Earth Surf. Dynam. Discuss.,
https://doi.org/10.5194/esurf-2018-6-RC2, 2018
© Author(s) 2018. This work is distributed under
the Creative Commons Attribution 4.0 License.



# *Interactive comment on* "Glacial Isostatic Adjustment modelling: historical perspectives, recent advances, and future directions" *by* Pippa L. Whitehouse

**H. Steffen (Referee)**

holger.steffen@lm.se

Received and published: 28 February 2018

Review papers can be a dangerous task to undertake, and can also be challenging to comment on. Arguments of different referees can be condratictory: too long, too short, too many references, too few, not all is covered, too much is covered, too much focus on one issue, chapters order should be the other way around and so on and so forth. As an author, it is challenging to satisfy all those views and partly needs a thick skin, also once it is published and more people comment on it.

From my perspective, Pippa Whitehouse reviews glacial isostatic adjustment (GIA) modelling very well and I think that this paper will be highly regarded and cited, es-



Printer-friendly version

Discussion paper

pecially as it draws a bow from the historical development over recent advances to possible future directions posing a few interesting research questions to take on for the wider community.

The paper is in most parts well written and additionally supported by a couple of figures that help explain major GIA-related processes. Much thought was given on recent and future developments and may likely reflect many personal views, I note though many discussions that Pippa does on conferences, thus I think she has a good overview of ongoing and future works.

I recall the GIA workshop in Reykjavik in September 2017 where the 10 top research questions in GIA research were collected. I guess some of them also arise while reading this paper and perhaps it is an option to pick that up in the Conclusions pointing to the SCAR-SERCE website.

There also are a few paragraphs/sections that are very brief with a few common references while others are well developed with a large number of references. I guess this is due to the personal research interest of the author, and I try to give some help below so that brief parts can be extended.

I hope that my comments in the following are taken in the positive manner with which they are intended. I apologize right away that some comments and mentioned references are due to my "Fennoscandia-biased" eye, so please take them as suggestion only, especially when I write "I'd suggest"...

General remarks

L12: I would not agree with "in detail" when you mean "field of GIA" - there is so much more to discuss - but I would support it when you say "field of GIA modelling".

First paragraph of Introduction: I'd suggest to add 1-2 sentences about the term "postglacial rebound" which you mention three times in this paper, e.g. L780 "postglacial rebound is not the only GIA-related process". It would be good for the reader to learn





Printer-friendly version

Discussion paper

about this term and how it relates to GIA, especially as it is still often used synonymously in publications.

L44-59: as your paper has next to modelling a strong bias to sea level, it is perhaps good to mention a couple of other review papers the reader can look at, e.g. Whitehouse (2009, I really missed that in the references), Steffen & Wu (2011), Milne (2015), Spada (2017)

L64/65: The sentence is per se ok but I note that Celsius was not the first to cut marks for the sea level in rocks, see Mörner (1979). Celsius' intention though was to allow rigorous measurements, especially for future generations. See Martin Ekman's new book (2016) about Celsius, section 5.4 therein.

Section 2.2: This section discusses only GIA models applying the sea-level equation but misses among others flat Finite Element models. Also GIA-fault models are not yet connected to it. I'd suggest to either alter the title slightly including the SLE or add another short section with a discussion of models not involving the SLE, see my comments on L216-218.

L183/184: you can well mention here that the "system Earth" has further contribution that you will pick up later.

L209: I'd suggest to add references Lambeck et al. (2001) and Milne et al. (2002) here and add a few words on the issue briefly discussed in both papers, that is that inconsistent use of this term has caused some confusion earlier, thus one should be aware that some publications may use it in a wrong way.

L216-218: Although this paragraph intends to make a link to following sections, I became irritated while reading the next sections. I expected a discussion of the different quantities of the SLE, especially as you began in 2.2.2 with the solid Earth, thus I expected the ice thickness evolution next and so on. Putting 2.2.2 aside (and perhaps move it somewhere else) Section 2.2 would deal with the SLE only because 2.2.3-2.2.5





Printer-friendly version

Discussion paper

deal with SLE but not with GIA models as indicated in the title of 2.2. So a suggestion could be to rename section 2.2 to "Development of the sea-level equation" or something similar, section 2.2.1 to "The original form of the sea-level equation", moving 2.2.2 after 2.2.4 to have old 2.2.1, 2.2.3 and 2.2.4 as new 2.2.1, 2.2.2 and 2.2.3. Then put old 2.2.2 together with 2.2.5 and perhaps other GIA models without application of the SLE including GIA-faults models (R. Steffen et al. 2014a) to a longer new "Numerical methods for modelling GIA" section with old 2.2.2, missing GIA without SLE, old 2.2.5 to new 2.3.1, 2.3.2 and 2.3.3. This should also fit the title of section 2.

Section 2.2.5: I'd suggest if possible add a few words on the temporal and spatial resolution of the models and how it has changed over the years. Anything easy to say about the run time for such models - really general in terms of minutes, hours or days?

Section 2.3: (1.) You briefly mention optimal location later but I'd suggest to place a few words already here. I note that there is not only the study by Wu et al. (2010) on optimal GPS, later on Steffen et al. (2012, 2014) also discussed optimal gravity and RSL data, respectively. (2.) You miss a quite interesting, though also difficult to analyse data set: tide gauges - just mentioned two times in the manuscript. However, it is a crucial data set in all sea-level rise discussions. I'd suggest to add a section here.

Section 2.3.3: I miss the studies by Nerem & Mitchum (2002) and Kuo et al. (2004) using SAR together with tide gauges.

L396-398: I'd suggest to mention the GIA-frame approach introduced in Kierulf et al. (2014) that deals with this problem and can be regarded quite successful when checking the discussion therein.

L398-401: Getting information on the subsurface structure from horizontal velocities was the aim of Milne et al. (2004), Steffen et al. (2007) and Steffen and Wu (2014). The latter two papers are quite technical and I admit rather complex for reading but they support your conclusion that horizontal rates have not yet been used to their full potential. However, studies exist.





Printer-friendly version

Discussion paper

L416: suggest to add "e.g." to the references

L424-426: in view of the relationship between uplift and gravity change, the study by Olsson et al. (2015) should be mentioned.

L439: strongly suggest to change "may not be" to "are not"

L449/450: Argus et al. (2014) should be mentioned along the three papers.

Section 2.3.6: one of the rather short sections where much research has been undertaken, see the works by Wu, Johnston, Klemann, Kaufmann, Lund, R. Steffen etc. This section should be expanded. Stewart et al. (2000) is certainly a key paper but important studies were already published in the late 70s and much research was triggered by the studies of Spada et al. (1991), Wu & Hasegawa (1996a,b) and Arvidsson (1996), to name a few.

L455/456. The unloading is not only able to trigger postglacial faulting but also more recent (historic) earthquakes can be linked to GIA, see Brandes et al. (2015). Since a few years the term "postglacial fault" or "postglacial faulting" is thus under discussion, see e.g. Lund (2015). My personal preference is "glacially induced fault".

L458: triggering slip on pre-existing faults was a major result of R. Steffen et al. (2014b).

L495: I'd suggest to add Nordman et al. (2015) to Fennoscandia (Lev Tarasov's North-European model), and Lambeck (1995) for the British ice sheet. What about Patagonia and the work of Ivins and James (2004)?

L498: Lambeck et al. (e.g. Lambeck et al. 2014) and Tarasov also work on global models and should be named.

L577: Klemann et al. (2008) should be cited for the effect of plate boundaries.

L578: Wang & Wu (2006a,b) also analyzed the effect of a 3D lithosphere (it's in the paper titles).





Printer-friendly version

Discussion paper

Section 3.3: In view of this section, L677/678, Section 4.2 and the Conclusions you can state that GIA is part of Earth System Modelling and should always be investigated in an interdisciplinary context.

L688-691: I miss a reference here.

L725: This relates to the concept of "underwater GPS". Future measurements may help solving this question and it is perhaps worth to mention that research is going on in this field (e.g. Ramesh et al. 2016, Honsho & Kido, 2017).

L729: I'd suggest stating "use of satellite gravity data". Terrestrial gravity data are not a gap-filler for GPS in view of the effort to perform a single measurement.

L777: The studies by Schmidt et al. (2013) and Kutterolf et al. (2013) should also be mentioned.

L830: "central component of any GIA model" implies that flat FE models are no GIA models..., suggest "any GIA model"="the majority of GIA models"

Figure 1: In view of the basic equations the outputs are not complete. Rotation and stress are missing, which are both quantities that you discuss in your manuscript. Should be added.

Technical corrections

L97: The first ice(-)cap appearance should be without dash

L827: correct brackets for Daly (1925)

References (not cited in the manuscript)

Arvidsson, R. (1996), Fennoscandian earthquakes: Whole crustal rupturing related to postglacial rebound, Science, 274, 744–746, doi:10.1126/science.274.5288.744.

Brandes, C., Steffen, H., Steffen R. and Wu, P., 2015. Intraplate seismicity in northern Central Europe is induced by the last glaciation. Geology 43, 611-614.





Printer-friendly version

Discussion paper

Ekman, M., 2016. The man behind "Degrees Celsius": A pioneer in investigating the Earth and its Changes. Summer Institute for Historical Geophysics, 159 pp., ISBN: 978-952-93-7732-9 (see also http://www.historicalgeophysics.ax/#nyarebok)

Honsho, C., & Kido, M.(2017). Comprehensive analysis of traveltime data collected through GPS-acoustic observation of seafloor crustal movements. Journal of Geophysical Research: Solid Earth, 122. https://doi.org/10.1002/2017JB014733

Klemann, V., Martinec, Z., Ivins, E. R. (2008): Glacial isostasy and plate motion. - Journal of Geodynamics, 46, 3, pp. 95-103. doi:10.1016/j.jog.2008.04.005

Kuo, C.Y., Shum, C.K., Braun, A., Mitrovica, J.X., 2004. Vertical crustal motion determined by satellite altimetry and tide gauge data in Fennoscandia. Geophys. Res. Lett. 31, L01608, doi:10.1029/2003GL019106.

Kutterolf, S., Jegen, M., Mitrovica, J. X., Kwasnitschka, T., Freundt, A. and Huybers, P. J. (2013) A detection of Milankovitch frequencies in global volcanic activity. Geology, 41 (2). pp. 227-230. DOI 10.1130/G33419.1.

Lambeck, K., 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. J. Geol. Soc. Lond. 152, 437-448.

Lambeck, K., Yokoyama, Y., Johnston, P., Purcell, A., 2001. Corrigendum to “Global ice volumes at the Last Glacial Maximum and early Lateglacial”. Earth and Planetary Science Letters 190, 275.

Lund, B., 2015. Palaeoseismology of glaciated terrain. In: M. Beer et al. (eds.) Encyclopedia of Earthquake Engineering, Springer-Verlag, Berlin, Heidelberg, pp. 1765-1779, doi: 10.1007/978-3-642-36197-5_25-1.

Milne, G. 2015. Glacial Isostatic Adjustment. In: Shennan et al. (eds.) Handbook of Sea-Level Research. John Wiley & Sons. pp. 421-437, ISBN: 978-1-118-45258-5



Printer-friendly version

Discussion paper

Mörner, N.-A., 1979. The Fennoscandian uplift and late Cenozoic geodynamics: geological evidence. GeoJournal 3.3, 287–318, doi:10.1007/BF00177634.

Nerem, R., and G. Mitchum (2002), Estimates of vertical crustal motion derived from differences of TOPEX/POSEIDON and tide gauge sea level measurements, Geophys. Res. Lett., 29(19), 1934, doi:10.1029/2002GL015037

Maaria Nordman, Glenn Milne, Lev Tarasov. Reappraisal of the Angerman River decay time estimate and its application to determine uncertainty in Earth viscosity structure, Geophysical J. Int., 201, 811–822, doi: 10.1093/gji/ggv051, 2015.

P.-A. Olsson, G. Milne, H.-G. Scherneck, and J. Agren. The relation between gravity rate of change and vertical displacement in previously glaciated areas. Journal of Geodynamics, 83:76{84, 2015.

Ramesh, R., Jyothi, V.B.N., Vedachalam, N., Ramadass, G.A. & Atmanand, M.A. 2016, "Development and Performance Validation of a Navigation System for an Underwater Vehicle", Journal of Navigation, vol. 69, no. 5, pp. 1097-1113

Schmidt, P., B. Lund, C. Hieronymus, J. Maclennan, T. Árnadóttir, and C. Pagli (2013), Effects of present-day deglaciation in Iceland on mantle melt production rates, J. Geophys. Res. Solid Earth, 118, 3366-3379, doi:10.1002/jgrb.50273.

Spada, G. (2017). Glacial Isostatic Adjustment and Contemporary Sea Level Rise: An Overview. Surv Geophys (2017) 38:153–185

Spada, G., D. A. Yuen, R. Sabadini, and E. Boschi (1991), Lower-mantle viscosity constrained by seismicity around deglaciated regions, Nature, 351, 53–55, doi:10.1038/351053a0.

Steffen, H., Wu, P., Kaufmann, G., 2007. Sensitivity of crustal velocities in Fennoscandia to radial and lateral viscosity variations in the mantle. Earth Planet. Sci. Lett. 257 (3–4), 474–485, doi:10.1016/j.epsl.2007.03.002.





CC BY

Steffen, H., Wu, P., and Wang, H.: Optimal locations for absolute gravity measurements and sensitivity of GRACE observations for constraining glacial isostatic adjustment on the northern hemisphere, Geophys. J. Int., 190, 1483–1494, doi:10.1111/j.1365-246X.2012.05563.x, 2012.

Steffen, H. and Wu, P.: The sensitivity of GNSS measurements in Fennoscandia to distinct three-dimensional upper-mantle structures, Solid Earth, 5, 557-567, https://doi.org/10.5194/se-5-557-2014, 2014.

Steffen, H., Wu, P., and Wang, H.: Optimal locations of sea-level indicators in glacial isostatic adjustment investigations, Solid Earth, 5, 511-521, doi:10.5194/se-5-511-2014, 2014.

Steffen, R., Wu, P., Steffen, H., Eaton, D.W., 2014a On the implementation of faults in finite-element glacial isostatic adjustment models. Computers & Geosciences 62, 150-159.

Steffen, R., Steffen, H., Wu, P., Eaton, D.W., 2014b. Stress and fault parameters affecting fault slip magnitude and activation time during a glacial cycle. Tectonics, 33, 1461–1476.

Wang, H., Wu, P., 2006a. Effects of lateral variations in lithospheric thickness and mantle viscosity on glacially induced relative sea levels and long wavelength gravity field in a spherical, self-gravitating Maxwell Earth. Earth Planet. Sci. Lett. 249, 368–383.

Wang, H., Wu, P., 2006b. Effects of lateral variations in lithospheric thickness and mantle viscosity on glacially induced surface motion on a spherical, selfgravitating Maxwell Earth. Earth Planet. Sci. Lett. 244, 576–589.

Whitehouse, P., 2009. Glacial Isostatic Adjustment and Sea-level Change: State of the Art Report. TR-09–11, Svensk Karnbranslehantering AB.

Wu, P., and H. S. Hasegawa (1996a), Induced stresses and fault potential in eastern





Printer-friendly version

Discussion paper

BY

Canada due to a realistic load: A preliminary analysis, Geophys. J. Int., 127, 215–229, doi:10.1111/j.1365-246X.1996.tb01546.x.

Wu, P., and H. S. Hasegawa (1996b), Induced stresses and fault potential in Eastern Canada due to a disc load: A preliminary analysis, Geophys. J. Int., 125, 415–430, doi:10.1111/j.1365-246X.1996.tb00008.x.

---

Interactive comment on Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2018-6, 2018.