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Interactive Comment

Interactive comment on "Numerical simulations of the Cordilleran ice sheet through the last glacial cycle" *by* J. Seguinot et al.

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To S. J. Marshall,

We thank you very much for this positive review of our manuscript.

1 Summary comments

Seguinot and colleagues provide the first detailed glaciological modelling of that I am aware of for the Cordilleran Ice Sheet in western North America, making this a novel and long overdue contribution. The authors have not only made new advances with this contribution, they have done so in an impressive leap forward. This is an excel-

lent and carefully-presented study which is likely to rejuvenate interest and debate in Cordilleran Ice Sheet reconstructions. The balance between numerical modelling and glacial geological/geomorphological considerations is unusually strong, and the authors can be commended for this emphasis. This adds tremendous value to the results and increases confidence in the modelling, and I also appreciate that the authors point out areas where the numerical model is not in accord with the geological record.

The manuscript is well-written and beautifully illustrated, and I have very few substantive comments. The choices made by the authors are logical and well-explained, and they reach several well-substantiated conclusions: a two-phase Cordilleran glaciation, a reasonably robust estimate of CIS volume at LGM, the general model of CIS growth through multiple alpine icefields, and the importance of the Skeena Mountain inception centre. One can always quibble with specific aspects of the model design and climate scenarios, but the authors have explored a reasonable span of 'solution space' and these aspects of the Cordilleran ice sheet history appear to be robust features of the simulations.

The modelling strategy and results presented here stand to be widely cited, and I expect that it will serve as a springboard for additional studies from others in the international community. I recommend this manuscript for publication in The Cryosphere without reservations.

2 Specific comments

The Cordilleran Ice Sheet is difficult to model due to its complex topography and multiple inception centres (and possibly multiple domes/divides), strong regional climatic gradients, which require relatively high-resolution climate input fields, and a dearth of paleoclimate proxies for western North America to inform spatial and temporal varia-

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tions in climate conditions during the glacial period. The authors confront these challenges well, with a adequate ice sheet model resolution (5 to 10 km) and ice physics, carefully calibrated 'control' climatology (published in Seguinot et al., 2014), and a good exploration of different paleoclimate time series histories in this contribution.

Thank you for summarizing so well the most challenging aspects of our study.

Nevertheless, it is not clear that ice-core based paleoclimate proxies from Greenland or Antarctica are appropriate for western North America. This may be particularly true of Greenland proxies, where the amplitude of D-O (millennial) climate variations is exceptionally strong and is likely to be regional. Because these remote ice core records are 'scaled' based on only one constraint, producing a CIS maximum configuration that resembles the geological record, it is difficult to assess the pre-LGM simulations or the details of the modelled ice divide structure, ice thickness, etc. The robustness of the conclusion that Greenland and Antarctic ice core records are good proxies of glacial climate variability in western North America is therefore not so clear, but it is admittedly hard to do better at this time. I do wonder if there is any hope from more regional climate proxies such as the Logan ice cores or the off-shore Vancouver Island sediment records that are cited from Cosma et al. This is worth a short discussion.

Thank you for raising this point. Before explaining our choice of palaeo-climate proxy records, we would like to clarify that we do not consider the GRIP and EPICA ice core records, our preferred climate drivers, as satisfactory proxies of climate variability in western North America. Instead, we think that more regional proxy records are needed in order to better understand the dynamics of the Cordilleran ice sheet through the last glacial cycle, and have updated the conclusions to highlight this fact in the manuscript.

To choose palaeo-climate proxy records to force the model, we first focused on records that are recognized as proxies for temperature. These include oxygen isotope (δ^{18}O) records from the Greenland and Antarctic ice sheets. Besides ice core records, we use alkenone unsaturation index ($U_{37}^{K'}$) series from oceanic sediment cores, a known proxy

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for sea-surface temperatures (Prahl and Wakeham, 1987; Prahl et al., 1988; Müller et al., 1998). However, we do not use δ^{18}O records from benthic foraminifera, which have been evaluated worldwide (Lisiecki and Raymo, 2005), including for core MD02-2496 near Vancouver Island (Cosma et al., 2008), but are commonly interpreted as proxies for global ice volume on land rather than for temperatures (Shackleton, 1967). Second, we chose to use only records that span over the last 120 ka in order to avoid spinning-up the model using a different record than the one being tested. The Mount Logan ice core δ^{18}O record covers only the last 30 Ka and has been interpreted as a proxy for source region rather than for palaeo-temperature (Fisher et al., 2004, 2008) and thus does not fit our criteria.

Concerning sediment cores offshore Vancouver Island, sea-surface temperatures have been reconstructed for core JT96-09 from alkenone unsaturation indices over the last 16 ka (Kienast and McKay, 2001), and for the nearby core MD02-2496 from the Mg/Ca ratio in planktonic foraminifera (*N. pachyderma* and *G. bulloides*) between 12 and 21 ^{14}C cal ka (Taylor et al., 2014). Very recently, this planktonic foraminifera record has been extended to cover the period from 10 to ca. 50 ^{14}C cal ka (Taylor et al., 2015), and thus it could perhaps be used to model the growth and decay of the Cordilleran ice sheet during the Marine Oxygen Isotope Stage (MIS) 2, but such a simulation could not be directly compared with other runs without spinning-up the model using a different proxy record.

A shortened version of the preceding explanation has been added to the climate forcing section of the manuscript.

Similarly it is difficult to know the errors and uncertainties associated with the assumption of fixed modern-day spatial patterns for temperature and precipitation. I suspect that the sensitivity of this assumption far exceeds that associated with the different paleoclimate proxies. Such that, for example, one could readily imagine different assumptions, such as a maritime effect that gives reduced glacial cooling near the coast

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vs. in the interior, that is a stronger effect than the difference between different paleoclimate proxies with respect to the timing of LGM, ice divide structure, etc. But this is a very reasonable start, what the authors have done – there is always going to be more parameter space to explore in future studies. As above, I would perhaps just suggest a small discussion of the authors' opinion on this question, the uncertainty or possible influence of this assumption of modern-day climate patterns.

Indeed, we chose to keep modern-day spatial patterns for temperature and precipitation constant in order to limit the number of degrees of freedom in our study.

Regarding temperature, it is reasonable to think that the changes were greater inland than near the coast. However, our simulations already produce an excess of ice inland. Including such a temperature continentality gradient in the model while keeping the precipitation pattern constant would thus cause an even greater mismatch between the model results and the geologically reconstructed Last Glacial Maximum (LGM) ice margins. We have introduced a short comment of this effect in Sect. 5.1.2 (previously 4.1.2, Ice configuration during MIS 2).

However, the mismatch we observe between the modelled and reconstructed LGM ice margins let us think that the assumption of fixed modern-day precipitation patterns is more critical than the assumption of fixed modern-day temperature patterns. During phases of ice sheet growth, the presence of mountain ice caps on the Coast Mountains likely resulted in a decrease of precipitation inland (Sect. 5.1.2). Furthermore, the adiabatic warming associated with moisture depletion in the interior (Sect. 5.1.2) may have counterbalanced the potential continentality gradient discussed above.

Several minor points and grammatical corrections are included in the attached text. Nothing that will require much thought – this is a really impressive piece of research, overall, and I am hard-pressed to find any criticism of it. It is one of the easiest reviews I have ever done. Congratulations to the authors and thanks for this fine work.

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We have corrected grammatical mistakes given in the attachment. Thank you for spotting them. And thank you again very much for supporting our manuscript with such enthusiasm!

References

Cosma, T., Hendy, I., and Chang, A.: Chronological constraints on Cordilleran Ice Sheet glaciomarine sedimentation from core MD02-2496 off Vancouver Island (western Canada), Quaternary Sci. Rev., 27, 941–955, doi:10.1016/j.quascirev.2008.01.013, 2008.

Fisher, D., Osterberg, E., Dyke, A., Dahl-Jensen, D., Demuth, M., Zdanowicz, C., Bourgeois, J., Koerner, R. M., Mayewski, P., Wake, C., Kreutz, K., Steig, E., Zheng, J., Yalcin, K., Goto-Azuma, K., Luckman, B., and Rupper, S.: The Mt Logan Holocene–late Wisconsinan isotope record: tropical Pacific–Yukon connections, The Holocene, 18, 667–677, doi: 10.1177/0959683608092236, 2008.

Fisher, D. A., Wake, C., Kreutz, K., Yalcin, K., Steig, E., Mayewski, P., Anderson, L., Zheng, J., Rupper, S., Zdanowicz, C., Demuth, M., Waszkiewicz, M., Dahl-Jensen, D., Goto-Azuma, K., Bourgeois, J. B., Koerner, R. M., Sekerka, J., Osterberg, E., Abbott, M. B., Finney, B. P., and Burns, S. J.: Stable Isotope Records from Mount Logan, Eclipse Ice Cores and Nearby Jellybean Lake. Water Cycle of the North Pacific Over 2000 Years and Over Five Vertical Kilometres: Sudden Shifts and Tropical Connections, Géogr. phys. Quatern., 58, 337, doi: 10.7202/013147ar, 2004.

Kienast, S. S. and McKay, J. L.: Sea surface temperatures in the subarctic northeast Pacific reflect millennial-scale climate oscillations during the last 16 kyrs, Geophys. Res. Lett., 28, 1563–1566, doi:10.1029/2000GL012543, 2001.

Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records, Paleoceanography, 20, PA1003, doi:10.1029/2004pa001071, 2005.

Müller, P. J., Kirst, G., Ruhland, G., von Storch, I., and Rosell-Melé, A.: Calibration of the alkenone paleotemperature index $U_{37}^{K'}$ based on core-tops from the eastern South Atlantic and the global ocean (60°N-60°S), Geochim. Cosmochim. Ac., 62, 1757–1772, doi: 10.1016/s0016-7037(98)00097-0, 1998.

Prahl, F. G. and Wakeham, S. G.: Calibration of unsaturation patterns in long-chain ketone com-

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9, C2634–C2640, 2016

positions for palaeotemperature assessment, Nature, 330, 367–369, doi:10.1038/330367a0, 1987.
Prahl, F. G., Muehlhausen, L. A., and Zahnle, D. L.: Further evaluation of long-chain alkenones as indicators of paleoceanographic conditions, Geochim. Cosmochim. Ac., 52, 2303–2310, doi:10.1016/0016-7037(88)90132-9, 1988.
Seguinot, J., Khroulev, C., Rogozhina, I., Stroeven, A. P., and Zhang, Q.: The effect of climate forcing on numerical simulations of the Cordilleran ice sheet at the Last Glacial Maximum, The Cryosphere, 8, 1087–1103, doi:10.5194/tc-8-1087-2014, 2014.
Shackleton, N.: Oxygen Isotope Analyses and Pleistocene Temperatures Re-assessed, Nature, 215, 15–17, doi:10.1038/215015a0, 1967.
Taylor, M., Hendy, I., and Pak, D.: Deglacial ocean warming and marine margin retreat of the Cordilleran Ice Sheet in the North Pacific Ocean, Earth Planet. Sc. Lett., 403, 89–98, doi: 10.1016/j.epsl.2014.06.026, 2014.
Taylor, M. A., Hendy, I. L., and Pak, D. K.: The California Current System as a transmitter of millennial scale climate change on the northeastern Pacific margin from 10 to 50 ka, Paleoceanography, 30, 1168–1182, doi:10.1002/2014pa002738, 2015.

Interactive comment on The Cryosphere Discuss., 9, 4147, 2015.