Referee Report on Lucas et al. (2026): ICE-NADI-1

General Comments

The last deglaciation, during which the climate system transitioned from a glacial to an interglacial state, is a key period in paleoclimate research. One of the major challenges in studying and simulating this transition is constraining the timing and magnitude of ice sheet retreat and thinning, and consequently the amount and timing of meltwater input to the oceans. Lucas et al. (2026) address this problem by presenting a new set of reconstructions of the North American Ice Sheet Complex from 25 to 1 ka. They employ the ICESHEET model and use the North America Deglaciation Isochrones (NADI-1; Dalton et al., 2023) to prescribe and constrain the ice sheet margins. The authors also investigate the sensitivity of their reconstructions and GIA predictions to different viscoelastic Earth models. Their results are compared with three previous North American ice sheet reconstructions (ICE-7G, LW-6, and NAICE) and with several relative sea-level (RSL) datasets.

The updated NADI-1 margin chronology, the resulting three-dimensional ice thickness fields, and the accompanying GIA calculations constitute a useful new data product with potential applications in GIA studies, paleoclimate modelling, paleogeography, and deglacial sea-level research. The manuscript addresses relevant scientific questions that fall clearly within the scope of Climate of the Past.

The study reaches several potentially important conclusions. These include a lower peak North American ice volume than in ICE-7G and LW-6, substantial ice-volume growth associated with the formation of the Laurentide–Cordilleran saddle, a smaller North American contribution to Meltwater Pulse 1A, and substantial sensitivity of RSL, paleotopography, and vertical land motion predictions to the adopted NADI-1 margin scenario.

Nevertheless, in its current form, the manuscript does not sufficiently support some of its interpretations and claims. In particular, the reconstructions consist of independently calculated steady-state ice geometries for prescribed margin positions rather than transient ice sheet simulations. Consequently, the model does not directly simulate transient ice dynamics, the physical mechanism of saddle collapse, or physically resolved short-term melt rates. These limitations should be reflected more clearly in the interpretation of the results. Similarly, the NADI-1 minimum and maximum reconstructions represent end-member margin scenarios and should not be interpreted as formal probabilistic uncertainty bounds. Therefore, the manuscript needs a more careful distinction between sensitivity to prescribed margin scenarios and formal uncertainty quantification.

I also think that the authors should qualify their statement that the ICE-NADI-1 reconstructions were not tuned to RSL observations. Although the NADI-1 margins

themselves were not directly adjusted to fit the RSL datasets used in this study, the adopted basal shear-stress maps were taken from Gowan et al. (2016b), where the shear-stress estimates were adjusted using GIA observations. In addition, the Earth_1 model is selected for the main RSL analysis because it was previously identified as providing a good fit to eastern North American RSL observations. Thus, the new reconstructions are not entirely independent of observational constraints used in previous GIA studies, and this distinction should be stated more clearly.

The manuscript is generally well written and structured. However, in several places the main storyline, namely, how the updated NADI-1 ice margins affect the reconstructed geometry and volume evolution of the North American Ice Sheet Complex, becomes difficult to follow. This is partly because the authors simultaneously compare several combinations of ice-margin scenarios and Earth models with multiple previous reconstructions and observational datasets. The aims of these different comparisons, and the rationale for selecting the particular viscoelastic Earth models and reference ice sheet reconstructions, should therefore be stated more explicitly. A clearer separation between the effects of ice-margin choice, Earth-structure choice, and differences among existing ice sheet reconstructions would considerably improve the presentation.

Overall, I consider the manuscript scientifically worthwhile and potentially suitable for publication. However, substantial methodological clarification, additional analysis, and moderation of several interpretations and claims are required before the manuscript can be considered for publication. Therefore, I recommend major revision**.**

Specific Comments

In this part, I write the specific comments on the paper's sections as the same order they have in the paper:

1. Introduction

    - **Lines 45 - 49:** I would recommend including PaleoMIST (Gowan et al., 2021) among the previous reconstructions introduced here.

    - **Line 50:** Should refer the studies using Dyke et al. (2004) as the margin constraints. You just wrote “Most of these numerical studies”. Which ones?

    - In the last paragraph, Lines 70 to 75, you only mentioned two aims of the paper: impacts of NADI-1 margins on the ice thickness during the last deglaciation and comparing your reconstructions with the RSL observations. However, the paper also partially investigates the effect of different Earth models and attempts to quantify the sensitivity of GIA predictions to the NADI-1 margin scenarios. The introduction needs to be clear about what the authors did in this study.

2. Methods

   - **Line 85:** “We use 5 km flowline intervals throughout this study.” Why 5 km? Is it a standard resolution?

   - ICESHEET is described in Section 2.1 as a time-independent, steady-state model that calculates an equilibrium ice geometry independently for each prescribed NADI-1 margin. Therefore, as I understand the methodology, the successive ICE-NADI-1 time slices do not constitute a transient ice sheet simulation. This distinction should be stated more explicitly because some interpretations later in the manuscript appear to imply dynamically simulated ice sheet evolution. For example, the manuscript refers to “ice thinning dynamics associated with saddle collapses” and states that widespread thinning is “triggered by saddle collapse” (Section 3.2.2). However, the model does not explicitly simulate the transient physical response of the ice sheet to saddle collapse; rather, a new equilibrium geometry is calculated after the prescribed margin changes. I recommend that the authors clarify this methodological limitation and revise the corresponding causal language throughout the Results and Discussion. A short limitations paragraph discussing the absence of transient ice flow, surface mass balance, and mass conservation between successive reconstructed time slices would also be useful.

   - Since the basal shear stress is a very important tuning factor for the ice sheet thickness, I would recommend adding a plot of the basal shear stress that you used in the supplement.

   - **Line 126:** “We only generate ice sheet reconstructions with the NADI-1 minimum and maximum margins using the Earth_1 and Earth_2 models.” Why did you skip Earth_3 and Earth_4 for the minimum and maximum margins?

   - The purpose of considering four Earth models is currently unclear. Is this ensemble intended to quantify the sensitivity of the reconstructed ice geometry to Earth structure, or to identify a preferred Earth model? Since Earth_1 is already selected based on the results of Parang et al. (2024), please clarify the role of the other Earth models and the rationale for the experimental design.

3. Results & Discussion

   - Getting back to the last comment in "2. Methods", if you want to show that Earth_1 is the best choice, I would recommend having first a subsection to show Earth_1 outperforms other Earth models, and then only focus on

comparing and analyzing your reconstructions using Earth_1. Otherwise, I would recommend clarifying explicitly in the method that Earth_1 is chosen for the main text and sending the information regarding the reconstructions employing Earth_* to the supplement.

- I would recommend reminding readers that you compare the results for Earth_1.

- **Line 155:** It should be explained why ICE-7G, LW-6, and NAICE are chosen.

- NAICE is a logical comparator because it uses ICESHEET and related basal shear-stress assumptions. However, PaleoMIST is a newer ICESHEET-based reconstruction and provides a substantially revised global and North American ice geometry. The authors should explain why PaleoMIST was not included alongside NAICE. I do not suggest replacing NAICE, because NAICE provides a particularly direct methodological comparison. Nevertheless, comparison with PaleoMIST would help place ICE-NADI-1 within the context of more recent ICESHEET-based reconstructions. The standard PaleoMIST temporal resolution may be too coarse (2500 years) for detailed analysis of MWP-1a, but comparisons of LGM geometry, selected time slices, or broad GMSL contribution would be useful.

- To improve readability, I would recommend starting the discussion with Figures 2–3 before moving to Figure 4.

- **Line 202:** The cited figures do not show the 12 ka reconstruction. Please provide the relevant figure/data supporting this timing or cite the appropriate supplementary material.

- A shorter title for Section 3.2: **"**Ice-margin controls on ice volume and sea level"

- **Lines 248–251:** I think the statement that "we do not tune the ICE-NADI-1 reconstructions" needs to be qualified. Although the NADI-1 margins themselves are not adjusted to fit RSL or geodetic observations in this study, the adopted basal shear-stress maps are taken from Gowan et al. (2016b), where the shear-stress estimates were adjusted to fit GIA observations. In addition, Earth_1 is adopted for the main RSL analysis because it was previously identified as an optimal Earth model for fitting RSL observations in eastern North America. Therefore, ICE-NADI-1 is not entirely independent of observational constraints used in previous GIA studies. I suggest that the authors distinguish more clearly between not directly tuning the NADI-1 margins/reconstruction in the present study and inheriting previously calibrated model parameters and Earth-structure choices**.** This distinction is

also important when interpreting the RSL comparison as an independent evaluation of ICE-NADI-1.

- A shorter title for Section 3.2.1: “North American ice volume at the LGM”

- **Lines 261-262:** Comparison with NAICE is missing.

- **Figure 4:** Earth_2 and Earth_4 dashed lines are not distinguishable in (a) and (b). I would suggest removing them from the figure and only showing the Earth_1 reconstruction. As I mentioned earlier, you may analyze the effect of Earth models in a separate subsection with its specific figures.

- **Lines 291–299:** The 13 m SLE contribution from Laurentide–Cordilleran saddle merging is not fully clear from the values given here. I would recommend adding a table showing the contribution from the different regions/components, their time intervals, and the total contribution, so that the 13 m value can be followed more easily.

- **Lines 326-330:** Comparison with NAICE is missing.

- Section 3.2 mostly focuses on the comparison between ICE-7G and ICE-NADI reconstructions, and comparing with NAICE is missing in some places. Since both NAICE and NADI-ICE are built based on ICESHEET, comparing them would highlight the effect of margins on the reconstruction.

- A figure, like Figures 2 and 3, showing ice sheet thickness differences (NADI-ICE-1 minus ICE-7G, LW-6, NAICE) for key time slices (e.g., LGM, 14 ka, 14.5, 9, and 7) mentioned in Section 3.2, would be very informative and support the claims. I would recommend this figure to enhance the paper.

- **Section 3.2.2 / Figure 5:** Since ICE-NADI-1 has a 500-year resolution, the reported 13 mm yr^{-1} “peak” rate appears to be a 500-year mean rate. Please clarify how the rates in Figure 5 are calculated and revise the terminology if needed. Short-lived melt pulses should also be interpreted with caution given the 500-year resolution and steady-state reconstruction approach.

- A more neutral section title would be better for Section 3.3. I would recommend: “Evaluation against relative sea-level observations”

- I have two questions regarding the definition of the χ^2misfit. First, the sum is normalized by (N-1). This resembles a reduced chi-squared statistic, but in that case the denominator should represent the number of degrees of freedom (N - P). Please explain the rationale for using (N -1) and define precisely which statistic is being reported. Second, σ_i is described as the 2-sigma elevation uncertainty, whereas a conventional chi-squared statistic

normally uses the 1-sigma standard deviation. Please check the definition and provide an appropriate reference.

- Data-model comparisons in Figures 6 and 7 are from 0 to a maximum of 14 ka. What about further back in time? LGM? The authors should mention why they do not make comparisons for the entire last deglaciation.

- Figure 8 shows that NAICE slightly outperforms ICE-NADI-1 in terms of fitting to RSL observations. Because NAICE and ICE-NADI-1 both use ICESHEET and related basal shear-stress assumptions, one of the principal differences is the adopted ice margins. Therefore, I think the authors should explain more explicitly what additional information or advantages ICE-NADI-1 provides relative to NAICE, beyond the aggregate RSL fit.

- **Section 3.4:** I think the terminology of “uncertainty quantification” should be reconsidered. ICE-NADI-1_min and ICE-NADI-1_max represent end-member reconstructions obtained by combining the regional minimum and maximum NADI-1 margins. They do not constitute probabilistic confidence bounds, and they do not account for other important sources of uncertainty such as basal shear stress, ice rheology, bed topography, model structure, or pre-25 ka ice loading. Therefore, I suggest describing the analysis primarily as a sensitivity analysis to NADI-1 end-member margin scenarios, rather than as a complete quantification of ice-loading uncertainty.

- **Section 3.4.3 / Figure 10:** The “present-day” vertical land motion is calculated using the change from 0.5 to 0 ka, so it represents a 500-year average rate. Please clarify whether this is a good approximation of the present-day rate. Also, ICE-NADI-1 is described as covering 25–1 ka, so please explain how the reconstruction is extended from 1 ka to the present.

4. Conclusions

- NAICE is missing in the second paragraph (Lines 513-521).

- In the last sentence, the authors state that ICE-NADI-1 will be useful for future paleoclimate modelling. I would recommend explaining more clearly what advantages ICE-NADI-1 provides over existing reconstructions such as NAICE, and in which applications the authors particularly recommend its use.

After addressing the major comments above, I recommend revising the Abstract, Introduction, and Conclusions accordingly, so that the aims, limitations, and main claims are fully consistent with the revised analysis.

Technical corrections

1. **Line19:** “64 m of at the Last Glacial Maximum” should be corrected.
2. **Line 55:** It is written “500-year timesteps” but in line 66 is written “0.5 ky”. Be consistent
3. **Line 125–126:** “present and discussion” should be “present and discuss.”
4. **Line 145:** “Global mean sea level” should be removed. “GMSL” has been defined in line 144.
5. **Line 146:** Remove “sea-level equivalent”. “SLE” has been defined in line 144.
6. **Line 147:** Use “GMSL” instead of “global mean sea-level”.
7. **Line 153:** Use “GMSL” and “RSL” instead of “global mean sea-level” and “relative sea-level”
8. Please check the usage of acronyms that you define in the script.
9. **Figure 2 caption:** The caption gives the wrong panel ranges. (a–f) should be (a-e), (g-l) should be (f-j), and (m-r) should be (k-o). Therefore, the text references to Figure 2 should be corrected.
10. **Line 203:** Instead of “Figs. 3e” it should be “Figs. 3f”.
11. **Line 245:** “Figs. 2–5,” not “Fig. 2–5.”
12. **Figure 4 caption/Line 268:** “discrepancies … arises” should be “discrepancies … arise.”
13. **Line 275:** Y-axis of Fig. 4a is from 0 to 25 ka, not 26 ka.
14. **Line 291:** “neither … nor,” not “neither … or.” And add a comma after “instead”.
15. **Line 303:** “ice melt from North America,” not “from North American.”
16. **Line 321:** Do you mean “global mean sea-level rise” instead of “global sea-level”?
17. **Figure 5 caption/Line 357:** A comma is missing between ICE-NADI-1_min and ICE-NADI-1_max.
18. **Figure 5 caption:** “c–e,” not “c–d,” for Laurentide, Cordilleran, and Innuitian panels.
19. **Equation 1:** There is an extra “(“ or a missing “)” in the equation.
20. **Line 432:** “differences … arise,” not “difference … arises.”
21. **Line 451:** “opposite signs,” not “opposite-signs.”
22. **Line 452:** Remove duplicated “in” from “variability in in the timing.”
23. **Figure 9 legend:** Check the reconstruction label; it appears inconsistent with ICE-NADI-1_max. It has been written “ICE-NADI_max”.
24. **Figure 10 caption:** Remove the comma after “(c).”
25. **Supplement Text S1:** “differences … arise,” not “differences … arises.”
26. **Supplement Text S2:** “Hudson Bay,” not “Hudon Bay.”
27. **Supplement Text S3:** Use ICE-NADI-1_max consistently rather than NADI-1_max.

28. **Figure S3 caption:** Correct panel ranges to a–f, g–l, and m–r.

29. **Reference corrections:** The reference list requires a complete cross-check. Several references cited in the text do not appear in the bibliography, including:

- Stokes et al. (2015).
- Gomez et al. (2015).
- Vacchi et al. (2025).
- Coonin et al. (2025).
- Peltier et al. (2014). Some of these support central conclusions.