Mass loss of Greenland and Antarctica from GRACE and IceSat

Rene Forsberg, Valentina Barlettea, Louise Sandberg Sørensen
Dept. of Geodynamics, DTU-Space
Measurement of ice sheet mass balance from space
"The geodetic methods"

*Height measurements:*
  - Radar altimetry (ERS-1, ERS-2, EnviSat, CryoSat, Sentinel-3 ..)
  - Laser altimetry (NASA IceSat 2003-9; IceSat-2 2015 ..)

  *Provide height changes … must be converted to mass balance by snow compaction and density assumptions.*

*Mass change measurements:*
  - Satellite-to-satellite ranging (NASA/DLR GRACE 2002- ..)

  *Provide direct estimate of mass-balance, but limited resolution affected by ocean, land and atmosphere mass changes.*

*Velocity measurements:*
  - SAR interferometry (ERS, EnviSat + ALOS/Palsar, TerraSAR-X ..)

  *Outlet glacier velocities converted to overall mass changes by assumptions on snow accumulation and glacier thickness*

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*Do methods agree? NASA-ESA IMBIE study 2011-12*
Ice sheet melting concerns …

• Freshwater input to ocean may change ocean circulation / deep-water formation..

• Global sea level rise
  - But sea-level rise is not uniform across the oceans due to self-attraction and isostasy

=> Antarctica dominate sea-level rise in Europe!!

Current rate ~ 0.7 mm/yr on average for Greenland, ~ 0.3 mm/yr for Antarctica

Sea-level change due to current Greenland melt

Sea-level change due to Antarctica

[Global sea level equation solutions / Barletta-DTU 2012]
Ice sheets are in dynamic balance

- Snow accumulate on top
- Turns into ice at depths of 20-40 m
- Flows to coastal area and melt or breaks off as icebergs
- Large outlet glaciers move up to 30 m/day

_Greenlandf: Total mass balance / year: ~ 650 km³_
_Current mass loss: ~ 230 km³/yr_
Ice velocities from SAR interferometry ..

Rignot (NASA/JPL, Science 2006),
Greenland mass loss:
1996: 91 km$^3$/yr
2000: 138 km$^3$/yr
2005: 224 km$^3$/yr

European set-up for Greenland-wide Velocity products: "ice_sheets_cci" project (2012-15) [ESA climate initiative]

Greenland ice velocity [Joughin, UWash]  Ice velocity vectors, Kangerlussuaq [DTU]  SAR interferogram, Petermann Gl.
Analysis of GRACE ice sheet data 2002-10

Data: Monthly spherical harmonic solutions (Release 4):
CSR [Center for Space Research, University of Texas], 89
GFZ  [Geoforschungszentrum, Germany], 86
JPL  [NASA-JPL, GRACE validation solutions], 82
C20-term substituted with SLR values

Processing:

- Expansion to harmonic degree \( N = 30 \) or 60
  Degree 60 corresponds to \( 3^\circ \) resolution

\[
T(r, \varphi, \lambda) = \frac{GM}{R} \sum_{n=2}^{N} \sum_{m=0}^{n} \left[ C_{nm} \cos m\lambda + D_{nm} \sin m\lambda \right] P_{nm}(\sin \varphi)
\]

- Potential fields: geoid \( N \) or gravity disturbance \( \delta g \) equivalent,
  function of potential \( T \) (units: mm or \( \mu \text{gal} = 10^{-8} \text{ m/s}^2 \))

\[
N = \frac{T}{\gamma} \quad \delta g = \frac{\partial T}{\partial r}
\]

- 4-parameter trend and seasonal analysis: \( \delta g(t) = a + b t + c \cos(\omega t) + d \sin(\omega t) \)
Global analysis – yearly trend (CSR RL4 dg at 480 km, deg 60)

Units: 10^{-9}g (\mu gal)
Antarctica – trend analysis of 8 year period sharpen change areas

Trends (μgal/yr ≈ 10⁻⁹g/yr)
Converting gravity change to ice mass change by point mass inversion

Obs. \( y = \{ \delta g_i \}, i = 1, \ldots, n \) at altitude (grid)

Modelpar. \( x = \{ m_j \}, j = 1, \ldots, m \) at surface,

\[
\delta g_i = Gm_j \frac{R^2 r - R^3 \cos \psi}{[r^2 + R^2 - 2Rr \cos \psi]^{3/2}}
\]

Model masscons only in Antarctic area .. assuming no signal from ocean

Obs.eq. \( y = Ax \) ... need regularization

Generalized inverse \( x = [A^T A + \lambda I]^{-1} A^T y \) -> \( dM/dt \) (Tychonov regularization)
Examples of mass inversion, shown as mm/year eq. water change

CSR deg 60

GFZ deg 60
Glacial isostatic adjustment corrections

GIA corrections from finite-element spherical harmonic modelling
[SELEN code, G. Spada/GIA COST action]

- 3 ice history models:
  ICE-5G (Peltier), IJ05 (Ivins), Lambeck
- 3-layer viscosity model, lithosphere thickness 120 km
- Geoid response converted to gravity spherical FFT

*GIA corrections increase mass loss by about 50%*
Total mass loss estimates of Antarctica 2002-9

GRACE mass loss - Antarctica

Time

Mass loss (GT)

2003 2004 2005 2006 2007 2008 2009 2010

JPL -90 GT/yr
GFZ -80 GT/yr
CSR -75 GT/yr
CSR (no J2) -149 GT/yr

ICE-5G GIA
GRACE mass loss estimates 2002-9 – different GIA models

**ANTARCTICA**

- CSR-Lambeck: -95 GT/yr
- CSR-IJ: -122 GT/yr
- GFZ-ICE5G: -80 GT/yr
- CSR-ICE5G: -75 GT/yr
ICESat laser altimetry 2003-9
2-3 month epochs / year

ICESat analysis:
• Repeat-track height changes (relative to reference DEM)
• Interpolation to grid
• Trend analysis
ICESAT height changes compared to GRACE

ICESat height changes (mm/yr) filtered to GRACE resolution

GRACE equivalent water height changes (CSR deg. 60)
Greenland: IceSat elevation changes 2003-9

Elevation changes converted to mass changes using firm compaction / snow density model (Simonsen et al):
Mass loss from IceSat: \(-240 \pm 28 \) GT/yr
Greenland: GRACE – solve for masscons in ice covered area

Gravity trend at altitude (CSR degree 60)
Greenland – high resolution possible in average trend

degree 60
degree 90
degree 120
Glacial isostatic adjustment corrections (Greenland)

Gravity change (μGal/year)

ANU
ICE-5G

Vertical Movements (mm/year)

ANU
ICE-5G

DTU Space
National Space Institute
Masscon solutions (uniform area masscons)

Mass changes expressed as equivalent water mass layer
Greenland mass trends 2002-11 (yearly mass loss)

<table>
<thead>
<tr>
<th>Year</th>
<th>Mass loss (GT)</th>
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<tbody>
<tr>
<td>2003</td>
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<td>2010</td>
<td>266</td>
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</table>
Greenland mass trends 2002-10 .. basins (ice2sea)

Refined analysis (Barletta):
Solve for multiple ice sheets
GIA, elastic, low-order harmonics corr.
Kusche destriping, error estimation
Conclusions:

GRACE and IceSat shows consistent Greenland and Antarctica mass loss

Our "best" current estimates from GRACE:
(Barletta et al, TCD, 2012)

Greenland  -234 ± 20 GT/yr (~ 0.68 mm/yr)
Antarctica  -83 ± 36 GT/yr  (~ 0.24 mm/yr)

Need for improved GIA models ..
GPS uplift and absolute gravity changes provide additional constraints

Key application of geodesy for climate change studies!