Viscoelastic deformations due to recent Greenland ice sheet mass changes : issues and consequences

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Introduction :

Sea level rise represents one the major geophysics issue and is estimated to be 3,3 ± 0,4 mm/y with one third due to polar ice sheet melt. The losses are usually estimated to be -260 ± 80 Gt/y for Greenland ice sheet and -67 ± 60 Gt/y for Antarctic ice sheet but there are important variations according to the method used and the considered period. The most commonly-used methods are gravimetry and altimetry. One of the main difficulty with these approaches is that they measure on the one hand mass evolution due to current ice loss but in the other hand Earth deformations due to current and past load changes.

The principal objective of this study is to better understand Earth deformation mechanisms in response to Greenland ice sheet recent mass changes and their impact on ice sheet mass balance.

A brief introduction to viscoelastic and elastic deformations :

In response to different excitation sources – mass repartition changes, tidal forces or Earth rotation axis modification – Earth deforms itself. This deformations could be elastic or viscoelastic depending on the timescale involved. Here we'll focus on deformations due to ice sheet mass evolution.

Elastic deformations :
The elastic flexure of the lithosphere immediately accommodates load changes (lithosphere bending for loading, lithosphere uplift for unloading). This type of deformations occur for short timescales (years to decades).

Viscoelastic deformations :
For short timescales elastic deformations are observed and after longer periods – decades to millennium – viscous deformations occur. The latter are due to mass redistributions in the viscous mantle and both their amplitude and earliness depends on Earth's rheology.

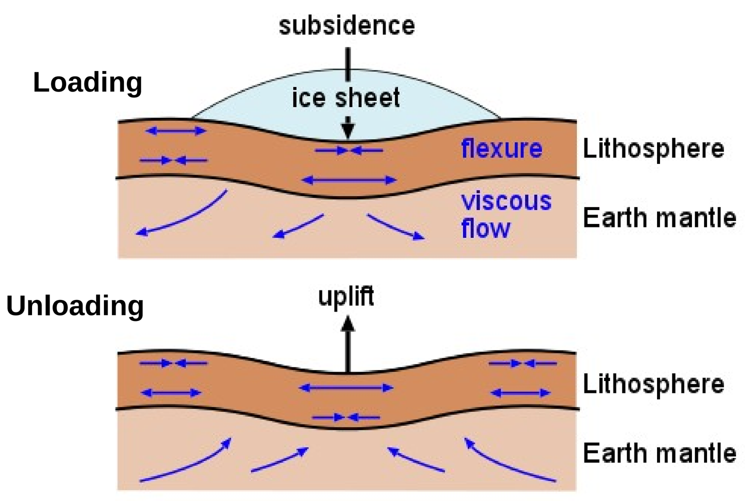
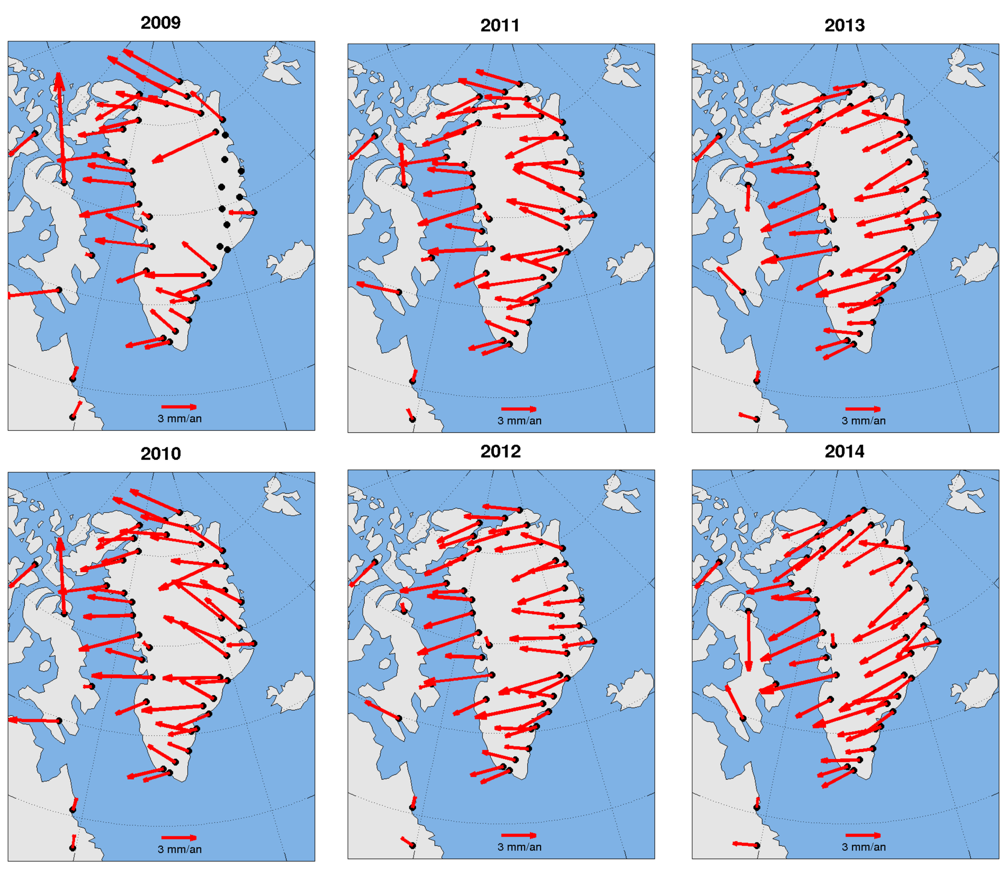


Figure 1 : elastic flexure of the lithosphere and mass viscoelastic redistribution in the mantle in response to mass changes. (reference : GFZ)

2 types of deformations in Greenland :
→ viscoelastic deformations for the Global Isostatic Adjustment (GIA) due to ice sheet melt since the Last Glacial Maximum.
→ Currently elastic deformation models are used for recent ice sheet mass changes. Considering that ice losses started in Greenland approximatively 20 years ago, elastic deformation models could be inappropriate for current ice changes.

Problematic : could viscoelastic deformations linked to recent Greenland ice losses been already present ?

Tangential GPS velocities : a global westwards direction with a fast southwards rotation



A good tool to investigate early state viscoelastic deformations is to study tangential GPS velocities. Indeed in the case of elastic deformations, tangential displacements are weak, when large scale mantle mass redistributions due to viscoelastic deformations make them more important.

2 observations :
→ global westwards movement.
→ fast shifting of the velocities towards the south.

Figure 2 : Greenland tangential GPS velocities between 2009 and 2014.

What could explain these unexpected GPS velocities ?

Global westwards movements :

→ Tectonic ?
It's unlikely because the region is tectonically stable.

→ GIA ?
The ICE-5G/VM2 reference model predicts 1,5 mm/y eastwards velocities but Caron and al, 2015 new model shows a very good agreement with westwards GPS velocities (figure 3).

Rotation towards the south :

→ Tectonic ?
No for the same reason than previously.

→ GIA ?
It can't lead to a fast rotation of the velocities. An additional process has to be added with velocities growing towards the south.

→ Unsuitable models for the treatment of polar wander and the 18,6 tide ?
Their impact on velocities is lower than 0,2 mm/y.

→ Elastic or viscoelastic deformations due to recent ice losses ?
Our models predict tangential velocities less than 1mm/y therefore insufficient. As for our viscoelastic models, predicted tangential velocities are quickly growing southwards in the major part of the ice sheet with the exception of the south (figure 4). This may be the origin of GIA velocities rotation.

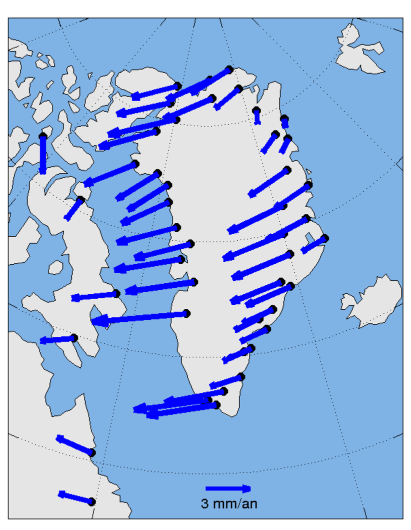


Figure 3 : tangential velocities predicted by Caron and al, 2015 GIA model.

in association with

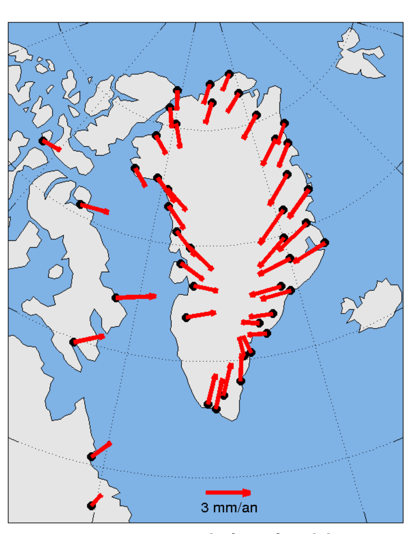


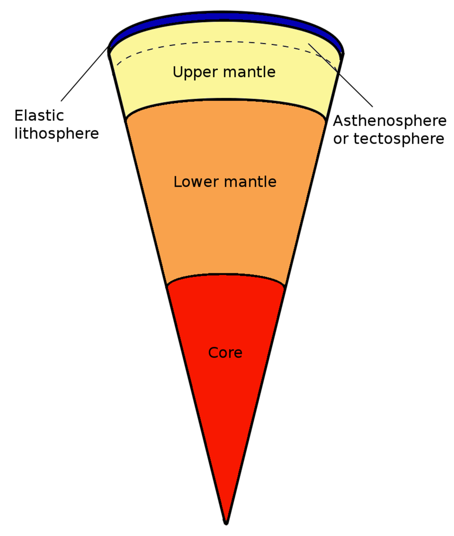
Figure 4 : 2014 tangential velocities predicted by recent ice loss viscoelastic models. These velocities are increasing over time.

What implies this result concerning Earth's rheology ?

Viscoelastic deformation computation requires an Earth rheological profile. In this study we've considered a six layers profile including a lithosphere elastic and a viscous asthenosphere (figure 5). According to tangential velocities the rheology used by Caron and al, 2015 seems to be more suitable than that of ICE-5G/VM2. The more relevant viscoelastic models linked to recent ice loss are those which lead to a global southwards rotation of the velocities.

Recent ice mass change models :

→ Asthenosphere :
thickness = 300 – 400 km
viscosity = 2.10^{18} – 5.10^{18} Pa.s



Caron et al, 2015 GIA model

→ Tectosphere : thickness = 100 km
viscosity = 10^{22} Pa.s
→ Upper mantle viscosity : 3.10^{20} Pa.s
→ Lower mantle viscosity : $2{,}3.10^{22}$ Pa.s

Figure 5 : The 6 layers rheological model used for deformation computing.

Implications of viscoelastic deformations linked to current ice loss in Greenland :

→ Ice loss of the Greenland ice sheet has to be reassessed

Current estimations of Ice sheet loss consider that recent ice loss produce only elastic deformations. We find that using purely elastic models leads to an overestimation of ice losses between 10,7 and 13,6% on average and which could reach more than 20 % especially in the south where ice losses are maximal. Conversely a little underestimation is observed in the central portion of the ice sheet but it doesn't have an important effect on the global mass budget as this region seems to be stable.

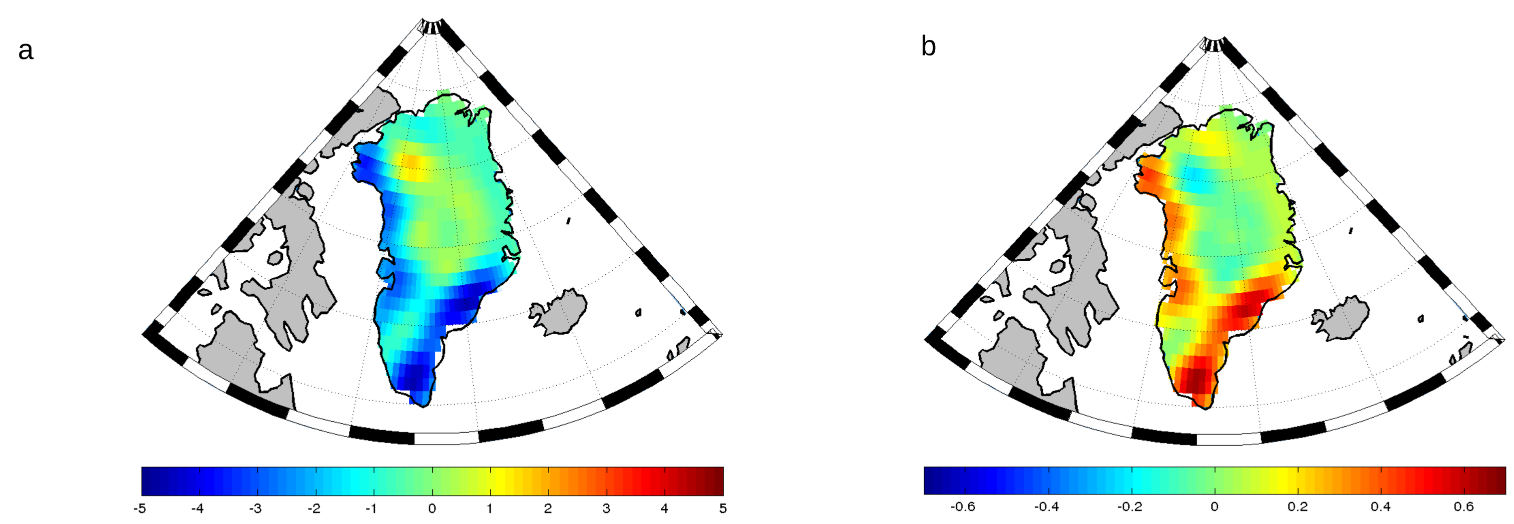


Figure 6 : (a) 2014 load model. (b) Load difference between elastic and viscoelastic models. The values are given in meters of equivalent water thickness.

→ The ITRF may be affected by non-linear effects of viscoelastic deformations

The ITRF is used for determining position on Earth surface. It's a system of axis in co-rotation with Earth and with a center corresponding to the mass center of our planet. It's established every five years by combining data of Satellite Laser Ranging, VLBI, DORIS and GPS velocities.
Viscoelastic deformations linked to recent ice mass changes are responsible for non-linear effects on the velocities, which are not taken into account in the current version of the ITRF. Future versions of the ITRF should deal with these effects.

GIA may skew geodetic plate tectonic models

Figure 7 shows GIA velocities expressed in a referential attached to the North American plate. In this referential velocities must to be negligible in the rigid center of the plate (in gray). But :
→ GIA velocities in the plate rigid part are significant, especially for Caron et al 2015 model.
→ GIA velocities predictions differ a lot between the two GIA models.
As a result velocities expressed in this referential – and therefore geodetic plate tectonic models – could be biased by large scale GIA effects.

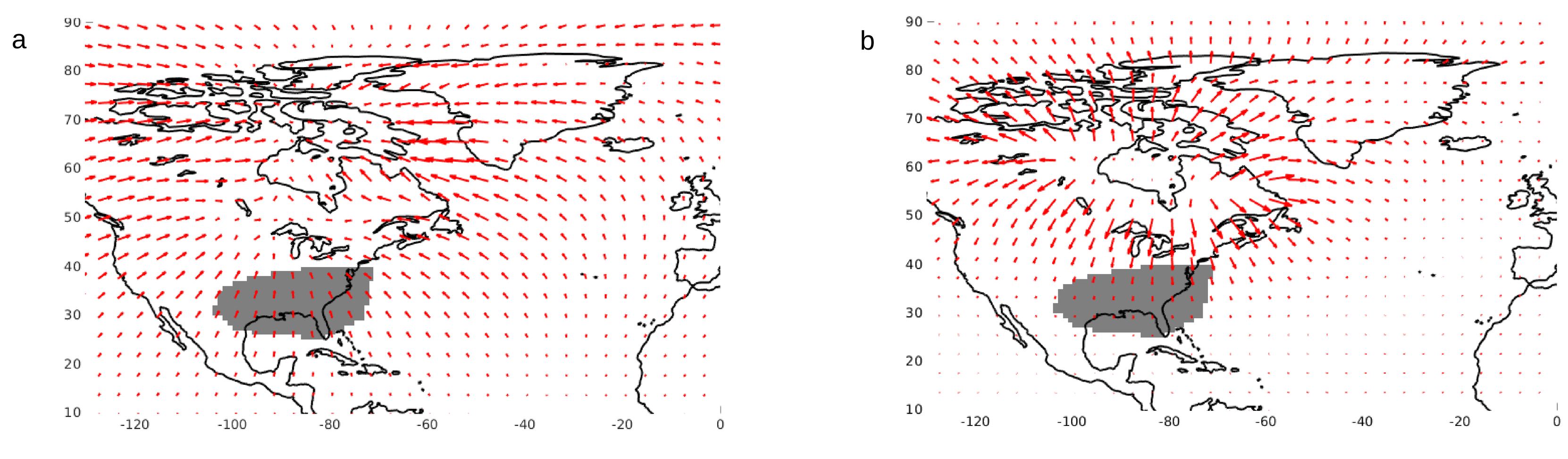


Figure 7 : GIA tangential velocities. The gray zone represents the rigid part of the North American plate.
(a) Caron and al 2015 GIA model. (b) ICE-5G/VM2 GIA model.

Conclusion :

The study of Greenland GPS velocities comportment has shown a global westwards direction with a fast evolution southwards. This unexpected comportment in a tectonically stable region could only be explained – to the best of our knowledge – by the combination of velocities predicted by a new model of GIA, proposed by Caron and al 2015, and the presence of viscoelastic deformations linked to current ice losses.

This model implies :
→ Estimations of Greenland ice sheet mass balance using gravimetric or altimetric methods result in an overestimation of losses ranging between 10,7 and 13,6 % on average.
→ Viscoelastic deformations due to contemporary mass changes are responsible for non-linear effects on GPS velocities which could affect the ITRF.
→ GIA tangential velocities could occur at a larger scale than previously through and could significantly affect geodetic plate tectonic models.

A future work has to be done in order to improve the models of both GIA and viscoelastic deformations in response to current ice losses which have been developed during this study. In a second step same models has to be developed for both Antarctic and large continental glaciers.