Space and Time Variations of Surface Mass Anomalies over Greenland using Grace

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IPCC report

The 2007 Intergovernmental Panel on Climate Change (IPCC) report is asserting:
"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."

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"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level." One of the most troubling consequences of global warming is the rise of sea-level (SLR). One process is the increase of the volume of the ocean by thermal expansion (the steric component). The other process is an increase of the mass of water due to the melting of ice on land (the eustatic component).

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During the last century sea-levels have been rising by nearly 2 mm/yr; however *Leuliette et al.* show that in the last 12 years SLR has been about 3 mm/yr. The greatest potential for significantly increasing sea-level lies in the Greenland Ice Sheet and the Antarctic Ice Sheets. Variuous measurements show that both ice sheets are losing mass. The fourth IPCC report explains that losses from the ice sheets in Greenland and Antarctica have *very likely* been contributing to sea level rise over 1993 to 2003. The Greenland Ice Sheet (GIS) with a total volume of 2.9 million km^3 is one of the greatest fresh water reservoirs on Earth and contains the equivalent of seven meters of sea-level.

Climate change and sea level rise

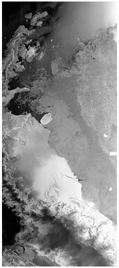

Figure: Advanced Synthetic Aperture Radar (ASAR) image of Larsen-B Ice Shelf captured by Envisat on 22 February 2007

The desintegration of this 200-metre-thick ice shelf shows the susceptibility of Antarctica's perimeter to a warming atmosphere and ocean.

Mission Overview

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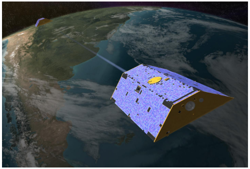

Figure: the two GRACE satellites in orbit Credit: the University of Texas Center for Space Research

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Measurement concepts

Two low earth orbit (LEO) satellites are placed in the same orbit but separated by some hundreds of kilometers. Range rates between the satellites are measured accurately by a ranging system. The position of the LEO's is determined by GPS satellites. The orbit of each LEO satellite is affected by perturbing accelerations which correspond to the first derivatives of the gravitational potential.

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Main mission parameters

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- the satellites are separated from each other by approximately 220 km (orbit maneuvers are required every one or two months to maintain the separation)
- intended lifetime of the mission was initially five years, based on a report by GFZ Potsdam a considerably longer lifetime of about ten years may now be expected.

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  satellite-to-satellite tracking between the GRACE satellites and the GPS satellites is realized. The precise orbits are determined on ground.
- attitude and orbit control system
  the satellite's orientation and orbit control are controlled by a system of sensors, actuators and software; the satellites are "three-axis stabilized"; their orientation is fixed in relation to space; they do not spin for stability.

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  they are mounted at the center of gravity of each satellite and measure all non-gravitational accelerations on the satellites (e.g. due to air drag in the atmosphere or solar radiation pressure)
- laser retroreflector
  mounted on the underside of each satellite they provide a means of terrestrial laser tracking of the satellites: by reflection of short laser pulses transmitted by ground stations, the distance between the ground station and a GRACE satellite can be measured with an accuracy of 1-2 cm.

Shape of the geoid

Earth's global gravity field is represented by the shape of the geoid, the equipotential surface that coincides with mean sea level over the ocean. The geoid N can be expanded as a sum of normalized associated Legendre functions $\tilde{P}_{lm}$:

$$N(\theta, \phi) = a \sum_{l=0}^{\infty} \sum_{m=0}^{l} \tilde{P}_{lm}(\cos\theta)\{C_{lm}\cos m\phi + S_{lm}\sin m\phi\} \qquad (1)$$

with colatitude θ, longitude ϕ and the mean radius of the Earth a. C_{lm} and S_{lm} are dimensionless Stokes coefficients. Using these coefficients one can determine changes in the gravity field and study processes involving redistribution of mass within the Earth and or above its surface.

Change in surface mass

Wahr et al. develop a spatial averaging method to estimate the variability in the geoid due to mass redistribution processes. A local change in surface mass density $\Delta\sigma(\theta,\phi)$ can be related to changes in the Stokes coefficients, ΔC_{lm} and ΔS_{lm}:

$$\Delta\sigma(\theta,\phi) = \frac{a\rho_E}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{(2l+1)}{(1+k_l)}\tilde{P}_{lm}(\cos\theta)\{\Delta C_{lm}\cos m\phi + \Delta S_{lm}\sin m\phi\} \tag{2}$$

Spatial Averaging 1

An exact averaging kernel, $\vartheta(\theta, \phi)$, describes the shape of the basin:

$$\vartheta(\theta, \phi) = \begin{cases} 0 & \text{outside the basin} \\ 1 & \text{inside the basin} \end{cases} \tag{3}$$

Change in surface mass density averaged over an arbitrary region is

$$\overline{\Delta\sigma}_{\text{region}} = \frac{1}{\Omega_{\text{region}}} \int \Delta\sigma(\theta, \phi)\vartheta(\theta, \phi) d\Omega \tag{4}$$

$d\Omega = \sin\theta d\theta d\phi$ is the element of solid angle.

Spatial Averaging 2

Equation (4) can be reexpressed by using the Stokes coefficients. The mass anomaly over a region is

$$\overline{\Delta\sigma}_{\text{region}} = \frac{a\rho_E}{3\Omega_{\text{region}}} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{(2l+1)}{(1+k_l)} (\vartheta_{lm}^C \Delta C_{lm} + \vartheta_{lm}^S \Delta S_{lm}) \quad (5)$$

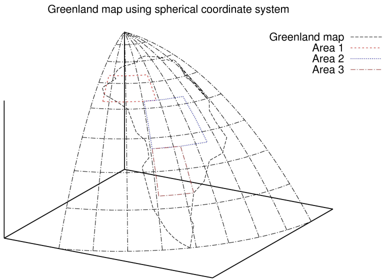
where ϑ_{lm}^C and ϑ_{lm}^S are the spherical harmonic coefficients describing $\vartheta(\theta, \phi)$:

$$\vartheta_{lm}^C = \int \vartheta(\theta, \phi) \tilde{P}_{lm}(\cos\theta) \cos m\phi d\Omega$$

$$\vartheta_{lm}^S = \int \vartheta(\theta, \phi) \tilde{P}_{lm}(\cos\theta) \sin m\phi d\Omega$$

Map of Greenland

Monthly mass variability for three regions of Greenland is estimated by applying equation (5) to the GRACE data fields of Stokes coefficients from Jul 2006 to Jul 2007.



Preliminary results 1

The largest loss in surface mass density is observed for the high-latitude region 1: the best line fit yields a mass decrease of 24 mm/yr of equivalent water thickness for this region.

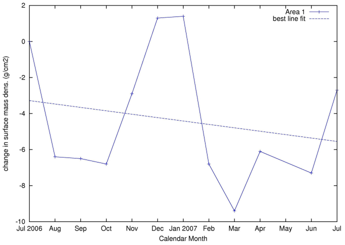


Figure: change in surface density for area 1

Preliminary results 2

A gain in surface mass density is observed for the region 2: the best line fit yields a mass gain of 20 mm/yr of equivalent water thickness for this region.

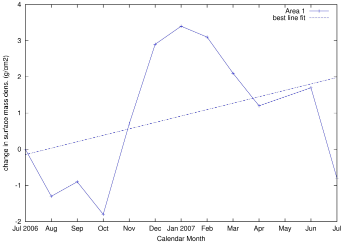


Figure: change in surface density for area 2

Limitations and sources of error

GRACE solutions are limited over time. To investigate climate change, one has to combine GRACE with other techniques. GRACE solutions have no vertical resolution: they don't reveal where the gravity variations come from. The two most important sources of error in the mass estimates are:

- postglacial rebound (PGR). The solid Earth is responding to glacial unloading over the past several thousand years.

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- postglacial rebound (PGR). The solid Earth is responding to glacial unloading over the past several thousand years.
- change in atmospheric mass.

These effects have to be taken into account separately. Further corrections are necessary to minimize leakage error and satellite measurement error.

Conclusions

These preliminary mass estimates seem to confirm that:

- ice sheet margins are shrinking significantly. *Rignot and Kanagaratnam 2006* have observed a widespread acceleration of outlet glaciers.

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- ice sheet margins are shrinking significantly. *Rignot and Kanagaratnam 2006* have observed a widespread acceleration of outlet glaciers.
- the interior of the ice sheet is growing thicker. Measurements of *Johannessen et al. 2005* show a thickening of the interior of the ice sheet by a few cm per year.

While there is disagreement on the relative magnitudes of these competing effects, it is very likely that the Greenland Ice Sheet is a major contributor to near-term sea-level rise.