*Lecture course on*

# Sea level variations and global geodynamics

## 5. Greenland uplift and sea level change

(November 11, start 10:40)


Giorgio Spada

DiSBeF, Urbino University "Carlo Bo"

http://www.fis.uniurb.it/spada

giorgio.spada@gmail.com


Charles University in Prague, Department of Geophysics
*November 7–11, 2011*

last revised november 11 2011

*Overview:*

- A few words on the "sea level rise" problem *skip intro*

- Contribution of *Greenland* to past and present sea level variations,

- Modeling the effects of melting of Greenland : the *global* view point and

- ... the *regional* view point

- Discussion, problems, directions, ETC...

# The results are from:

G. Spada† ⋆, G. Ruggieri†, L. S. Sørensen∗, K. Nielsen∗, D. Melini§, F. Colleoni, 2011: "Greenland uplift and regional sea–level changes from ICESat observations and GIA modeling", GJI, under revision.


Acknowledgements:

Louise S. Sorensen (DTU Space), Copenhagen, Denmark
she is the PI of the "The cryopshere" paper where the Greenland mass balance is published

Daniele Melini Istituto Nazionale di Geofisica e Vulcanologia (INGV) Rome, Italy
He has developed a parallelized multi-platform version of the Sea Level Equation solver (SELEN)

Karina Nielsen (DTU Space), Copenhagen, Denmark
Now in Italy thanks a COST ES0701 grant. Main objective: regional elastic rebound

Shafaqat Abbas Khan (DTU Space), Copenhagen, Denmark
GPS analysis of the Greenland data

Tom James, Jerry Mitrovica for discussion about the SLE

Bert Wouters, Matt King and Erik Ivins for providing data, suggestions, and discussions

Valentina Barletta (now at DTU Space), Copenhagen, Denmark for benchmark computations and discussion.

## *Overview:*

- A few words on the "sea level rise" problem,

- Contribution of *Greenland* to past and present sea level variations,

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- ... the *regional* view point

- Discussion, problems, directions, ETC...

Outline map of Greenland with ice sheet depths.

GISP refers to a main site of the Greenland Ice Sheet Project, where a 3 km deep ice core was taken.

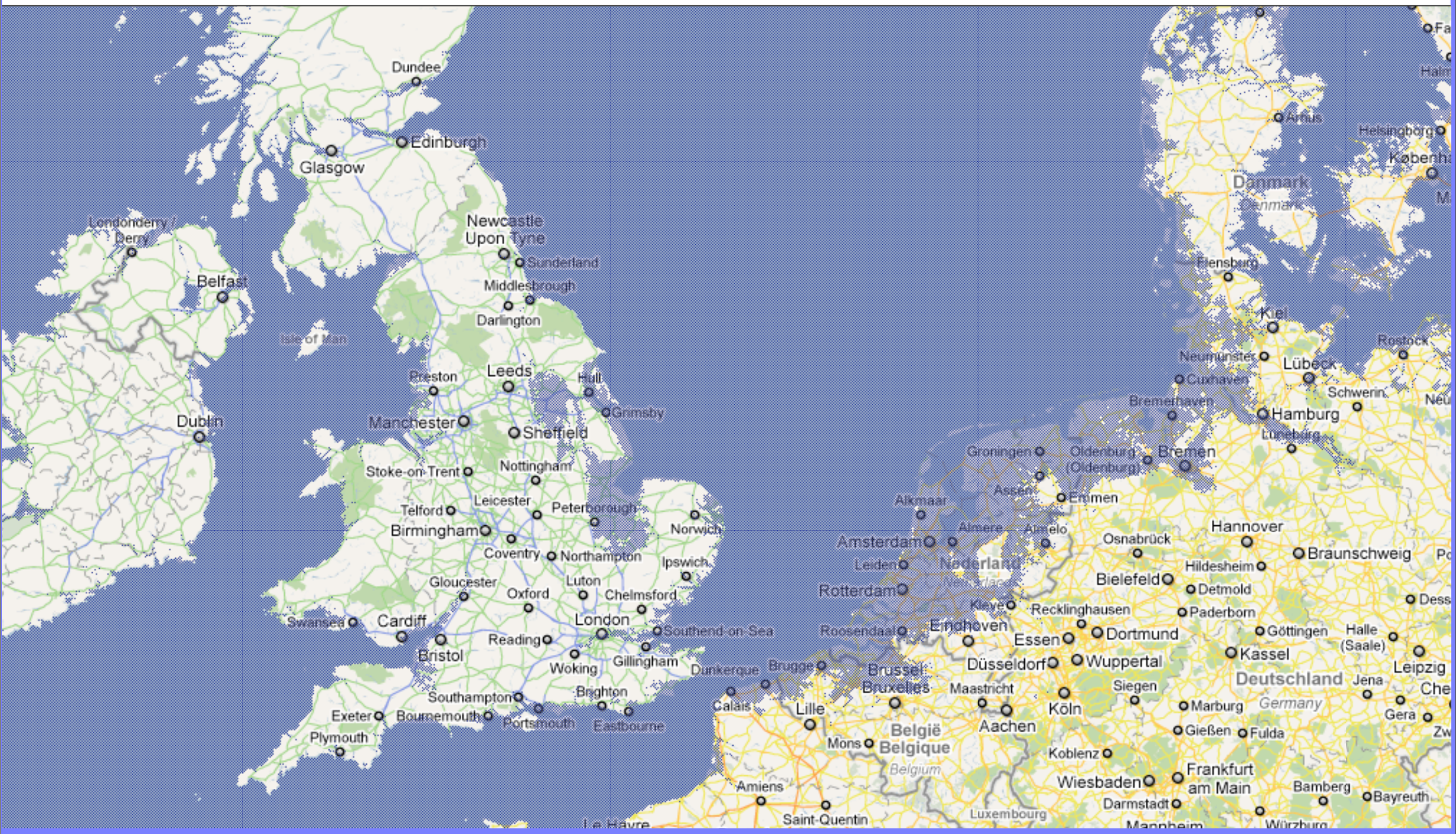
**global sea level rise of 7.2 m**




http://en.wikipedia.org/wiki/Greenland_ice_sheet

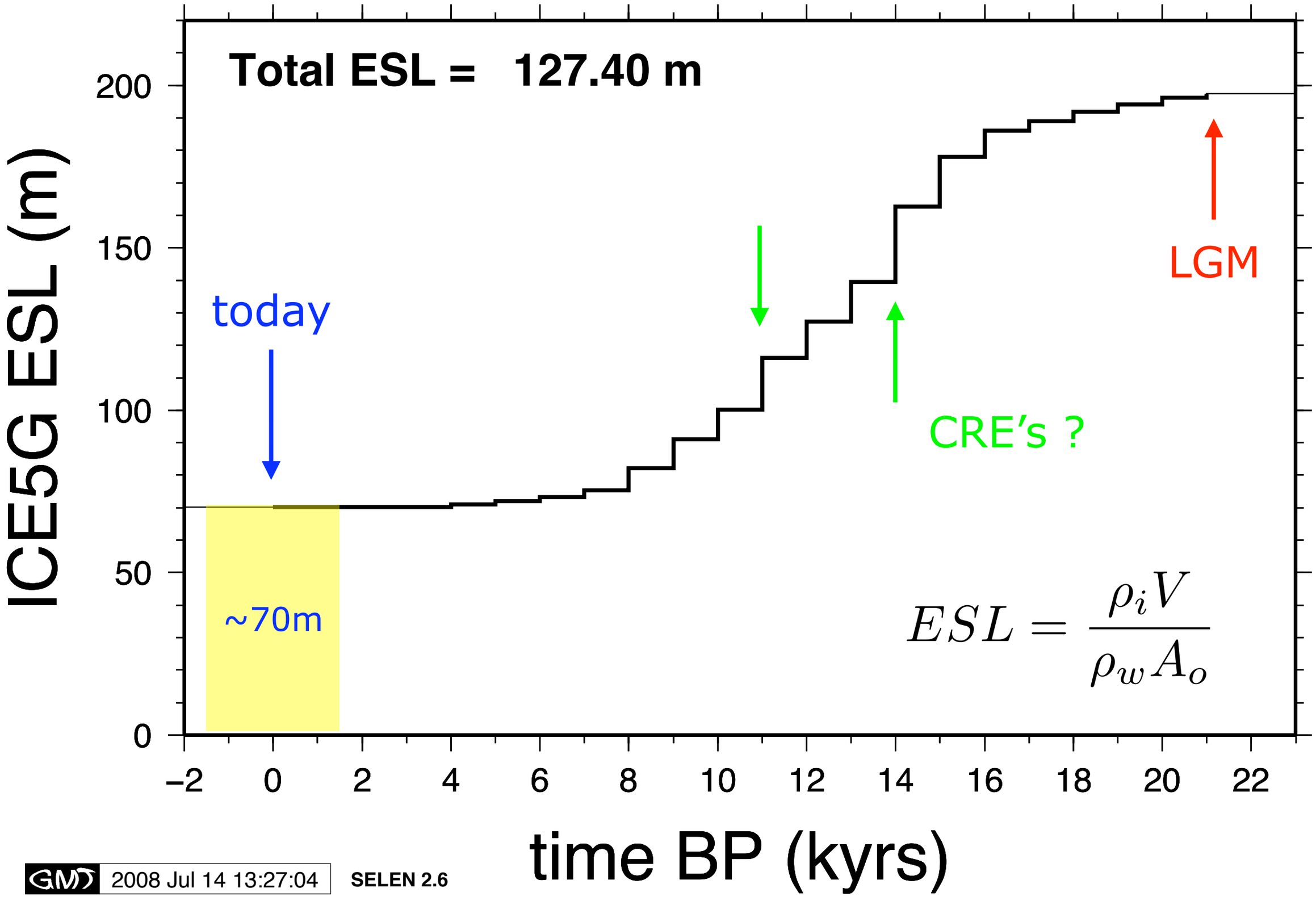
**Sea level rise:** +12 m

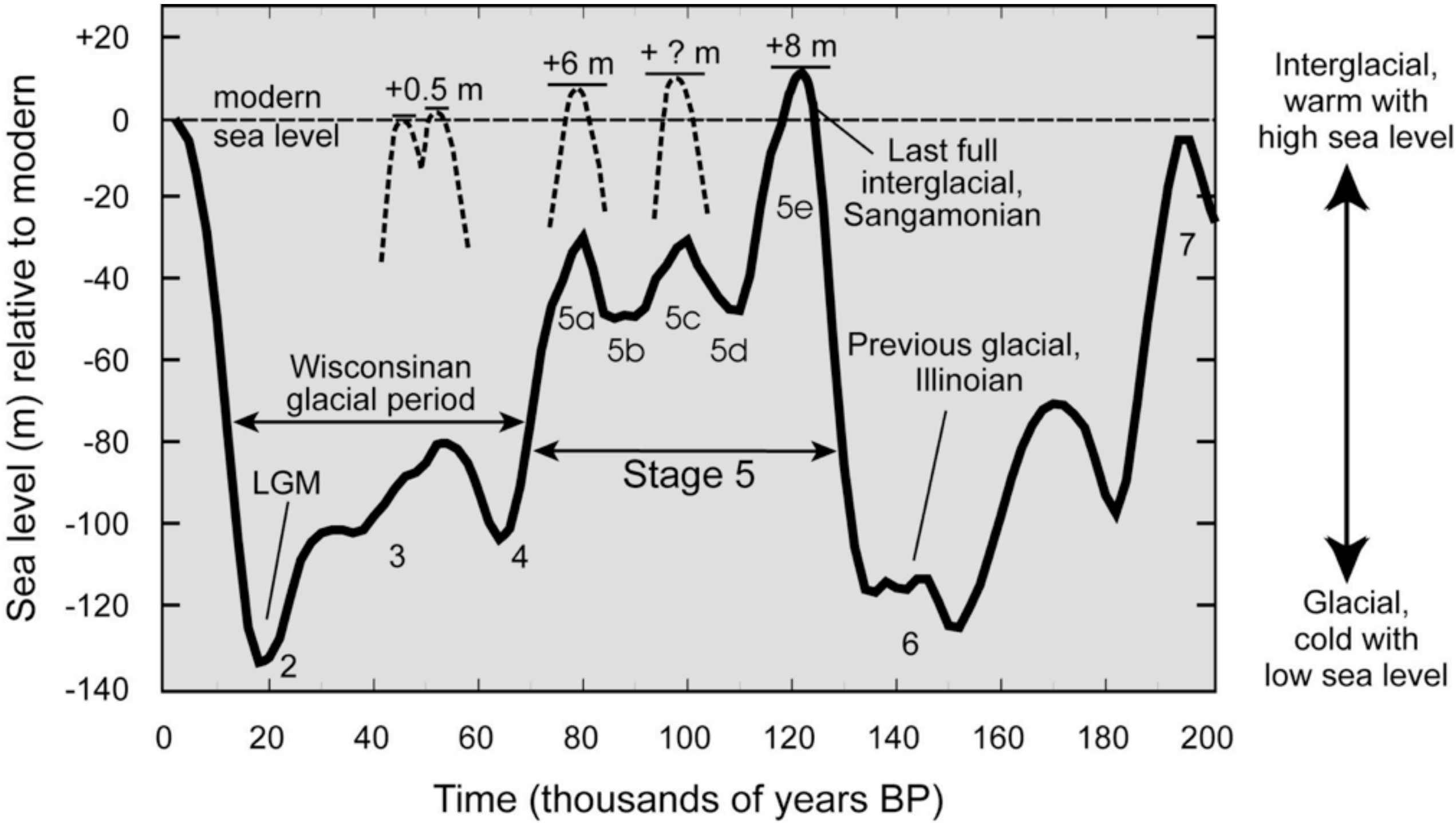
Europe N. America S. America Africa SE. Asia China & Japan Australia






# sea level + 12 m


Total ESL = 127.40 m
ICE5G ESL (m)
200
150
100
50
0
today
~70m
CRE's ?
LGM
$ESL = \frac{\rho_i V}{\rho_w A_o}$
–2
0
2
4
6
8
10
12
14
16
18
20
22
time BP (kyrs)
GMT 2008 Jul 14 13:27:04
SELEN 2.6


+20
0
-20
-40
-60
-80
-100
-120
-140
Sea level (m) relative to modern
modern
sea level
+0.5 m
+6 m
+ ? m
+8 m
Last full
interglacial,
Sangamonian
5e
5a
5b
5c
5d
7
Wisconsinan
glacial period
Previous glacial,
Illinoian
Stage 5
LGM
2
3
4
6
0
20
40
60
80
100
120
140
160
180
200
Time (thousands of years BP)
Interglacial,
warm with
high sea level
Glacial,
cold with
low sea level

# Land ice contribution to sea level

## Recent estimates for 1993-2003

## (mm/yr)

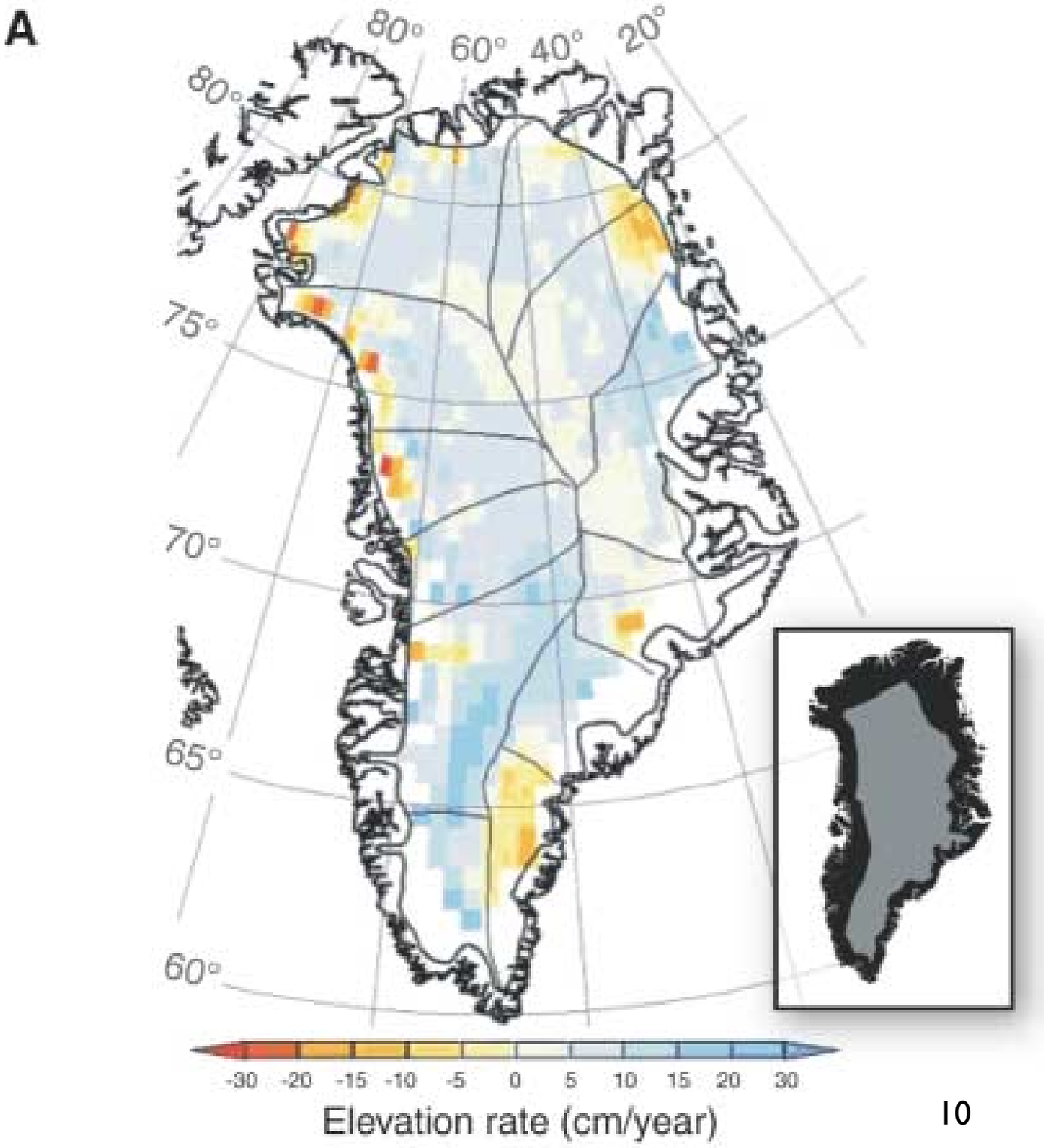
| | Glaciers | Greenland | Antarctica West | Antarctica East |
|---|---|---|---|---|
| Dyugerov&Meier (2005) | 0.8 +/ 0.5 | | | |
| Krabill et al. (2004) | | 0.1-0.2 | | |
| Rignot & Kanagaratnam (2006) | | 0.23-0.57 | | |
| Velicogna &Wahr (2005) | | 0.23 | | |
| Zwally et al. (2005) | | ~0 | | |
| Ramillien et al. (2006) | | 0.35 | | |
| Davis et al. (2005) | | | >0 | - 0.12 |
| Thomas et al. (2004) | | | 0.16 | |
| Zwally et al. (2005) | | | >0 | <0 |
| Velicogna & Wahr (2006) | | | 0.4 | |
| Ramillien et al. (2006) | | | 0.3 | - 0.16 |
| **IPCC's estimate** | **0.8 +/- 0.5** | **0.2 +/- 0.07** | **0.2 +/- 0.35** | |

**(Adapted from a slide of Anny Cazenave et al.)**

# Recent Sea-Level Contributions of the Antarctic and Greenland Ice Sheets

Andrew Shepherd[1] and Duncan Wingham[2]*

Sheperd & Wingham, Science, April 3, 2008



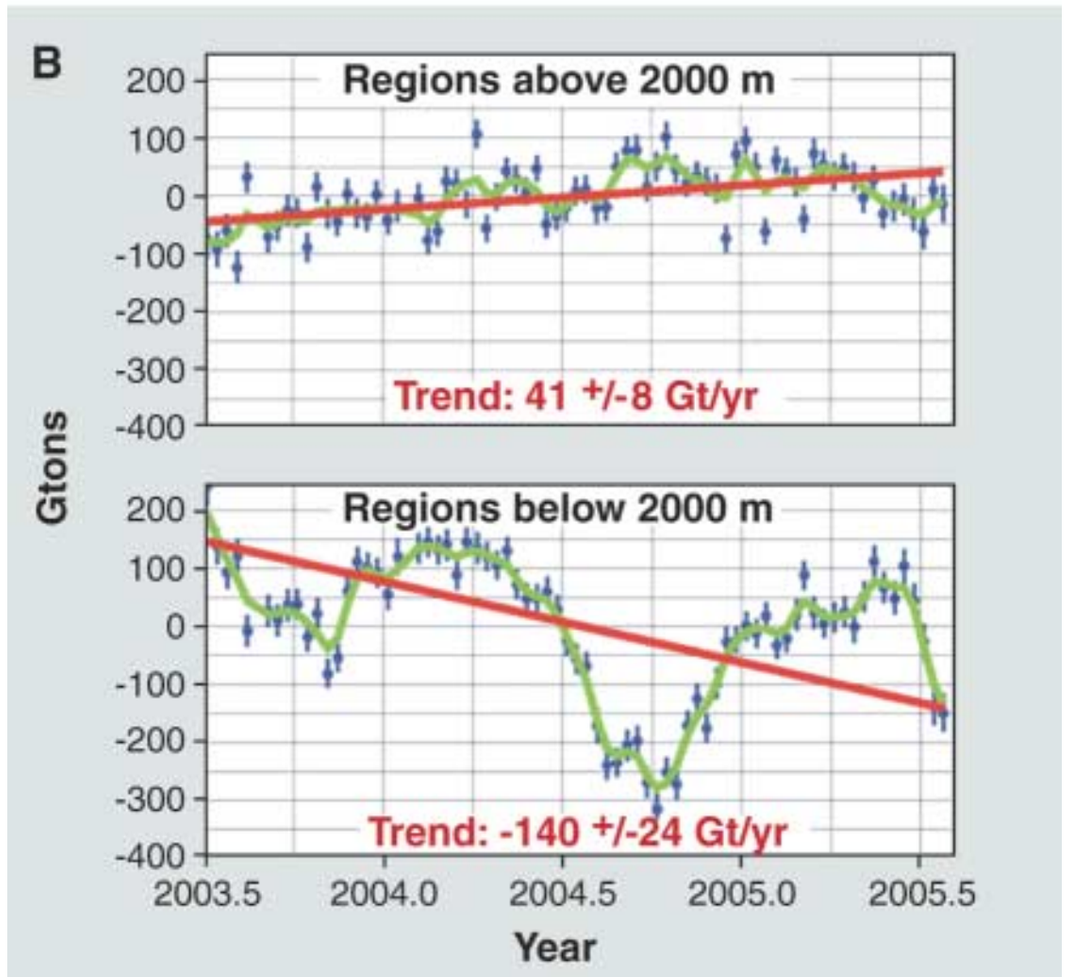
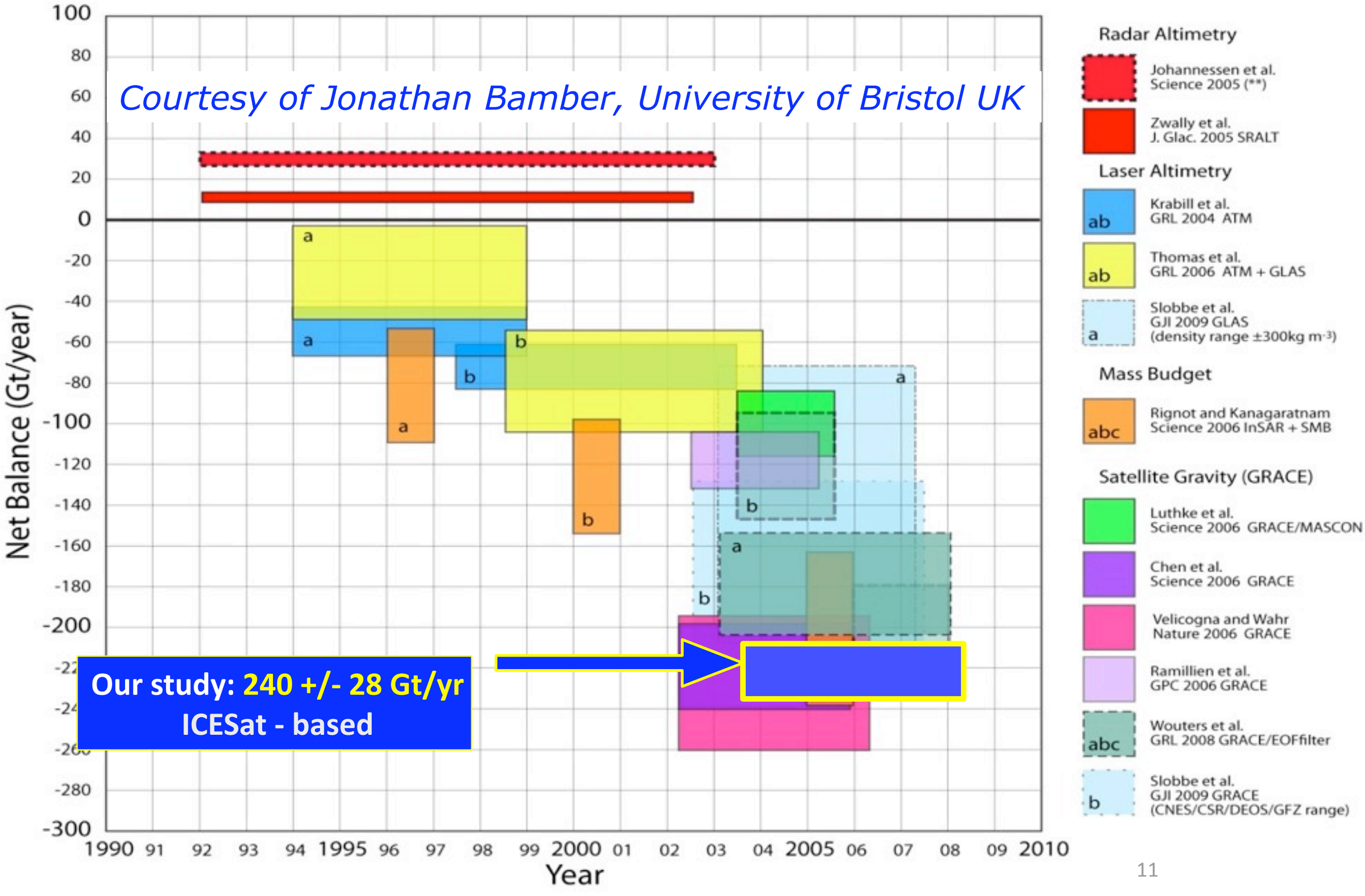




**Fig. 3.** (**A**) Rate of elevation change of the Greenland Ice Sheet, 1992 to 2003, determined from satellite radar altimetry [from (*22*)], and (**B**) time series of elevation change of individual sectors, 2003 to 2005, determined from satellite gravimetry [from (*16*)]. Also shown (inset) is the ice surface geometry, highlighting areas above (gray) and below (black) 2000 m elevation. Both instruments concur that high elevation areas are growing and low elevation areas are losing mass. According to gravimetry (*16*) and repeat InSAR measurements of ice discharge (*12*), the rate of mass loss at low elevations has increased over the past decade (see Table 1).

# Mass balance of Greenland since 1990 - from various sources -

*Courtesy of Jonathan Bamber, University of Bristol UK*



# Mass balance of Greenland since 1990 - from various sources -

*Courtesy of Jonathan Bamber, University of Bristol UK*

Net Balance (Gt/year)

Year

1st IPCC REPORT

2nd

3rd

4th

5th → 2014

**Our study: 240 +/- 28 Gt/yr**
**ICESat - based**

Radar Altimetry
- Johannessen et al. Science 2005 (**)
- Zwally et al. J. Glac. 2005 SRALT

Laser Altimetry
- ab: Krabill et al. GRL 2004 ATM
- ab: Thomas et al. GRL 2006 ATM + GLAS
- a: Slobbe et al. GJI 2009 GLAS (density range ±300kg m$^{-3}$)

Mass Budget
- abc: Rignot and Kanagaratnam Science 2006 InSAR + SMB

Satellite Gravity (GRACE)
- Luthke et al. Science 2006 GRACE/MASCON
- Chen et al. Science 2006 GRACE
- Velicogna and Wahr Nature 2006 GRACE
- Ramillien et al. GPC 2006 GRACE
- abc: Wouters et al. GRL 2008 GRACE/EOFfilter
- b: Slobbe et al. GJI 2009 GRACE (CNES/CSR/DEOS/GFZ range)

The Cryosphere Discuss., 4, 2103–2141, 2010
www.the-cryosphere-discuss.net/4/2103/2010/
doi:10.5194/tcd-4-2103-2010
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The Cryosphere Discussions

Goal: estimating the time-averaged mass variation over 2003-2008 (including density modeling...)

# Mass balance of the Greenland ice sheet – a study of ICESat data, surface density and firn compaction modelling

**L. S. Sørensen[1,2,*], S. B. Simonsen[3,4,*], K. Nielsen[5], P. Lucas-Picher[4], G. Spada[6], G. Adalgeirsdottir[4], R. Forsberg[1], and C. S. Hvidberg[3]**

[1]Geodynamics Department, DTU Space, Juliane Maries vej 30, 2100 Copenhagen, Denmark
[2]Planet and Geophysics, NBI, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark
[3]Centre for Ice and Climate, NBI, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark
[4]Danish Climate Centre, DMI, Lyngbyvej 100, 2100 Copenhagen, Denmark
[5]Geodesy Department, DTU Space, Juliane Maries vej 30, 2100 Copenhagen, Denmark







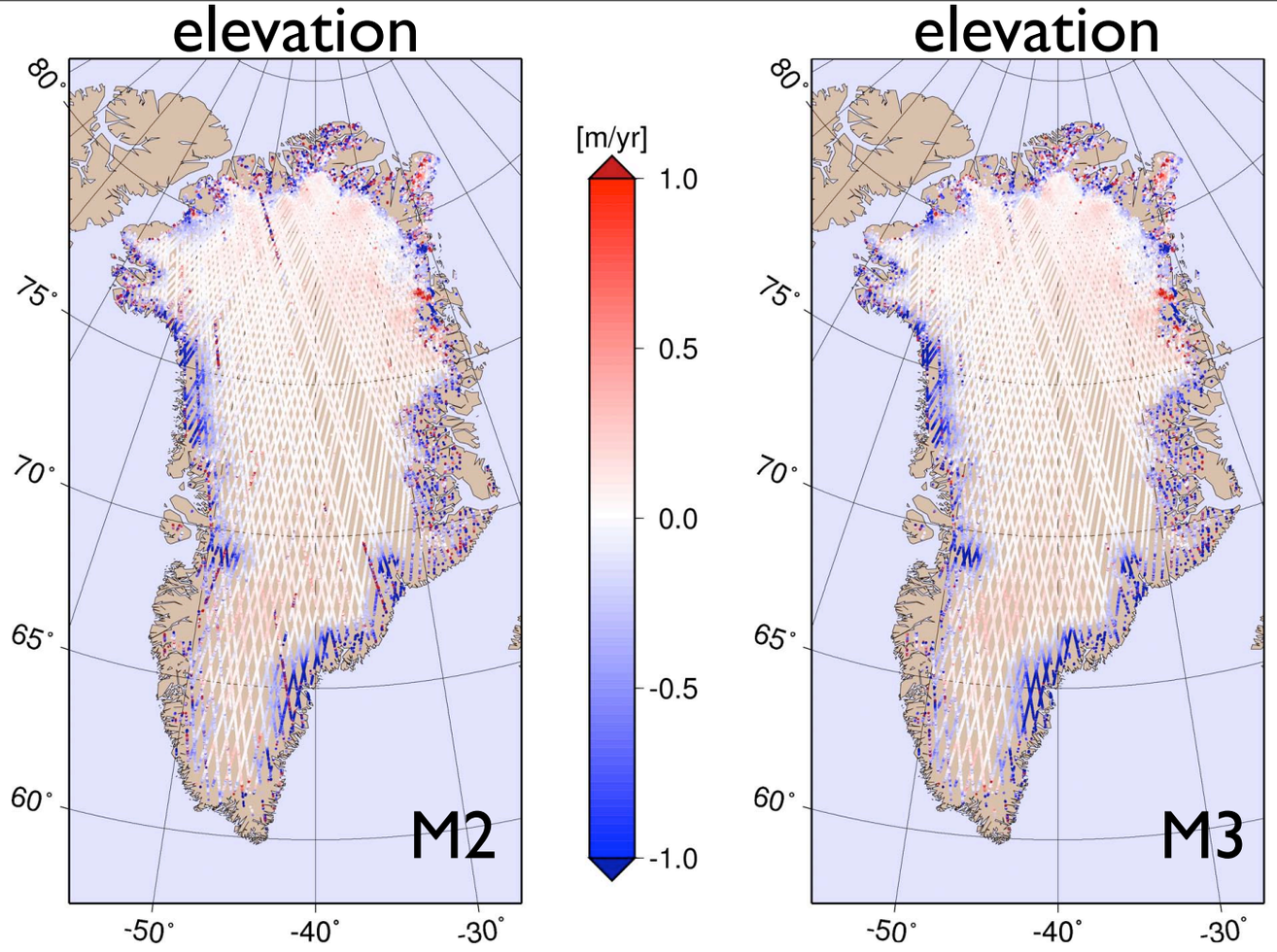



**Table 1.** ICESat data description. Shown is the laser campaign identifier (ID), data release number (RL), and time span of the campaigns. *N* and *M* are the number of measurements from the GrIS before and after the data culling, respectively.

| ID | RL | Time span | *N* | *M* |
|---|---|---|---|---|
| L2A | 531 | 4 Oct 2003–18 Nov 2003 | 1 095 647 | 941 052 |
| L2B | 531 | 17 Feb 2004–20 Mar 2004 | 815 998 | 695 242 |
| L2C | 531 | 18 May 2004–20 Jun 2004 | 739 672 | 680 031 |
| L3A | 531 | 3 Oct 2004–8 Nov 2004 | 851 789 | 727 425 |
| L3B | 531 | 17 Feb 2005–24 Mar 2005 | 829 689 | 704 680 |
| L3C | 531 | 20 May 2005–22 Jun 2005 | 800 876 | 679 827 |
| L3D | 531 | 21 Oct 2005–23 Nov 2005 | 821 825 | 695 949 |
| L3E | 531 | 22 Feb 2006–27 Mar 2006 | 883 492 | 752 123 |
| L3F | 531 | 24 May 2006–25 Jun 2006 | 743 702 | 626 463 |
| L3G | 531 | 25 Oct 2006–27 Nov 2006 | 809 655 | 698 710 |
| L3H | 531 | 12 Mar 2007–14 Apr 2007 | 838 647 | 778 350 |
| L3I | 531 | 2 Oct 2007–4 Nov 2007 | 761 576 | 705 639 |
| L3J | 531 | 17 Feb 2008–21 Mar 2008 | 375 239 | 368 148 |
| Total | | | 10 367 807 | 9 053 639 |

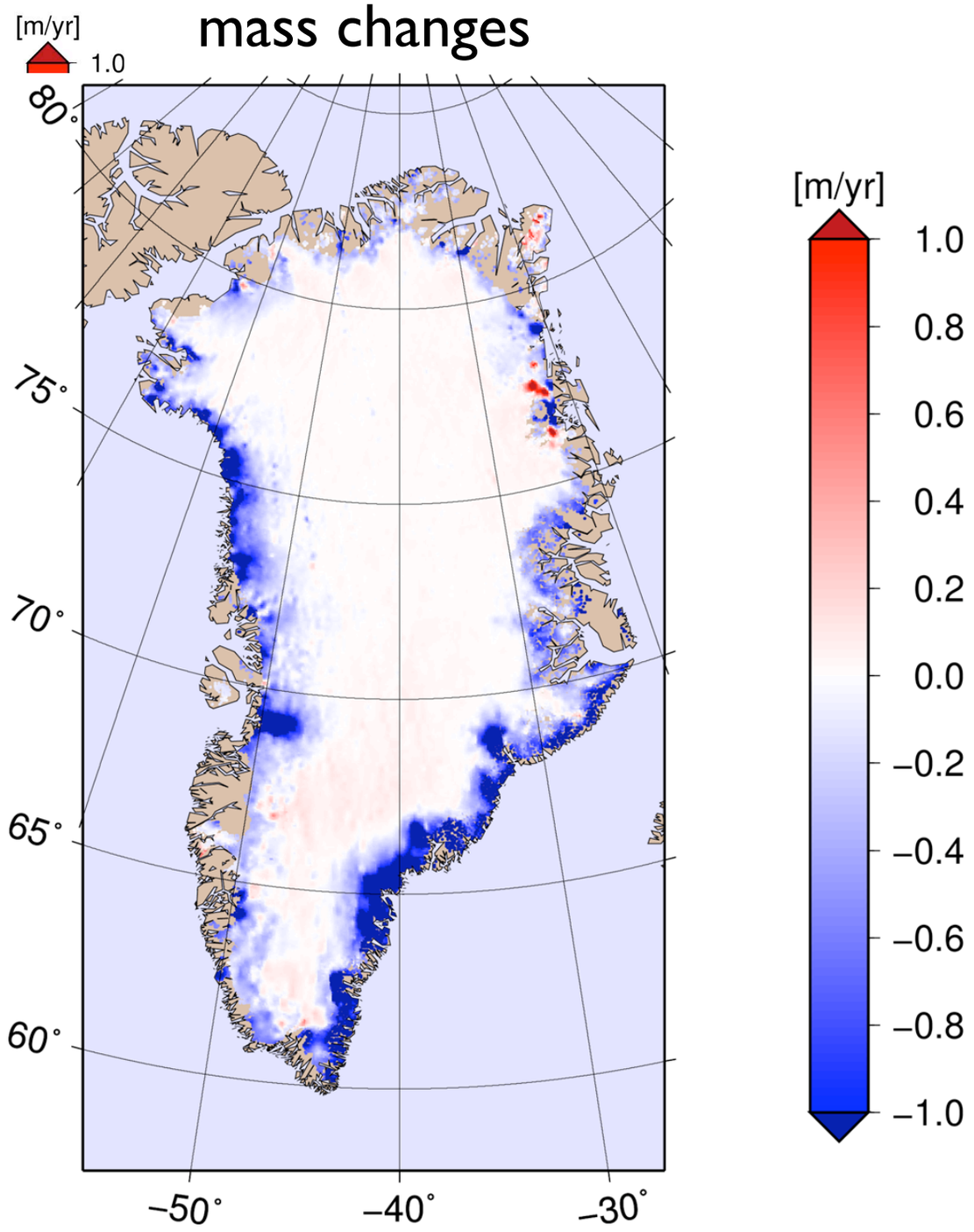
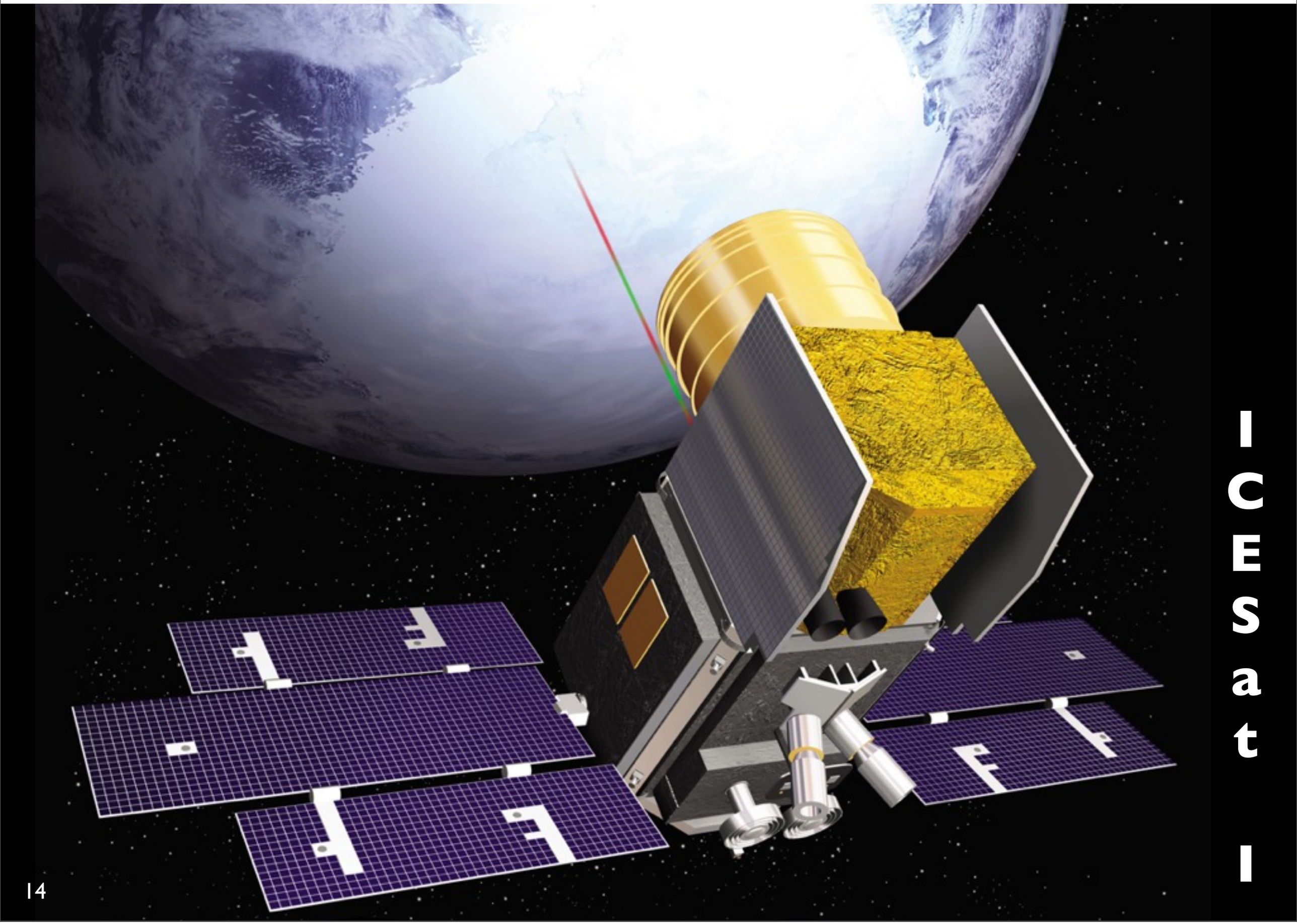


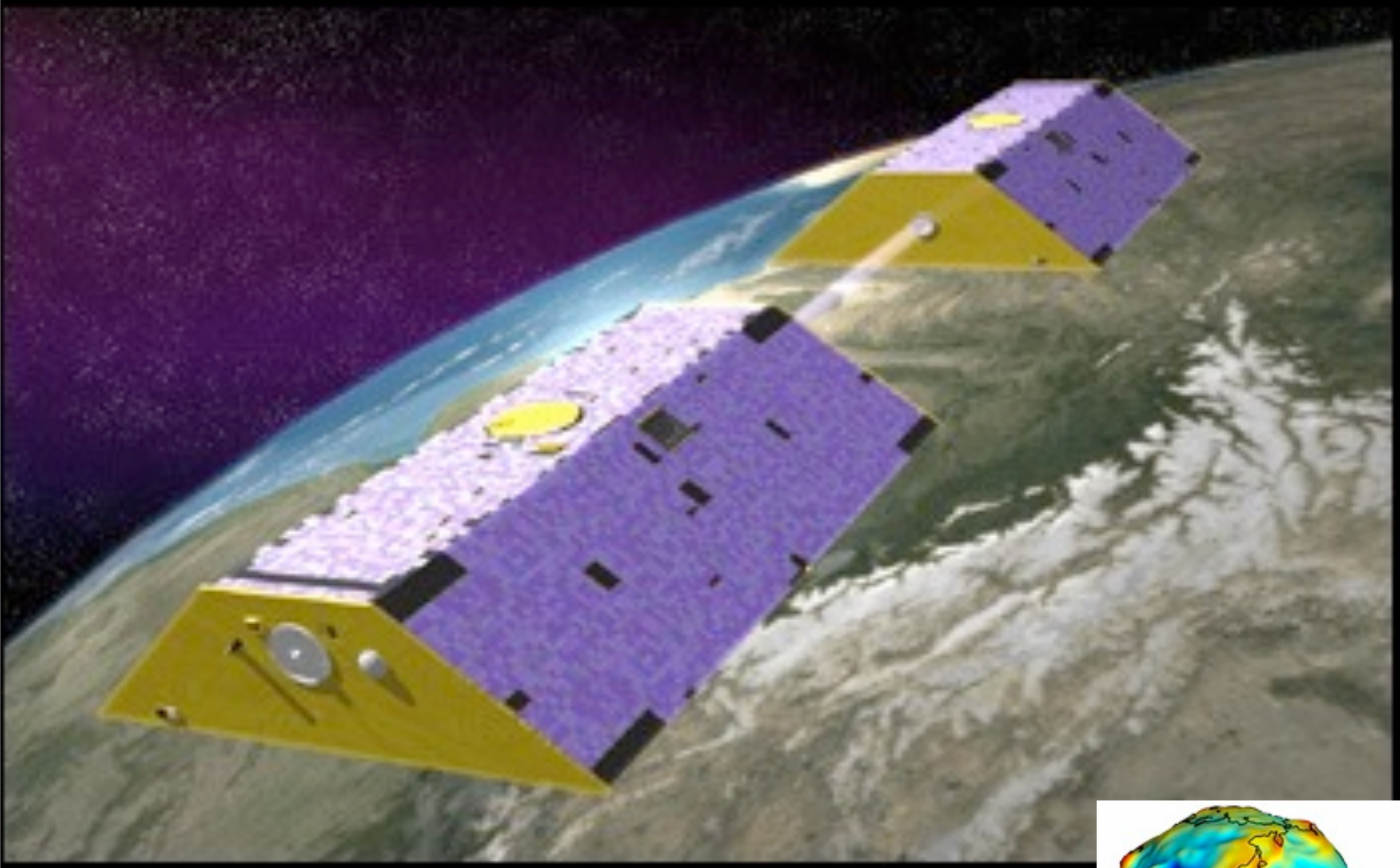

**Fig. 6.** The spatial distribution of the mass change of the GrIS, given in metres of ice equivalent. The result is based on the estimate derived by M3. The pattern of coastal thinning seen in Fig. 1 is also found in the mass change of the GrIS.

http://www.nasa.gov/centers/goddard/images/content/94740main_icesat_hires.jpg



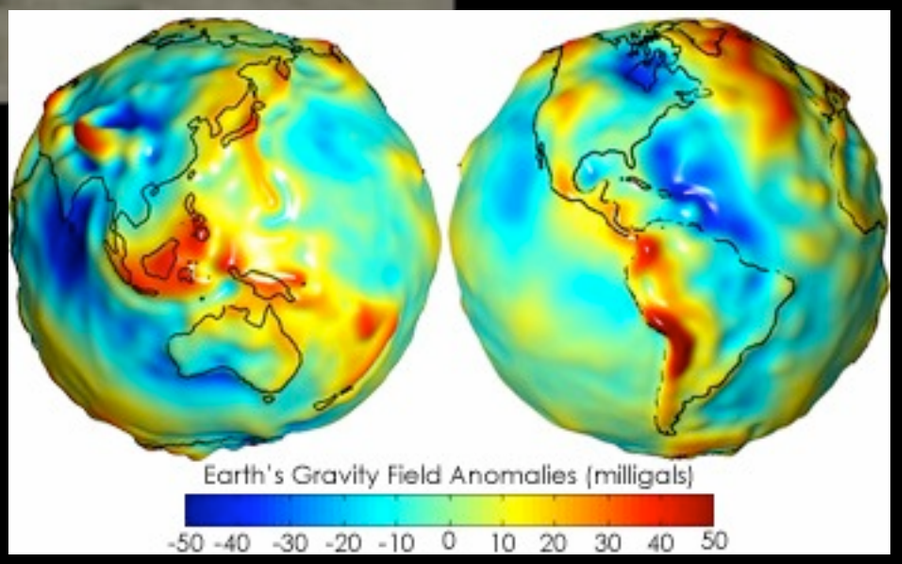
ICESat I

## Gravity anomaly map from the NASA GRACE (Gravity Recovery And Climate Change).



# GRACE

http://earthobservatory.nasa.gov/Features/GRACE/



# Program: Lageos

*LAser GEOdynamic Satellite*

**Series of satellites designed to provide an orbiting benchmark for geodynamical studies of the Earth.**

**Mission:**

***1) accurate measurement of satellite's position with respect to Earth;***

***2) determination of the planet's shape (geoid) and***

***3) determination of tectonic plate movements associated with continental drift.***



**1) The LAGEOS satellites are passive vehicles covered with retroreflectors designed to reflect laser beams transmitted from ground stations. By measuring the time between transmission of the beam and reception of the reflected signal from the satellite, stations can precisely measure the distance between themselves and the satellite. These distances can be used to calculate station positions to within 1-3 cm.**

**2) Long term data sets can be used to monitor the motion of the Earth's tectonic plates, measure the Earth's gravitational field, measure the "wobble" in the Earth's axis of rotation, and better detemine the length of an Earth day.**

**3) Ground tracking stations are located in many countries (including the US, Mexico, France, Germany, Poland, Australia, Egypt, China, Peru, Italy, and Japan) and data from these stations is available worldwide to investigators studying crustal dynamics.**

**4) LAGEOS 1 also contains a message plaque addressed to human and other beings of the far distant future with maps of the Earth from 3 different eras - 268 million years in the past, present day, and 8 million years in the future (the satellite's estimated decay date).**

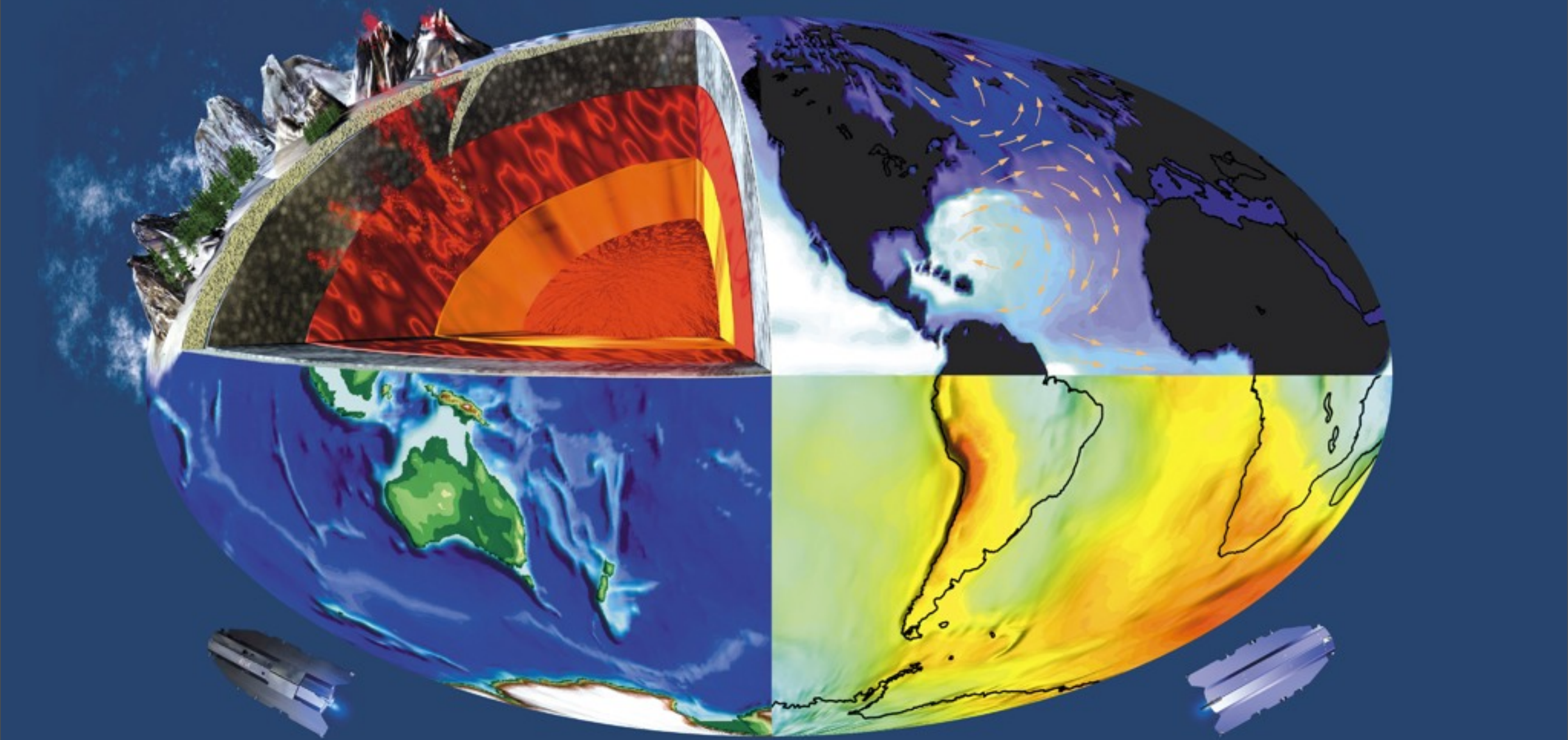
http://msl.jpl.nasa.gov/QuickLooks/lageosQL.html

# GOCE



# GOCE

Mapping the gravity field to advance research in *Earth-interior processes*, *oceanography* and *geodesy*.

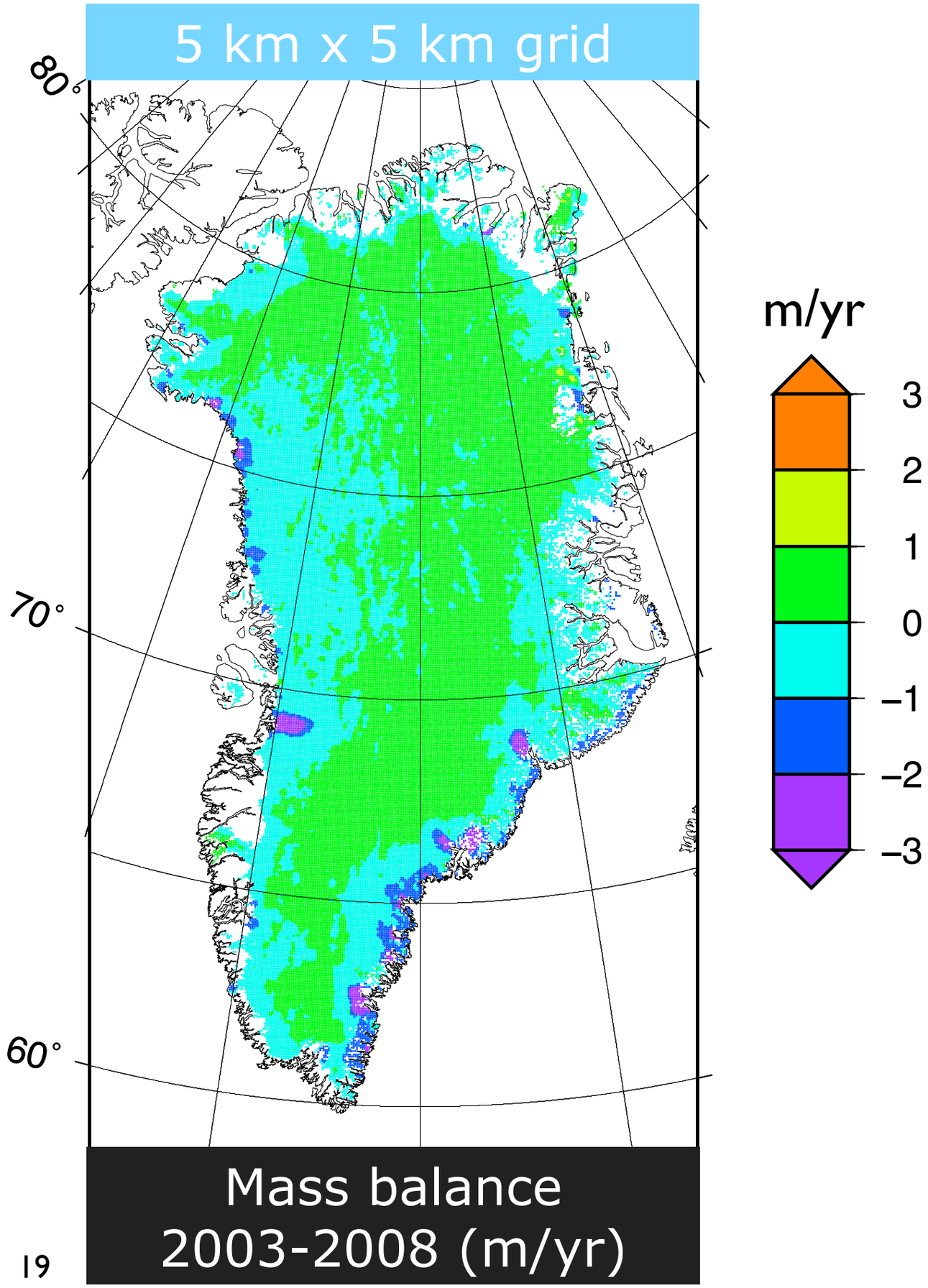


## *Two* targets:

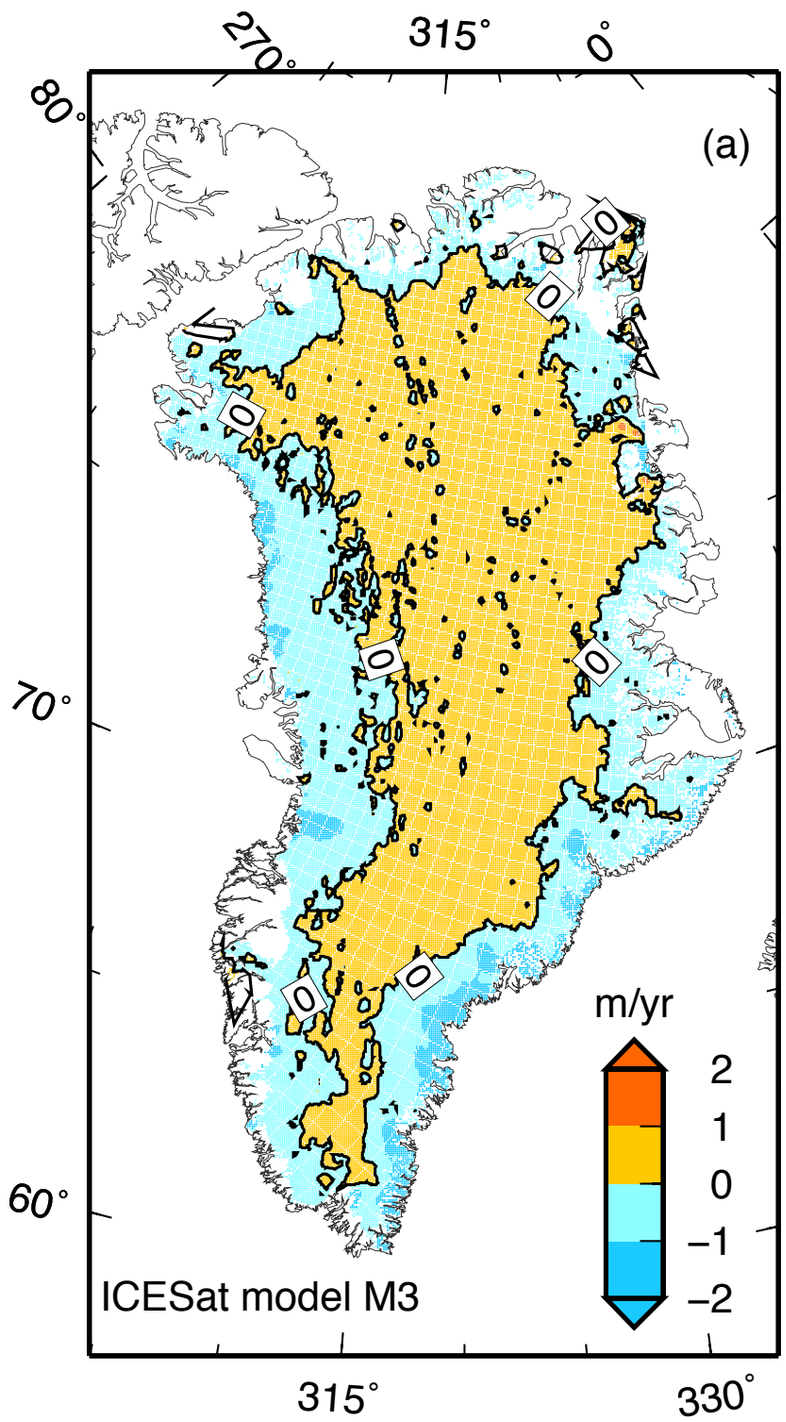
*-1-* Updating the mass balance of the **GrIS** by ICESat data elaboration and firn compaction modeling, *...done by DTU*

*-2-* Given the "preferred" mass balance (right), the problem is providing estimates for the present-day vertical movements along the coasts of Greenland. Implications for the i) *regional future sea level rise* and ii) *geodetic observations* -

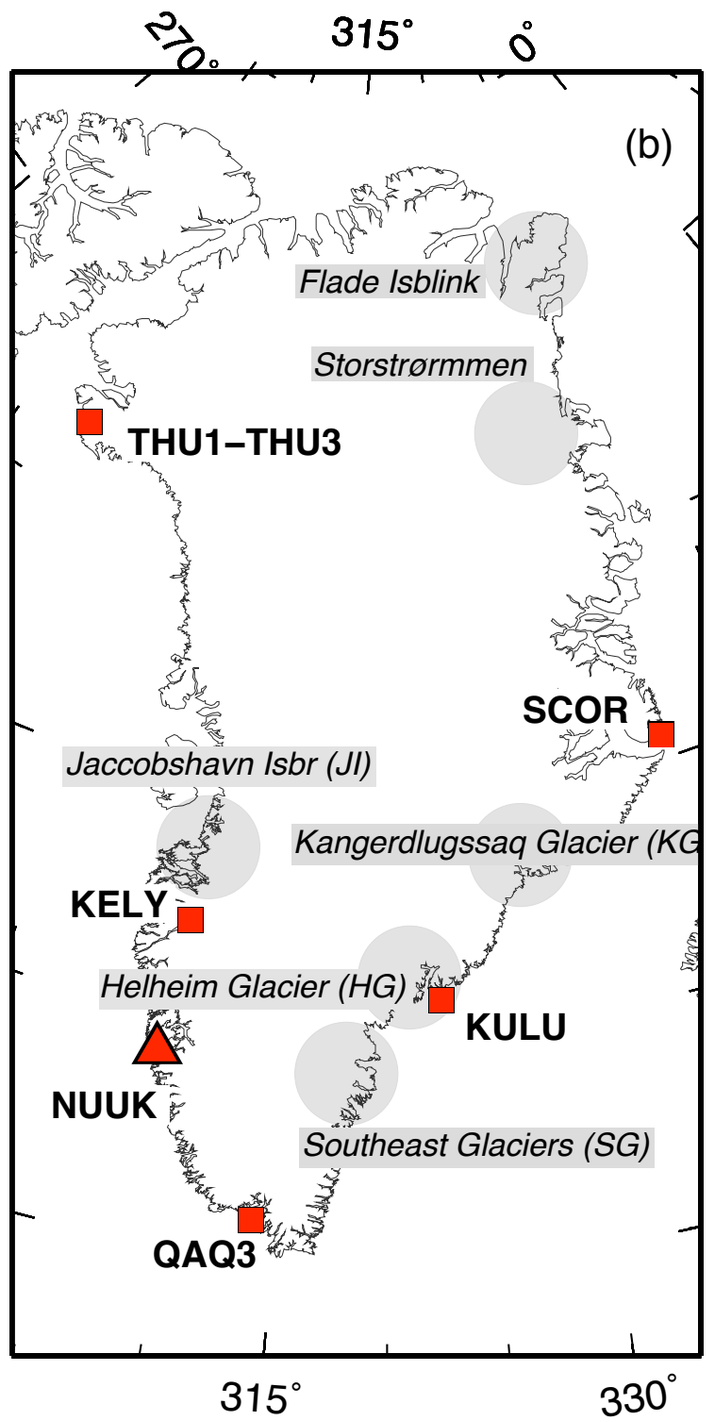
*(our role - work in progress...)*



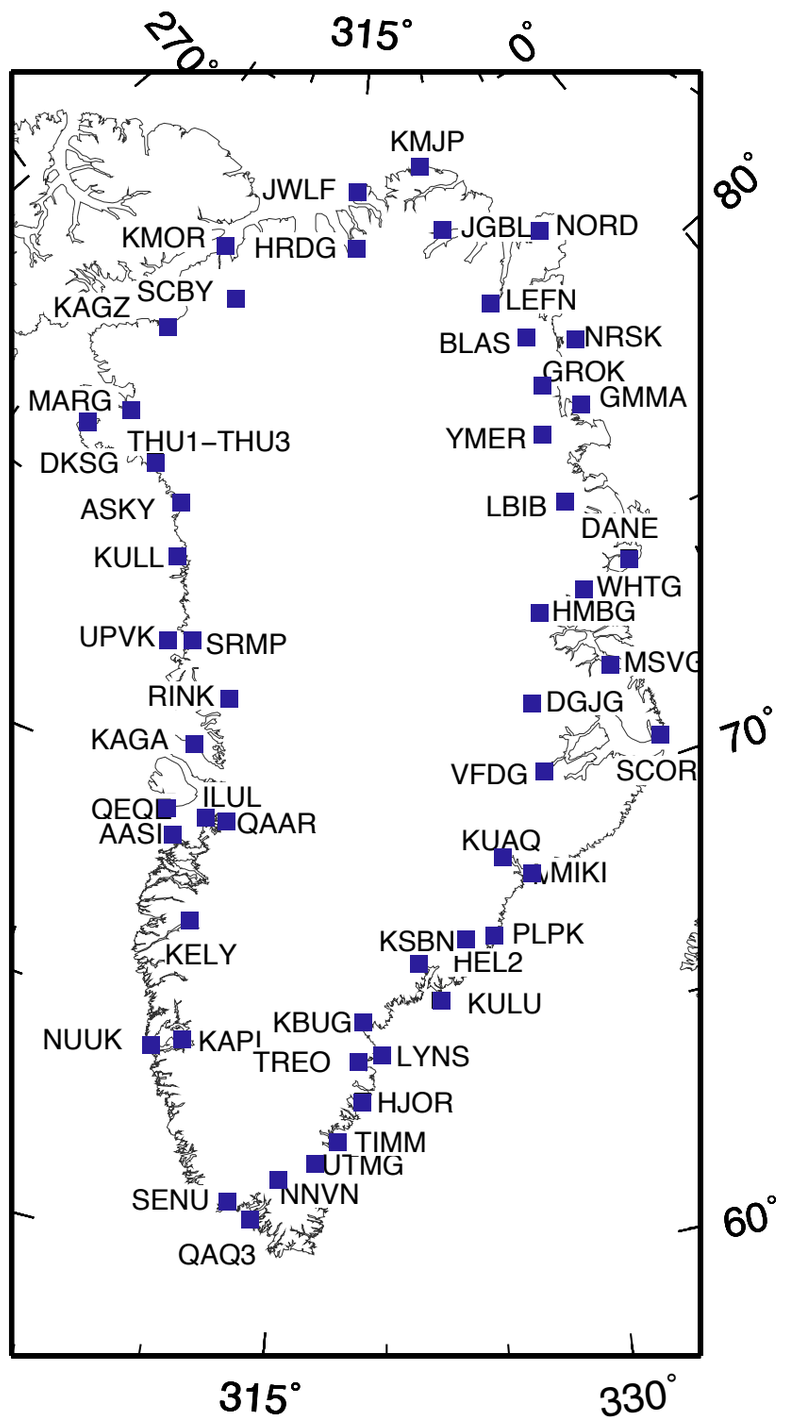
## Mass balance (m/yr)




## Main glaciers




## GPS sites (from UNAVCO)



Two different points of view:

*1) Solving the SLE globally:*

*Advantage*: this provides a self-consistent sea level variation and vertical movements.
BUT the *disadvantage is*: only the long-intermediate wavelengths of deformation can be captured (*because of our limited computing power! --- but we are making some progress*)

*2) Building a regional "elastic rebound" model for Greenland:*

Advantage: all the information derived by the inversion of ICEsat data can be employed.
*Main disadvantage*: some physical ingredients are lost: effects from melt-water load, "self-gravitation" of the oceans, etc.

In both cases: Maxwell time of the mantle is ~ 300 years:
an ELASTIC rheology is appropriate!

## *Overview:*

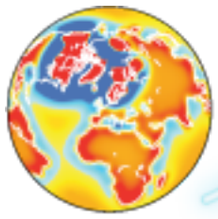
- A few words on the "sea level rise" problem,

- Contribution of *Greenland* to past and present sea level variations,

- Modeling the effects of melting of Greenland : the *global* view point

- ... and the *regional* view point

- Discussion, problems, directions, ETC...



# SELEN 3.0

SELEN solves the "Sea Level Equation" [Farrell, 1976]:

$$S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} \overline{G_s \otimes_i I} - \frac{\rho_w}{\gamma} \overline{G_s \otimes_o S}$$

*with:*

$S =$ sea level change

$\rho_i, \rho_w =$ ice and water density

$G_s =$ sea level Green function

$I =$ ice thickness variation

$m_i =$ ice mass variation

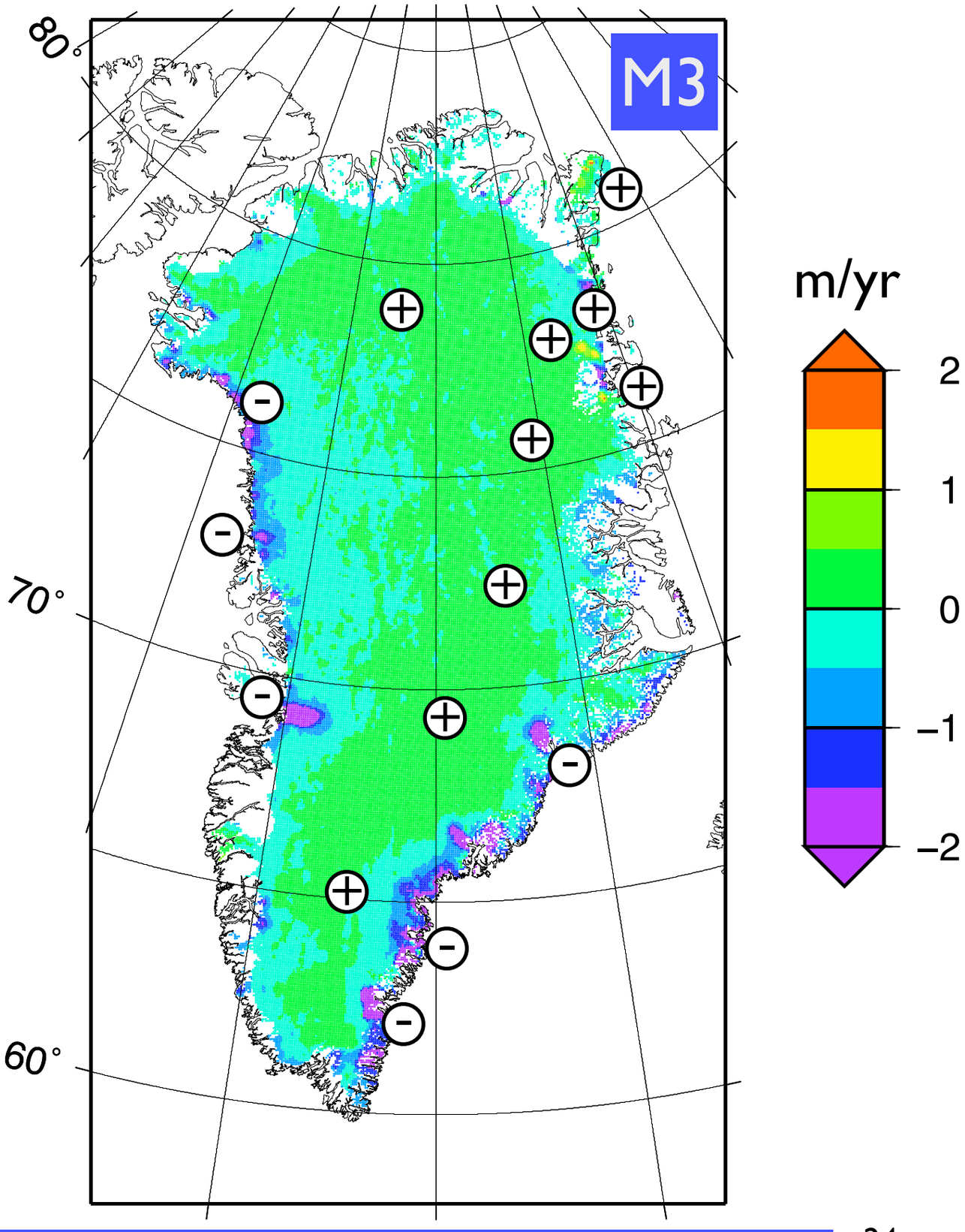
$A_o =$ area of the oceans

$\otimes_i, \otimes_o =$ 3(2+1)D convolutions

$\overline{(\ldots)} =$ ocean average

$$\left\{ \begin{array}{c} U_i \\ \Phi_i \end{array} \right\} (\omega, t) \equiv \left\{ \begin{array}{c} G_u \\ G_\phi \end{array} \right\} \otimes_i \rho_i I, \quad \text{and} \quad \left\{ \begin{array}{c} U_o \\ \Phi_o \end{array} \right\} (\omega, t) \equiv \left\{ \begin{array}{c} G_u \\ G_\phi \end{array} \right\} \otimes_o \rho_w S$$

# SLE input: Mass balance from ICEsat (M3): 240 +/- 28 Gt/yr







Outline map of Greenland with ice sheet depths. GISP refers to a main site of the Greenland Ice Sheet Project, where a 3 km deep ice core was taken.

http://en.wikipedia.org/wiki/Greenland_ice_sheet

Preferred mass balance of Sorensen *et al.* (2011)

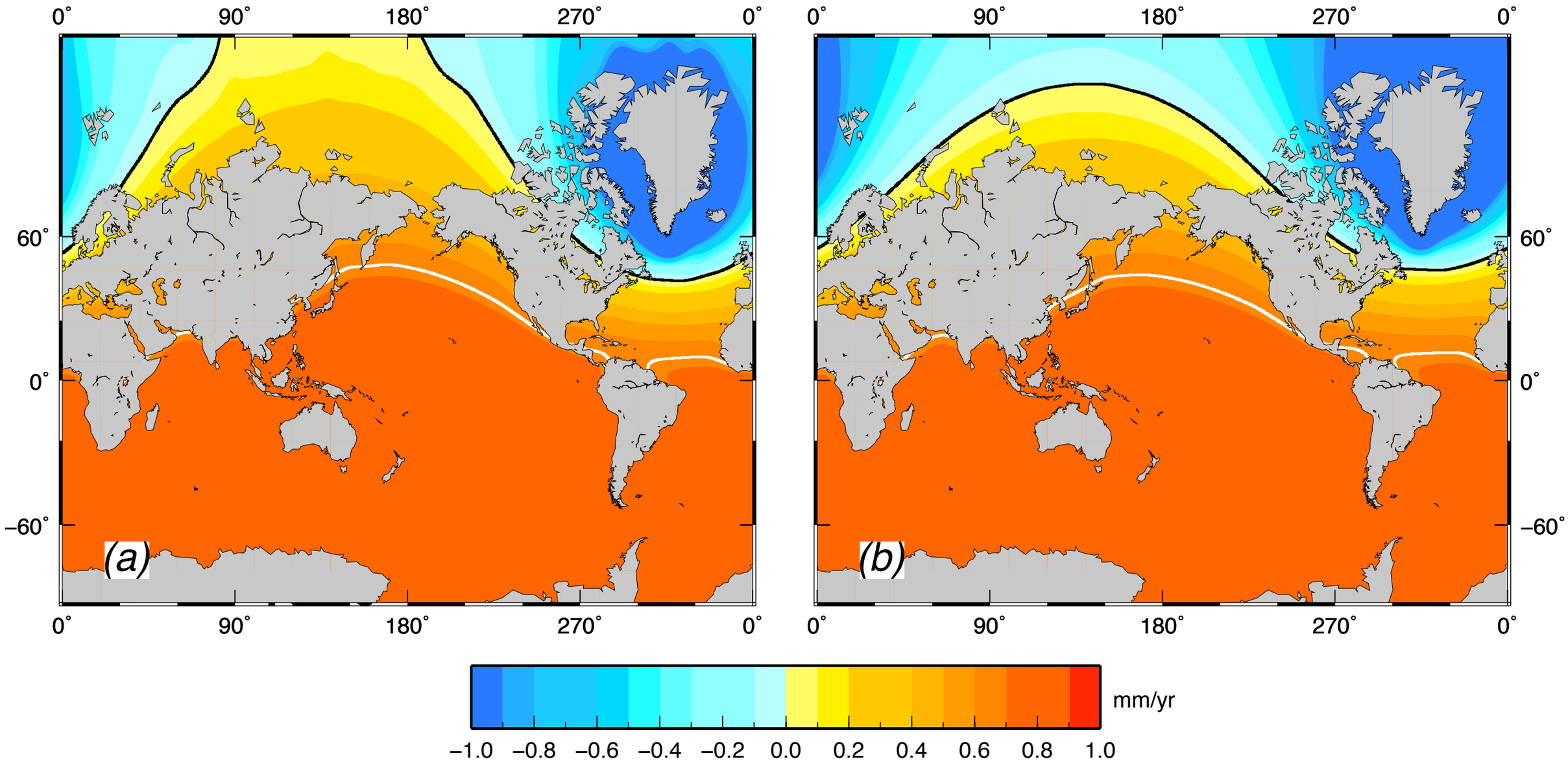
24

**global sea level rise of 7.2 m**

# SLE input: Mass balance from ICEsat (M3): 240 +/- 28 Gt/yr

## Actual M3 mass balance

## Uniform thickness

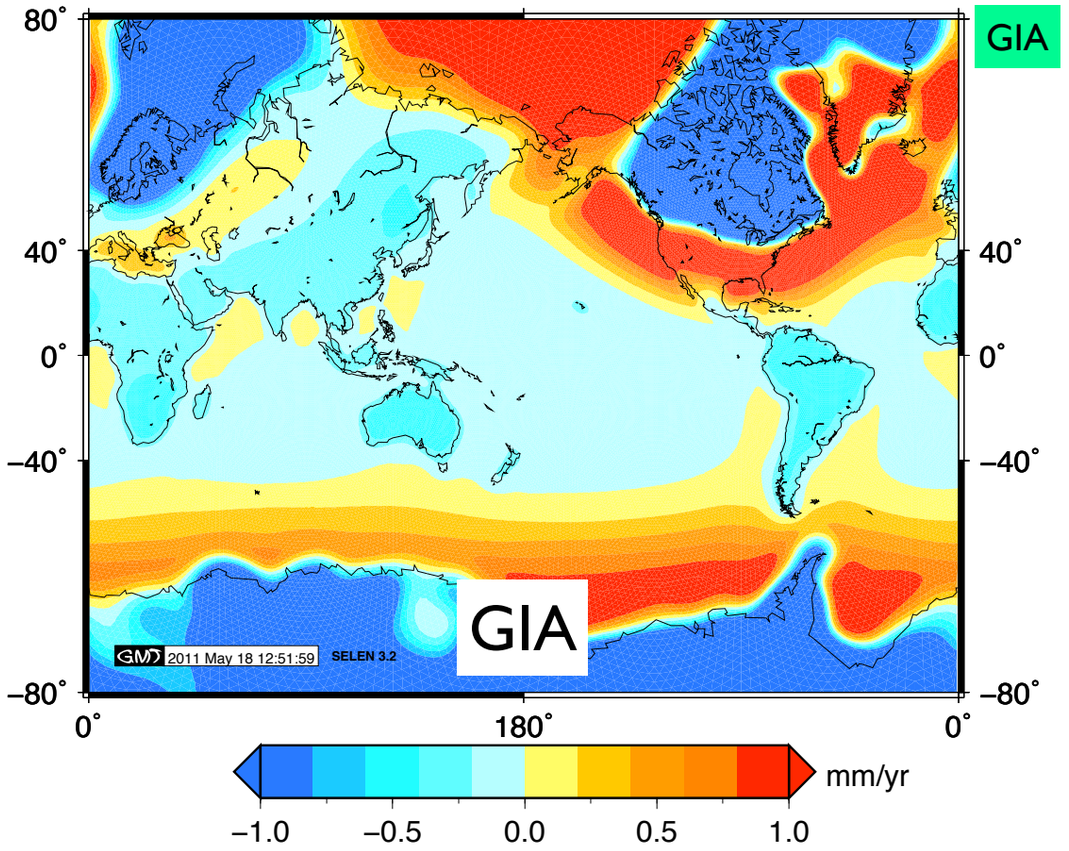



...- sea level falls
"close to Greenland"

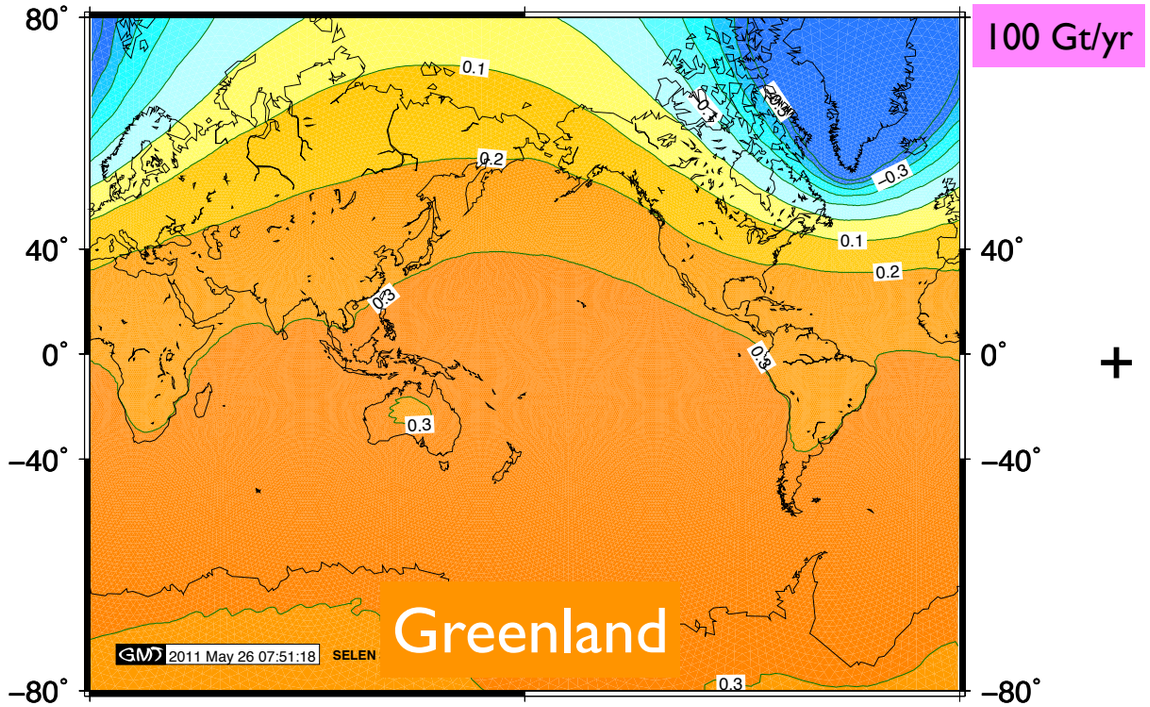
ESL = +0.67 mm/yr
(*average* sea level rise)

- sea level rises
"far away"

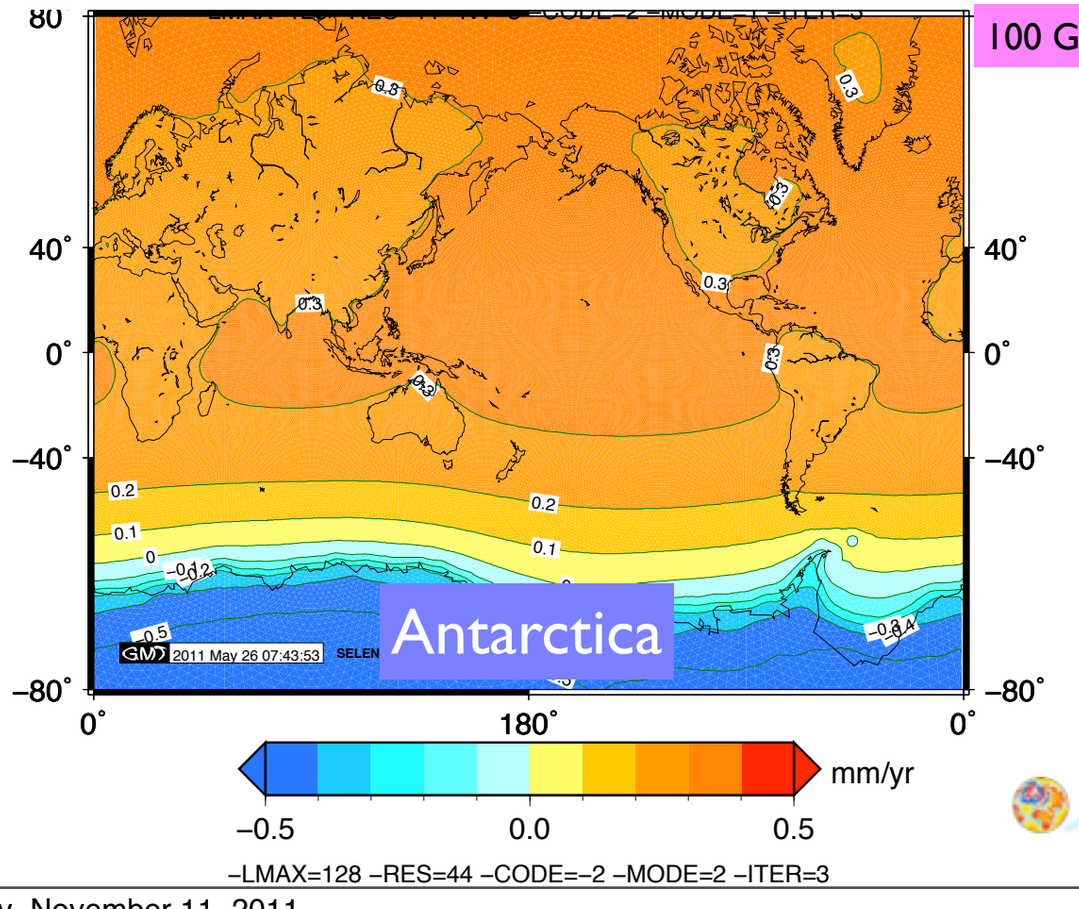
# GIA, Greenland, Antarctica, & Glaciers fingerprints



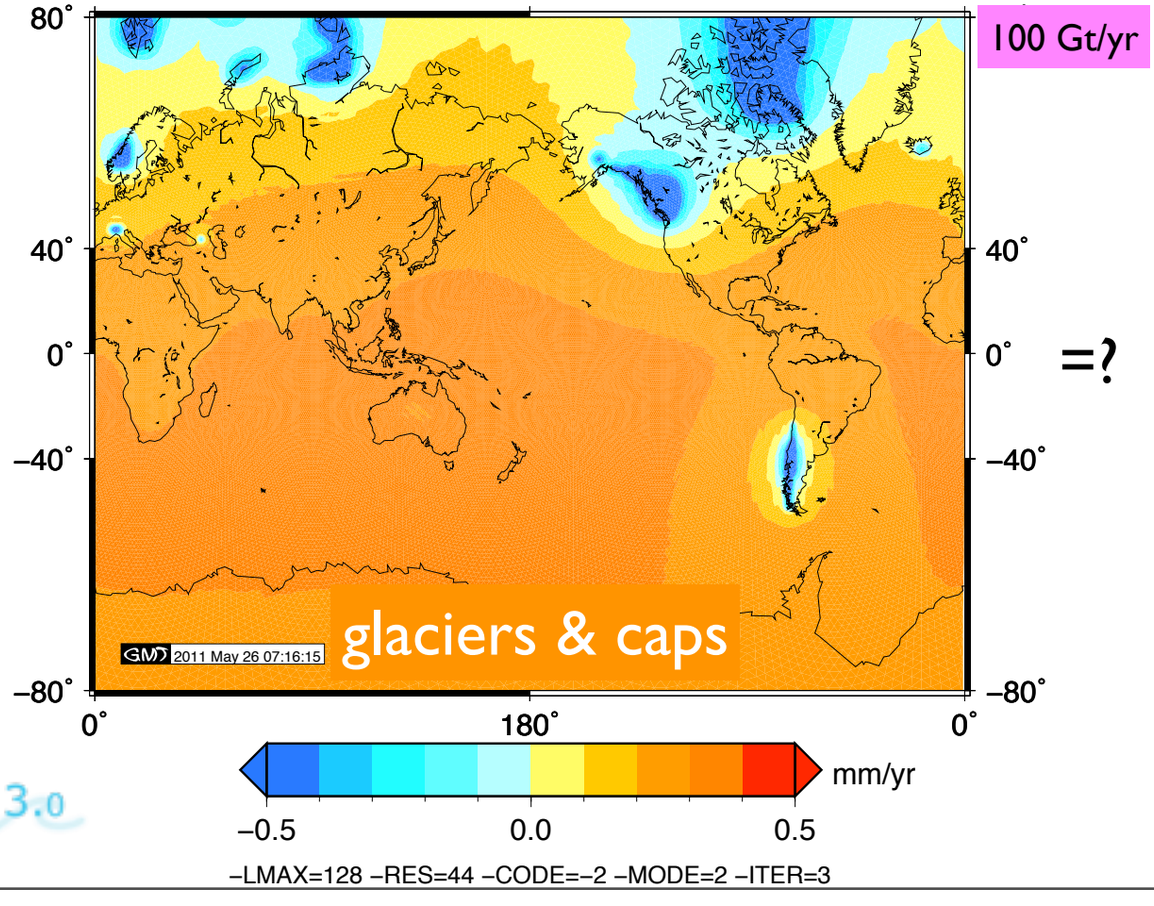

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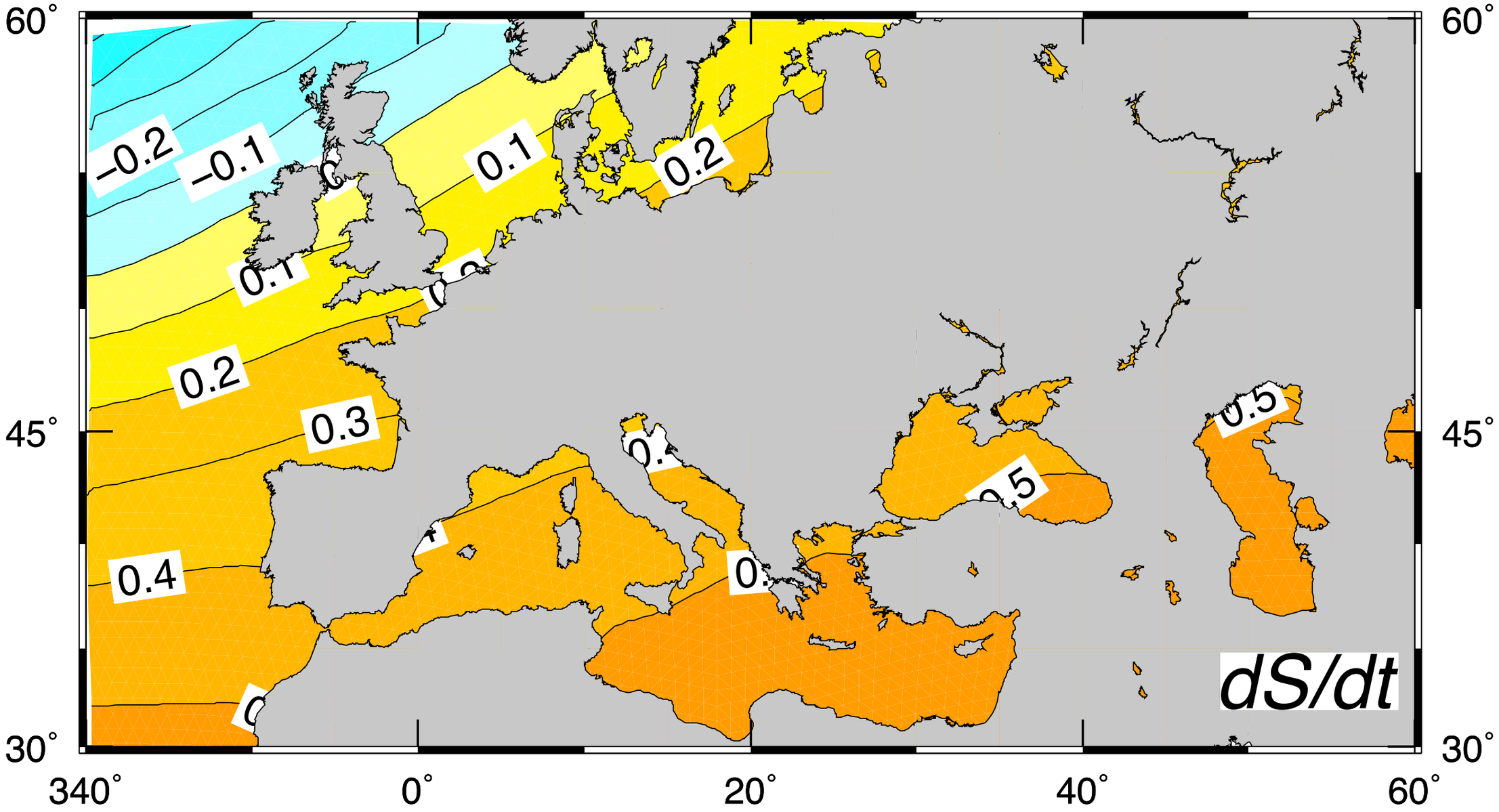

=?

SELEN 3.0

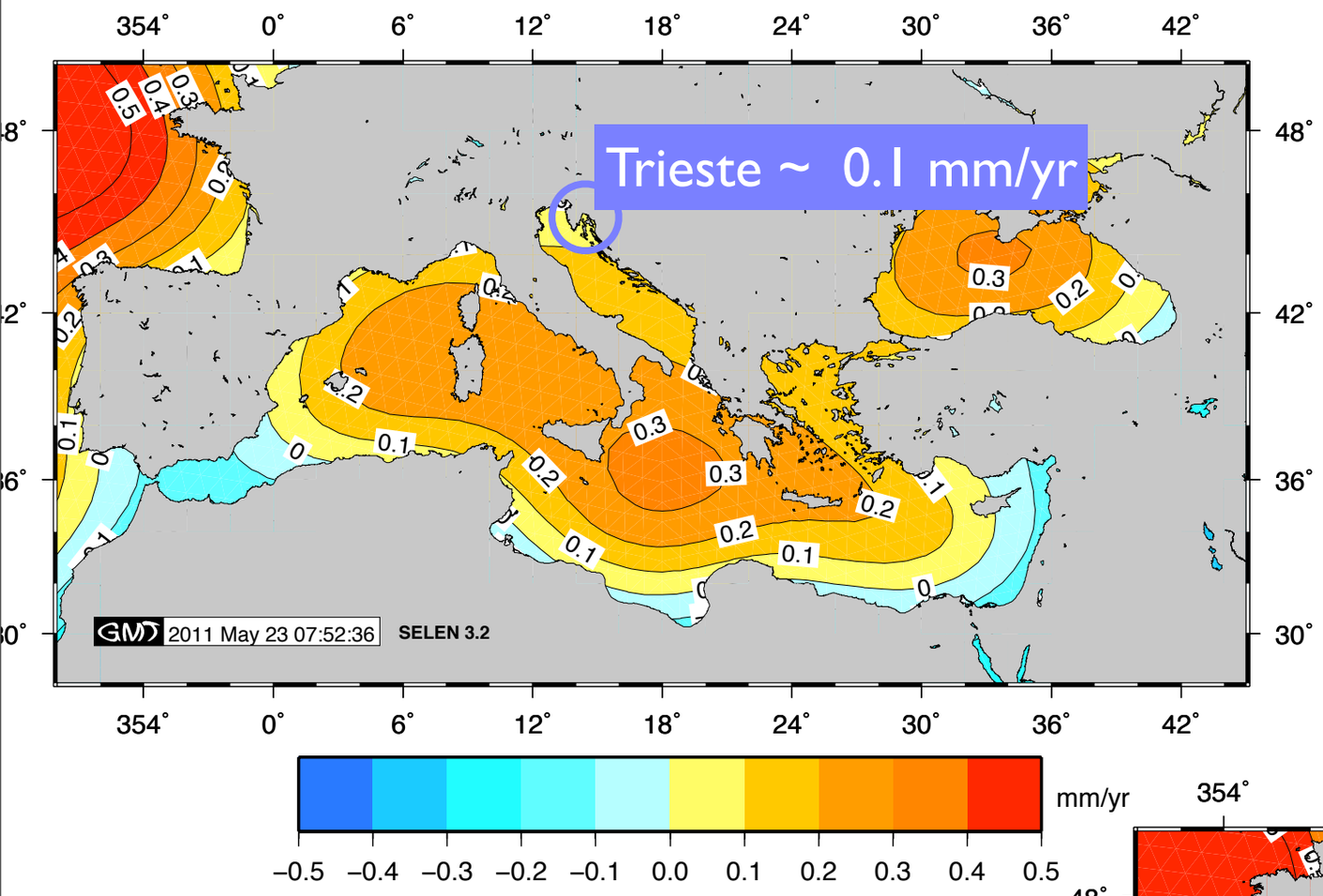
−LMAX=128 −RES=44 −CODE=−2 −MODE=2 −ITER=3

−LMAX=128 −RES=44 −CODE=−2 −MODE=2 −ITER=3

# SLE input: Mass balance from ICEsat (M3): 240 +/- 28 Gt/yr



# GIA sealevel fingerprints for the Mediterranean Sea (ICE-5G vs RSES)




## ICE-5G

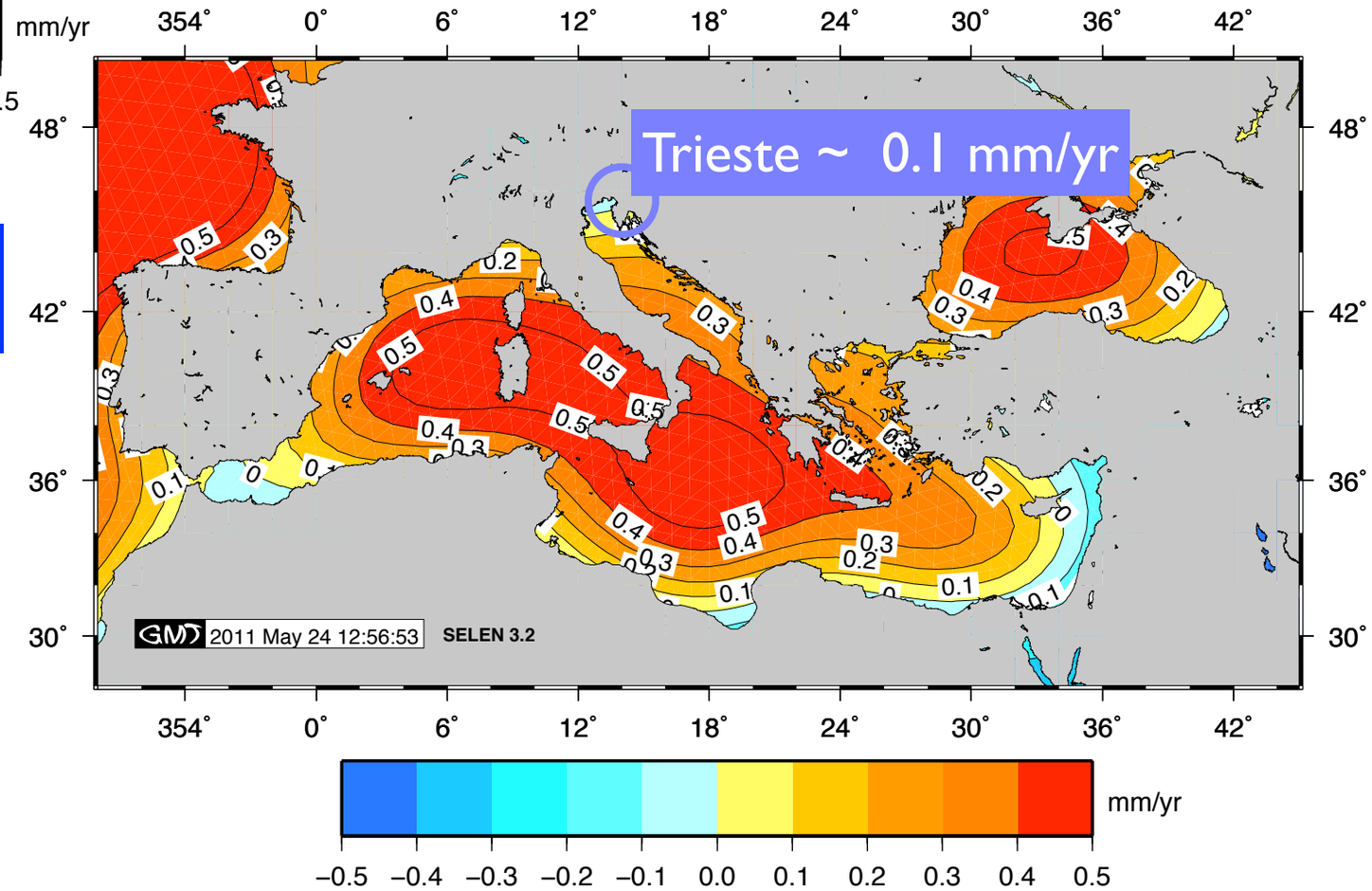
Close to equilibrium
*("low viscosity")*

~ 0.3 mm/yr

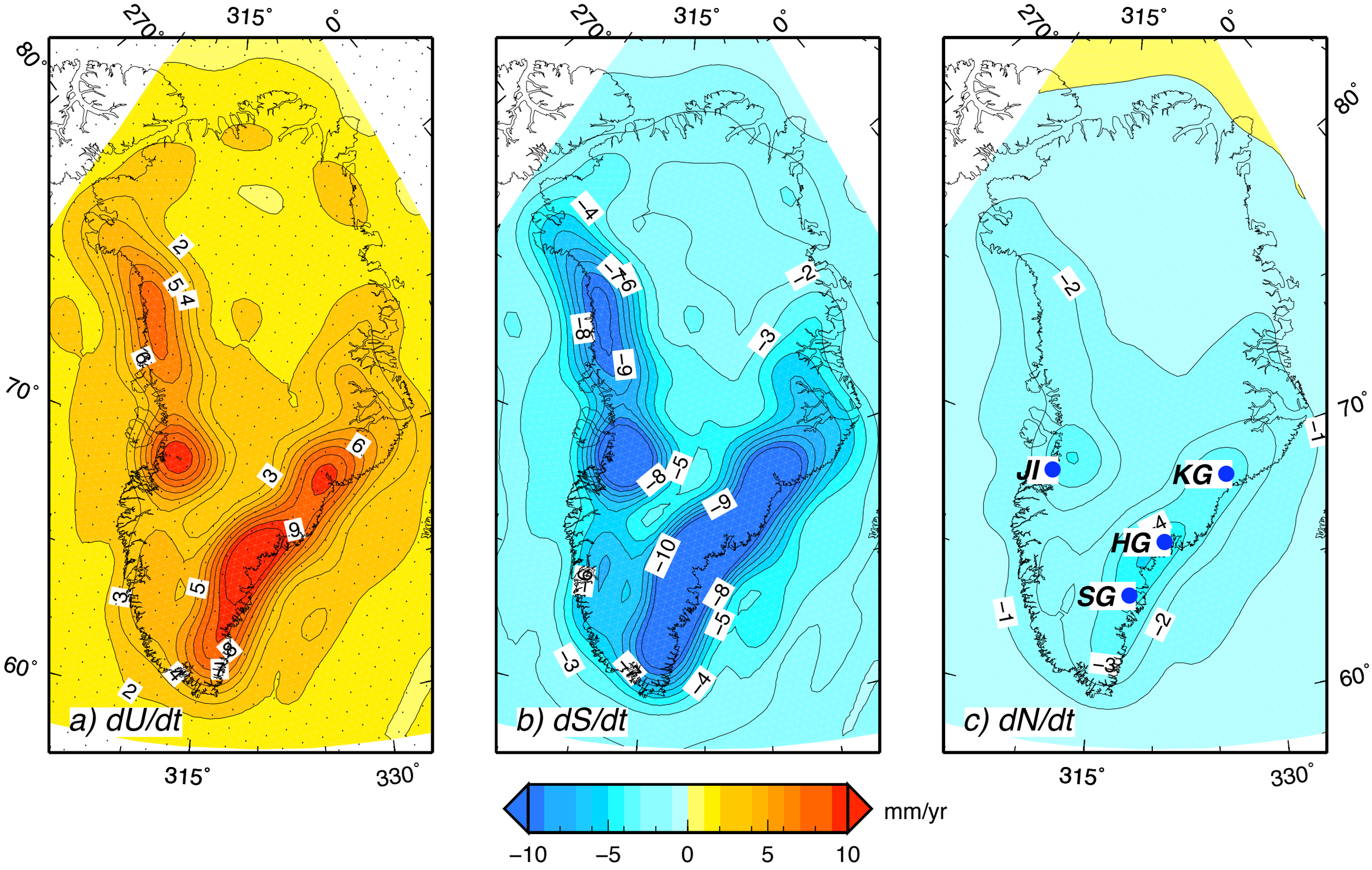
## ANU05

Far from equilibrium
*("high viscosity")*

~0.5 mm/yr

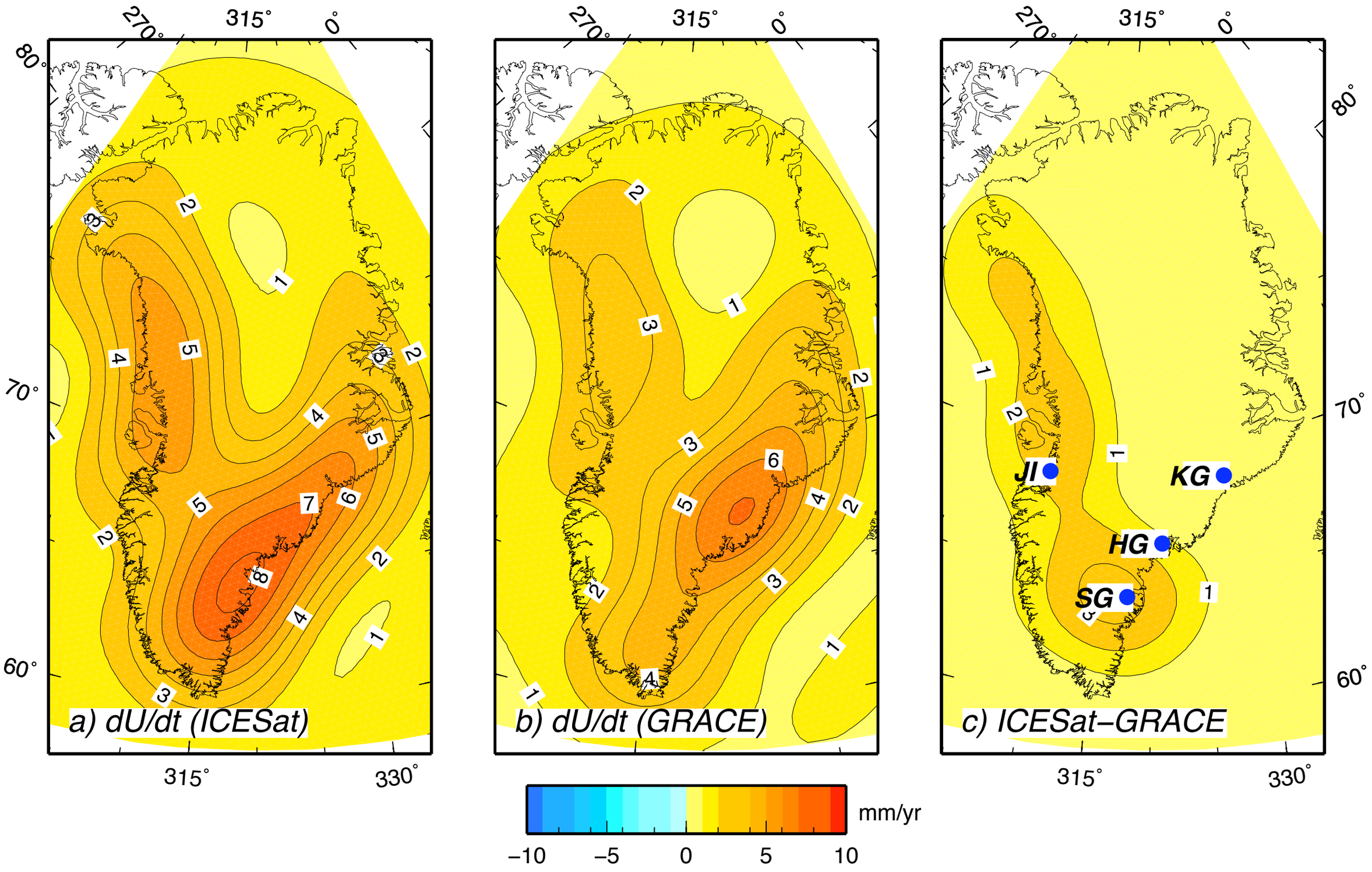


# SLE input: Mass balance from ICESat (M3): 240 +/- 28 Gt/yr




Elastic solution of the Sea Level Equation

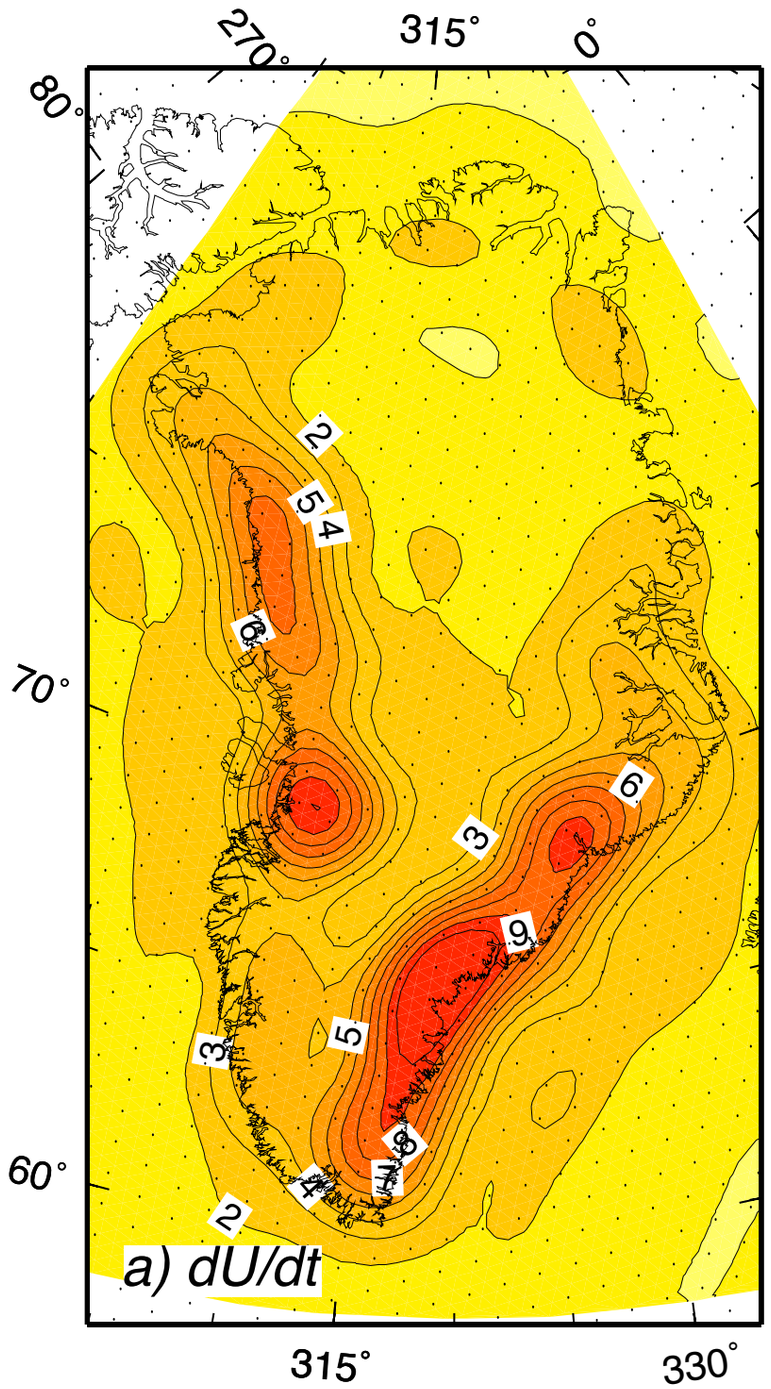
# SLE: ICESat vs GRACE (Wouters et al., 2008)



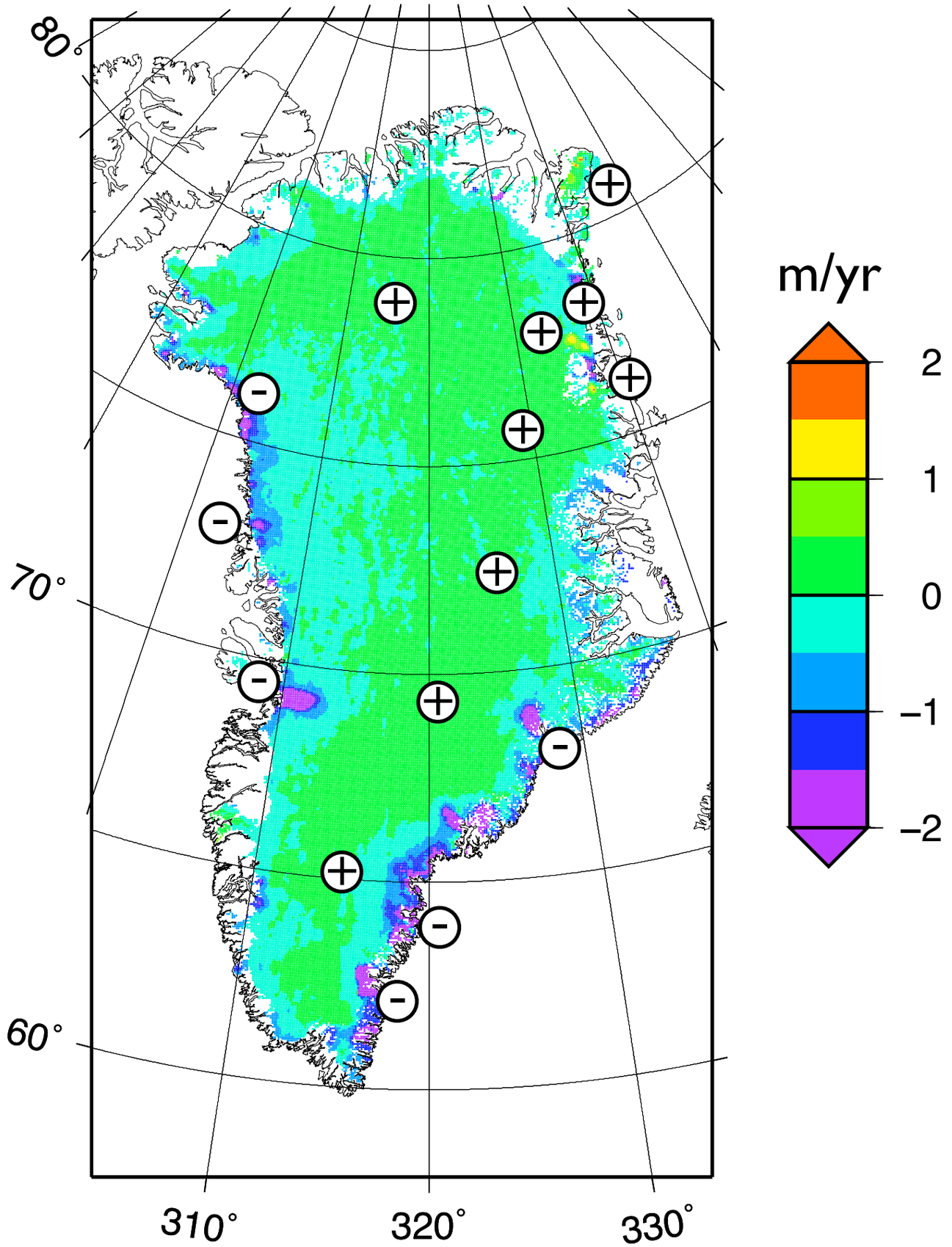

(this) GRACE mass balance: 179 +/- 25 Gt/yr (Feb 2003 - Jan 2008) < ICESat

# SLE input: Mass balance from ICEsat (M3): 240 +/- 28 Gt/yr

*Are we missing something?*




Elastic solution of the Sea Level Equation



## *Overview:*

- A few words on the "sea level rise" problem,

- Contribution of *Greenland* to past and present sea level variations,

- Modeling the effects of melting of Greenland : the *global* view point

- ... and the *regional* view point

- Discussion, problems, directions, ETC...

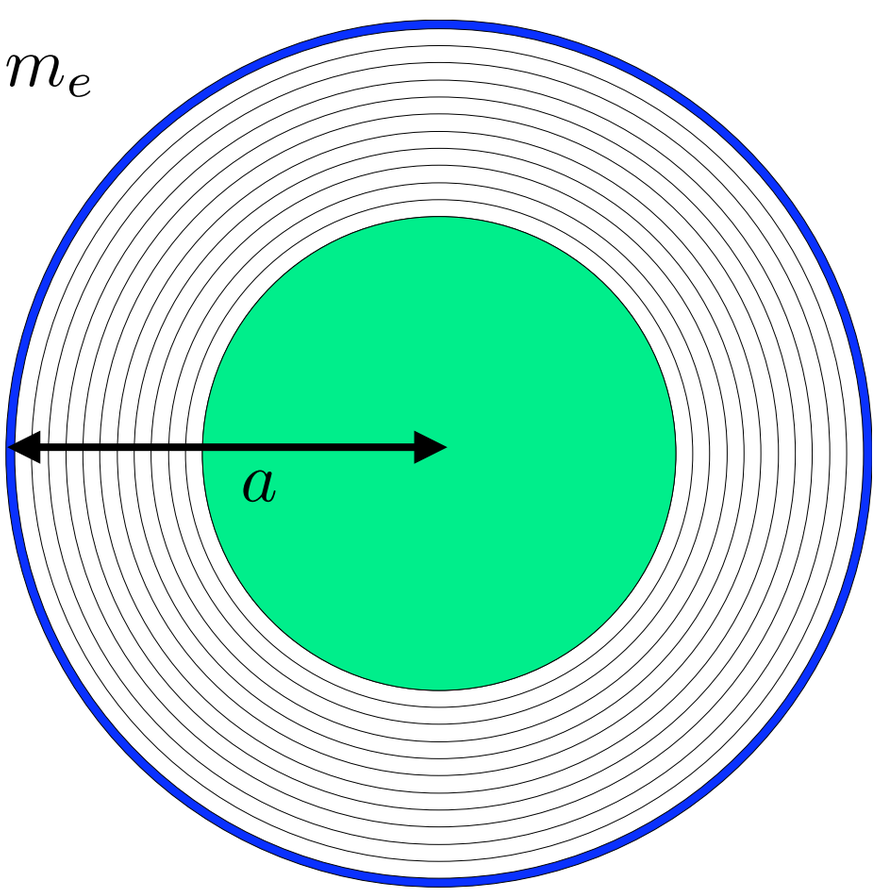
# *Spherical non-rotating elastic isotropic (**SNREI**) model*

$$\mu = \mu(r) \quad \lambda = \lambda(r)$$

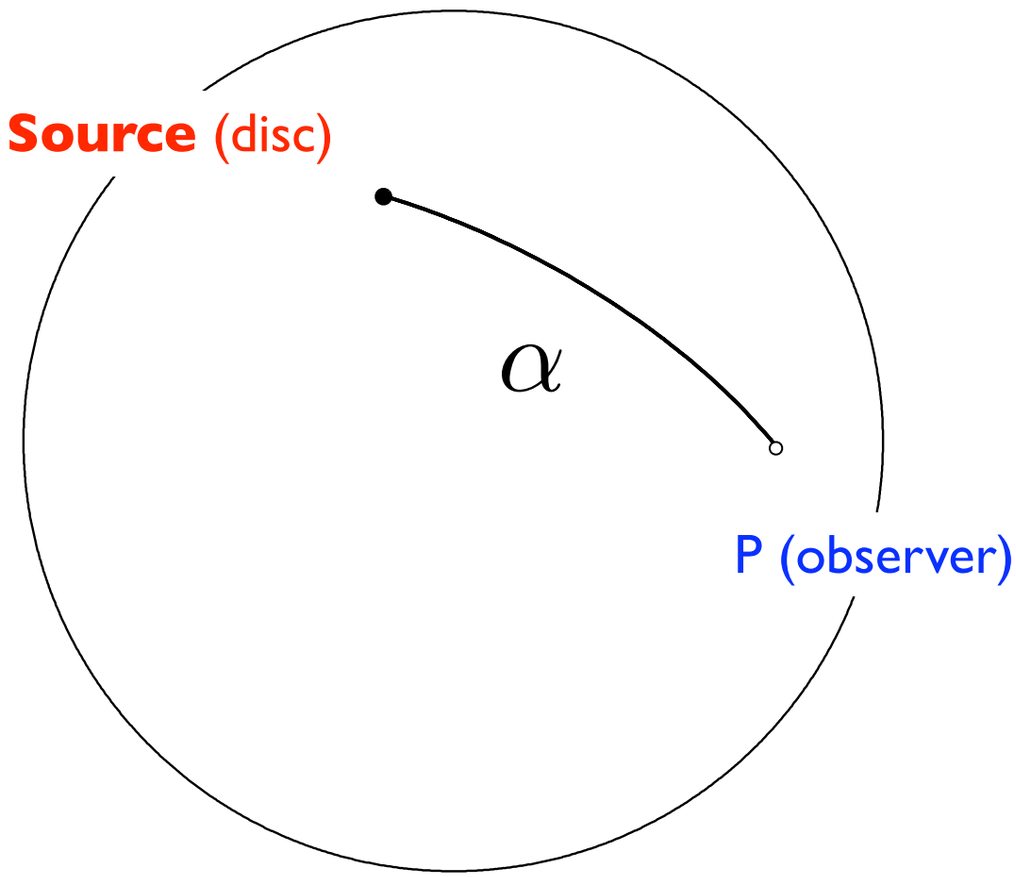
Lame constants

$$\rho = \rho(r)$$

Density




*Spherically symmetric Earth*




*Source-observer geometry*

# Vertical displacement due only to (un)loading:

$$U(\theta) = 3\Delta h \left(\frac{\rho_i}{\rho_e}\right) \sum_{n=0}^{\infty} \frac{\sigma_n(\alpha)}{2n+1} h_n P_n(\cos\theta)$$

| *with*: | |
|---|---|
| $\rho_i \quad \rho_e$ | ice and Earth average densities |
| $n$ | harmonic degree |
| $\alpha$ | half-amplitude of the disc load |
| $\sigma_n(\alpha)$ | load spectral density |
| $h_n$ | vertical "Love number" |
| $P_n(\cos\theta)$ | Legendre polynomial |
| $\theta$ | source-observer co-latitude |
| $\Delta h$ | *ice thickness variation* |

# Computing the elastic Love numbers $h_n$

*Two options:*

1) Use those available from the literature.

E.g. the "Gegout" Love numbers, based on **PREM**, to degree LMAX= 1024. Available from NASA. They are for a compressible multilayered Earth, Reference frame of the CM of the WHOLE EARTH.
(*) See *http://gemini.gsfc.nasa.gov/aplo/Load_Love2_CM.dat*.

2) Compute your own Love numbers.

E.g., using free software available from GS. ALMA works well for multi-layered models (N ~ 10^3). Advantages: LMAX can be of O(10**5), *ad hoc* regional layering, Lamé constants and density can be employed. Open source. Disadvantage: Assumes incompressible layers.
(*) *http://www.fis.uniurb.it/spada/ALMA_minipage.html)*.

Gegout Love numbers vs a ALMA based model

"LNs-JPBoy.txt" using 1:2
"h_2048.dat" using 1:2

$h_1 \neq 0$

$k_1 = -1$

$h_\infty$

n=2048

n=1024

?

$h_\infty$

$$h_\infty = -\frac{\lambda + 2\mu}{3(\lambda+\mu)} \frac{\rho_e g a}{\mu}\bigg|_{PREM} \approx -6.2129$$

Asymptotic Love number "h" is only sensitive to the outmost layers!
*(Farrell, 1972)*

h_n elastic Love number

harmonic degree, n

0 -1 -2 -3 -4 -5 -6 -7 -8

1 10 100 1000 10000

Farrell, 1972

## Gutenberg-Bullen A Earth model

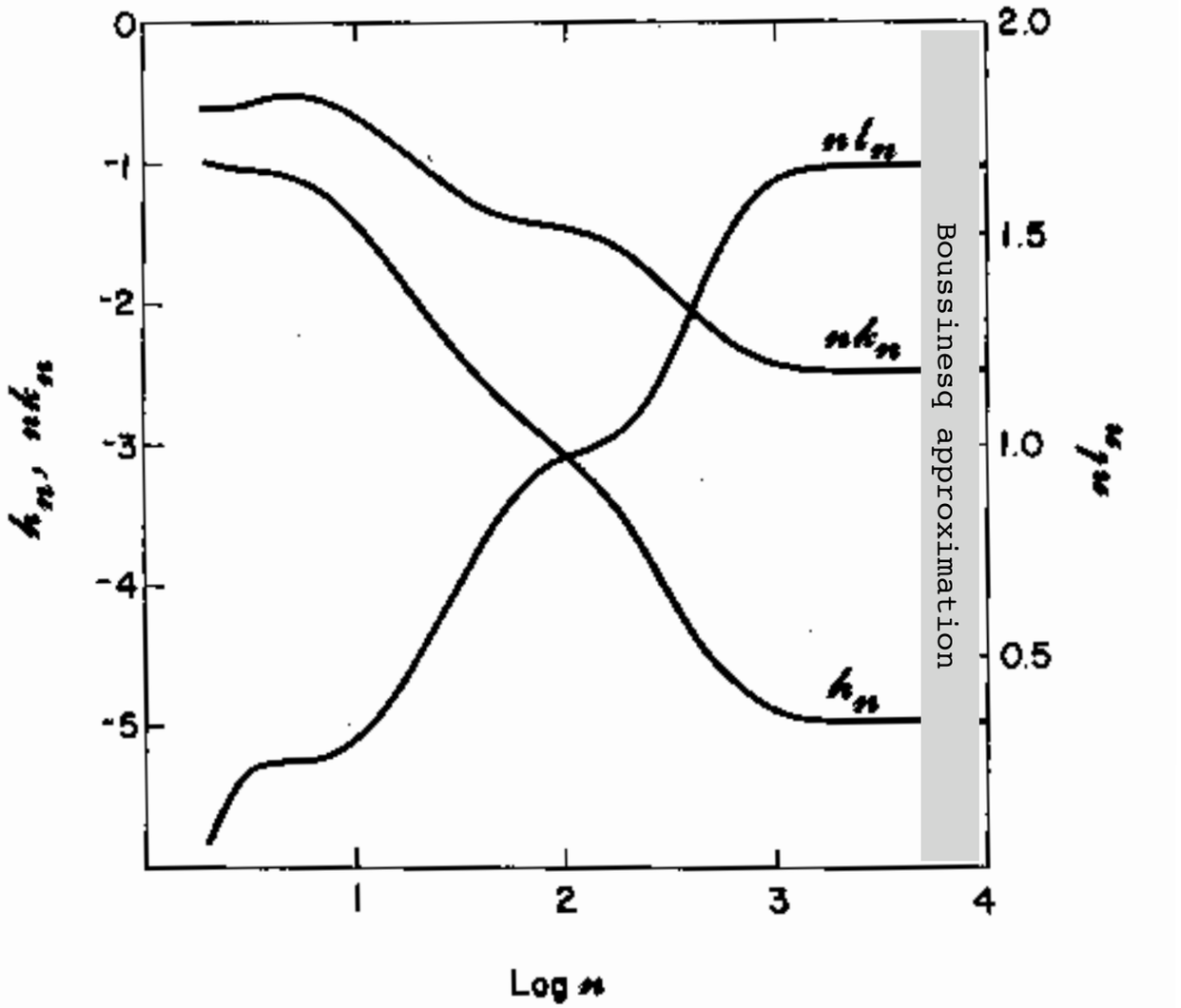
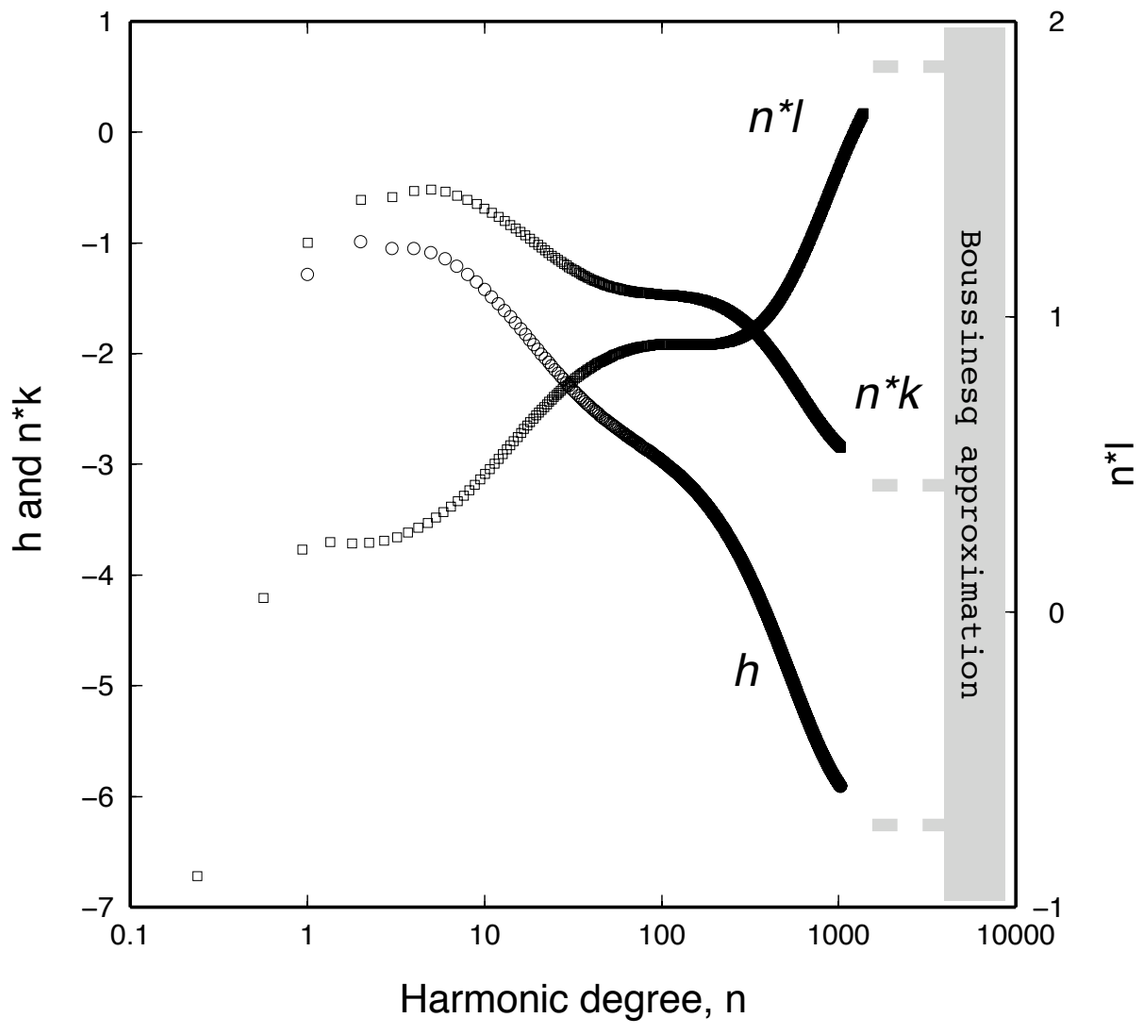


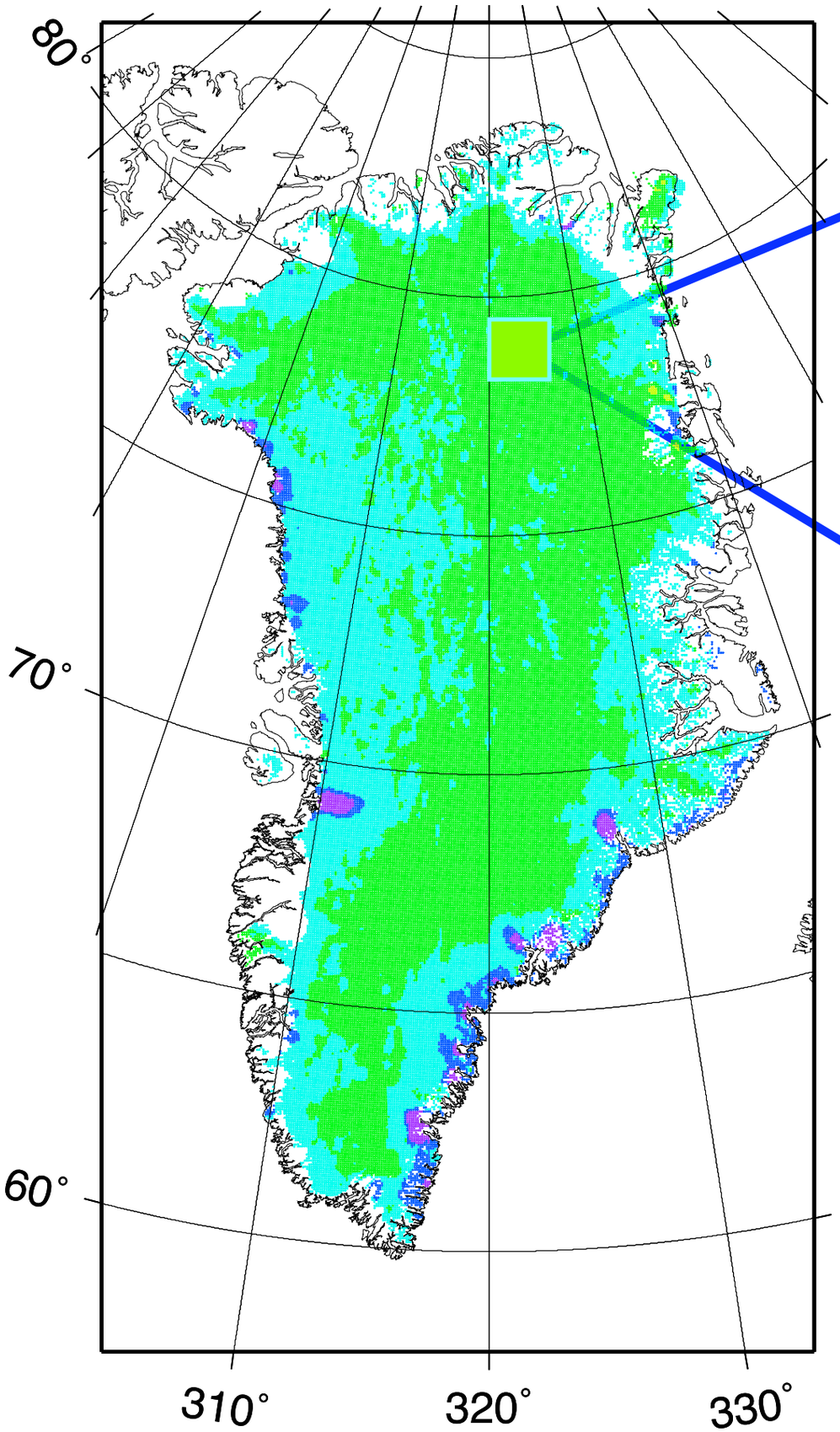

Fig. 1. Love numbers for a unit mass load on the surface of a Gutenberg-Bullen A earth model. Selected values are listed in Table A2. At $n = 10{,}000$, the computed Love numbers agree with the Boussinesq approximation to within 1%. The Love numbers for the other earth models differ significantly from these Love numbers above $n = 20$ to 30.

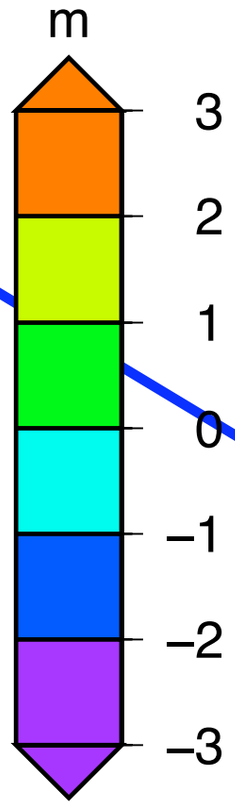
Gegout, 2010

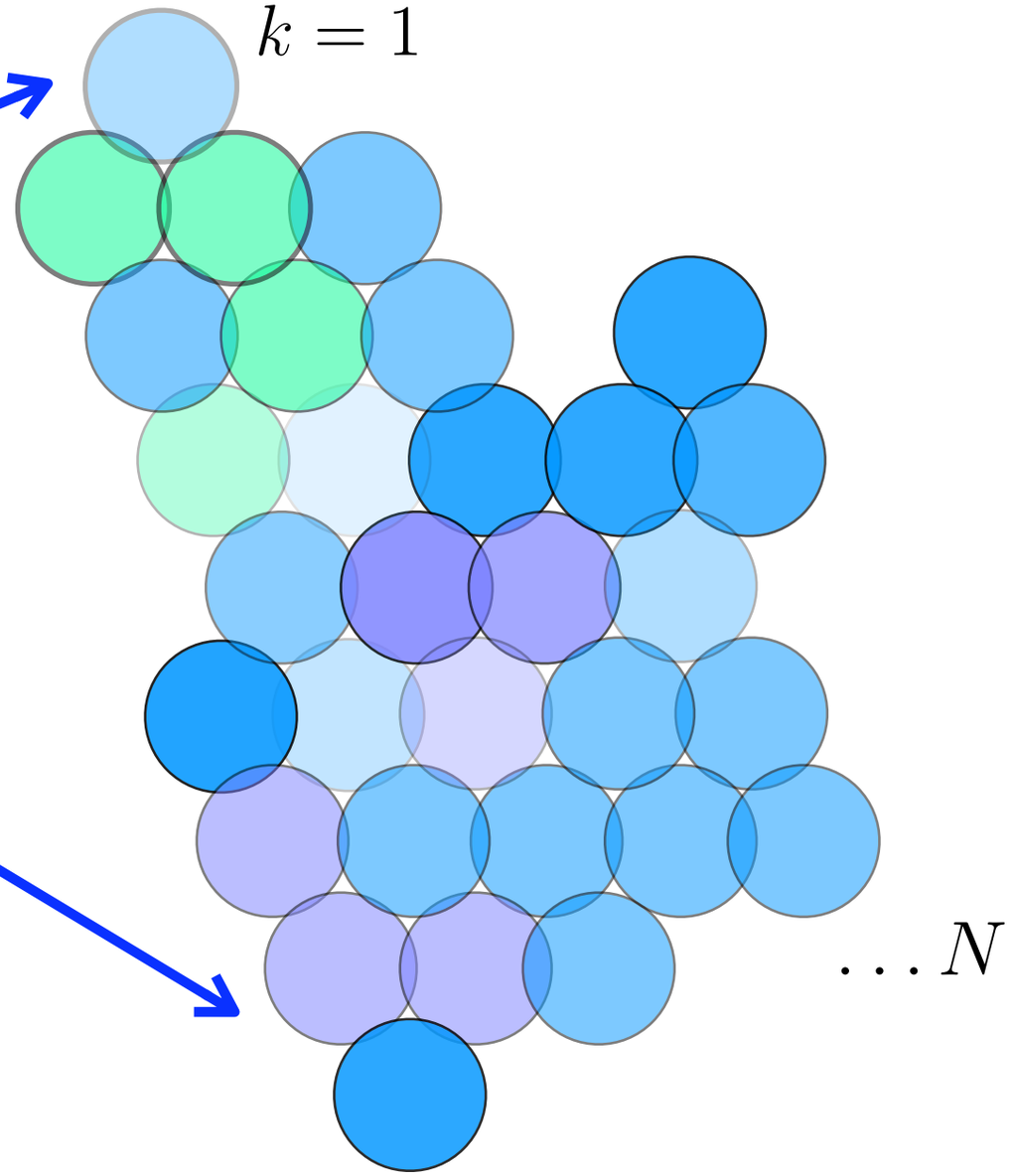
## Preliminary Reference Earth Model




C6. Love numbers of Farrell ('72, GBA model) vs those of *Gegout* (today, PREM model)

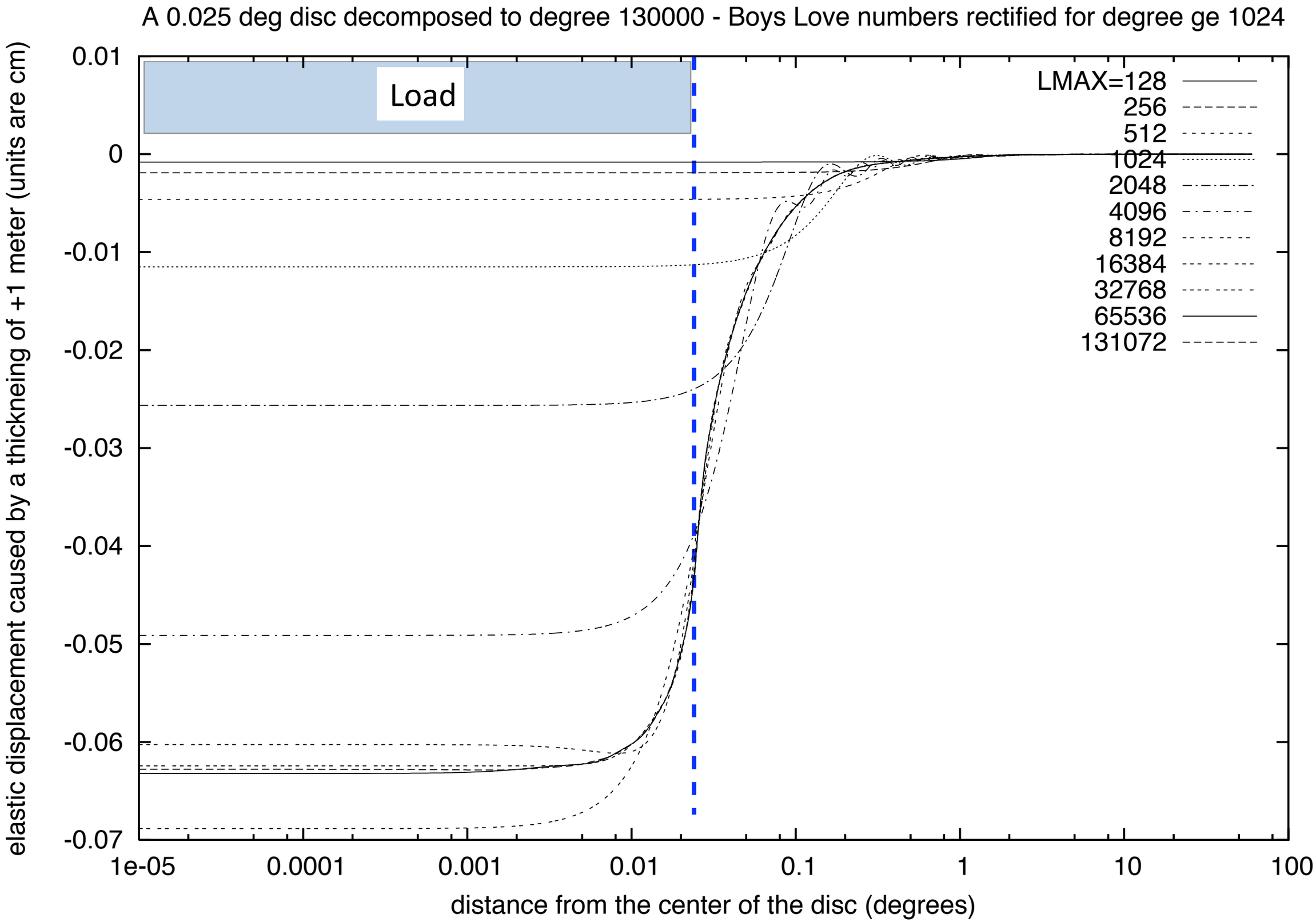


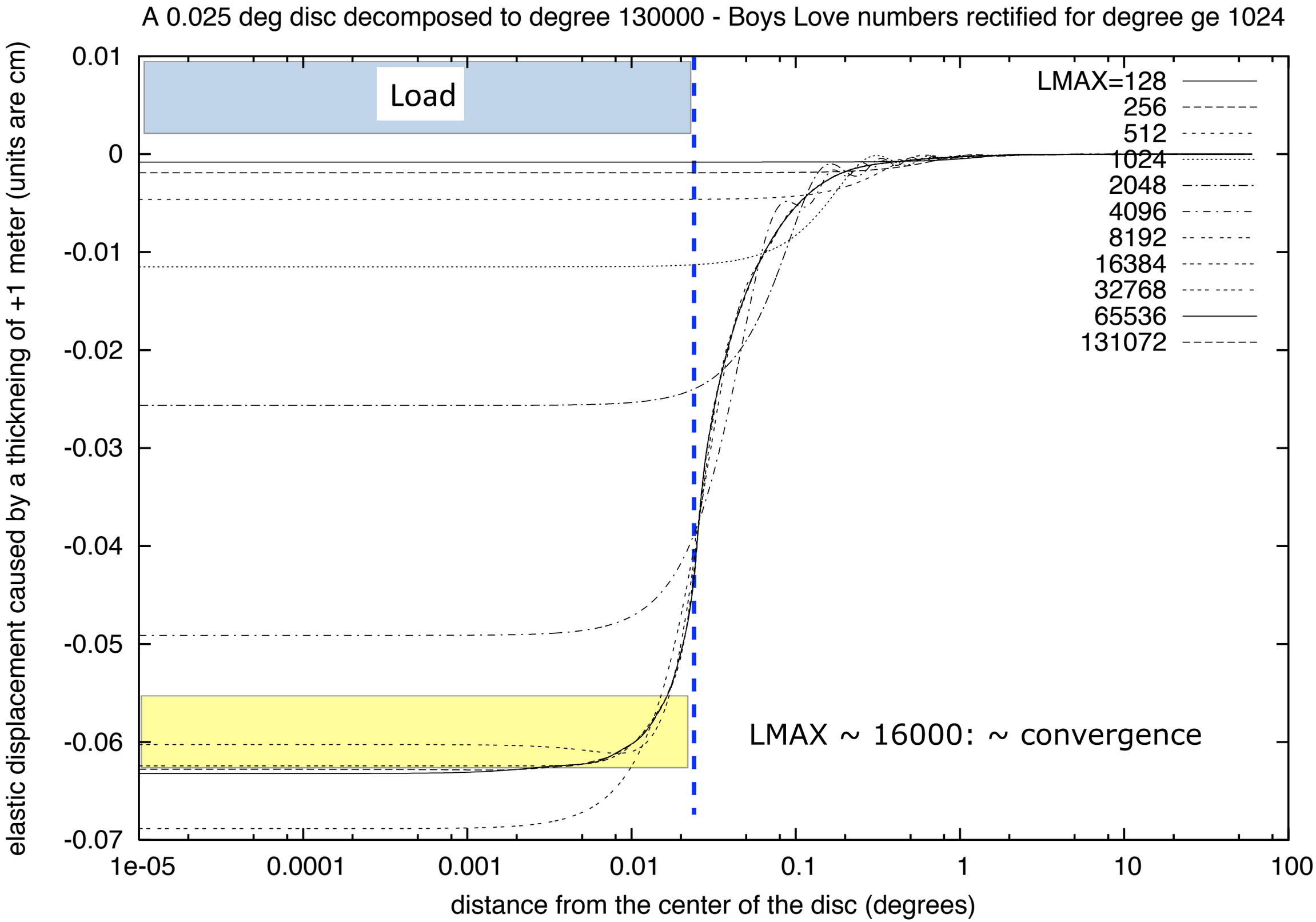




| | |
|---|---|
| Number of elements: | $N \approx 70 \times 10^3$ |
| Size of each element: | $\alpha_k \approx 0.025^\circ$ |
| Thickness is variable: | $\Delta h = F(k)$ |

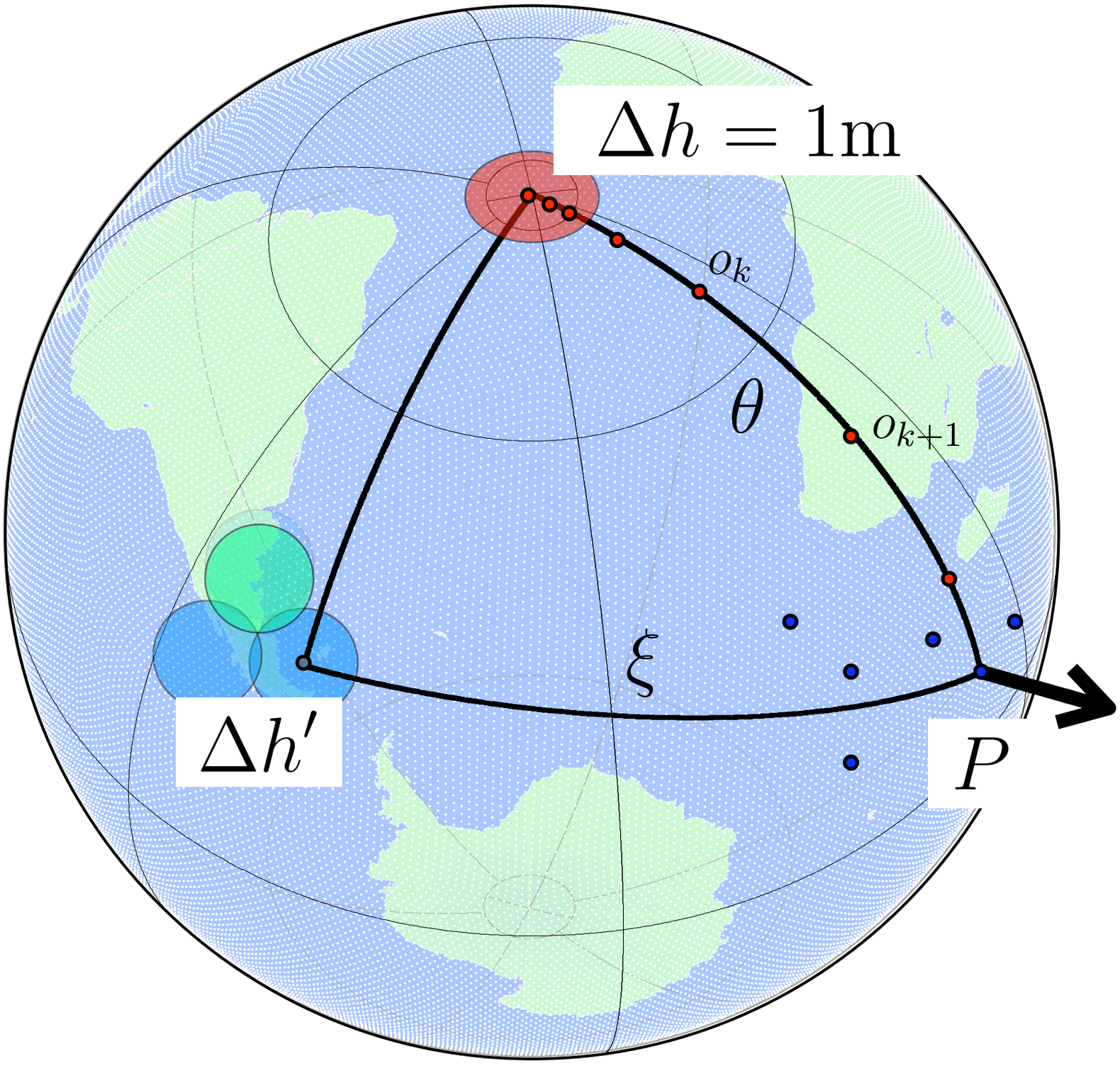
# Test displacement along the 1D grid to degree LMAX=131,072



# Test displacement along the 1D grid to degree LMAX=131,072



40




*RES= 36, N= 50412*

## Details of method

1. for all observers $o_k$ compute "U" to degree LMAX using previous formula. This 1D grid does not need to be equally spaced! Use a "test" unit disc;

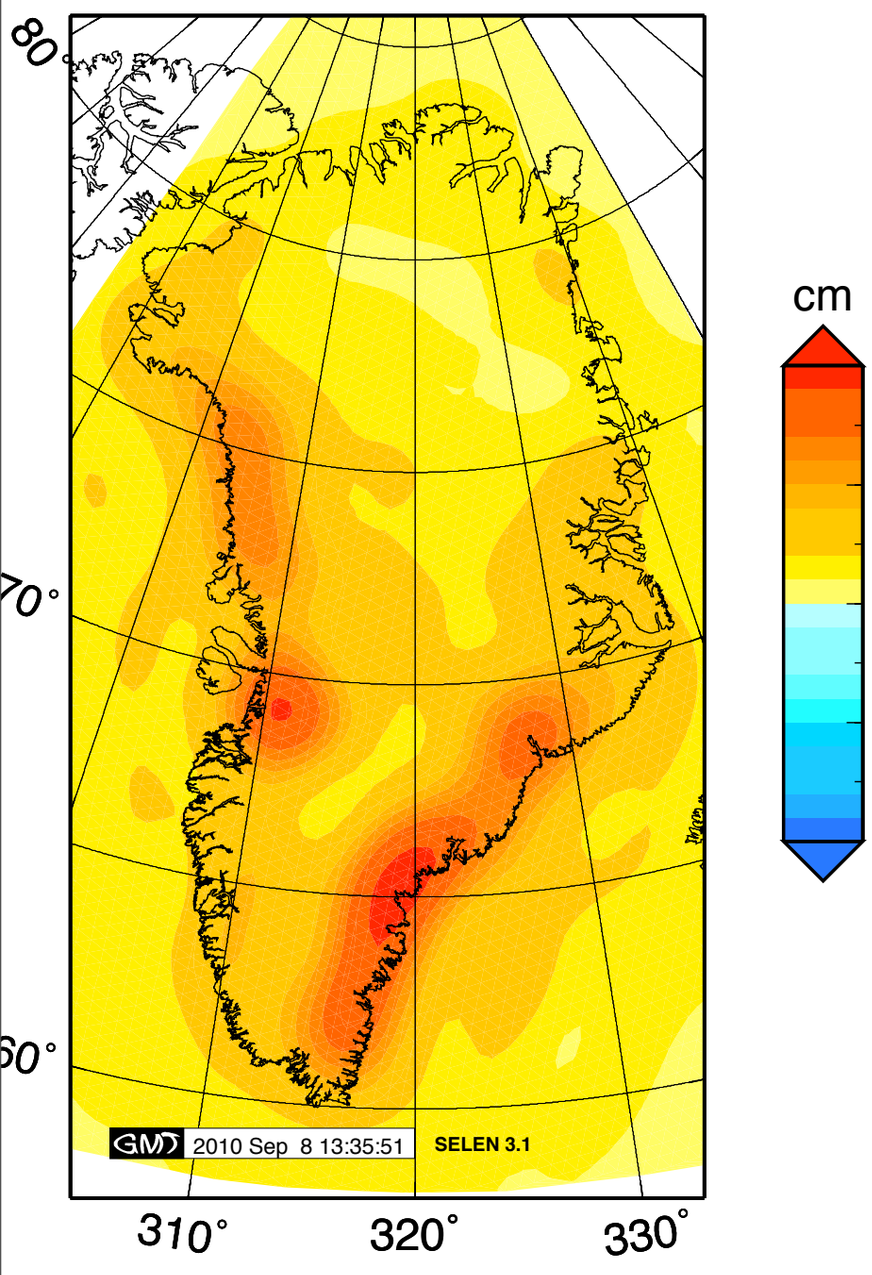
2. Given a point P of the ICO 2D grid, find its distance from a given ice element. In P, find U, possibly by interpolation, using the 1D grid above. Rescale to compensate for the actual disc thickness variation;

3. Repeat for all discs, and sum in P the individual contributions (for *all* discs, the radial unit vector is the same - note that this NOT true for horizontal displacement...);

4. Repeat for all points P of the 2D ("almost" equally spaced) ICO grid.

## spherical grid spacing = 25 km, LMAX=128

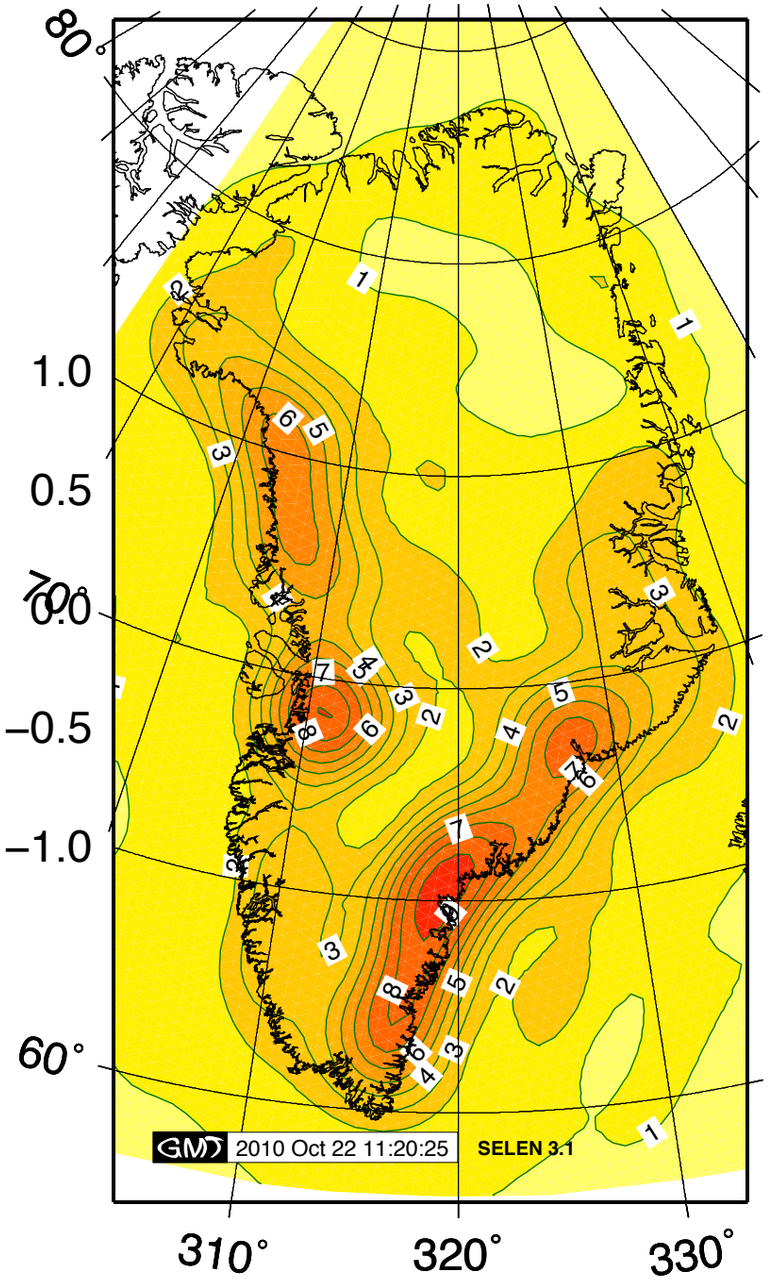
*vertical velocity*




Global

<0.55/10.08>

*vertical velocity*

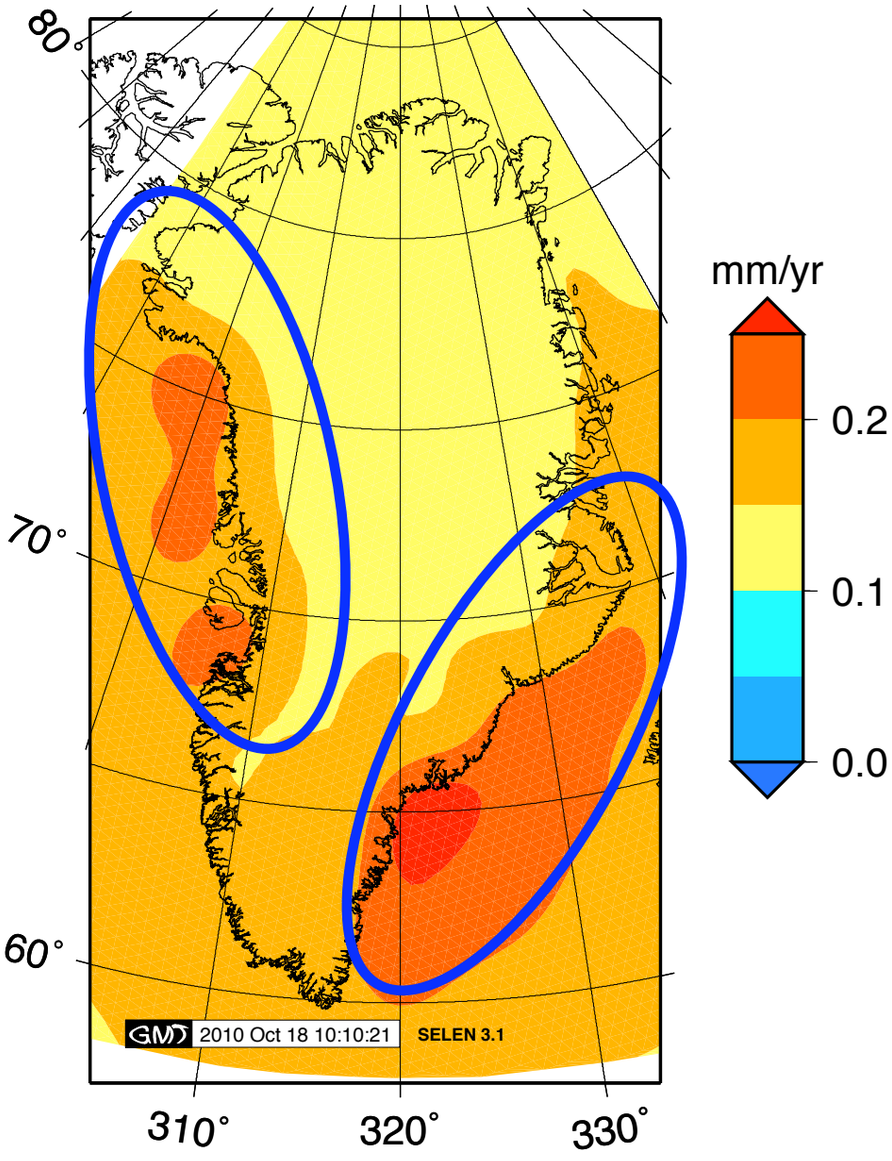



Regional

<0.42/9.85>

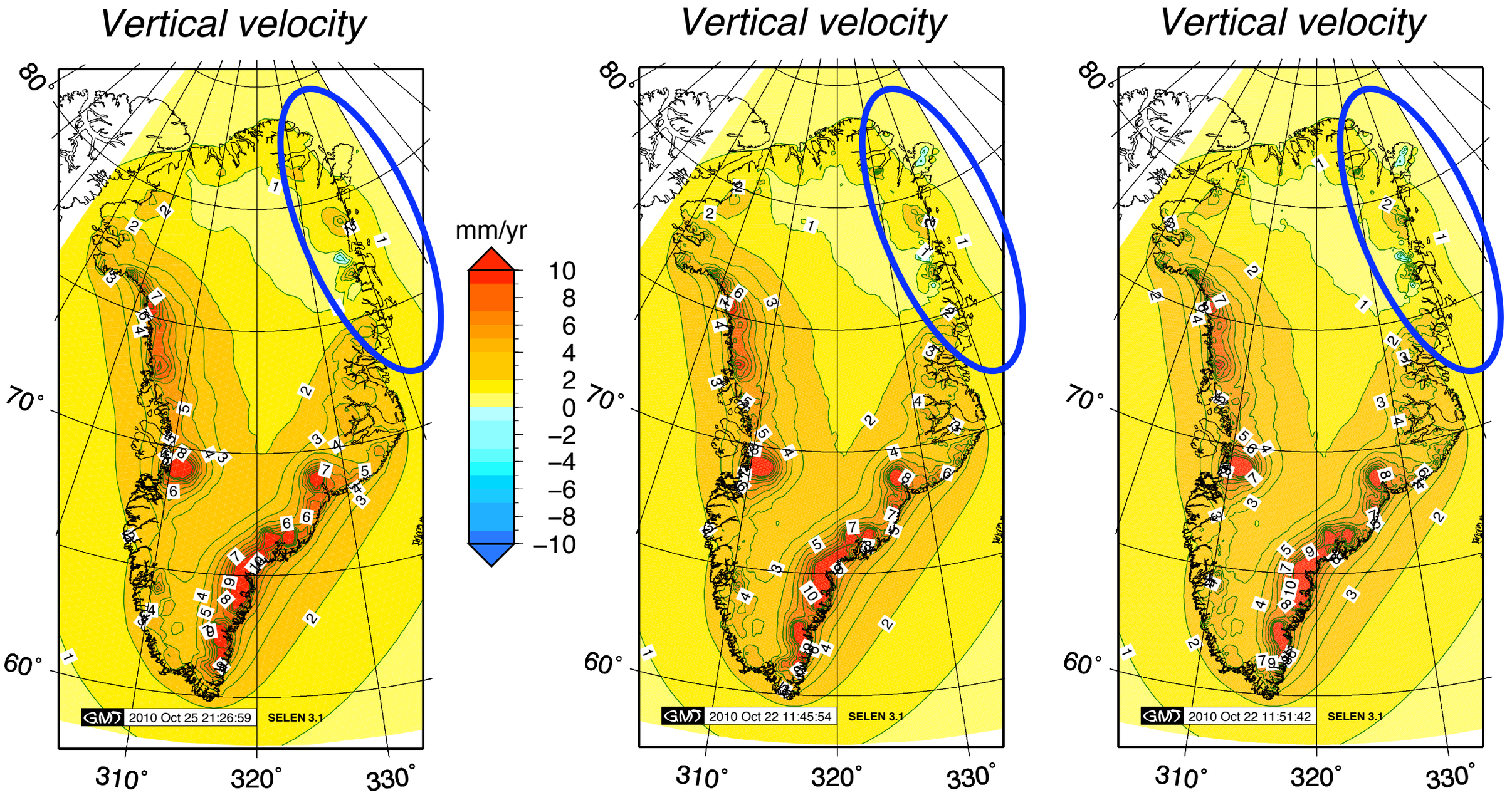
*(ONLY local ice is accounted for)*

*vertical velocity*




Global *minus* Regional

# LMAX >1E5, varying the pixels spacing...




–Ice model: GR3R –Elasticity: Gegout

–LMAX>10^5 OBS_SPAC= 25km

## Regional, 25 km

<-1.95/23.46>

–Ice model: GR3R –Elasticity: Gegout

–LMAX>10^5 OBS_SPAC= 10km

## Regional, 10 km

<-2.21/24.17>

–Ice model: GR3R –Elasticity: Gegout

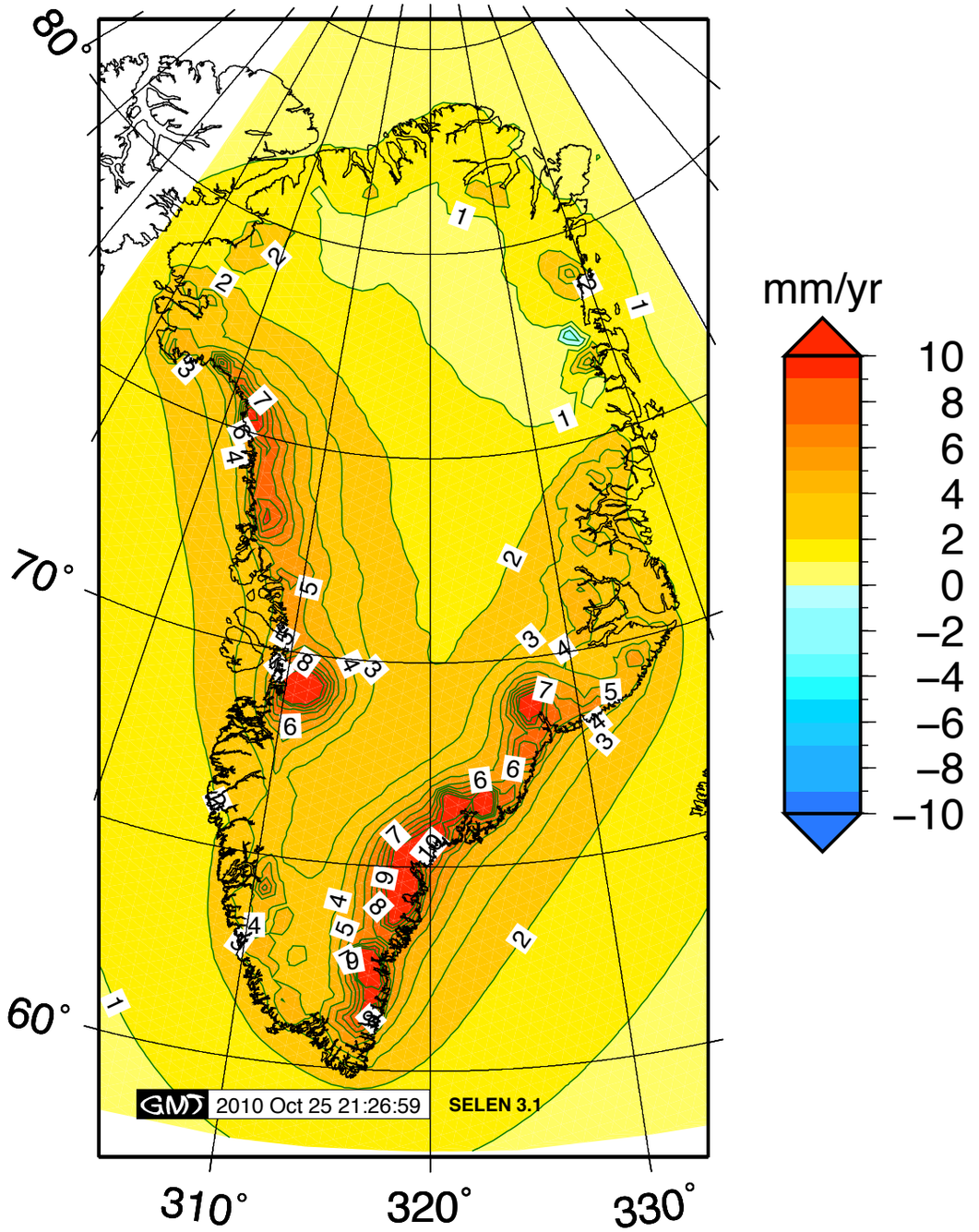
–LMAX>10^5 OBS_SPAC= 5km

## Regional, 5 km

<-2.18/25.41>

## Geguot Love numbers

*Vertical velocity*



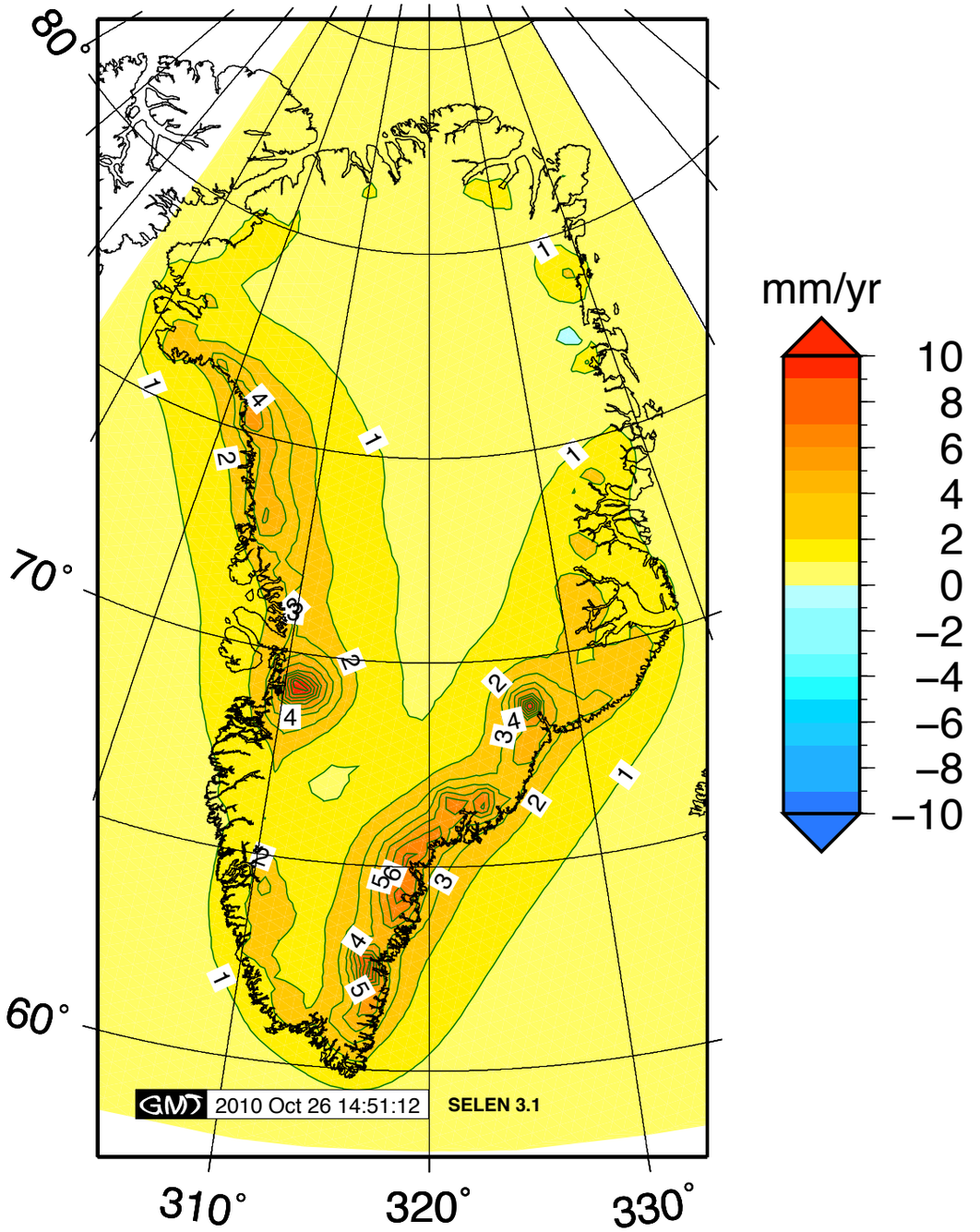

–Ice model: GR3R –Elasticity: Gegout

–LMAX>10^5 OBS_SPAC= 25km

Regional, 25 km <-1.95/23.46>

## ALMA Love numbers

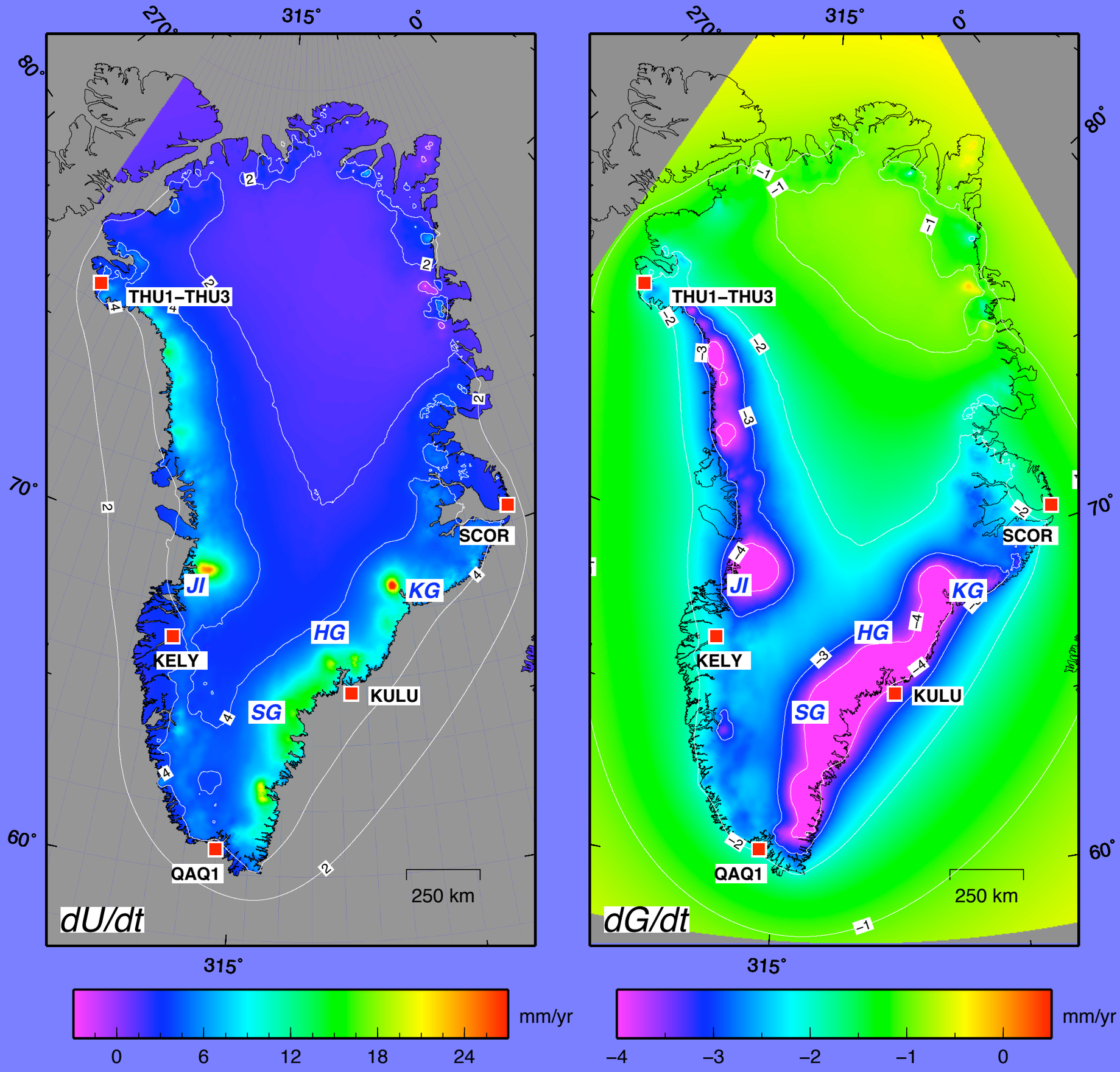
*Vertical velocity*




–Ice model: GR3R –Elasticity: ALMA

–LMAX>10^5 OBS_SPAC= 25km

Regional, 25 km <-0.74/11.26>


270°
315°
0°
80°
70°
60°
THU1–THU3
SCOR
JI
KG
HG
KELY
KULU
SG
QAQ1
250 km
dU/dt
dG/dt
mm/yr
0
6
12
18
24
−4
−3
−2
−1
0

(a)

50 km

(b)

50 km

(C)

QAQ1

250 km

(d)

SCOR

KG

100 km

(e)

200 km

KG

HG

KULU

(f)

THU1–THU3

100 km

(g)

100 km

JI

KELY

0 6 12 18 24 mm/yr

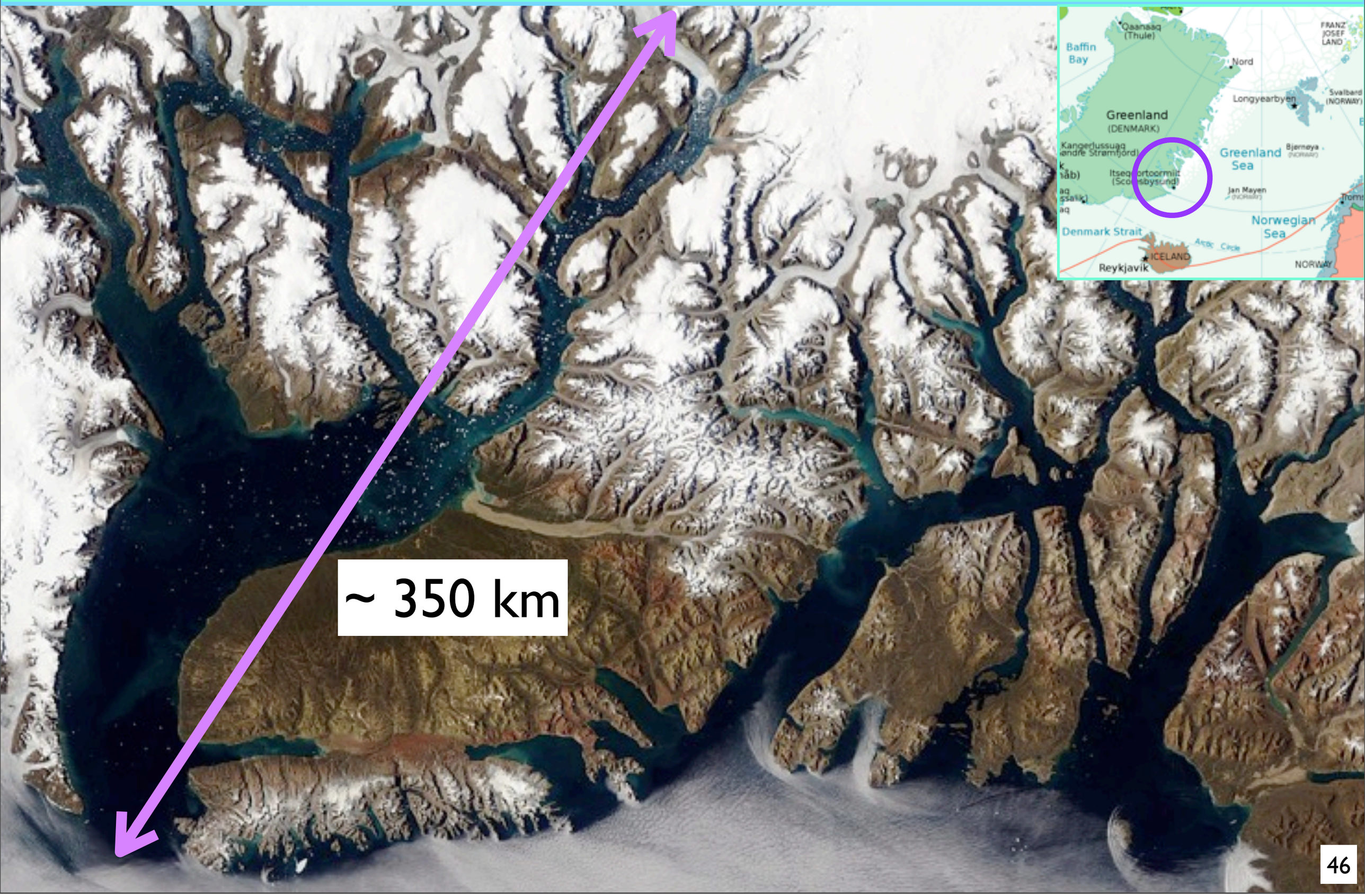
# Scoresby Sund in Greenland - 350 km (217 mi)

*- the LONGEST fjord of the world -*

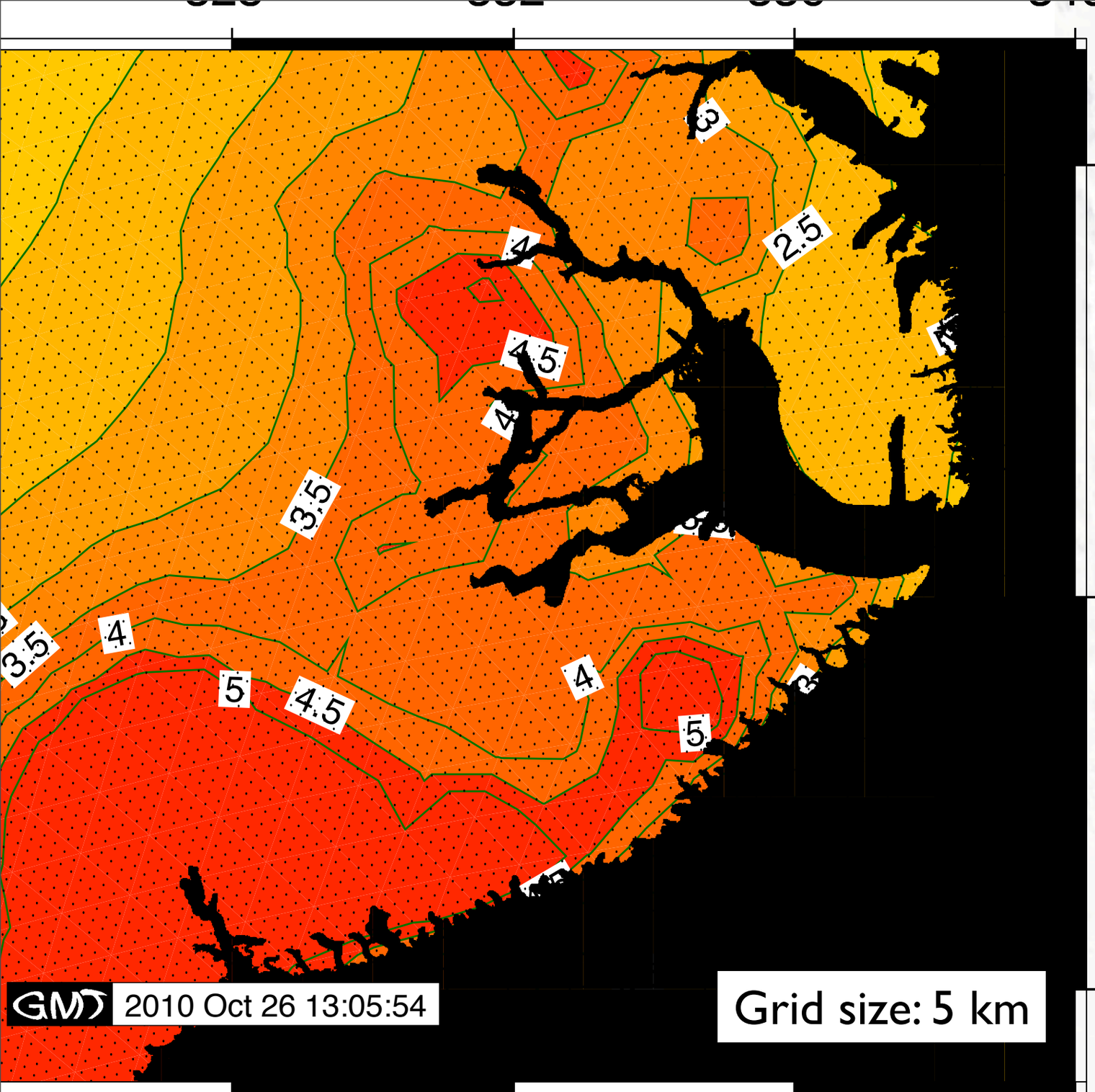


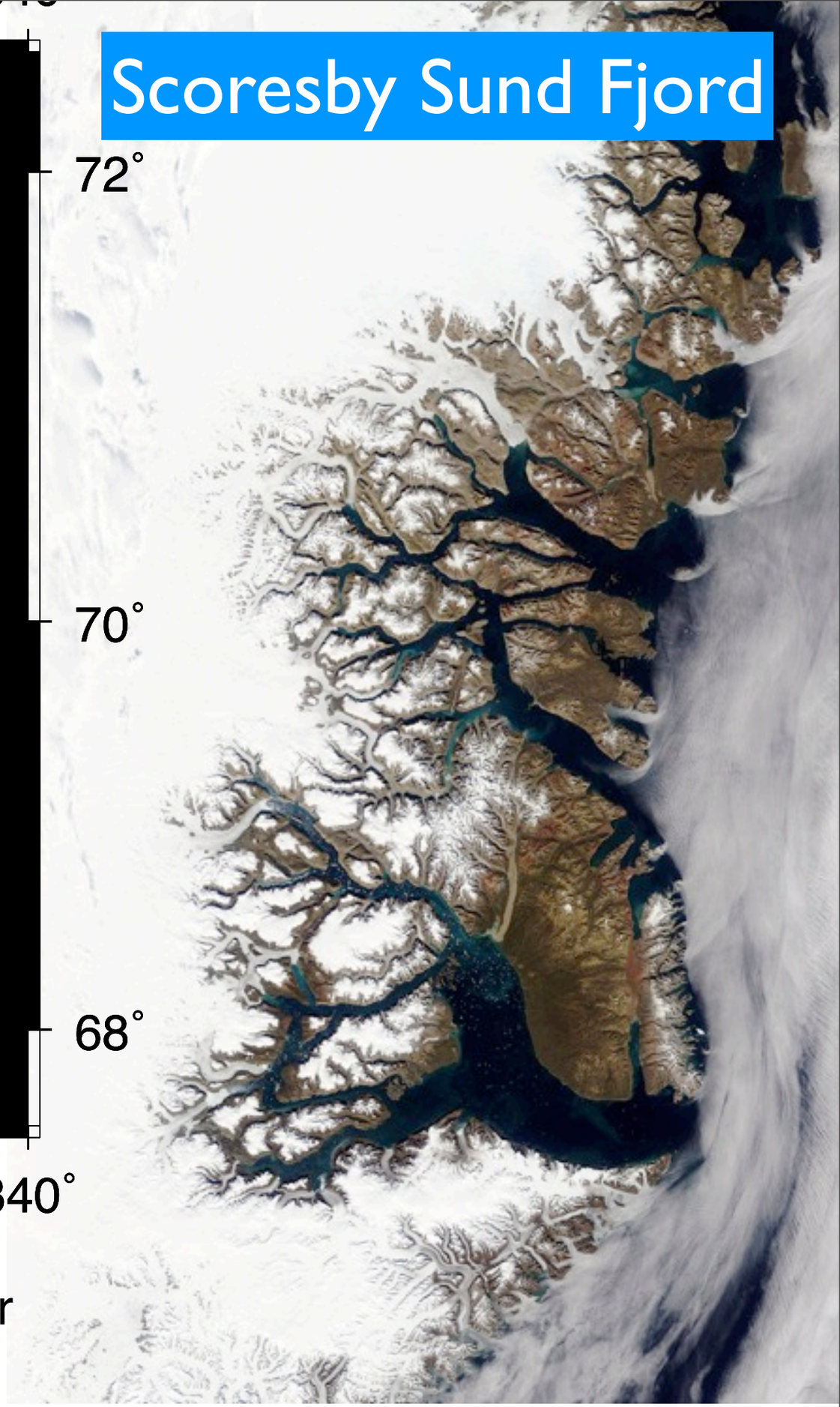
# Scoresby Sund in Greenland - 350 km (217 mi)

*- the LONGEST fjord of the world -*



# Scoresby Sund Fjord




328° 332° 336° 340°

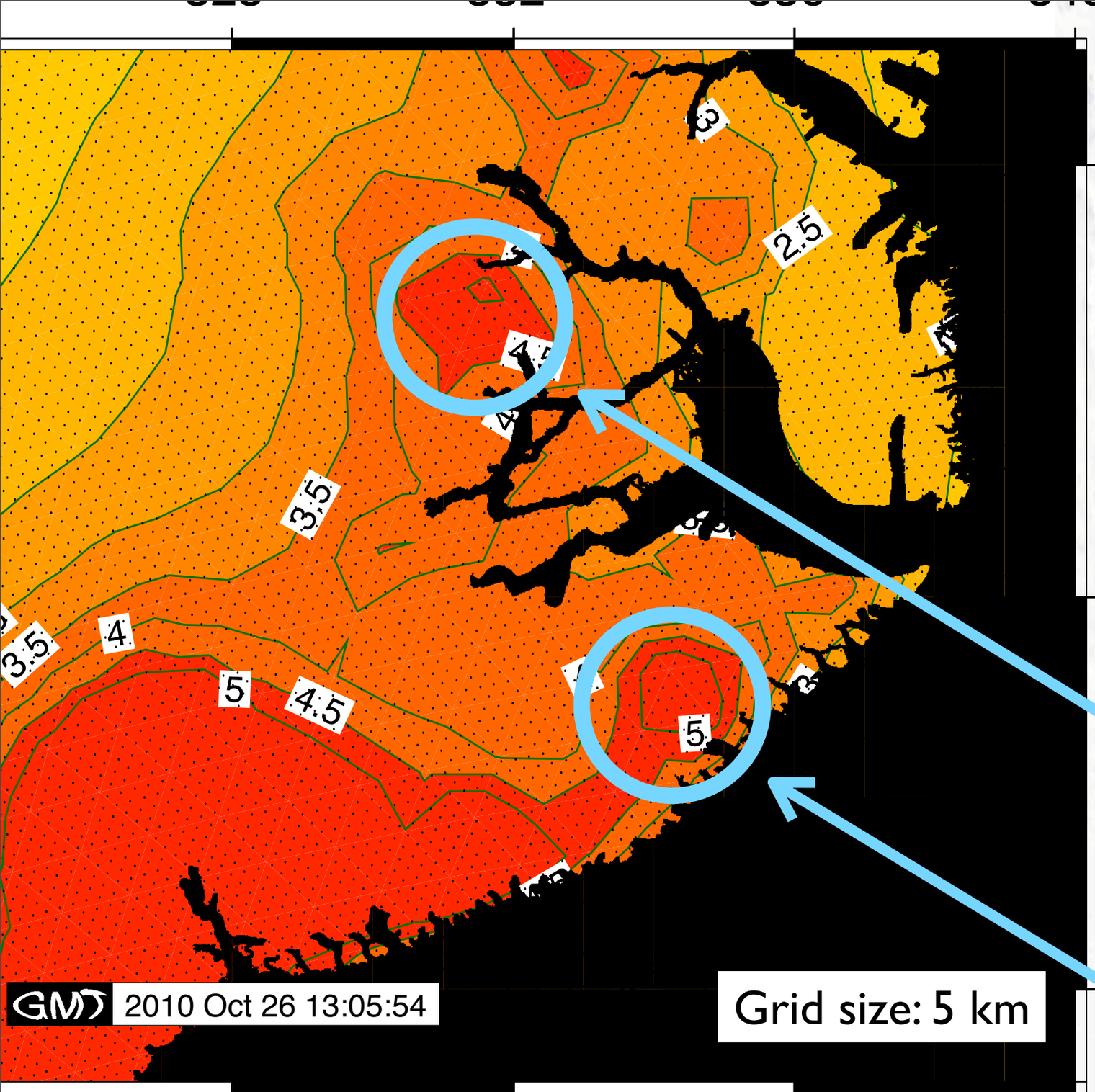
vertical uplift rate

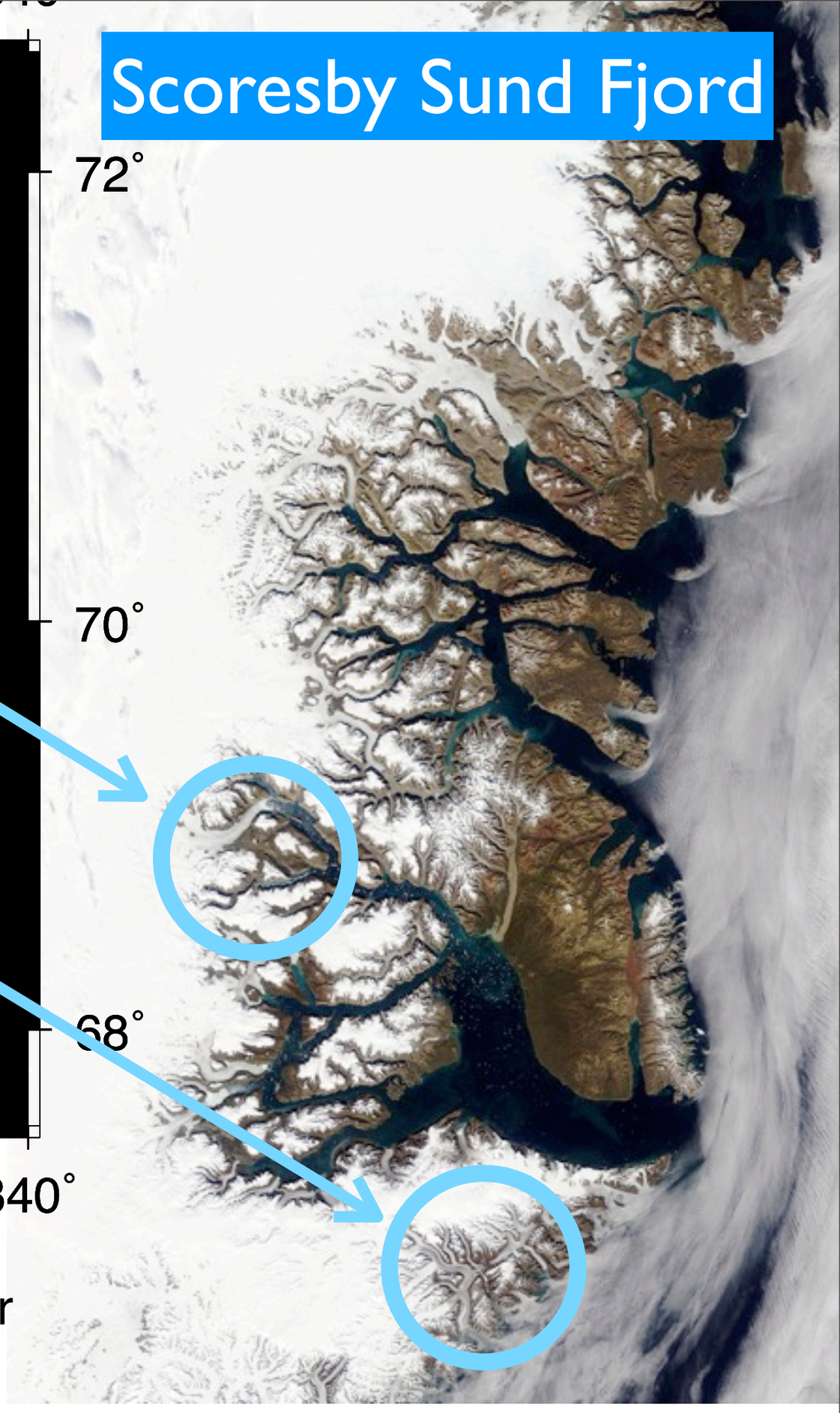
mm/yr

−4 −2 0 2 4

47

# Scoresby Sund Fjord



## *Overview:*

- A few words on the "sea level rise" problem,

- Contribution of *Greenland* to past and present sea level variations,

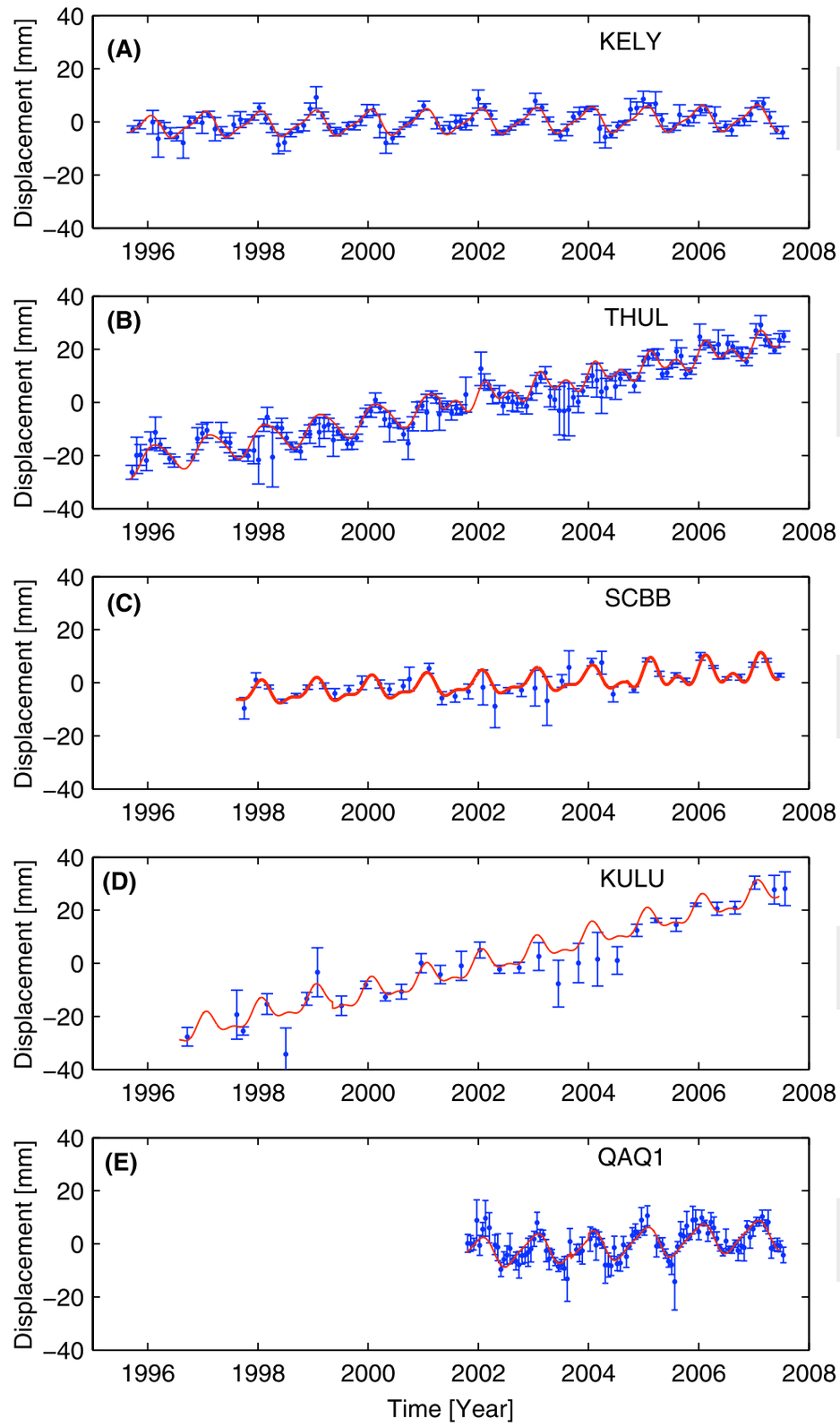
- Modeling the effects of melting of Greenland : the *global* view point

- ... and the *regional* view point

- Discussion, problems, directions, ETC...




**Figure 1.** Locations of the GPS sites (red dots), the tide gauge station (red triangle), DYE3 (yellow triangle), and Paamiut (green triangle).




+1.3 mm/a

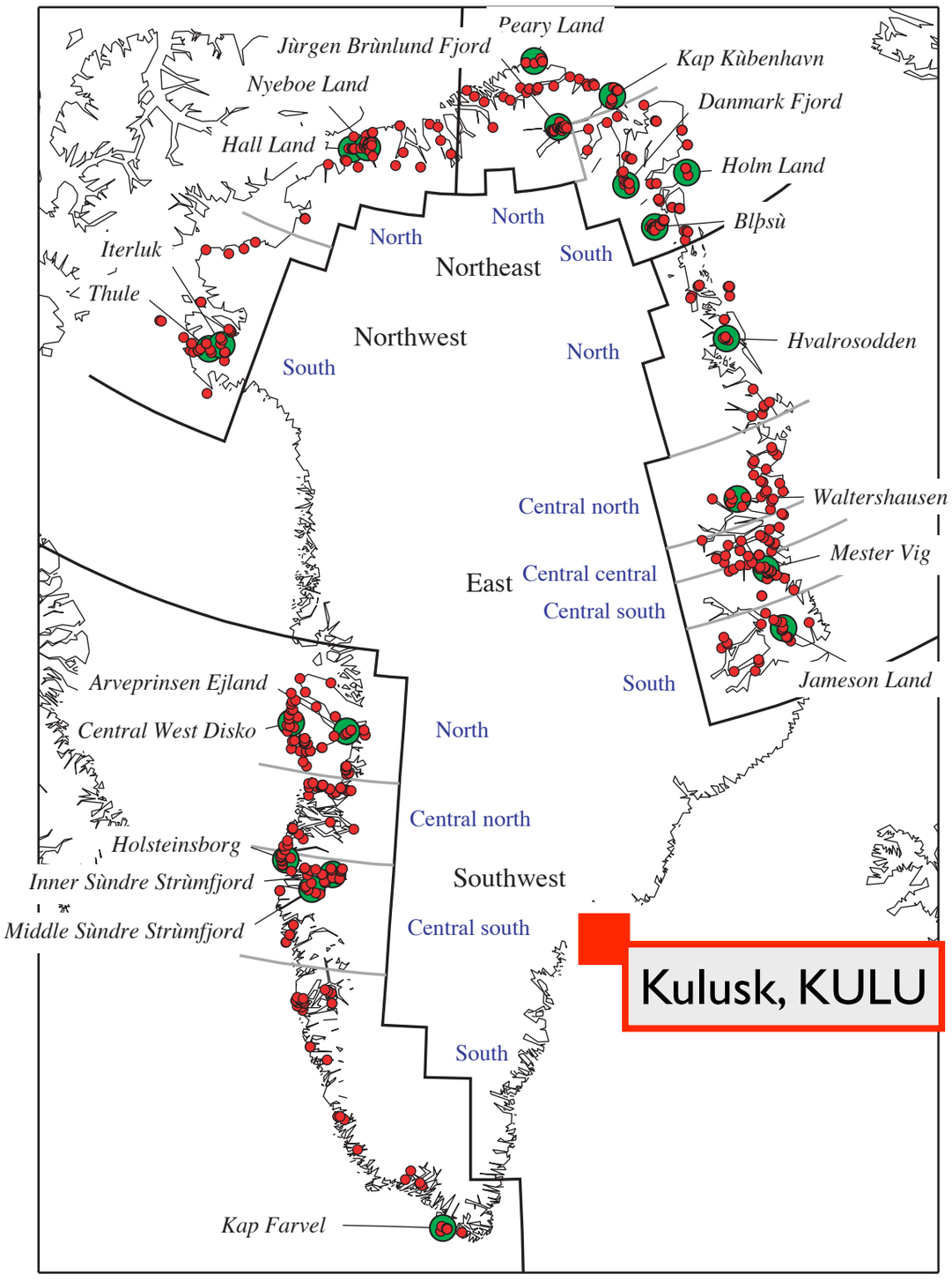
+5.0 mm/a

+2.0 mm/a

+6.3 mm/a

+2.1 mm/a

**Figure 4.** Multiday averages and their assigned errors at (a) KELY, (b) THUL, (c) SCBB, (d) KULU, and (e) QAQ1. The solid line shows the best fitting offsets, annual, semiannual, and secular terms.




tribution of relative sea-level data (filled red circles) used in this work. Also marked are the regional (black lines, bold font) and ue font) subdivisions, listed in Tables 2 and 3. The localities where predicted sea-level curves have been compared with 10–13 are labeled in italics (green-filled circles).

1057

# Constraints on the Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations and glacial-rebound models

Kevin Fleming[a,*], Kurt Lambeck[b]

[a] GeoForschungsZentrum Potsdam, Department 1: Geodesy and Remote Sensing, Telegrafenberg, D-14473, Potsdam, Germany
[b] Research School of Earth Sciences, Australian National University, Canberra, ACT, 0200, Australia

Received 1 August 2002; accepted 8 November 2003



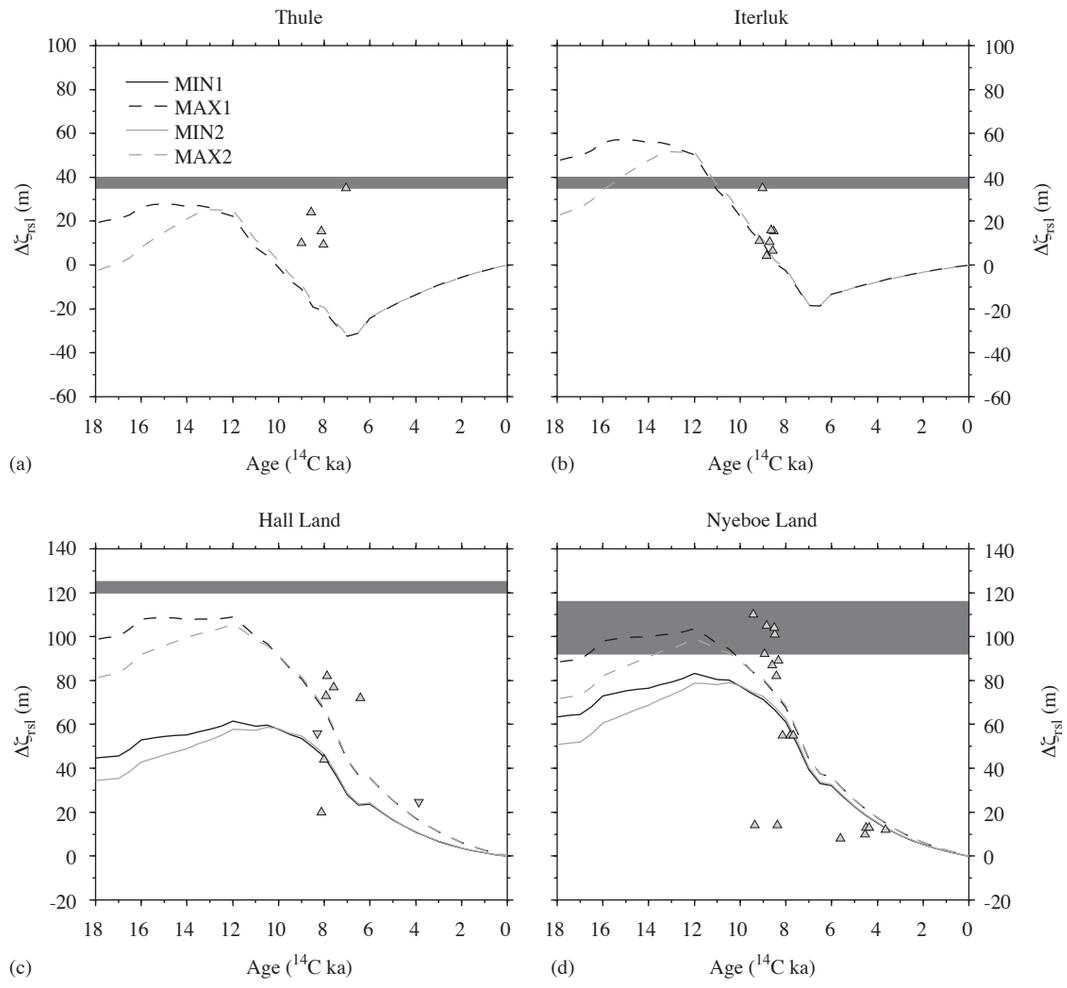
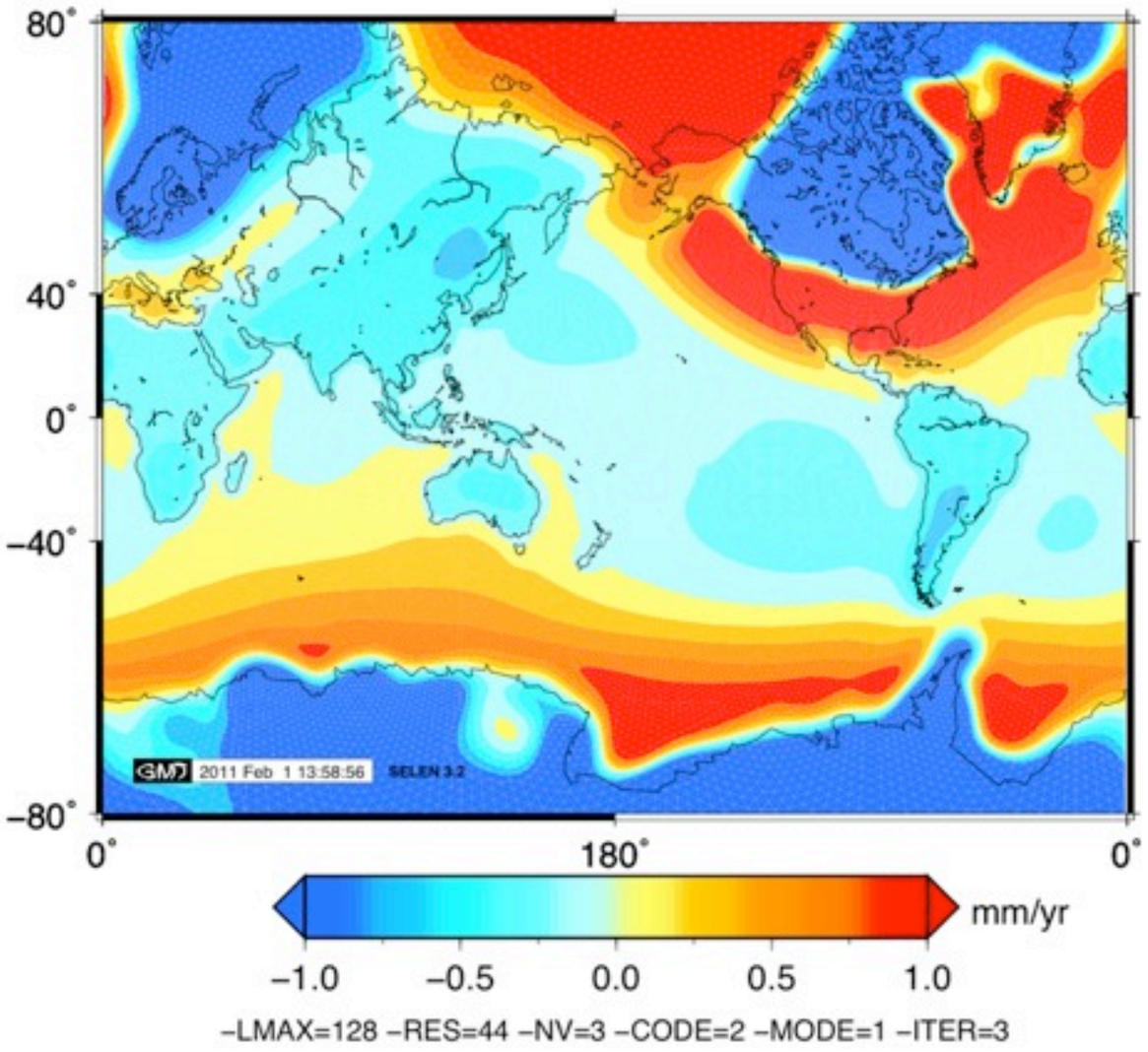



Fig. 13. Comparisons of observations and scaled-predicted relative sea-level curves (Table 2, lines 18 and 19) for various sites around Northwest Greenland (Fig. 2). Dark-grey shading indicates the estimated local marine limits (Fig. 1). Symbols: triangles—lower limits, diamonds—mean sea level, inverted triangles—upper limits.

## *Rate of sea level change today*

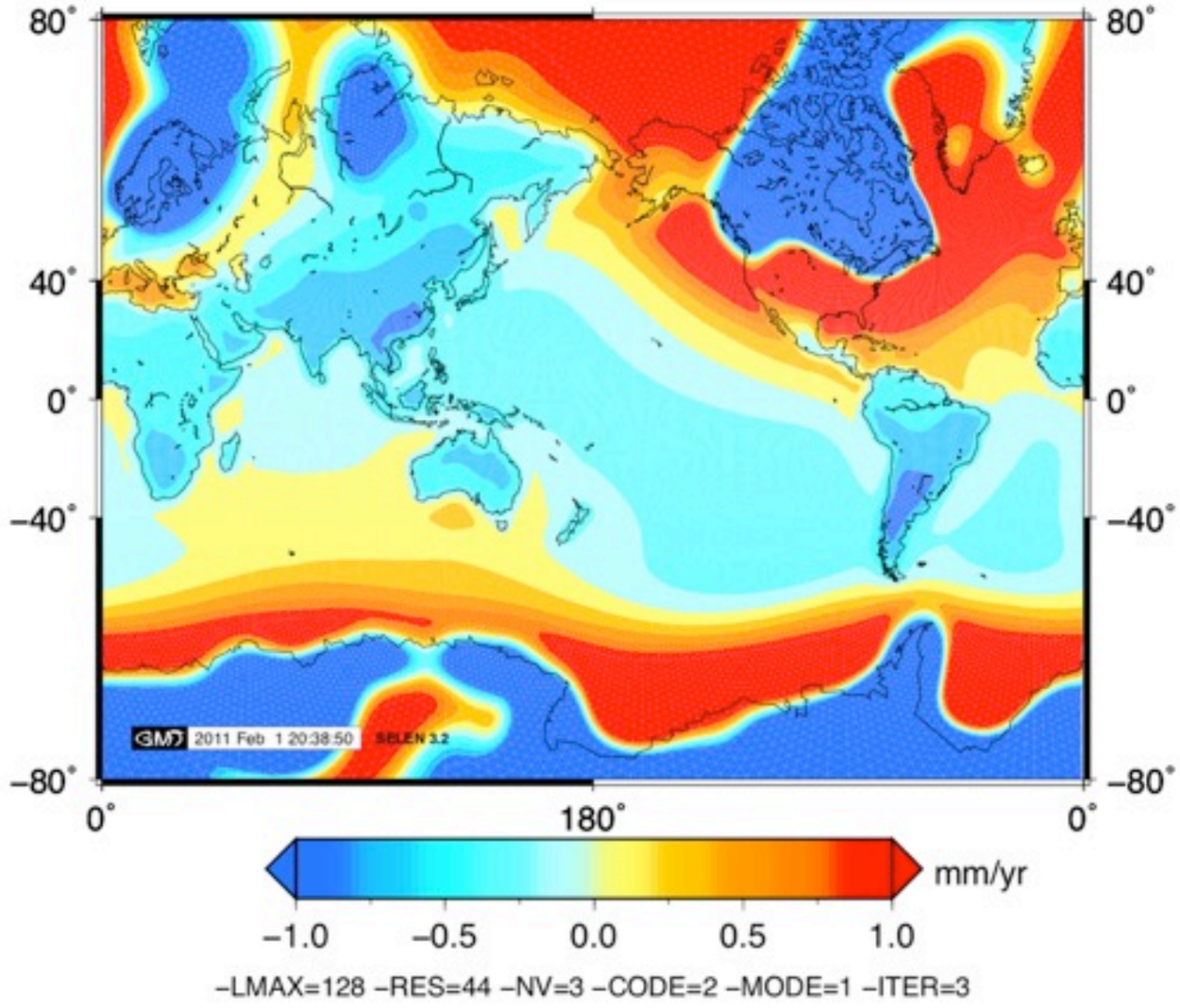
–Ice model: ICE5G –Viscosity profile: /4.0 0.4 0.4/




–LMAX=128 –RES=44 –NV=3 –CODE=2 –MODE=1 –ITER=3

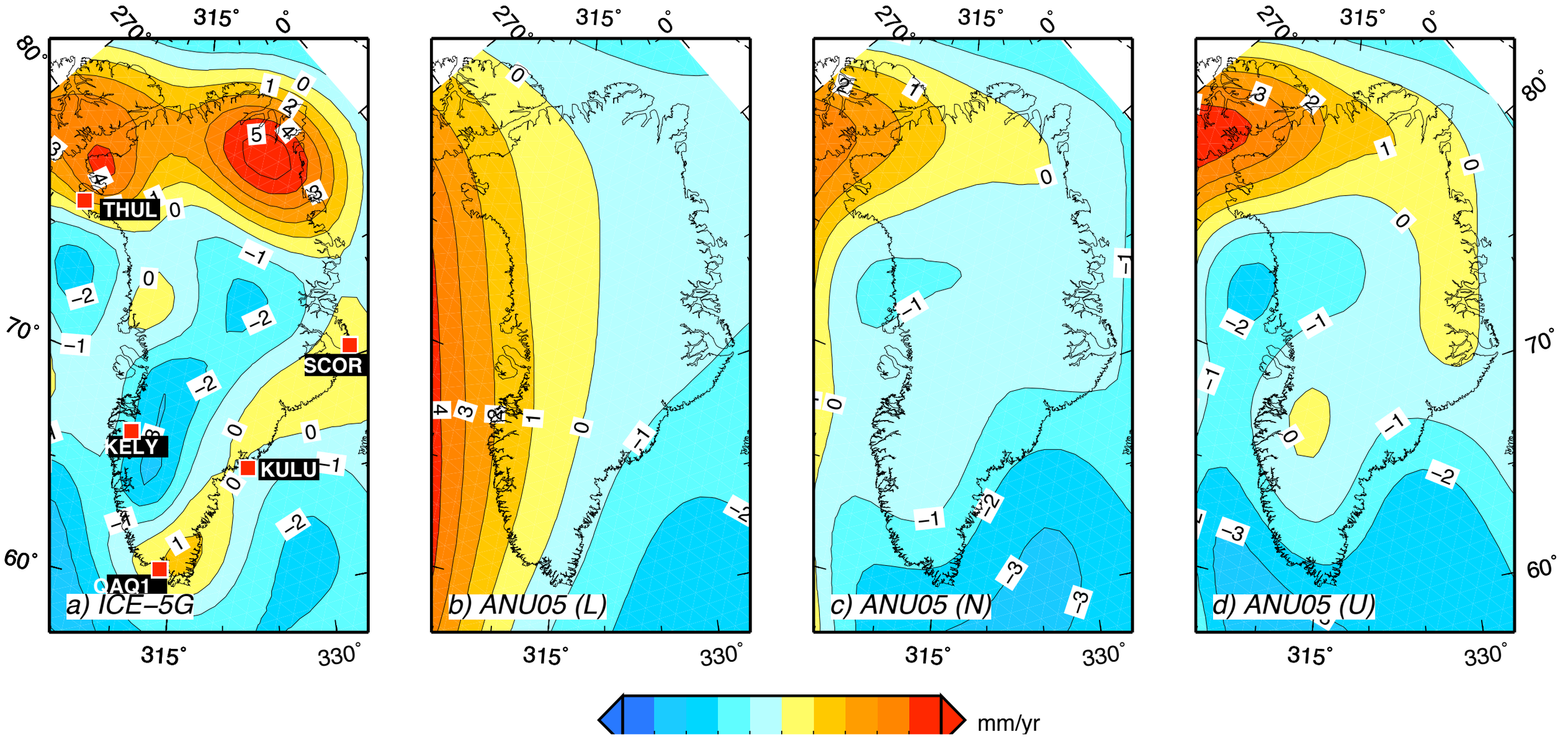
## *Rate of sea level change today*

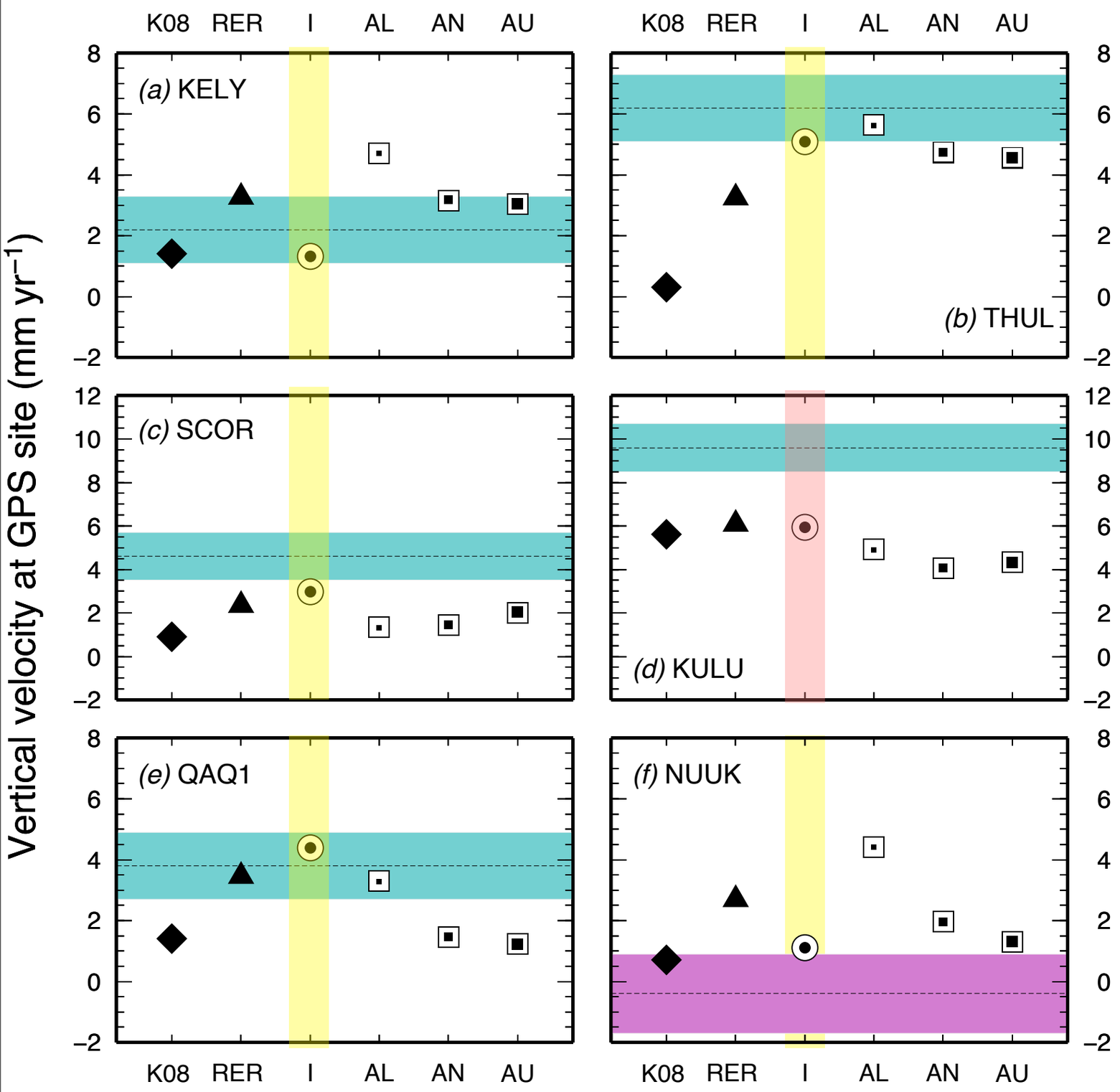
–Ice model: ANU05 –Viscosity profile: /20. 0.5 0.5/

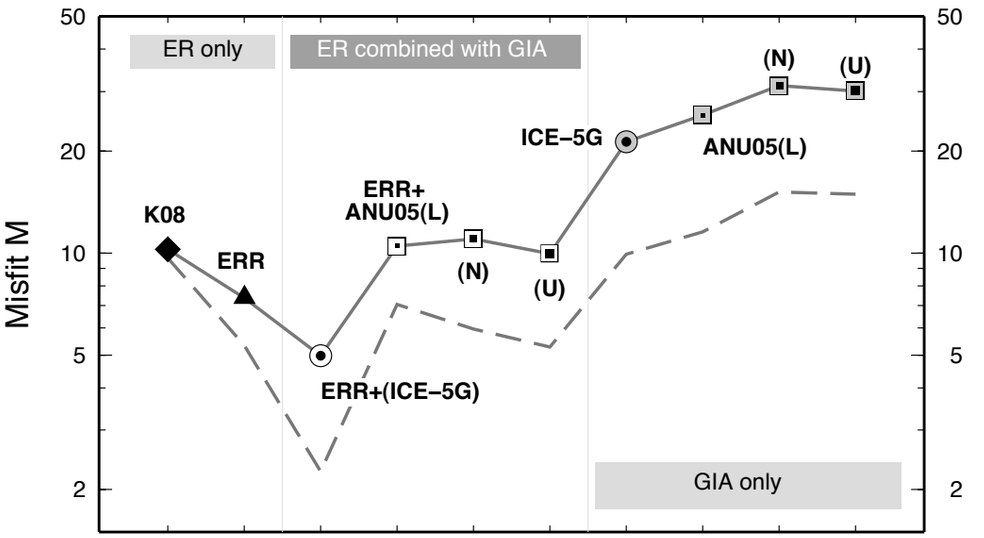


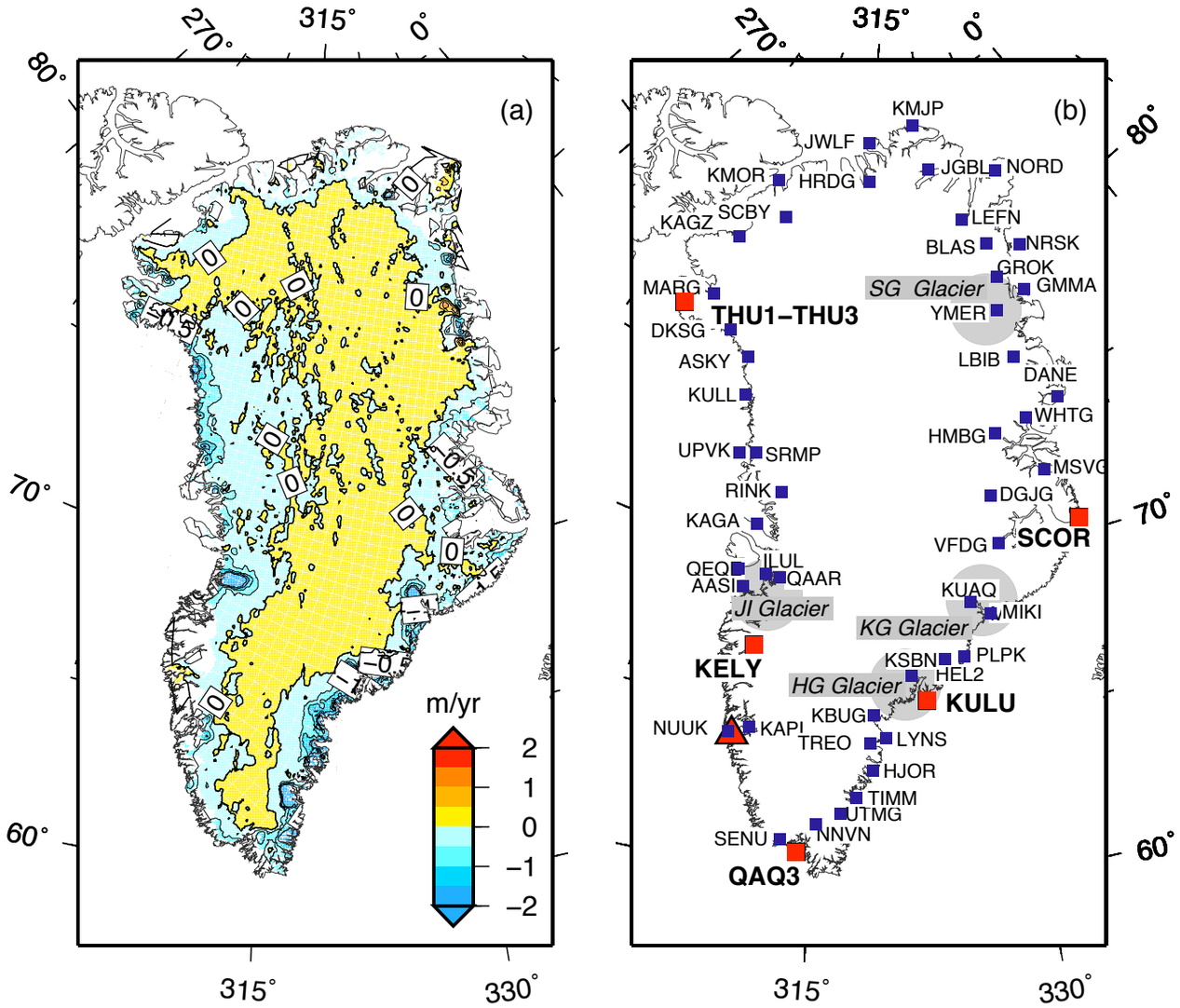

–LMAX=128 –RES=44 –NV=3 –CODE=2 –MODE=1 –ITER=3

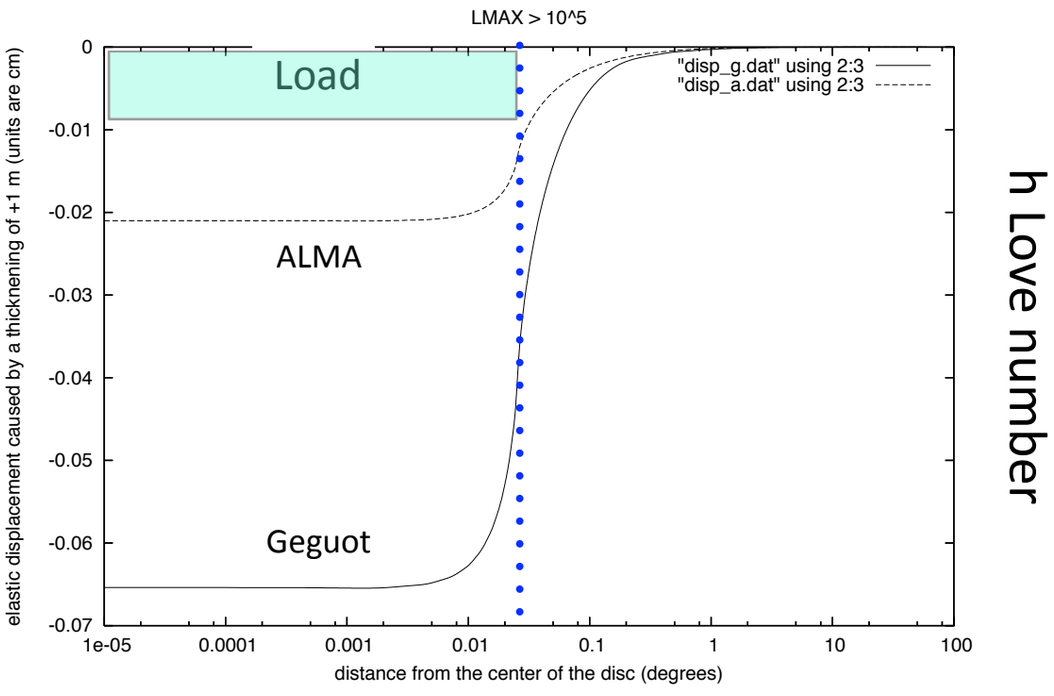
SELEN 3.0


270°
315°
0°
80°
70°
60°
315°
330°
THUL
SCOR
KELY
KULU
QAQ1
a) ICE–5G
b) ANU05 (L)
c) ANU05 (N)
d) ANU05 (U)
mm/yr


K08
RER
I
AL
AN
AU
(a) KELY
(b) THUL
(c) SCOR
(d) KULU
(e) QAQ1
(f) NUUK
Vertical velocity at GPS site (mm yr−1)
Model or combinations of models

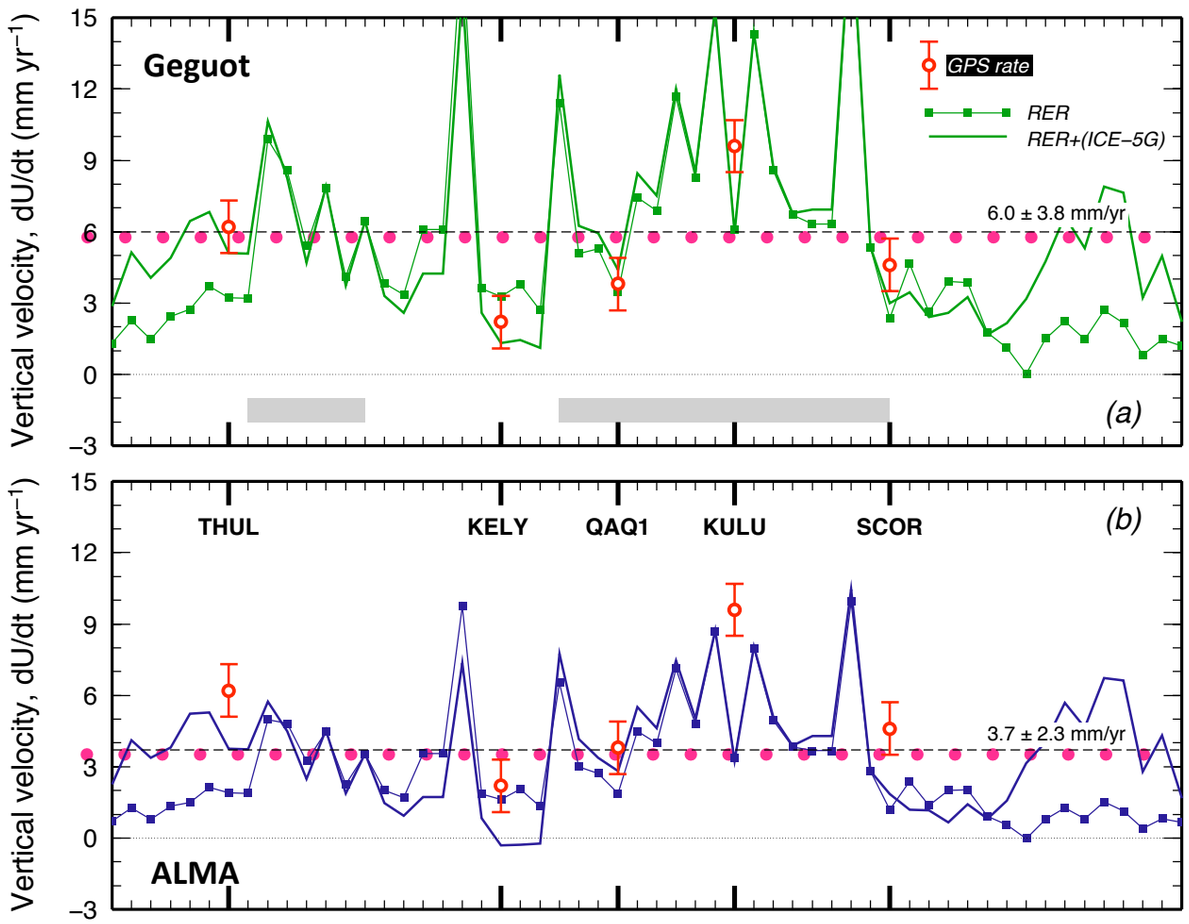

ER only
ER combined with GIA
K08
ERR
ERR+ ANU05(L)
ERR+(ICE−5G)
ICE−5G
ANU05(L)
(N)
(U)
GIA only
Misfit M
Model or combinations of models




h Love number

## Future projections - Uplift rate




*GPS / tide gauge* site