Sensitivity of GIA models with shallow low-viscosity earth layers to the ice-load history in relation to the resolving power of GOCE

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ABSTRACT

The GOCE satellite mission, which is planned by ESA for launch in 2006, is designed to map the static global gravity field with centimeter accuracy in geoid height at hundred km resolution. Such a global high resolution gravity field might be able to constrain properties of shallow low-viscosity zones using glacial isostatic adjustment (GIA) models. In van der Wal, Schotman and Vermeersen (2004) it is shown that a crustal low-viscosity zone (CLVZ) can introduce variations in geoid height up to several decimeters with spatial scales of hundred kilometers, and that this response is sensitive to changes in the properties of the CLVZ. In this study we show, using spherical harmonic degree amplitudes, that GOCE is sensitive to differences in the ice-load history up to degree 130 for a CLVZ. This means that GOCE could provide information on the ice-load history in the presence of a CLVZ, provided that our knowledge of the earth is sufficient. To extract information about the CLVZ from the degree amplitudes, we show that it is possible to largely remove the influence of the ice-load history and thus compute spectral signatures for different properties of the LVZ. We focus on the continental shelf-areas of western Europe to show the sensitivity of present-day sea level rise to the inclusion of a CLVZ. In future work we will introduce lateral heterogeneities in our earth model using the finite element method (see Wu, Wang and Schotman 2004) to obtain realistic estimates of the effect of a CLVZ.

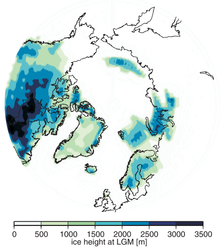
INTRODUCTION

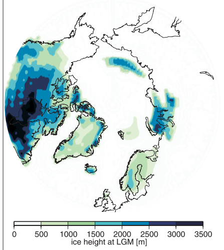
- Semi-analytical normal mode technique (Vermeersen & Sabadini 1997).
- Crustal low-viscosity zone (CLVZ) with a depth of 20 km, a thickness of 12 km and a viscosity of 10^{18} Pas (model Md20t12v18).
- Geoid height **perturbations:** differences in geoid height between an earth model with and without a CLVZ (models Md20t12v18 and Md20t12ela).
- Sensitivity to ice-load history: **perturbation differences** between an alternative ice model and a reference ice model.
- Sensitivity to ocean-load history: use of a time-dependent ocean function and meltwater influx (MWIF) in formerly glaciated areas.
- Also effect of an asthenospheric LVZ (ALVZ) below an elastic lithopshere of 80 km, with a thickness of 35 km and a viscosity of 10^{18} Pas (Ml80t35v18).
- Comparison with formal performance of **GOCE** and realized performance of **GRACE** (GGM01S).

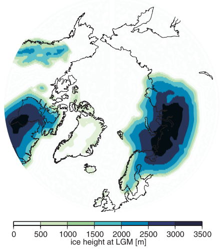
Ice-Load Histories

We use three different ice load histories: a modified version of ICE3G of Tushingham & Peltier (I3G, top right), this model with the Fennoscandian and Barentsz Sea part replaced by a model developed by Lambeck and co-workers (ANU, bottom left) and an ice sheet-dynamical model of the Institute for Marine and Atmospheric Research Utrecht (ISD, bottom right).

We have scaled the ICE3G model to include a total sea level equivalent ice volume of 120 m at LGM, but we have not scaled the Fennoscandian and Barentsz Sea part. We have complemented the ANU model for Fennoscandia and the Barentsz Sea with scaled other parts of ICE3G to have a total volume of 120 m. Of the ISD model we have used only the North American and Eurasian part, complemented by scaled parts of ICE3G.





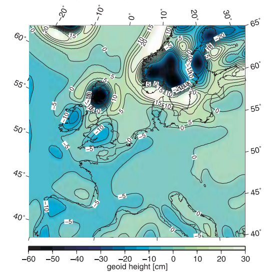


GOCE Satellite Gravity Mission

The GOCE mission, planned by ESA for launch In August 2006, is designed to map the static global gravity field with centimeter accuracy in geoid height at 100 km or better spatial resolution. The satellite will measure gravity gradients on an altitude of about 250 km using a gradiometer.

Geoid Height Perturbations

The geoid height perturbations induced by a CLVZ (model Md20t12v18 with the results of model Md20t12ela subtracted) are shown in the figure below. The induced signal shows amplitudes of tens of centimeters with spatial scales down to one hundred km. The pattern is mainly explained by the extra flow away from the formerly glaciated areas through the low-viscosity channel during the glaciation phase, leading to differential forebulges around the ice sheets. Due to the relatively long relaxation time of the extra buoyancy mode MC introduced by the CLVZ and the short deglaciation period, these areas have only slightly adjusted to isostasy.

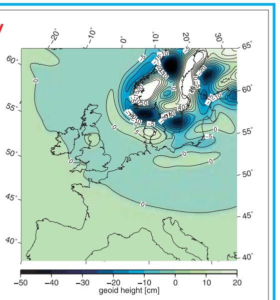


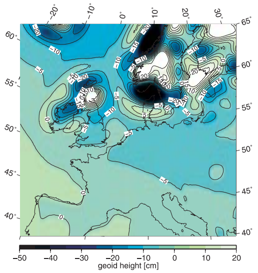
The postion of the ice sheets can clearly be distinguished in the figure, which already indicates the sensitivity to ice-sheet geometry. The slightly positive area beyond the differential forebulges can be explained by the increase in the total relaxation time for low degrees (l < 50) due to the inclusion of the CLVZ.

Spatial Sensitivity

We test the sensitivity of our GIA model with a CLVZ by subtracting the geoid height perturbations induced by using the I3G model from the geoid height perturbations using ice model ANU or ISD. Results are then geoid height perturbation differences as shown in these two figures.

The figure on the right shows the difference between model ANU and model I3G; the figure below between model ISD and model I3G.

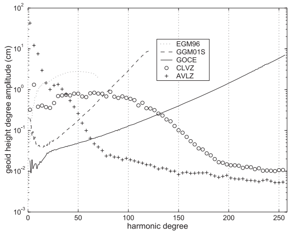


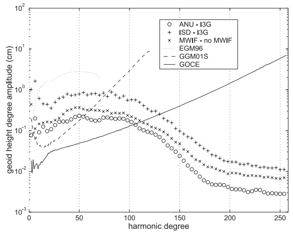


A common feature in both plots are the highs in areas where the ANU and ISD model define less ice than I3G and just outside the maximum extent of ANU and ISD, where the differential bulge is pushed southward. Another common feature is the large slightly negative area around the former ice sheets, which can be explained by the smaller mass of the Fennoscandian ice sheet for ANU and ISD and the slower collapse of the forebulge.

Spectral Sensitivity

We now show global results in the spectral domain, using a spherical harmonic expansion of the perturbation (difference) fields. We have plotted the CLVZ (circles) and ALVZ (pluses) induced geoid height perturbation degree amplitudes together with the error characteristics of EGM96 (Lemoine et al. 1997, dotted), the realized performance of GRACE for a 111-day period (GGM01S, Tapley et al. 2004, dashed) and the expected performance of GOCE (Pieter Visser, personal communication, solid).

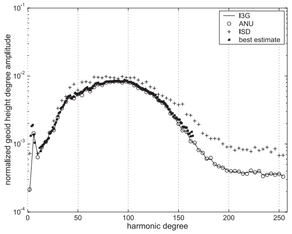




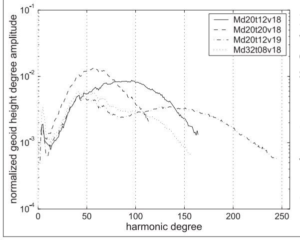
GOCE is also sensitive to changes in the used ice- and ocean-load history in the presence of a CLVZ. On the left we have plotted differences in CLVZ induced perturbations between ANU and I3G (circles), ISD and I3G (pluses), and a model with and without MWIF (crosses).

Spectral Signatures

In the figure on the right we show spectral signatures, which are perturbation degree amplitudes (using a certain ice model) normalized with the degree amplitudes of the best correlating ice model. This ice model is selected using degree correlation coefficients between the spectrum of the perturbations and the ice models.



We can also compute a least-squares fit to the curves weighted with the degree correlation coefficients. We have also plotted this best estimate of the spectral signature for values that are above the propagated error.



In the figure on the left, we have plotted best estimates of spectral signatures for different properties of the CLVZ.

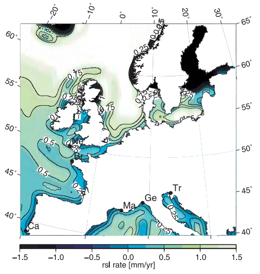
Md20t20v18: thicker (20 km) CLVZ

Md20t12v19: higher viscosity (10^{19} Pas)

Md32t08v18: deeper (32 km) and thinner (8 km) CLVZ

Effect on Present-Day Sea Level Change

In the figure on the left we show the predicted rate of relative sea level change due to GIA, computed using earth model Md20t12v18 and ice model I3G. This kind of computations is often used to correct estimates of present-day sea level change (SLC) from tide gauges for ongoing GIA, The effect of the CLVZ is mainly an extra tilting along the coastline.



The effect on the rate of SLC in Europe is to lower both the mean and the standard deviation, the first with a maximum of 4 % (from 1.26 to 1.21 mm/yr) and the latter with 10 %, see the table below

	Trend	Trend-GIA	No LVZ	CLVZ	ALVZ
MEAN 1991	1.42	1.65	1.32	1.31	1.18
SIGMA 1991	0.22	0.19	0.21	0.19	0.24
MEAN 2001	1.35	1.24	1.26	1.21	1.13
SIGMA 2001	0.24	0.36	0.25	0.23	0.22

Mean rate of present-day sea level change ('MEAN', in mm/yr) in Europe and the corresponding standard deviation ('SIGMA') for two estimates (1991, 2001) of the tide gauge measurements ('Trend', Douglas 1991, 2001) and these measurements corrected for GIA predictions ('Trend-GIA', Douglas 1991, Peltier 2001), and our corrected measurements, using a model without an LVZ ('No LVZ'), a model with a CLVZ ('CLVZ'), and a model with an ALVZ ('ALVZ').

CONCLUSION

- The response of a model earth with a shallow low-viscosity zone (LVZ) to loading and unloading during the last glacial cycle is a complex function of spherical harmonic degree and time.
- The incorporation of a crustal low-viscosity zone (CLVZ) leads to extra material flow away from the (formerly) loaded areas, especially for degrees 50 to 150. Coastlines experience additional tilting, thus lowering estimates of present-day sea level rise, with a lower standard deviation.
- The response is also very sensitive to the prescribed ice-load history and to a lesser extent the ocean-load history.
- The sensitivity to the ice-load history is mainly due to ice sheet geometry and volume, the effect is confined to an area of a few hundred kilometers around the formerly glaciated areas.
- CLVZ induced geoid height perturbation degree amplitudes are above the GOCE performance up to degree 130 and the GRACE performance up to degree 80.
- For a CLVZ, GOCE is sensitive to differences in the ice-load history from degree 100 to degree 130 (GRACE: 50-70), which means that GOCE, and to a lesser extent GRACE, should be able to discriminate between different ice-load histories if we know the properties of the CLVZ.
- Spectral signatures show a distinct behavior for different properties of the CLVZ and are largely independent of the ice-load history.
- In future work we will use simulated GOCE measurements to estimate how well the gravity signal due to a shallow LVZ can be extracted from these measurements in the presence of other high resolution gravity signals, noise and errors due to uncertainties in the ice-load history.

ACKNOWLEDGEMENTS

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