Present Uplift in Norway Due to Glacier Unloading Since the 'Little Ice Age'

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Abstract

The observed present rate of uplift in Scandinavia increases from zero on the western coast of Norway to ~1 cm/yr in the Baltic Sea area. This domelike uplift is generally assumed to be the result of glacial isostasy due to melting of the huge glaciers of late-glacial time. The mountain glaciers of Norway have previously not been considered to affect the present rate of uplift. We have now calculated the effect of the decaying glaciers since the Little Ice Age and found that the effect is a significant factor in the ongoing rate of uplift in Norway.

While the last huge sheet over Scandinavia melted away around 9 000 years ago, a cooling trend (Neoglaciation) some thousand years later was responsible for the establishment and growth of the Norwegian mountain glaciers. After several periods of glacier growth and decay most Norwegian glaciers probably culminated in mid 1700s AD during the Little Ice Age. From the Little Ice Age the glaciers started to decay and finally ended at the present thicknesses of the glaciers.

We calculated both the isostatic and elastic response of the unloading of the mountain glaciers. When a force (positive or negative) is applied to the Earth's surface, there is an immediate elastic deformation proportional to the stress. This will be followed by a time-dependent isostatic response. The elastic displacement is gradually recovered as the Earth adjusts toward isostatic equilibrium. When isostatic equilibrium is achieved, there will be no elastic deformation. There are thus basically two causes of elastic effects: (l) loading/unloading of ice caps, (2) isostatic movements caused by the loading/unloading.

The isostasy is calculated with a low-viscosity asthenosphere of 1.8 x 10^{19} Pas and an effective elastic lithosphere thickness Te ~30 km. The elastic modelling assumes the shear rigidity μ = 0.7x 10^{11}N/m^2. This unloading of the Norwegian glacier over the last 300 years lead to present rate of uplift in glaciated areas of more than 2.0 mm/yr in the areas of mountain glaciers.

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1. Introduction

The observed ongoing rate of uplift in Scandinavia increases from zero on the western coast of Norway to ~1 cm /yr in the Baltic Sea area. Figure 1 shows the observed current uplift in Fennoscandia according to the recent NKG2016LU (Vestøl et al., 2016). This domelike uplift is generally assumed to be the result of glacial isostasy due to melting of the huge late-glacial ice sheets. The last remains of the huge glaciers melted away around 9 000 cal yr BP. Mörner (1980) claimed that the post-glacial uplift is caused by two different mechanisms – one exponential and one linear factor. Mörner's idea is disputed; the consistent picture given by the observations of the deglaciation, palaeo-shoreline tilts and present rate of uplift does not require two different mechanisms. It has been shown previously (e.g. Fjeldskaar, 1997; Fjeldskaar and Amantov, 2017) that the best-fitting parameters for palaeo-shoreline tilts also are the best-fitting parameters for the present rate of uplift.

Even so, Mörner's idea about an additional factor in the current uplift may still be viable; the question is how significant this factor is. Clearly, most of the uplift signal can be explained by isostatic response to the deglaciation after the last ice age. However, the west coast of northern Norway is the most important exception here. Fjeldskaar et al. (2000), Amantov and Fjeldskaar (2013) and Fjeldskaar et al. (submitted) found that this is an area where the measured present rate of uplift is significantly greater than that predicted by glacial isostatic models.

This paper investigates the affects of the reduction of the mountain glaciers in Norway for the present rate of uplift. Most of the Norwegian glaciers were developed during a colder Late Holocene period and probably culminated in mid 1700s AD during the Little Ice Age.

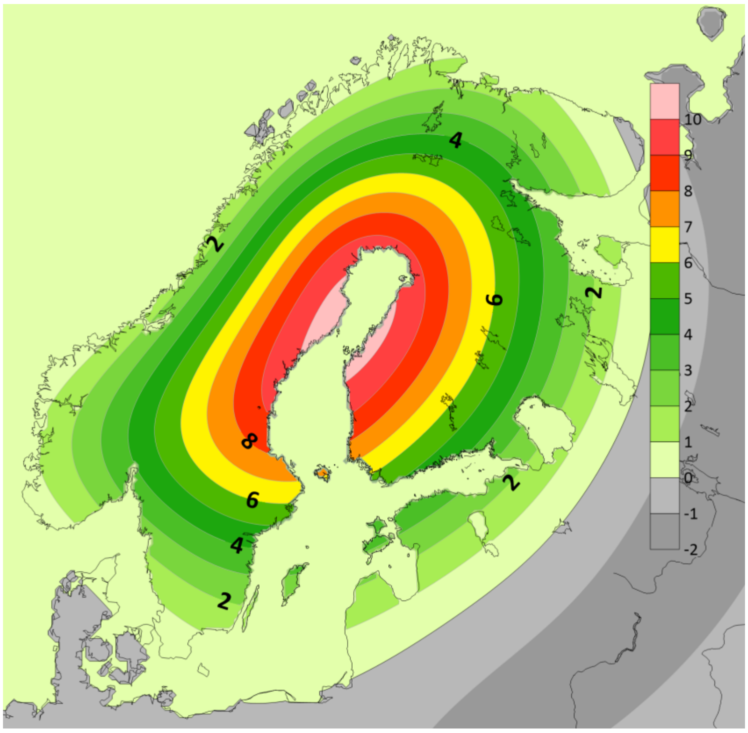

Figure 1. Observed present rate of uplift (in mm/yr) from Vestøl et al. (2016).

After the Little Ice age there has been a significant reduction of the glaciers, which will result in land uplift in both northern and southern Norway.

2. Mountain glaciers

Most Norwegian mountain glaciers melted away during the Holocene Climatic Optimum (HCO); as a consequence of warmer summer temperature (e.g. Nesje, 2009) between 8 000 and 6 000 cal yr BP (e.g. Nielsen et al., 2018). Following this warm period, glaciers started to reform during the Neoglaciation which started ~6 000 cal yr BP and ended with the Little Ice Age some 300 years ago (e.g. Nesje, 2009 and references therein).

After several periods of glacier growth and decay most of the Norwegian glaciers probably culminated in the Little Ice Age (Nesje, 2009). From the mid 1700s AD the glaciers started to decay and finally ended at the present glacier thicknesses. We have made a model of the glacier thickness growth and decay in which we assume that the glacial growth started at 6 000 cal yr BP and grew to a maximum 300 years ago (for maximum exceeding the current ice thicknesses, see Fig. 2). From 300 years ago the glaciers started to decay in thicknesses (as given in Fig. 2) before present status is achieved.

In the modelling the glacier growth from 6 000 to 300 cal yr BP is assumed to take place with uniform velocity, so is the decay from 300 to present. The spatial resolution in our modelling is 10 km; this high spatial resolution is a requirement (in addition to high temporal resolution) in order to do realistic modelling of the isostatic and elastic response due to the glacier changes of the Late Holocene.

Figure 2. Model of the unloading of mountain glaciers. Dark blue colour shows ice thicknesses exceeding 100 m compared to present day.

3. Isostatic response

The isostatic response to the load of the changing glaciers is in our study modelled by an incompressible viscous half-space in which the viscosity may vary with depth, i.e. the properties are constant within layers of variable thickness. The viscous fluid is overlain by an elastic lithosphere of uniform thickness. The mantle is considered fully adiabatic; no buoyancy forces affect the flow other than those related to the surface load redistribution. The method used here is described in Fjeldskaar (1994, 1997) and Fjeldskaar and Cathles (1991). The best-fitting model of the present rate of uplift based on the glacial history has a low-viscosity asthenosphere of 1.8 x 10^{19} Pa s and a weak lithosphere with flexural rigidity 2 x 10^{23} Nm (effective elastic thickness Te ~30 km) (Fjeldskaar et al., submitted). The mantle has a viscosity of 10^{21} Pa s. The Earth´s parameters are similar to the parameters found e.g. for Lake Mead area, USA. Based on the observed subsidence in the area around the lake Kaufman & Amelung (2000) found the best-fitting parameters to be an effective elastic lithosphere thickness of ~30 km over a mantle viscosity of 10^{18} Pa s.

The isostatic response of the assumed decay of the glaciers after the Little Ice Age was modelled with the same Earth rheology. The calculated ongoing isostatic uplift of the decreasing glaciers is close to 2 mm/yr for both northern and southern areas of Norway (Fig. 3). The theoretical present uplift due to the mountain glaciers decay is thus significant compared to the observed uplift in those areas (cf. Fig. 1). The reason for this significant effect is simply that

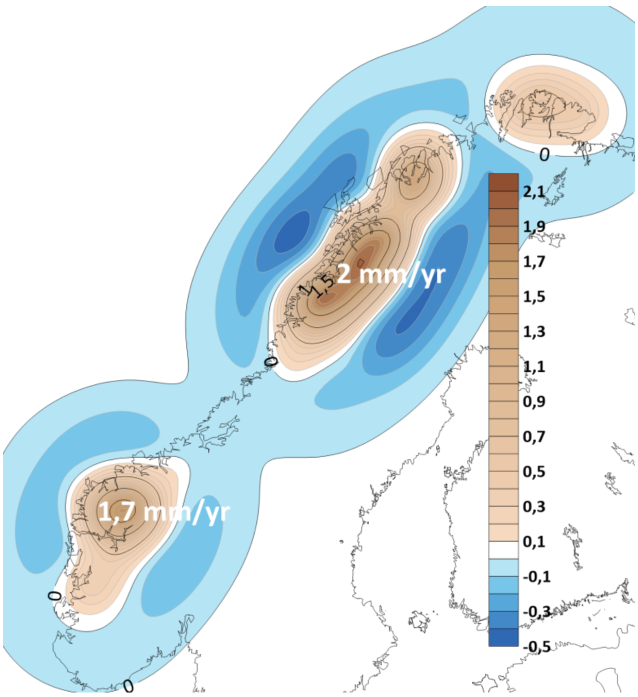

Figure 3. Calculated present rate of uplift due to isostatic response of the unloading of mountain glaciers (in mm/yr).

the decay of the mountain glaciers takes place much closer to present time. In addition the relaxation time for low wavelength deflections (like the this significant effect is simply that the decay of the mountain glaciers takes place much closer to present time. In addition the relaxation time for low wavelength deflections (like the mountain glaciers) is much lower than for the Fennoscandian type late-glacial huge ice sheets (for relaxation times vs. wavelengths, cf. Fjeldskaar and Amantov, 2017).

4. Elastic deflections

When a force is applied to the Earth's surface, there is an immediate elastic deformation proportional to the stress. Almost all solid rocks behave elastically when the applied forces are not too large, and return to their original shape when the force is removed. The elasticity of a crystalline solid arises from the action of interatomic forces, which tend to maintain each atom in its equilibrium lattice position. Rocks behave quite differently in response to applied forces, depending on the elastic properties of the rocks. Changes in rock type within the crust, vertically and horizontally, contribute to variations in the response. The elastic behaviour of a material can be characterized by specifying the Lame's parameters λ and μ.

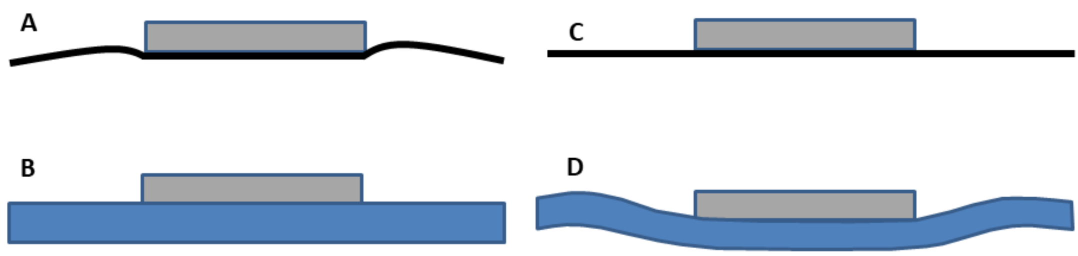

Figure 4. Illustration of the interrelation between isostatic and elastic deflections. (A) Immediate elastic deflection, (B) immediate isostatic deflection, (C) equilibrium elastic deflection after infinite time, and (D) equilibrium isostatic deflection after infinite time.

The elastic displacement is gradually recovered as the Earth adjusts toward isostatic equilibrium. When isostatic equilibrium is achieved, there will be no elastic deformation. There are thus basically two causes of elastic effects: (l) loading/unloading of ice caps, (2) isostatic movements caused by the loading/unloading. This is illustrated in Figure 4. At the loading of the ice sheet, there will be an immediate elastic response (A). The immediate isostatic response (B) will be close to zero, because of a finite viscosity of the mantle. After infinite time, the lithosphere reaches an equilibrium isostatic position (D), which means that the surface load is balanced by buoyant forces. Lower parts of the Earth will, thus, not 'see' any loads at the surface.

Elastic deflection is a function of the wavelength of the load, and also of the elastic properties of the crust. The response *u(k)* of an incompressible elastic medium to a surface load of wave number k is (Cathles, 1975):

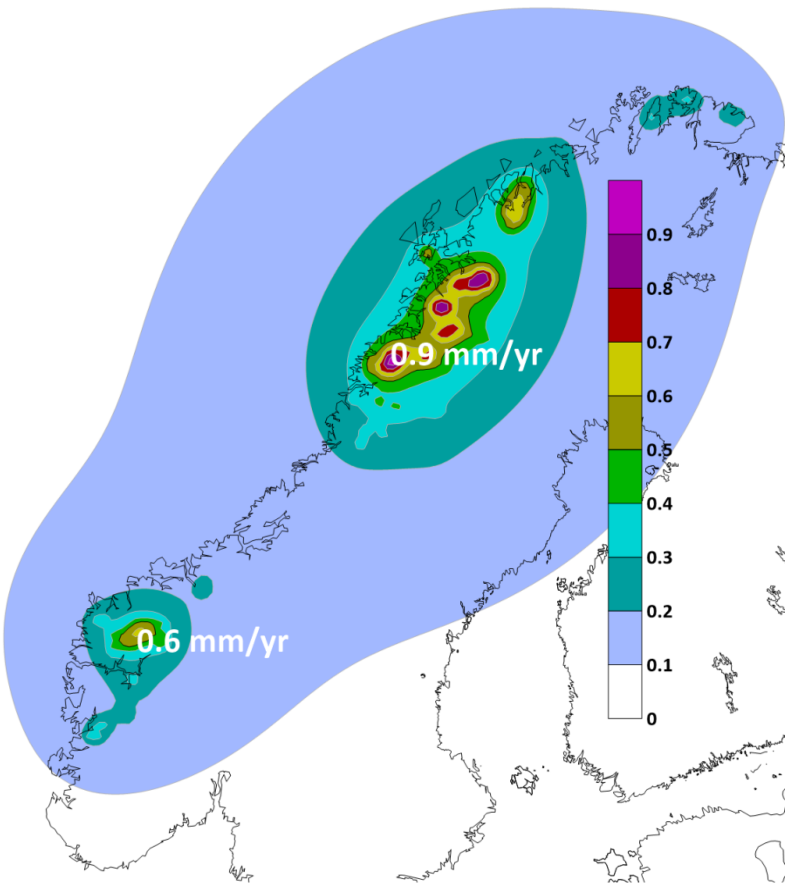

Figure 5. Present elastic response to the melting of the mountain glaciers (in mm/yr).

$$u(k) = \frac{\rho_0\, g\, h}{\mu\, k}$$

where μ is the shear rigidity, g is the gravity, h is the thickness of the load, and ρ_0 is the density. In the modelling we have used shear rigidity $\mu = 0.7 \times 10^{11}$ N/m^2. The method for the calculations is described in Fjeldskaar (2000). The calculated ongoing elastic uplift due to the unloading of the mountain glaciers has a maximum in northern Norway of 0.9 mm/yr, and in southern Norway of 0.6 mm/yr (Fig.5).

5. Total response of unloading of mountain glaciers

The total present uplift due to the combined isostasy and elastic response (Figs 3 and 5) of the decaying mountain glaciers is very close to 2.5 mm/yr in northern as well as southern Norway (Fig. 6a).

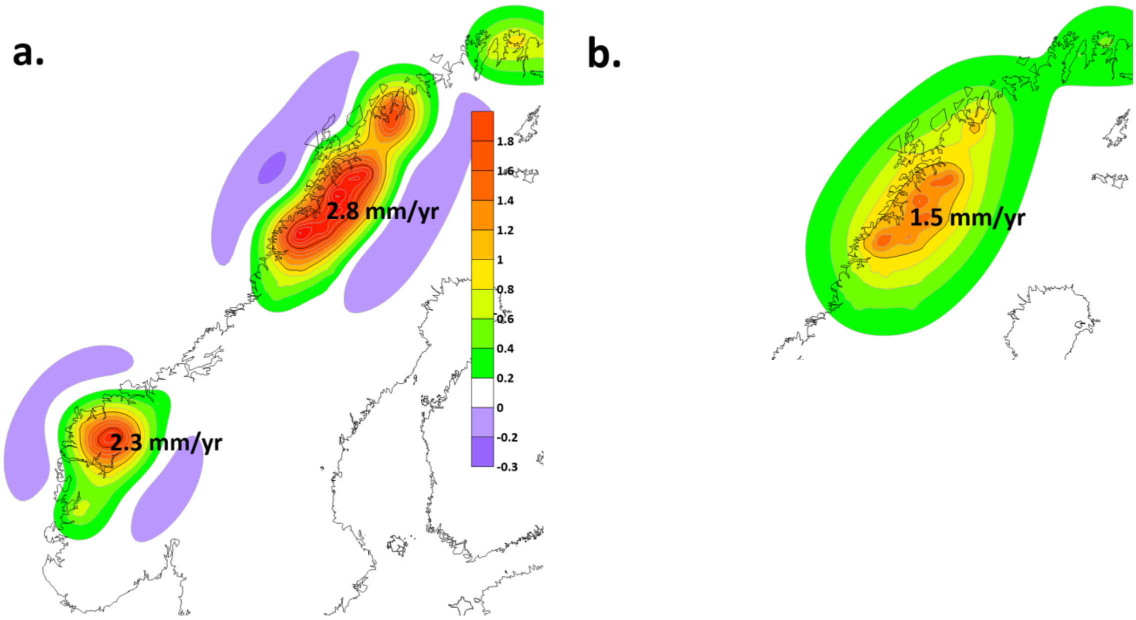

Figure 6. Calculated combined isostatic and elastic present uplift due to unloading of glaciers over the last 300 years. a) effective elastic lithosphere thickness Te = 30 km; b) for Te =80 km.

6. Discussion

We have added a second Earth rheology model with a thicker effective elastic lithosphere (Te = 80 km; fr = 5 $x10^{24}$ Nm) because Fjeldskaar and Bondevik (2020) found evidence of a possible increase in Te (or alternatively a significant tectonic component) towards the northernmost part of Norway in their study of the Tapes transgression. Present total uplift for northern Norway with a model of thicker effective lithosphere thickness is 1.5 mm/yr (Fig. 6b).

There are significant uncertainties in these calculations, however, related primarily to the timing of the maximum glaciations, and to the magnitude of the maximum ice thicknesses. The glaciers during the Neoglaciation changed over time and there were several intermittent periods with extensive glaciers (Nesje, 2009). Our modelling is limited to one period of maximum glaciers, set to 300 years ago, and we assume uniform velocity growth from 6000 cal yr BP to 300 years ago. The resulting isostatic effect could, however, be different if we had taken into account that glaciers experienced several periods of significant advances and retreats during the period before the Little Ice Age maximum. In addition, the maximum extension does not necessarily coincide in time with maximum volume.

We have tested various options of the Neoglacial glaciations and deglaciations, all assuming the glacial growth and reduction to take place simultaneously on all glaciers. This is probably a reasonable assumption over a limited areas like northern and southern Norway. If we change the maximum ice thickness to take place much earlier, e.g. at 2500 cal yr BP, the ongoing isostatic uplift will be reduced, but will still be significant (close to 1.5 mm/yr in northern Norway) and with a maximum in the same location. However, the elastic effect will be reduced because the areas will be closer to isostatic equilibrium.

The magnitude of the ongoing uplift will increase with a greater maximum ice thickness. As expected, there is a clear tendency of increasing ongoing uplift if the maximum ice thicknesses are of more recent time. The ice thicknesses during a tentative maximum carry significant uncertainties. Even for small glaciers the late thickness reduction is likely to exceed 100 m (e.g. Bakke et al., 2010). If, however, our model (Fig. 2) is exaggerating the ice loads, the magnitude of the uplift will be reduced, but the shape of the calculated uplift will still be similar to the uplift shape of Figure 6. On the other hand, with a doubling of the ice thickness, there will also be a doubling of the isostatic and elastic response.

It is also worth mentioning that many researchers use a different approach to glacial isostasy than we do, a global GIA model based on the correspondence principle (cf. e.g. Peltier, 1974). That model implies a significantly different Earth rheology from what we have used above. Steffen and Wu (2011) have reviewed modelling results on Fennoscandian rheology for such models based on observations of both postglacial and ongoing uplift. Their suggested Earth rheology for Fennoscandia consists of an effective elastic lithosphere thickness (Te) between 75 and 160 km, and a viscosity of the lower mantle up to 100 times higher than the upper mantle and without a low viscosity asthenosphere. Such thick effective elastic lithosphere will lead to insignificant ongoing isostatic response of the glaciers decay, but the elastic response will still be as shown in Figure 5.

Conclusion

Most Norwegian mountain glaciers melted away in a period between 8 000 and 6 000 cal yr BP. This (warm) period was followed by the Neoglaciation which startet around 6 000 cal yr BP and ended with the Little Ice Age. After several periods of glacier growth and decay most of the Norwegian glaciers probably culminated in mid 1700s AD. The last 300 years is characterized by a very significant decay of the Norwegian mountain glaciers.

The calculated ongoing isostatic response of the glaciers decay is close to 2 mm/yr in areas of northern and southern Norway, while the elastic response is close to 1 mm/yr in northern Norway. The total present uplift of the combined isostatic and elastic response of the mountain glaciers unloading exceeds 2 mm/yr both in northern as well as southern Norway.

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