

Reply to comments by Fuyuki Saito: "Estimating the impact of ice sheet surface height and ice divide variability on ice core based climate reconstructions"

Summary of Changes

We are grateful to the reviewer for evaluating our work, and for the valuable and constructive comments that help improve the manuscript. To address the major comments, we now

- state the distinction between the bias from the conditions at the deposition site and the bias from ice transport explicitly in the Introduction and restrict the scope of the study.
- cite the suggested divide-dynamics literature.
- compute the mean dome position separately for glacial and interglacial conditions.
- replace Table 1 by a grouped bar chart following the reviewer's example and move the table to the appendix.

Below, we respond to the reviewer's individual comments in detail and describe the actions we took to address them.

Detailed response

(Original report cited in italics; our replies in blue.)

General Comments

This paper presents a set of numerical simulations of the Antarctic ice sheet over the past 2 million years, utilizing two independent ice sheet models. The main focus is to evaluate variations in the elevation and position of major ice core sites to investigate their possible influence on paleo-climate reconstructions. Overall, I find the paper to be fairly well-written, with a few exceptions noted below, and I recommend that it be accepted for publication following minor revisions.

Reply: We thank the reviewer for the positive assessment and for the constructive comments.

Major Point

The motivation for this study is clear. As described at the beginning of the abstract—"as reconstructions are based on the history of surface climate at the ice core site, variations of the surface geometry and the ice flow patterns might result in biases within those reconstructions"—the goal is to evaluate the influence of the evolution of ice-sheet topography on core-based reconstructions. However, I feel that the discussion of ice flow patterns and their subsequent impacts is somewhat lacking in the current manuscript.

As far as I understand, there are two major sources of uncertainty in reconstructions due to ice-sheet variations: one is what is deposited on the ice-sheet surface, and the other is what is transported within the ice sheet. This paper primarily focuses on the former, while the latter is only briefly mentioned in limited sections (e.g., the abstract, Figure 1, and briefly in Sections 4.3 and 4.4).

I do not request the inclusion of a detailed study of flow patterns in this manuscript. Rather, I suggest carefully excluding the latter topic from the main focus and instead explicitly mentioning both aspects in the introduction to clarify the scope. As described in Section 4.4, a high-resolution nesting model will be necessary to properly address the latter topic, and this study indeed provides the regional constraints for such a sub-model. Furthermore, the simulated divide migration only highlights the potential for bias in the

reconstructions, as the transient dome may not actually be a source of ice in the core, as described in the paper. Therefore, I suggest explicitly stating that the evaluation of the influence of flow pattern variations is postponed to future studies.

Reply: We agree and will state the differentiation between both mechanisms explicitly in the Introduction (see next reply) and the postponement in Sect. 4.3 of a revised manuscript.

Nevertheless, I strongly suggest including references to past studies regarding divide positions and their influence on flow, either in the introduction or the discussion. There is a substantial body of literature on this topic that is currently not introduced in the paper. For example:

* Dahl-Jensen (1989) demonstrates that the horizontal scale of the ice divide is on the order of one ice thickness, and that depth profiles of vertical velocity and stress closely approach a profile computed in the shallow ice approximation at a distance of twice the ice thickness from the divide. This study illustrates the scale and magnitude of the influence of divide migration on flow patterns, which is particularly relevant since the present paper shows up to 120 km of variability in position—much larger than the theoretical perspective provided above.

* Weertman (1973) investigated the effect of changes in the ice sheet span and the spatial pattern of the accumulation rate on the divide's position, concluding that the steady-state position of a divide is much more sensitive to the span than to the spatial pattern of accumulation. This aspect directly links to your paper (e.g., how variations in grounded area can impact divide migration).

* Hindmarsh (1996) investigated the sensitivity of a divide position to stochastic, anti-symmetric accumulation distributions near the divide, showing that the time constant for divide relaxation to such a forcing is about 1/16 of the typical time scale (thickness divided by accumulation rate). This could be compared with the time lag presented in your paper.

* Anandakrishnan et al. (1994) estimated that lateral migration of the divide in Central Greenland is between 10 km and 50 km in response to changes in ice sheet margin positions and accumulation rates on glacial/interglacial time scales. This sensitivity is sufficiently large to affect simulated depth-to-age profiles.

* Nereson et al. (1998) estimated that even small changes in the accumulation pattern and lateral boundary elevations may have caused the Siple Dome divide to migrate by 0.05–0.50 m/yr over the past 1,000 years.

* Martin et al. (2009) presented the impact of divide migration on isochrone structures, which would also be an interesting point of discussion for this paper.

You do not necessarily need to cite all of these papers, but they are listed here for your reference as they are foundational to the topic.

Reply: We thank the reviewer for pointing us to these studies. We will cite them in the Introduction, of a revised version of the manuscript, where the two effects are introduced. As these studies treat divide migrations of a few ice thicknesses in idealized settings, while the simulated dome displacements reach 100 km and more, we do not compare them quantitatively in the manuscript.

Proposed text: " The position of the ice divide responds to changes in ice sheet extent and accumulation, among other factors (Weertman, 1973; Anandakrishnan et al., 1994; Hindmarsh, 1996). In these early studies, shifts are estimated to lie in the range of a few ice thicknesses to max 50 km. Such migrations were recognized to leave an imprint on the internal layering (Nereson et al., 1998; Martín et al., 2009b)."

“Such shifts could result in ice from different spatial sources being transported to and incorporated into the ice core column (see Fig. 1).”

“In this study, we use three different transient state-of-the-art ISM simulations, covering the last 2 million years of AIS evolution, to quantify ice sheet surface height variations and their potential impact on ice core based temperature reconstructions. As the ice flow path to the drill site is not explicitly modeled, a shift of the deposition site is assessed only through the variability of the simulated ice divide and dome position, which indicates at which sites such a shift cannot be excluded.”

Minor Points

* Table 1: It would be much better to summarize these data with a series of bar graphs. I have attached an example of such a graph that I generated for this review.

Reply: We thank the reviewer for preparing this example. We will replace Table 1 by a figure following the suggested layout (see Fig. below) and move the table to the appendix.

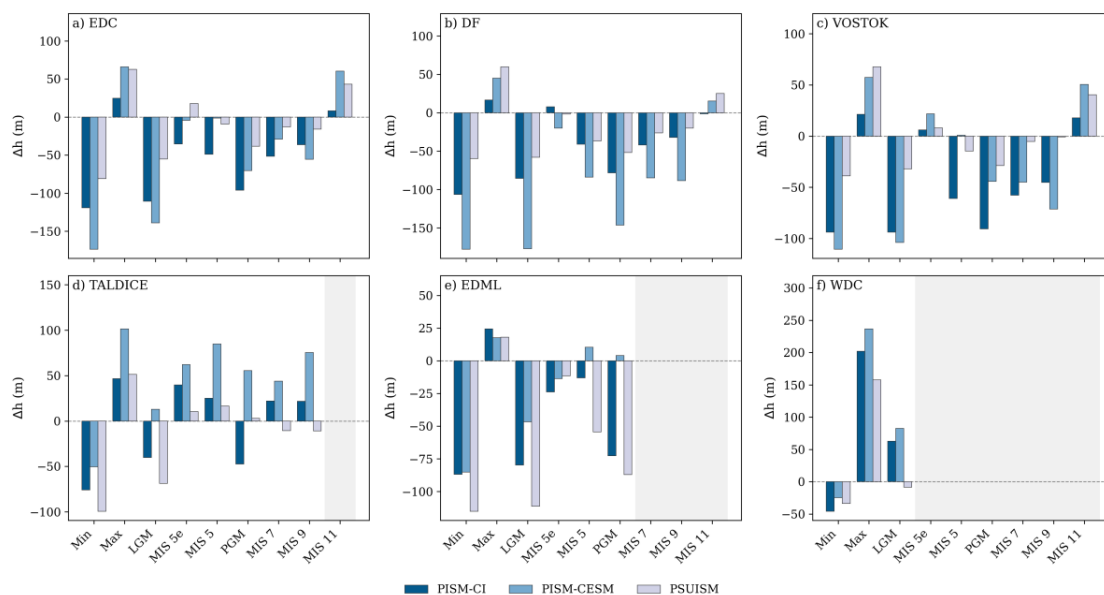


Figure R4. Simulated Δh at the six main ice core sites: minimum and maximum over the ice core covered period and Δh at the LGM, MIS 5e, MIS 5, PGM, MIS 7, MIS 9 and MIS 11 for PISM-CI, PISM-CESM and PSUISM. Grey shading marks time slices older than the respective ice core record.

* L19 ("orbital scale"): Providing a rough guide for the time scale (e.g., ~100 kyrs) would be helpful here.

Reply: Added for the revised manuscript.

Proposed text: "[...] and their high temporal resolution enable studies of climate variability from centennial to orbital time scales, i.e. from centuries to the roughly 20, 41 and 100 kyr periodicities of precession, obliquity and eccentricity (Brook and Buizert, 2018)."

* L37 ("at ice core sites closer..."): I understand the point, but there is a slight conceptual gap between the core site and ocean dynamics. I suggest rephrasing to something like, "surface height may be influenced by changes in grounded area due to ocean dynamics..."

Reply: We agree and adopt the reviewer's phrasing.

Proposed text: "In contrast, at ice core sites closer to the ice sheet grounding line, surface height variations may be primarily influenced by changes in the grounded area driven by ocean dynamics."

** Eq. (3): The symbol ϕ used here conflicts with the phase symbol shown later in the discussion section. Please use distinct symbols.*

Reply: We agree and will resolve the conflict.

** L113 ("The model was forced with time-evolving Northern Hemisphere ice sheet....."): What about the Antarctic ice sheet? If it was kept fixed throughout the climate-model simulation, it would be better to mention this explicitly.*

Reply: The Antarctic ice sheet was kept at constant present-day conditions. We will state this in the revised manuscript.

** Fig A3 & A4: It might be better to move the axis annotations (ΔT and the scale) to the right side of the figures for better readability.*

Reply: We will move the axis annotations of the figures to the right-hand side for the revised manuscript.

** Divide migration throughout the text: I am very interested in a systematic view of the divide migration. In the current figures, only the possible ranges of the dome positions are presented without any timing information. Is there any relationship between the position and forcing characteristics? For example, it would be quite interesting to know if the mean positions of a Dome over glacial and interglacial periods are fundamentally different. Adding this context may also help improve the interpretation of the results shown in Figures A5 and A6.*

Reply: We computed the mean dome position separately for the interglacial and glacial parts of the glacial cycle, using the $\delta^{18}O$ phase angle (see figures below). The two means coincide within one grid cell (16 km) at all sites in both PISM simulations, except for WDC in PISM-CESM (19 km): the dome wanders within its envelope over the glacial cycle, but its position is not tied to the climatic state. We add a statement to Sect. 3.2 and propose to add Figs. below to the appendix of a revised manuscript.

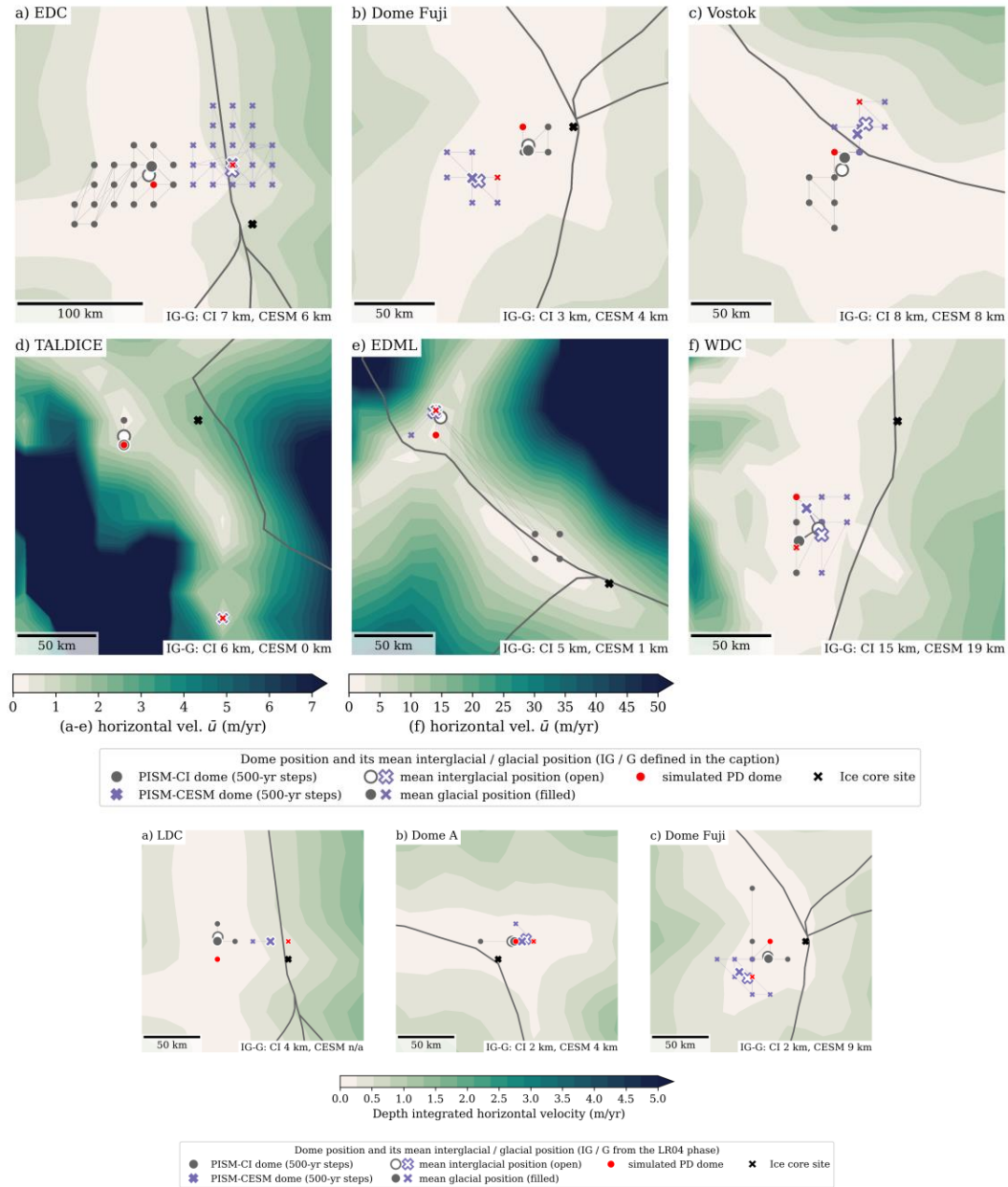


Figure R6. Tracked ice dome positions in 500 yr steps for PISM-CI (circles) and PISM-CESM (crosses) at the ice core sites over the period covered by the respective record (top) and at the prospective oldest ice sites between 2.0 and 1.2 Ma BP (bottom). Large open and filled markers give the mean dome position of each simulation under interglacial and glacial conditions. Red dots mark the simulated present-day dome, black crosses the drill site. Panels are cropped to the area covered by the dome migration. At Vostok the simulated dome lies about 280 km from the drill site and the drill site falls outside the panel.

Additional corrections: While recomputing the numbers for the revision we found that the PSUISM minimum and maximum values in Table 1 had been evaluated over twice the ice core covered period. We will present the corrected numbers in a revised manuscript.

We thank Fuyuki Saito again for the careful reading and the constructive comments, which have helped us to improve the manuscript.