Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2019-10
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 18 March 2019

Earth System Dynamics
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Discussions

ESD Ideas: Why are glacial inceptions slower than terminations?

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Abstract. The Earth's climate during the Quaternary is dominated by short warm interglacials and longer cold glaciations paced by external forcings such as changes in insolation. Although not observed in the solar radiation changes, the time series of the cycles display asymmetry since transitions to full glacial conditions are slower than termination of glaciations. Here an idea is proposed for the slower transition by identifying and describing two negative sea ice feedbacks, dominant during the glaciation process that could serve as a control of the intermediate stage and decrease the pace of the process.

Paleoclimate data show that the Earth's climate of the last 2.6Ma is dominated by cold glaciations lasting about a 100ka with extensive glaciers and warm interglacials with little global ice cover lasting 10-30ka (Imbrie et al., 1992). The termination of a glacial period occurs rapidly after a maximum in Northern Hemisphere (NH) summer insolation is crossed while glacial inceptions are similarly triggered by astronomical forcing when a threshold of insolation minimum is surpassed (Lisiecki, 2010). However, unlike terminations, which take thousands of years, the changeover to a glacial period takes tens of thousands of years to be completed resulting in an interesting asymmetrical shape for which there is yet no consensus on the mechanism(s) (Tziperman and Gildor, 2003). There is a plethora of previous research which have identified several feedback mechanisms to explain glacial-interglacial asymmetry, for example, varying ice sheet volumes (Le Treut and Ghil, 1983).

While it is mostly agreed that astronomical forcings trigger glacial-interglacial transitions, a similar shape is not observed in insolation changes suggesting a nonlinear response by the climate system (Lisiecki and Raymo, 2007). Negative feedbacks work to maintain the stability of an equilibrium state while positive feedbacks favor instability and regime transitions (Rial et al., 2003). Therefore, it seems intuitive that negative feedbacks would play critical roles in slowing the pace of a transition between equilibrium states. Here it is proposed that negative feedbacks are responsible for the development of the intermediary stage observed during the glaciation and two negative sea ice feedbacks are specified as the critical feedbacks.

This paper suggests that sea ice-precipitation is one of the first feedbacks to become dominant during glaciations as **Figure 1** illustrates. The red arrow in the inset of **Figure 1** for each of the four panels show the stage of the glacial inception process being addressed. Looking at the Arctic region with interglacial conditions, there is little sea ice formation but strong energy and mass ocean-atmosphere exchange (**Figure 1A**). The glaciation process is initiated after the insolation minimum is crossed and NH temperature decreases (Lisiecki 2010). This allows sea ice to extend rapidly, increasing albedo, further decreasing temperatures explaining the initial drop observed in the temperature data shown in the inset of **Figure 1**. Arctic sea ice controls climate by regulating albedo and air-sea exchange of both energy and gases (Weyl, 1968). Both proxy and modeling data indicate significant ice cover over the Arctic Ocean during the last glacial maximum (Colleoni et al., 2009; Jakobsson et al., 2016). The increased sea ice coverage and decreased air-sea exchange may have caused cold, dry atmospheric conditions to develop, reducing precipitation as depicted in **Figure 1B**. With less precipitation in the Arctic region, there is less ice accumulation, and sea ice growth is hindered. Hydrogen isotope ratios (d-excess values) confirm that sea ice controls regional Arctic precipitation by contributing to drier conditions on Greenland as sea ice extent increases (Kopec et al., 2016).

The extensive sea ice formed now becomes starved as precipitation and ice accumulation become limited, the newly formed sea ice thins and becomes more vulnerable to ablation. Enhanced ocean movements can result in a rapid ablation as shown in **Figure 1C** and inset (red arrow shows the stage of transition) and increased temperatures resulting in an intermediate stage with higher temperature or mild glacial conditions as described by Paillard (1998). This stage remains dominant allowing increased evaporation due to the newly uncovered ocean, and increased precipitation. As overall temperatures remain cooler than during interglacial with low insolation values prevailing, the broken sea ice reforms into a sturdier sheet that is more resistant to ocean turn over (**Figure 1D**).

The second dominant feedback proposed is sea ice-insulation feedback as portrayed in **Figure 1**. Results from the atmospheric HIRHAM regional climate model showed sea ice acts to regulate air-sea heat flux by allowing stronger heat flux when sea ice thickness is reduced (Curry et al., 1995). With the formation of sea-ice in the Arctic Ocean, as explained above and shown in **Figure 1B**, and air-sea energy exchange reduced, there is reduced heat loss and geothermal energy build up in the deep ocean increasing seawater buoyancy and at some critical point leading to vertical ocean turbulence and sea ice ablation, illustrated in **Figure 1C**. In a study of Dansgaard-Oescheger events, the ECBilt-Clio model demonstrates the effect of sea ice on deep ocean temperature where a 13-15 $x10^6 km^2$ sea ice extent led to the deep ocean temperature increase of 2-4^{o}C at 1.5-3.5km depth, and 2-5^{o}C (Rial and Saha, 2011). This induces instability with cold dense water at the surface and warmer water in the deep resulting in turbulent vertical mixing at some point, and sea ice ablation. The first proposed feedback sea ice-precipitation likely enhances this sea ice disintegration; where decreased precipitation results in thinning sea ice and increased susceptibility to perturbations such as turbulent mixing.

Sea ice disintegration decreases albedo resulting in higher temperatures and the development of the intermediary stage depicted in **Figure 1C**, where there is a return to almost interglacial conditions. This stage remains dominant temporarily with increased evaporation allowed by the newly uncovered ocean and increased precipitation. Overall, temperatures cooler than interglacial temperatures prevail during the intermediate stage as insolation values remain low, the broken sea ice reforms, shown in **Figure 1D**, and is much sturdier since not all the first-stage ice was lost. The more durable sea ice has greater resilience to ocean turnover, and instead of breaking up with ocean turbulence, there are changes in local North Atlantic convection sites. Shifting the position of the North Atlantic Deep Water (NADW) formation is demonstrated by previous studies, for example, Rahmstorf, (2006).

Paillard, (1998) showed the existence of an intermediate stage during glacial inception in which an ice volume threshold must be crossed before the transition to full glacial conditions can occur and help simulate the asymmetry of the glacial cycles. Building on this concept, two negative feedbacks, sea ice-precipitation and sea ice-insulation that provide a physical cause of the intermediary stage during glaciations that makes the process much slower than terminations are presented. The dominance of these two feedbacks have implications for models that will replicate the climate dynamics of the glacial-interglacial cycle transitions and similar critical transitions of dynamical systems by emphasizing the role of negative feedbacks. Given the unusually fast rate of anthropogenic changes the Earth system is currently undergoing, the risk of crossing thresholds and transitioning to another climate state becomes greater. Therefore improving understanding of how negative feedbacks facilitate climate regime change will help in estimating the speed of transitions.

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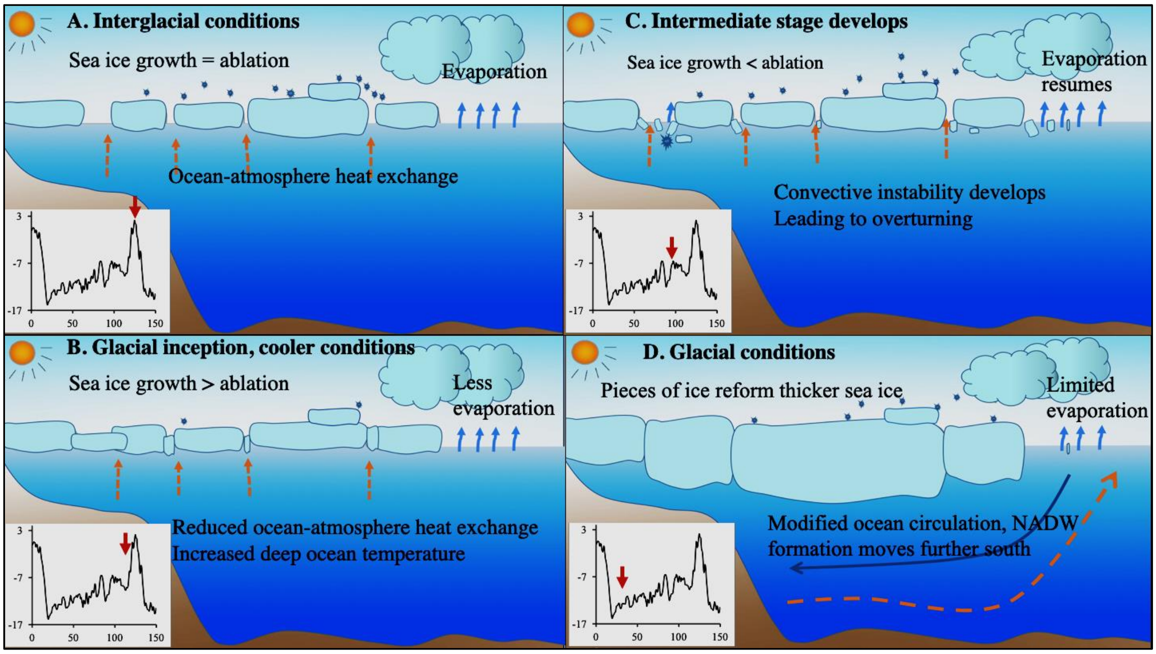

Figure 1. Illustration showing how the proposed two dominant negative feedbacks operate to slow down the glaciation process with an inset showing temperature change relative to present day north of ~ 45°N in (°C) (Bintanja and van de Wal, 2008) spanning the last 150ka. The red arrow shows the glacial transition stage described in the given panel. **A**. Interglacial conditions exist, there is strong exchange of energy (dashed orange arrow) and evaporation of moisture (red arrow) from the ocean. **B**. Initiation of glacial inception and sea ice extends, insulating the ocean while energy accumulates, increasing deep ocean temperatures and buoyancy, creating an unstable water column. **C**. At some critical point, when the water column is sufficiently unstable resulting in overturning and ablation of the young sea ice, albedo decreases and temperatures increases, creating the observed intermediary stage. **D**. Sea ice has reformed from the broken pieces of ice due to continued low summer insolation. This sea ice is thicker and sturdier, better able to resist ocean turnover, leading to changes in the ocean circulation patterns instead.