switch mechanism which says the sea ice acts as a control of the atmospheric moisture fluxes and precipitation through its albedo and insulating effects switching it between two modes: growing land ice and retreating land ice. A similar mechanism is presented here but differs in that it considers the effect of sea ice insulation on the temperature and stability of the deep ocean instead of land ice sheets.

Referee #1

6. The scenarios here do not consider the possibility of very thick ∼1 km ice-shelf cover over the entire Arctic Ocean during some past glacial maxima, proposed by Jakobbson et al. (2016) referenced here. These thick ice shelves would have been supplied primarily by ice-sheet flow and would introduce very different physics and processes than here. This could at least be mentioned, as the Jakobbson study is used as a reference.

Authors

There is indeed a possibility of the Arctic Ocean being covered by very thick sea ice which we think follows the intermediate stage developed during the glaciation transition process. We agree that the development of a thick ~ 1km ice cover over the Arctic has a high possibility and can lead to various other processes not considered in our proposal. However, the proposed mechanism in this paper and its resultant processes is thought to be dominant only during the transition where the extent of sea ice is most important.