EGSIEM Autumn School
September 2017, Potsdam

Ice sheet signals

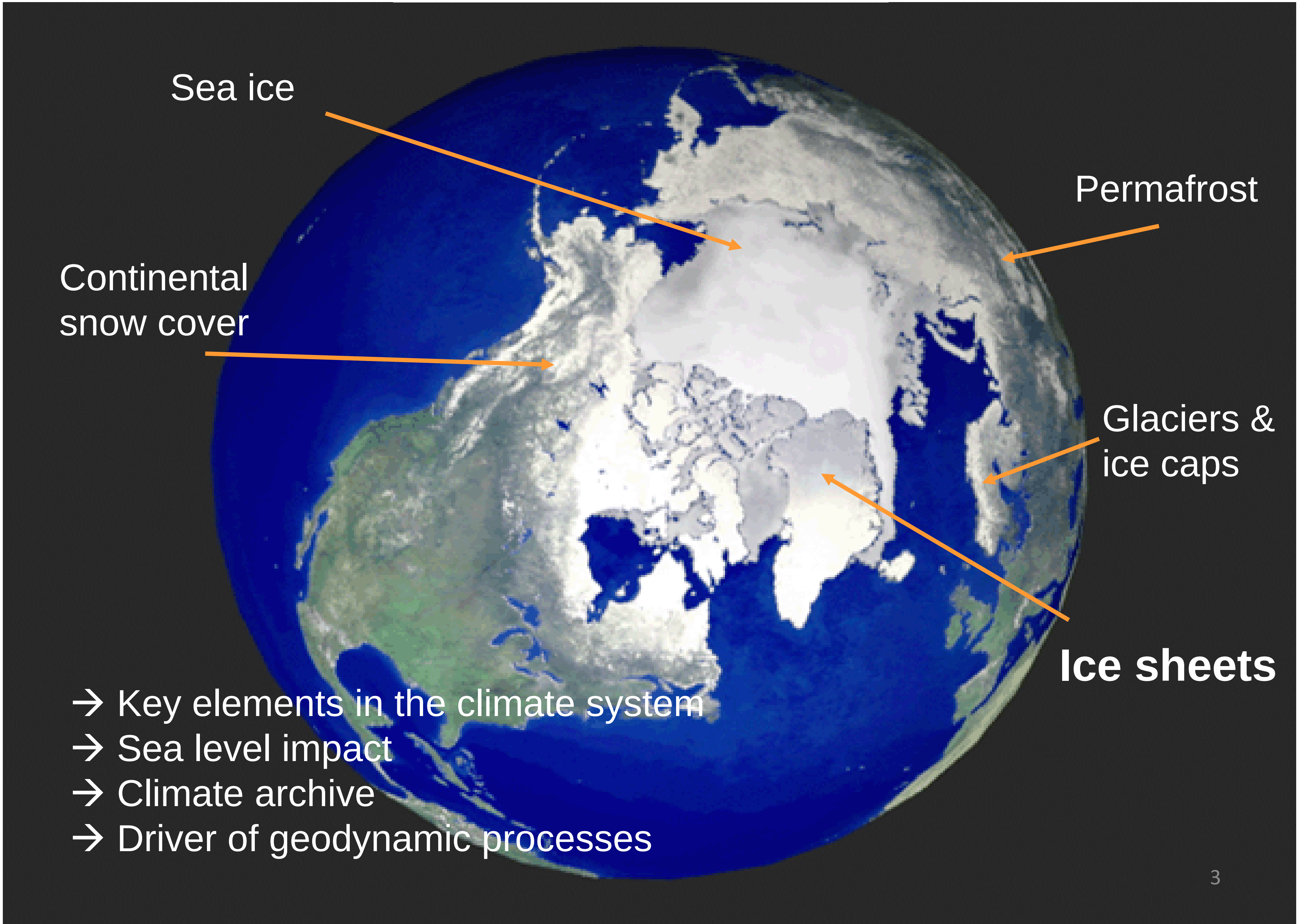
Martin Horwath

TU Dresden
Institut für Planetare Geodäsie
Chair of Geodetic Earth System Research

TECHNISCHE UNIVERSITÄT DRESDEN

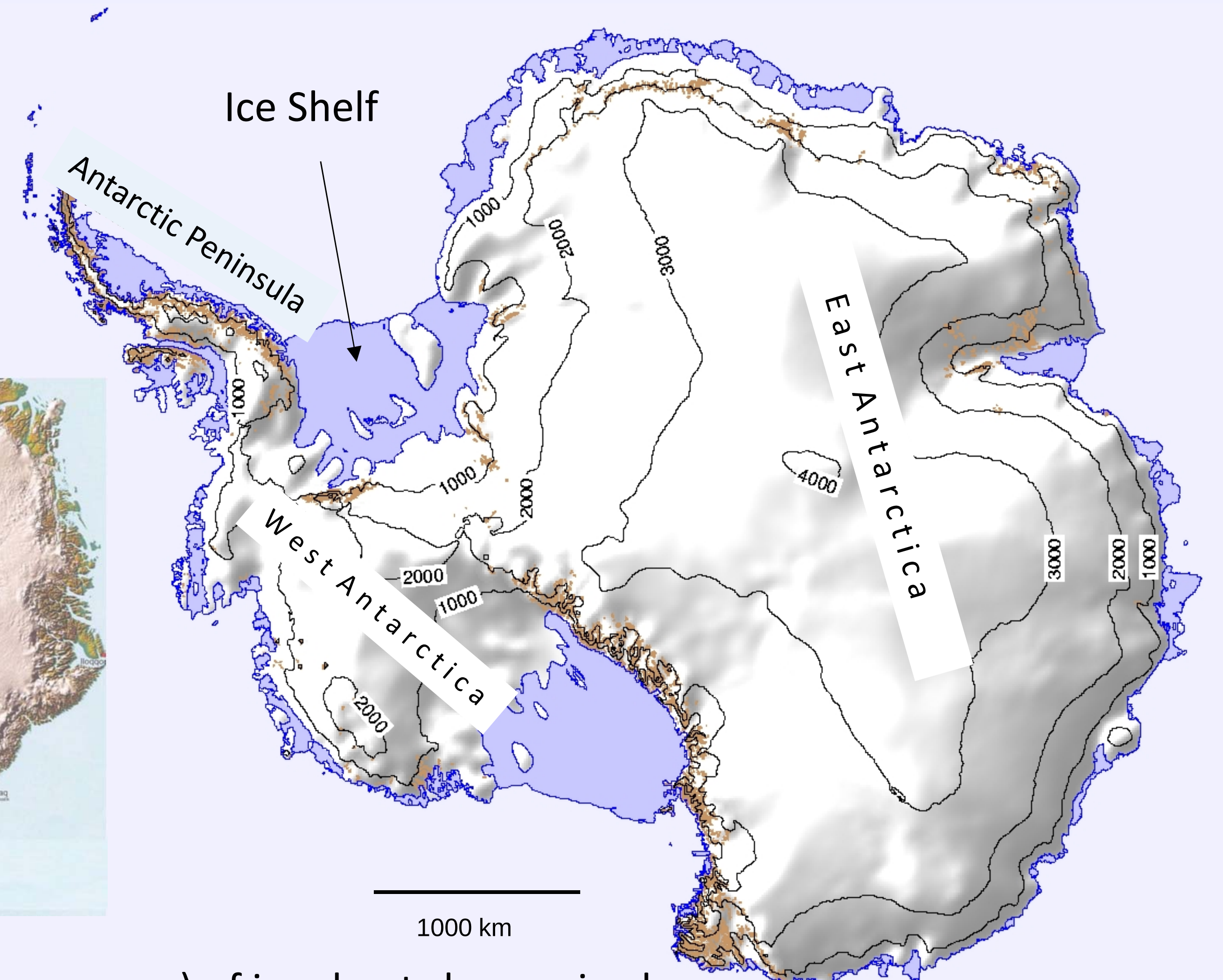
Contents

The Cryosphere

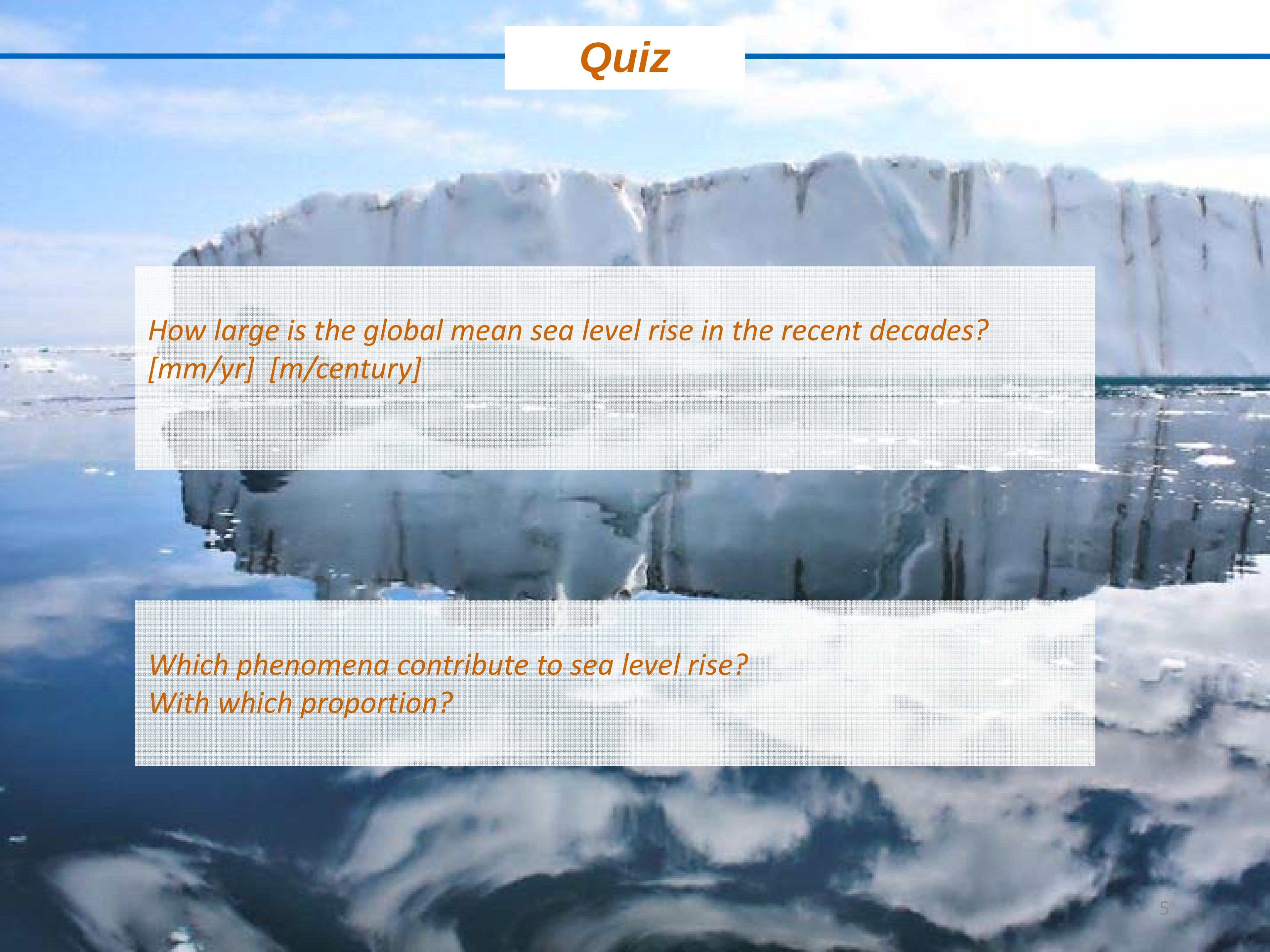


Ice sheets

Ice sheet: glacier ice covering terrain >50,000 km^2



Changes (and disappearance) of ice sheets have raised global mean sea level by ~120 m since the last glacial maximum 20 000 years ago. They bear the (theoretical) potential of another 64 m

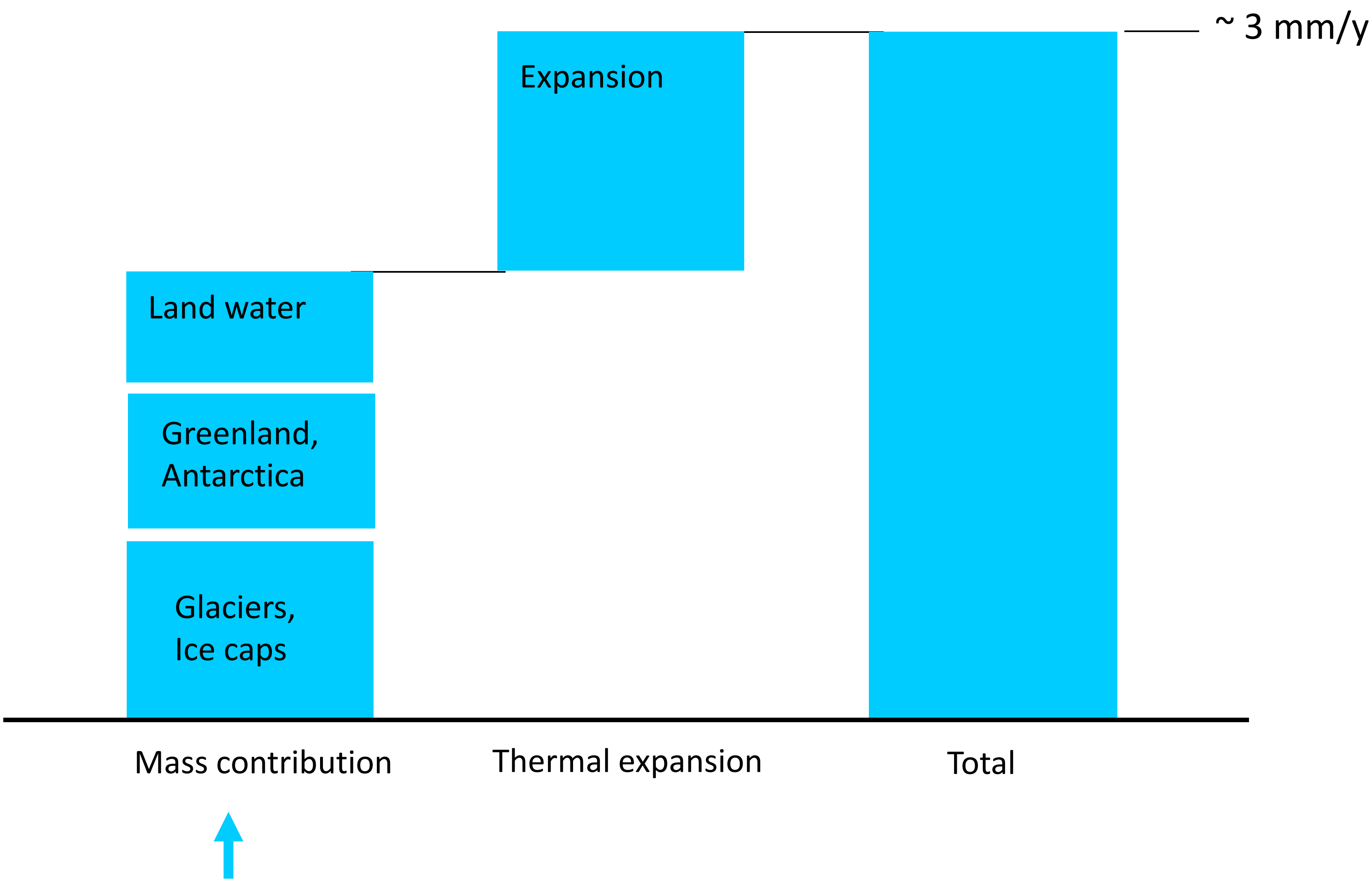


Quiz

How large is the global mean sea level rise in the recent decades?
[mm/yr] [m/century]

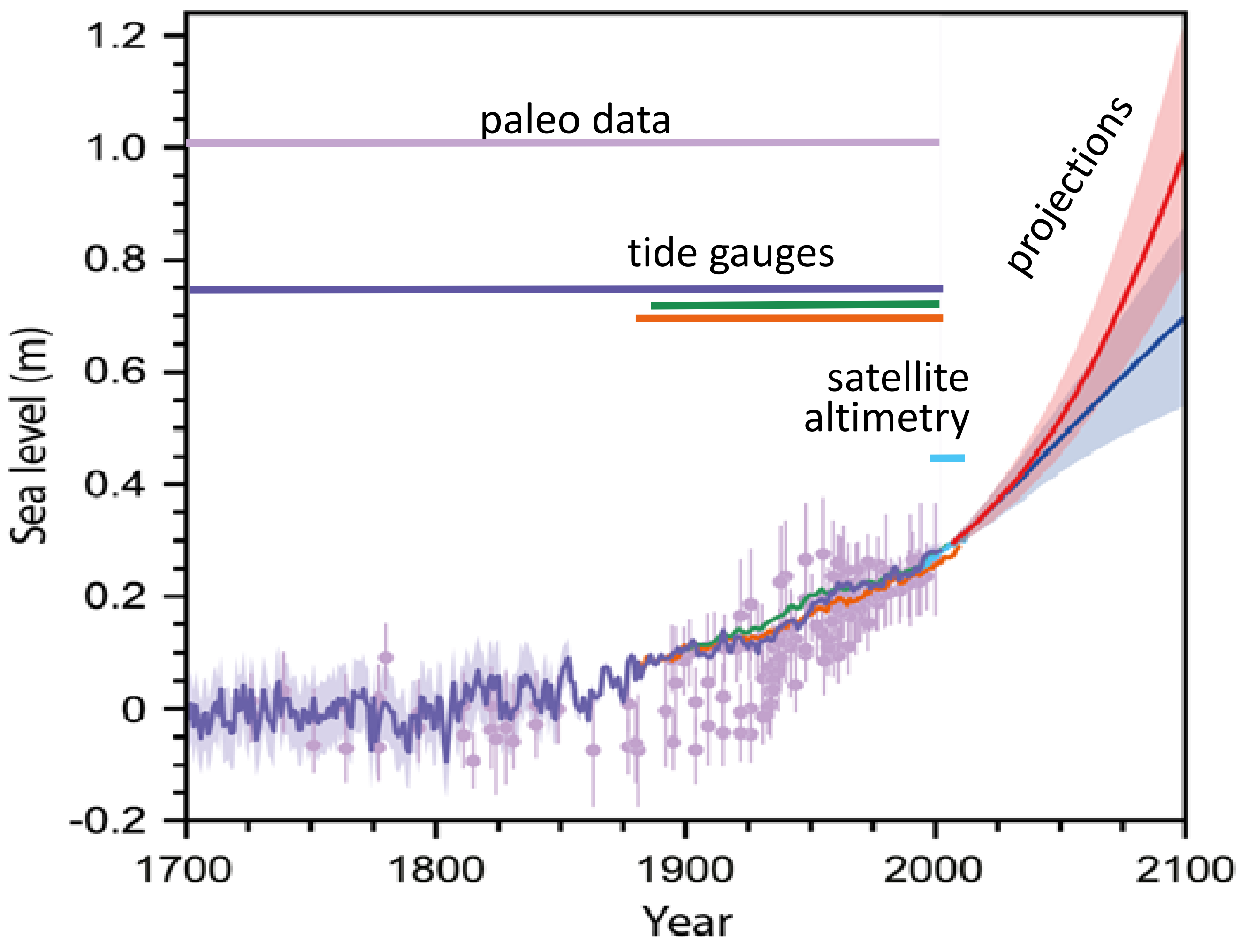
Which phenomena contribute to sea level rise?
With which proportion?

Sea level rise 1993 - 2010 [after IPCC 2013]



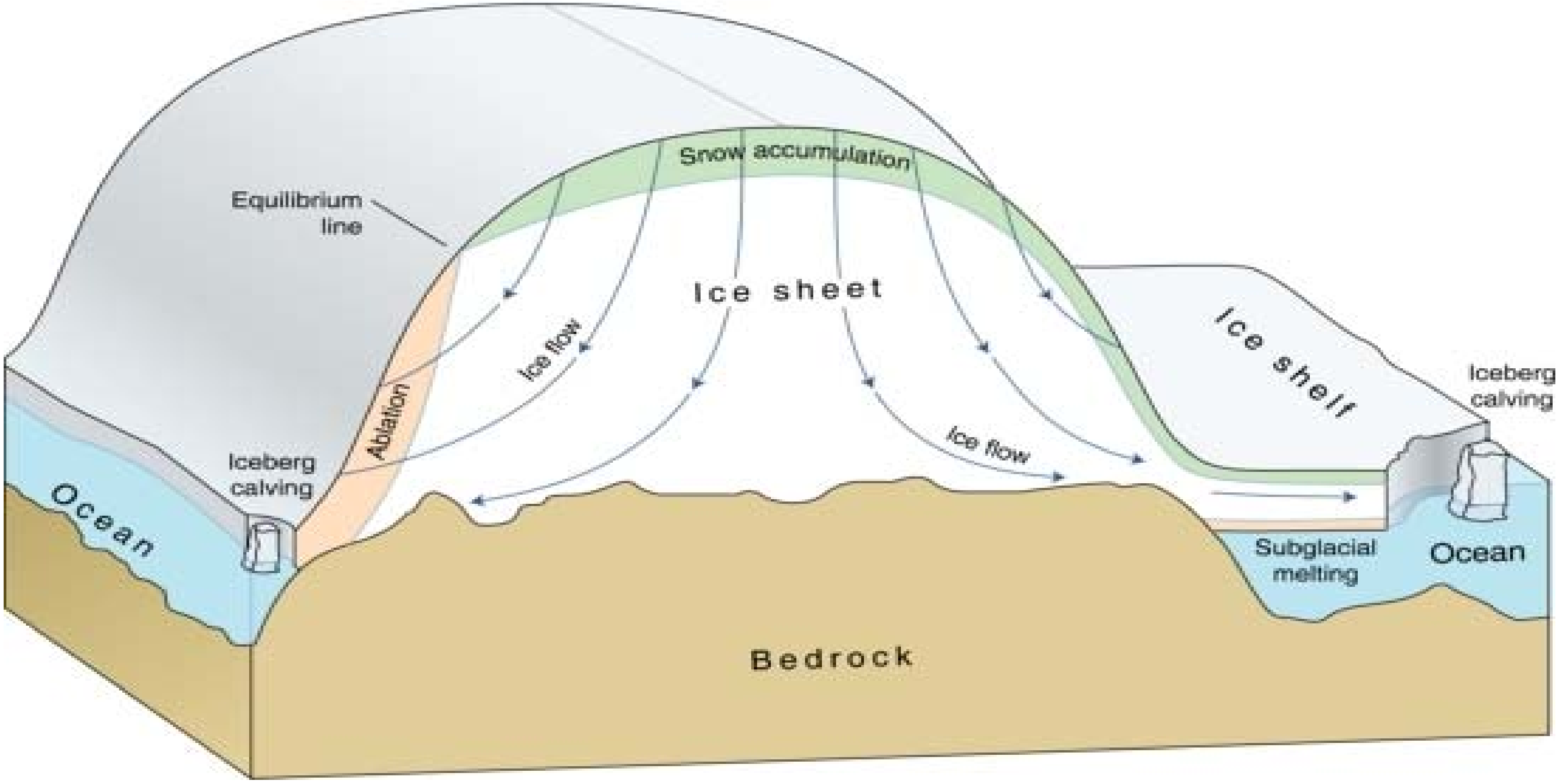
Note: uncertainties are substantial - on the order of 25 – 50%

Sea level observations and projections [IPCC 2013]



Note: Projections explicitly exclude effects of dynamic ice sheet instability, as those are poorly understood.

Components of ice sheet mass balance

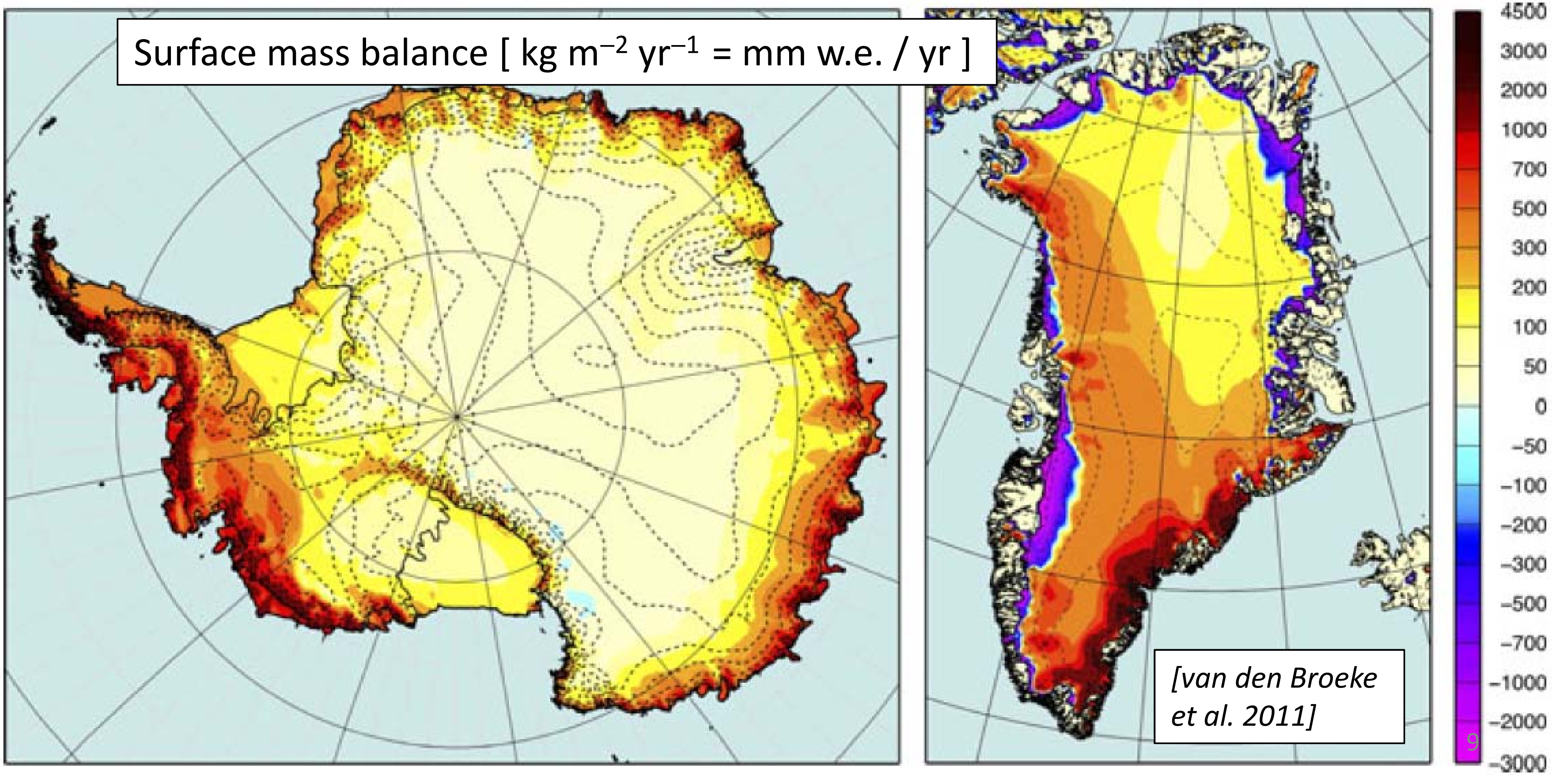


[K. Steffen, CIRES/Univ. of Colorado]

Surface mass balance

= + **Accumulation**
- Precipitation
- Drift snow deposition

- **Ablation**
- Sublimation
- Melt and runoff
- Wind erosion

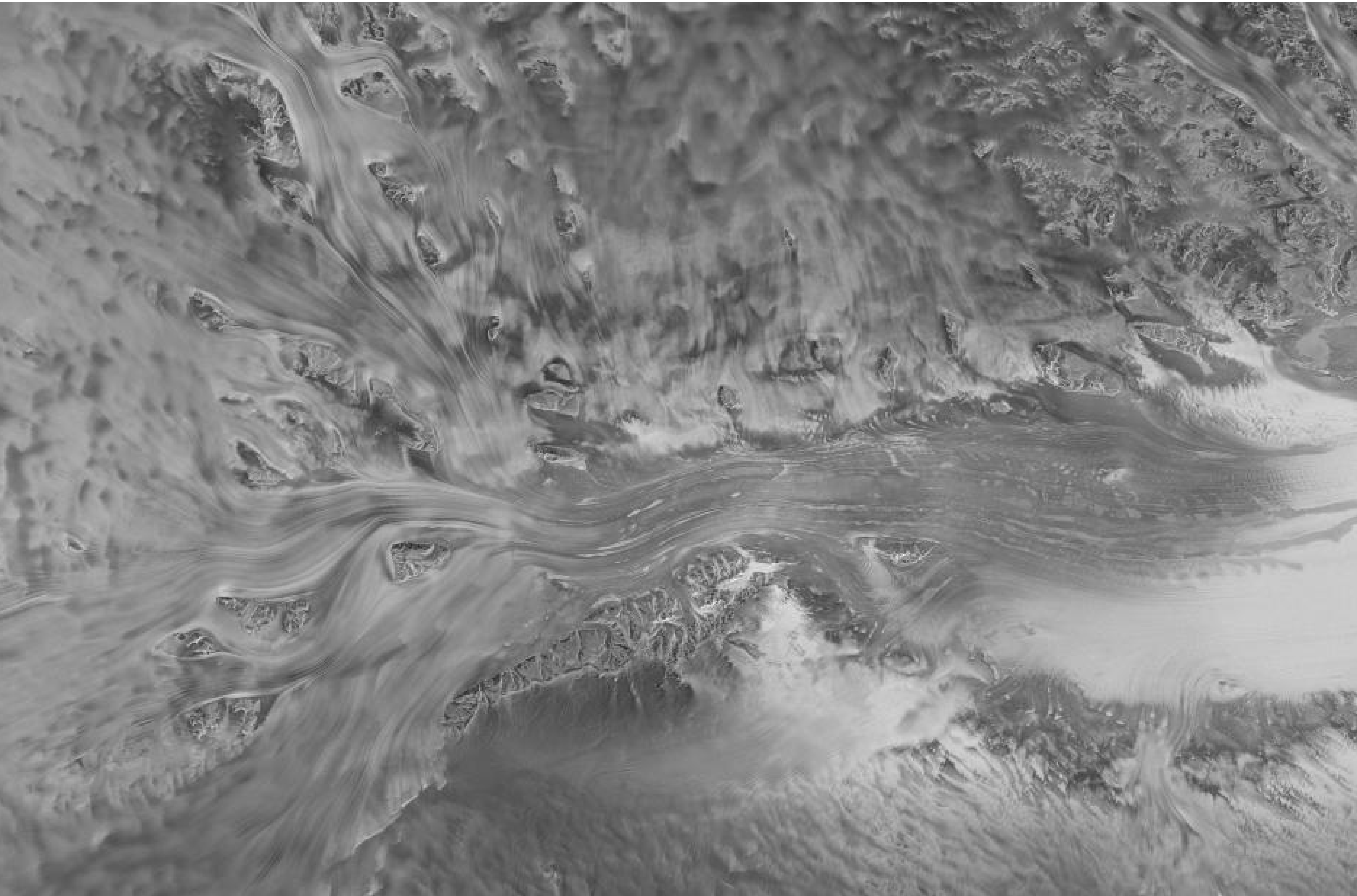


Features of surface mass balance

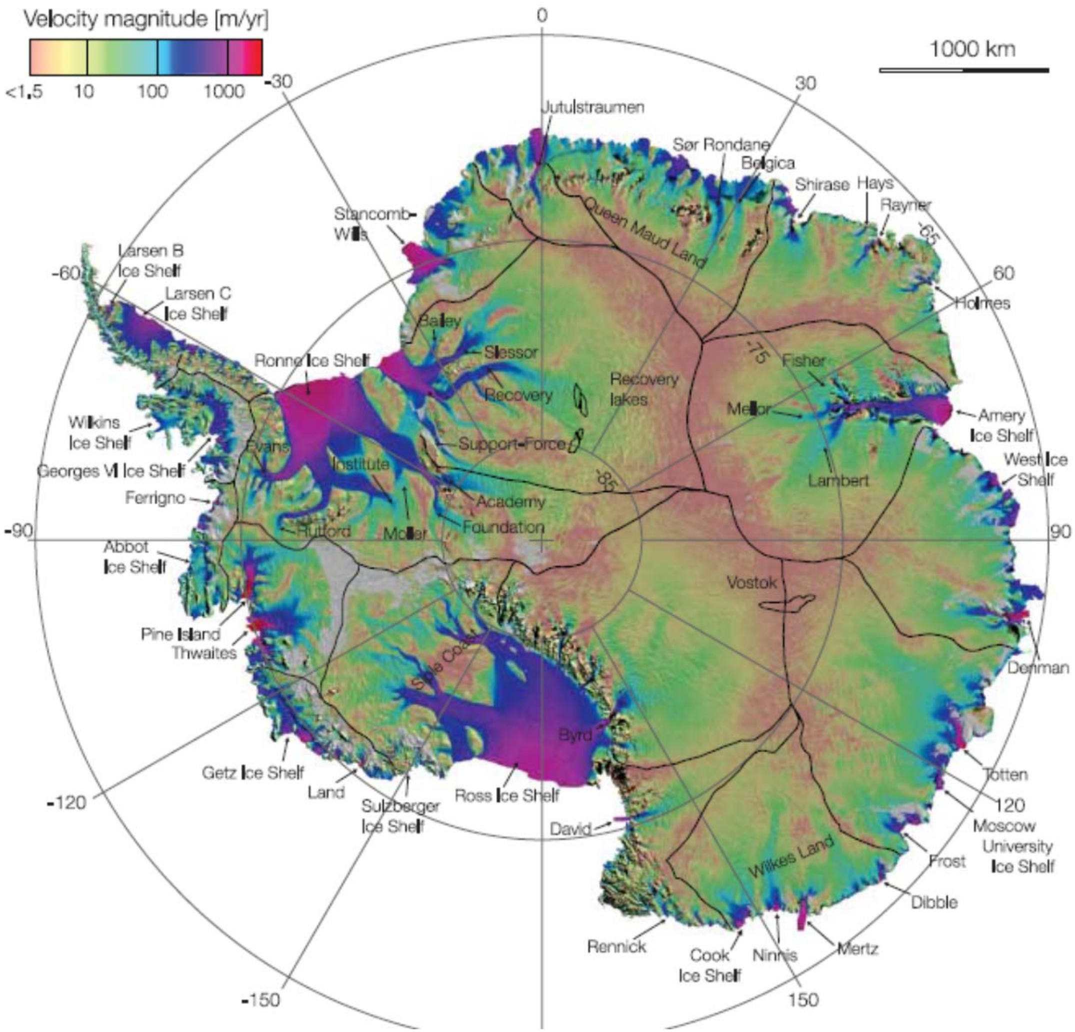
Meltwater river

Firn layers

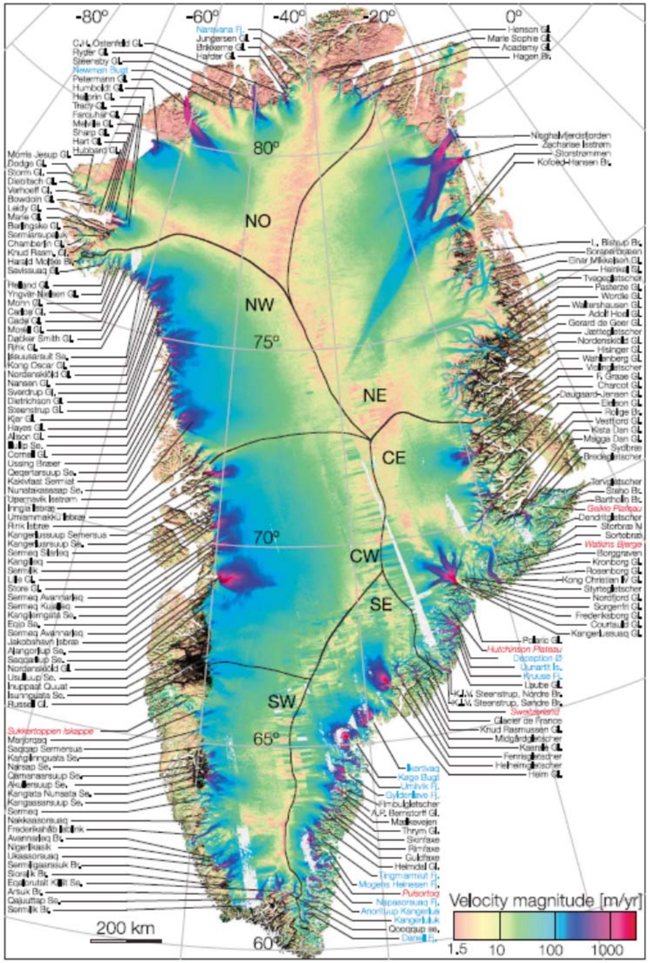
Ice flow … … is driven by gravity



Complex patterns of ice sheet flow



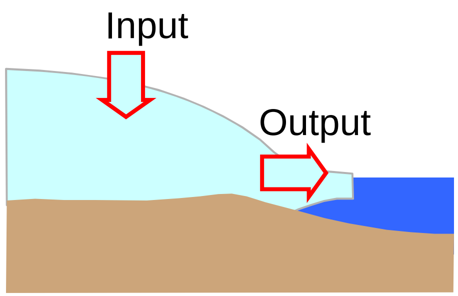
[Rignot et al. 2011]



[Rignot & Mouginot 2012]

Mass balance: Three observation approaches

Input-Output

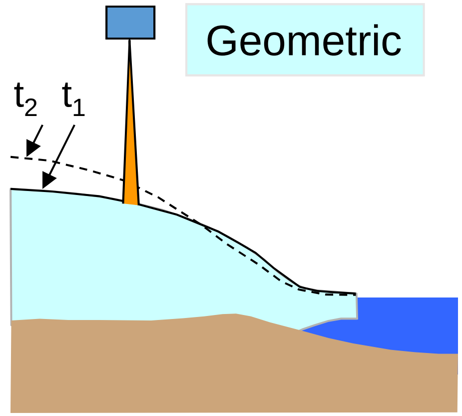


Integral mass balance over a drainage basin, temporal sampling according to remote sensing data for output

+ partitioning of mass balance into the underlying glaciological processes

- Relative errors in “input“ (surface mass balance) and “output” (ice flow) add up to large relative errors of their small difference

Geometric



High temporal and spatial resolution (e.g. 35d, 10km)

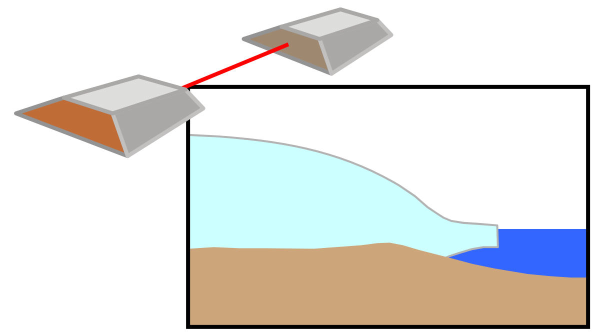
+ longest time series (different missions since 1992)

- Interpolation of point measurements to surface

- Conversion from volume to mass

- Small systematic errors may add up over large areas to large uncertainties

Gravimetric



Low spatial resolution (200-400km), high temporal resolution (1 month)

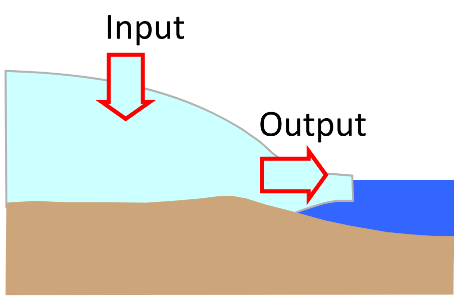
+ Direct sensitivity to *mass* changes

- Superimposed GIA is main source of uncertainty for Antarctica

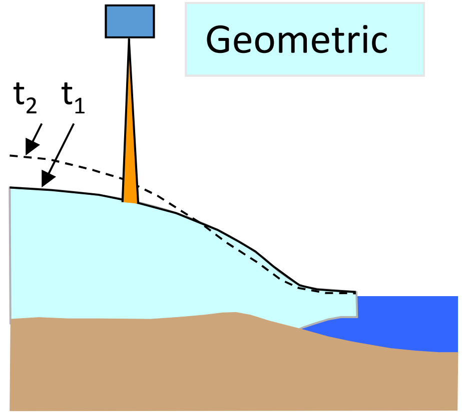
- More possible systematic uncertainties: degree 1, C_{20}

Antarctica: Three observation approaches

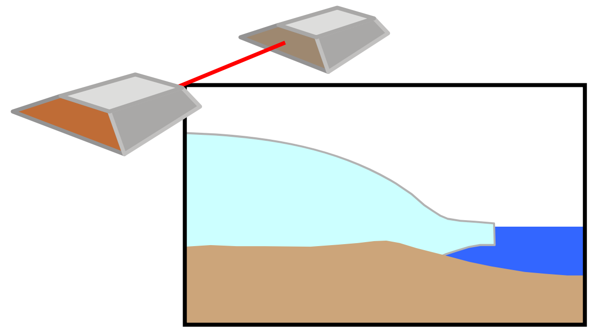
Input-Output

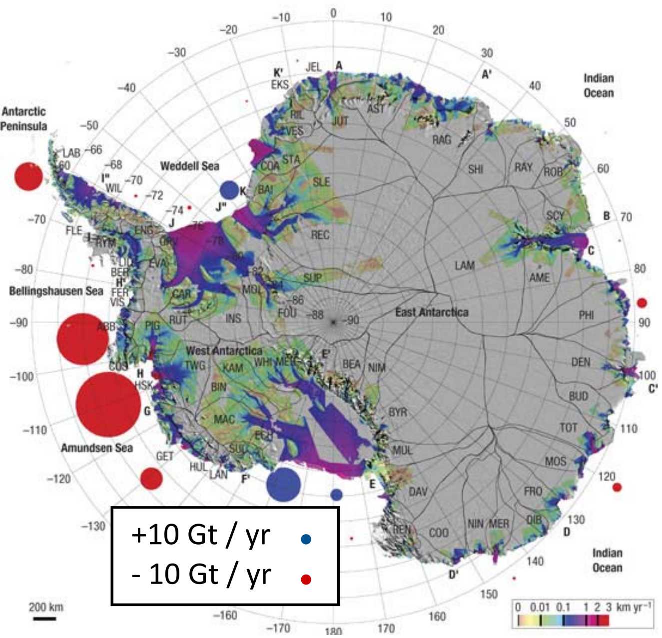


Geometric

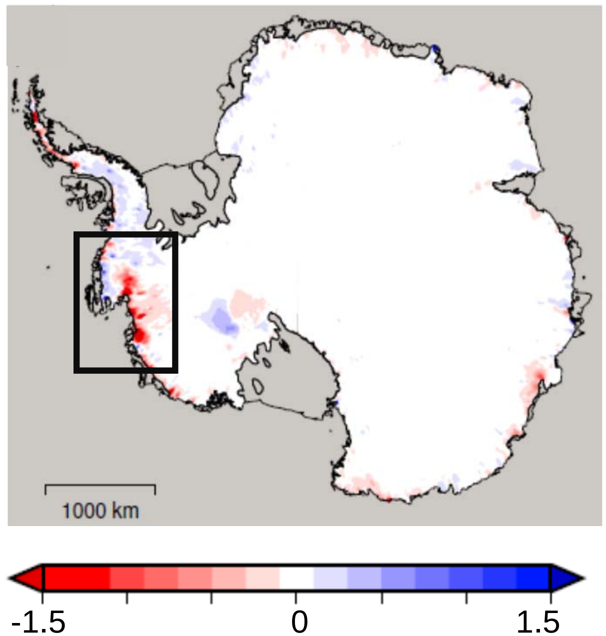


Gravimetric



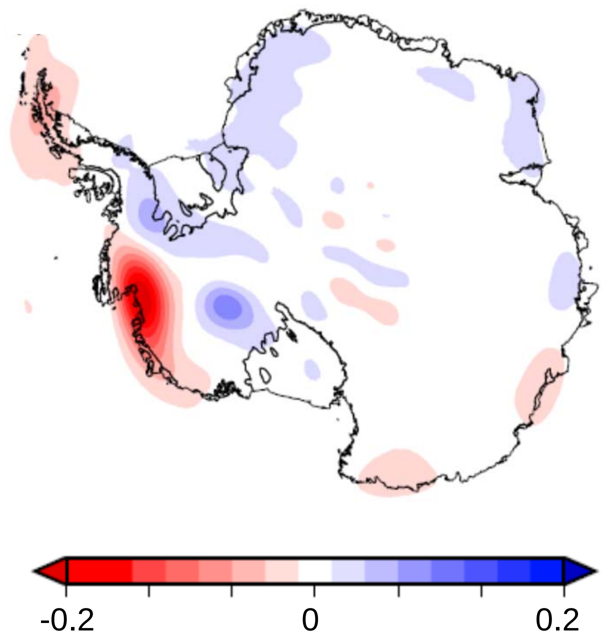


Mass balance 2000
[Rignot et al., 2008]



Surface elevation trend 2003-2008
From ICESat laser altimetry [m/yr]

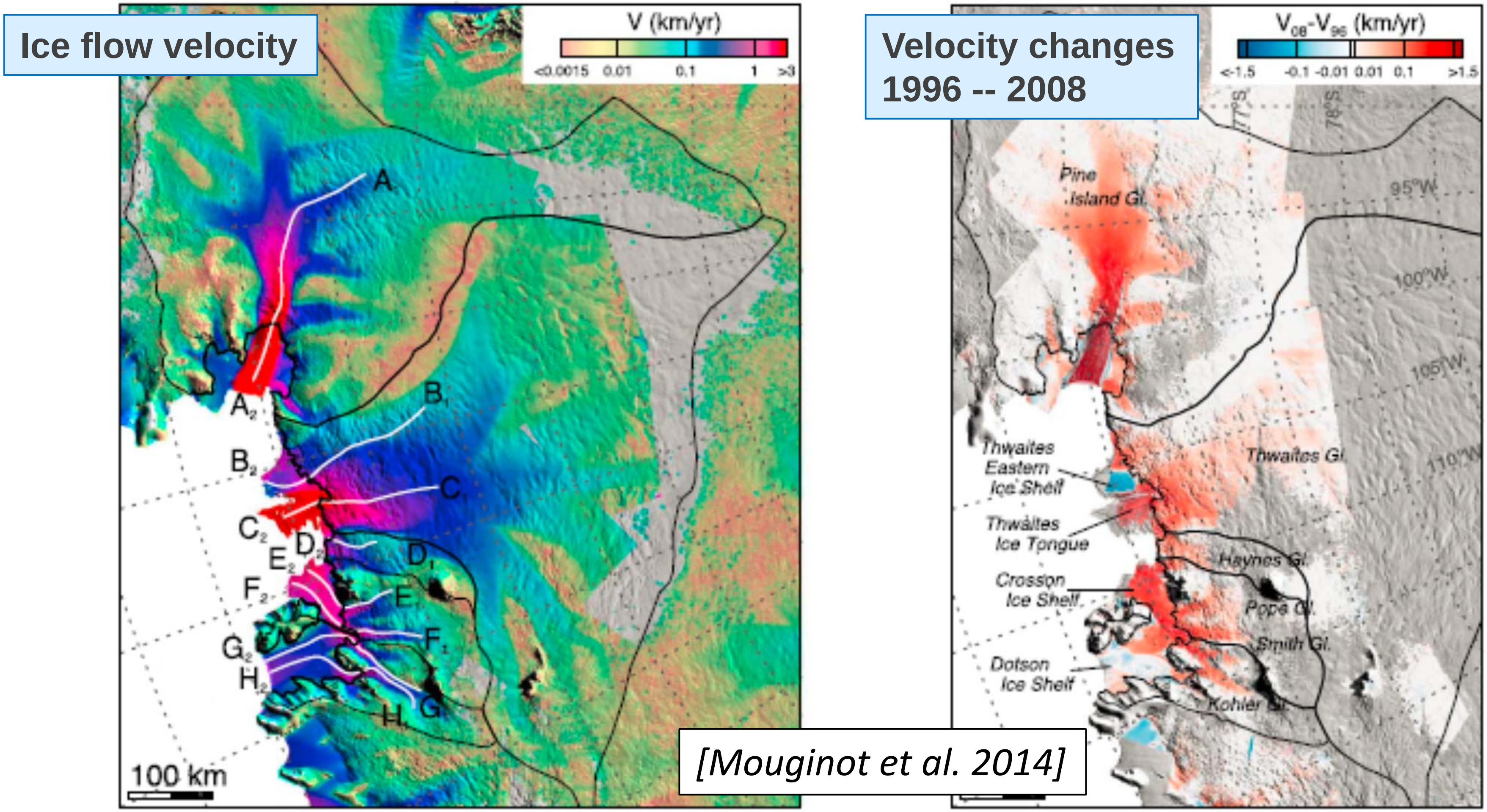
[Groh et al 2014]



Mass trend 2003-2008 from
GRACE [m w.e. / yr]

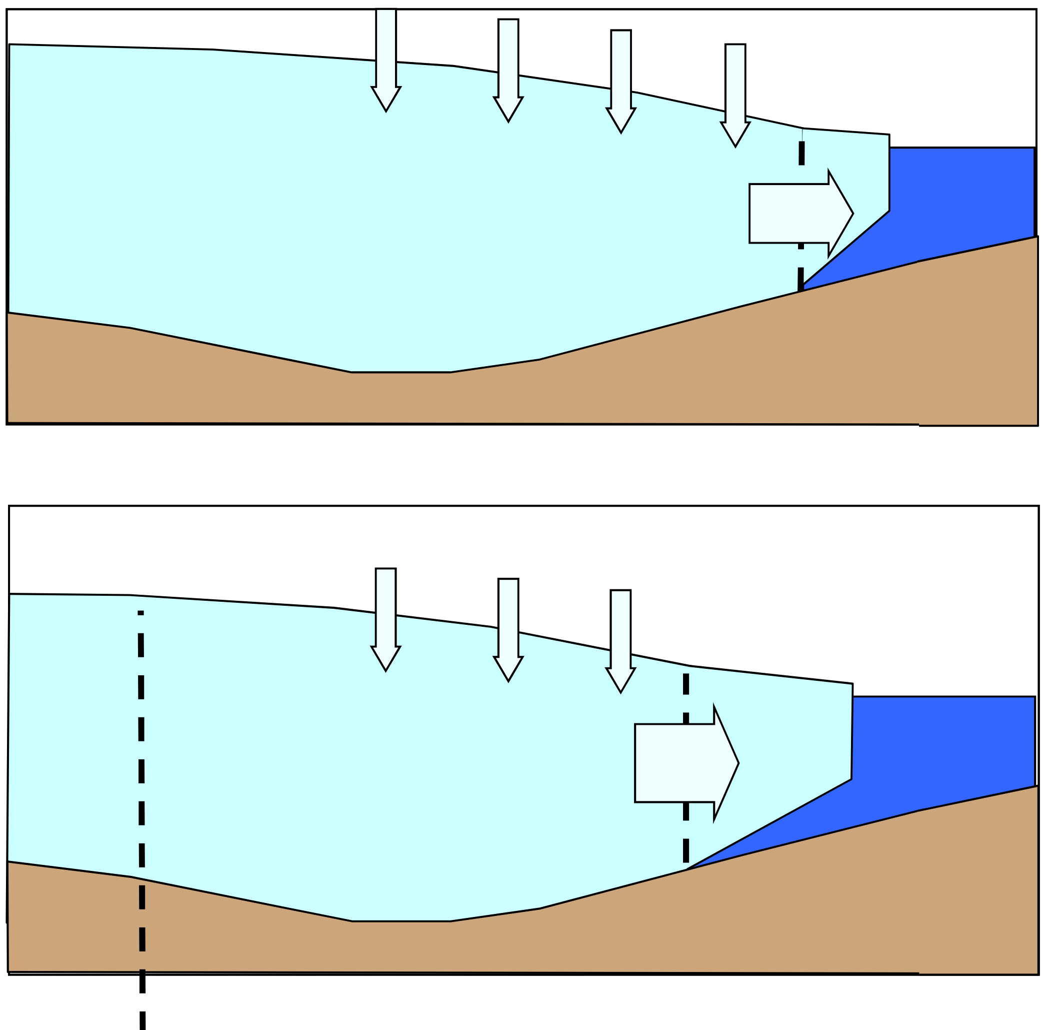
[Horwath 2015]

Dynamic thinning in West Antarctica



Enhanced ice discharge through Ice flow acceleration
← thinning of downstream ice shelves
← enhanced sub-ice-shelf melting
← warm ocean water intrusion

Possible instability of a marine-based ice sheet



Discharge exceeds accumulation
→ Retreat of the grounding line

Discharge exceeds accumulation even more
→ Further retreat

Next stable grounding line position

Antarctica: Synthesis

- Antarctic ice sheet is losing mass (on the order of 0.3 mm/yr global mean sea level equivalent)
- Main cause: changes in the ice flow dynamics in West Antarctica. Ice discharge is not compensated by net snow accumulation
- These changes were triggered by changes in the oceanic boundary conditions (warming and variation of currents) which led to increased bottom melt at the ice-ocean interface of the ice shelves, thinning of the ice shelves and a reduction of their resistive forces to ice flow of the grounded glaciers.

Antarctica: Prognosis

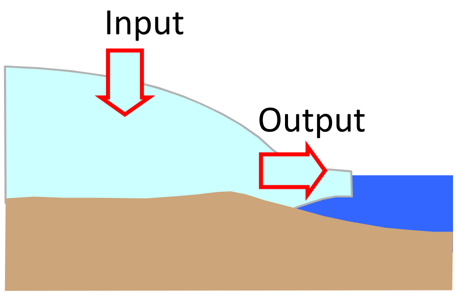
Surface mass balance: Increase with warming climate

Ice discharge: likely continues at the current level or further increases – but how much?

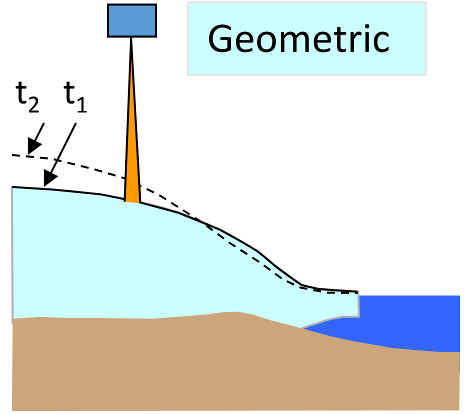
Total effect for the next century: ???

Greenland: Three observation approaches

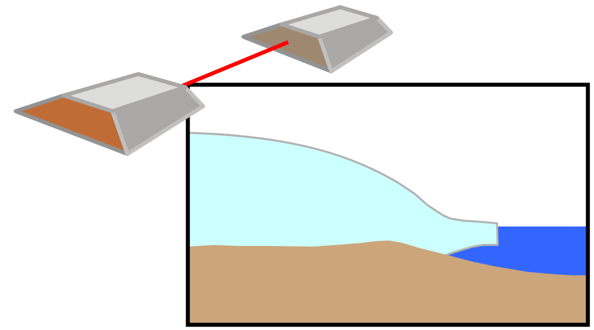
Input-Output

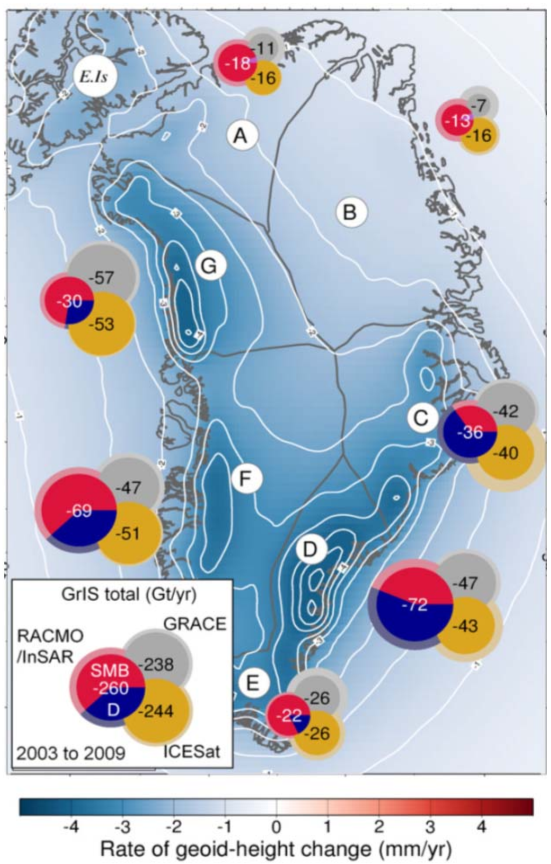


Geometric

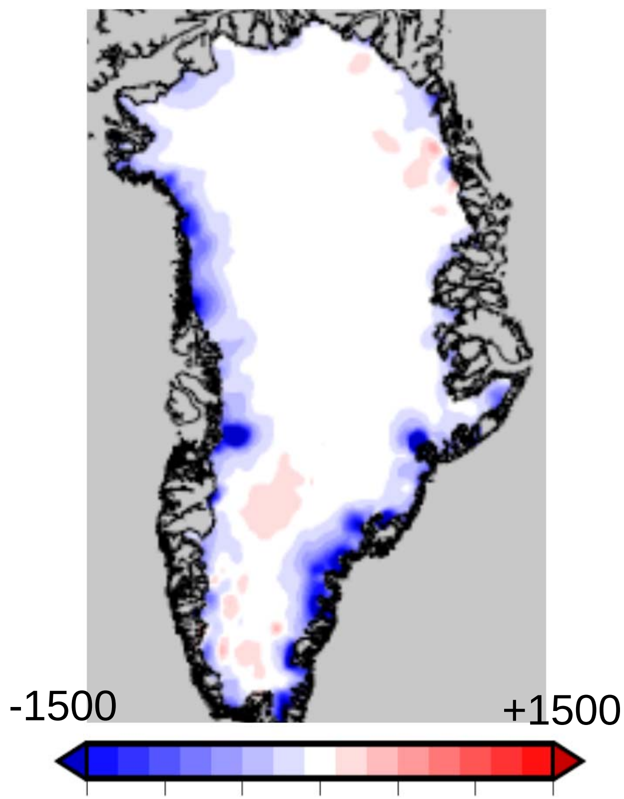


Gravimetric

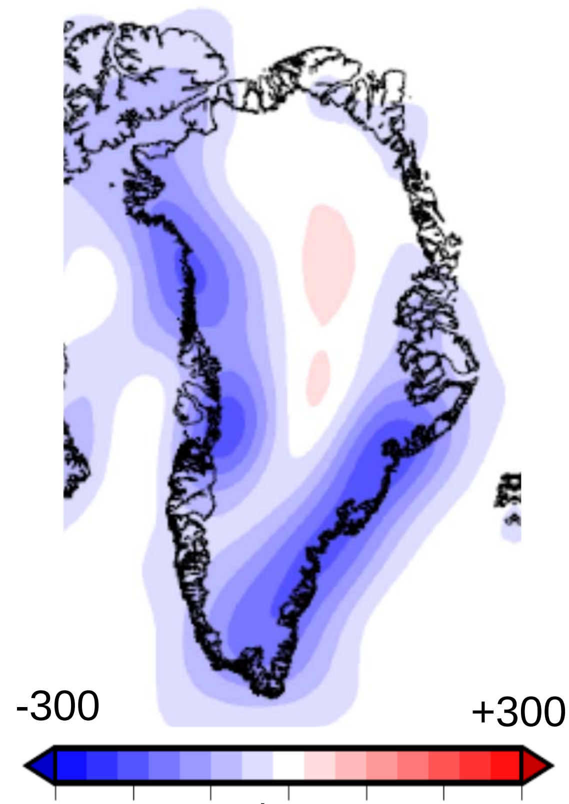




[Sasgen et al. 2012]



Surface height trend 2003-2008 [mm/yr] *[Groh et al 2014]*



Mass trend 2003-2008 [mm w.e. / yr] *[Horwath 2015]*

Greenland: Synthesis

Greenland ice sheet is losing mass (on the order of 0.7 mm/yr global mean sea level equivalent)

Two causes:

- Decrease in surface mass balance: increase of melt exceeds increase of snowfall
- Increase in discharge by ice flow due to ice-ocean interaction

Complex interplay between surface melt and ice flow dynamics, e.g. through lubrication of glacier beds by meltwater.

Greenland: Prognosis

Both surface mass balance and ice discharge act in the same direction (towards ice mass loss) when adapting to warming climate

Limited understanding of process details limits present predicting capability

Contents

Spherical harmonic representation of gravity field changes and surface mass changes

Geoid height changes

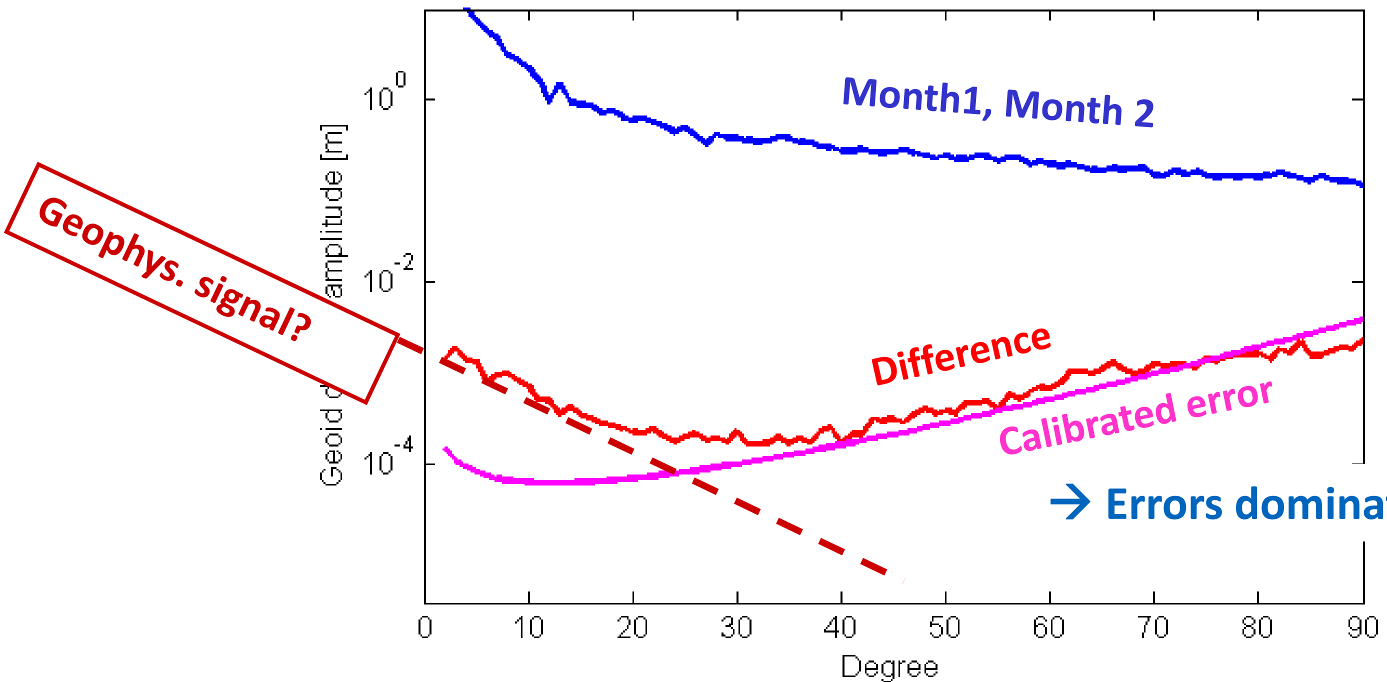
$$\Delta N(\lambda,\vartheta) = R\sum_{n=0}^{\infty}\sum_{m=-n}^{n}\Delta c_{nm}Y_{nm}(\lambda,\vartheta)$$

Stokes coefficients

Equivalent surface mass density changes

$$\Delta\kappa(\lambda,\vartheta) = \frac{M}{4\pi R^2}\sum_{n=0}^{\infty}\frac{2n+1}{1+k_n'}\sum_{m=-n}^{n}\Delta c_{nm}Y_{nm}(\lambda,\vartheta)$$

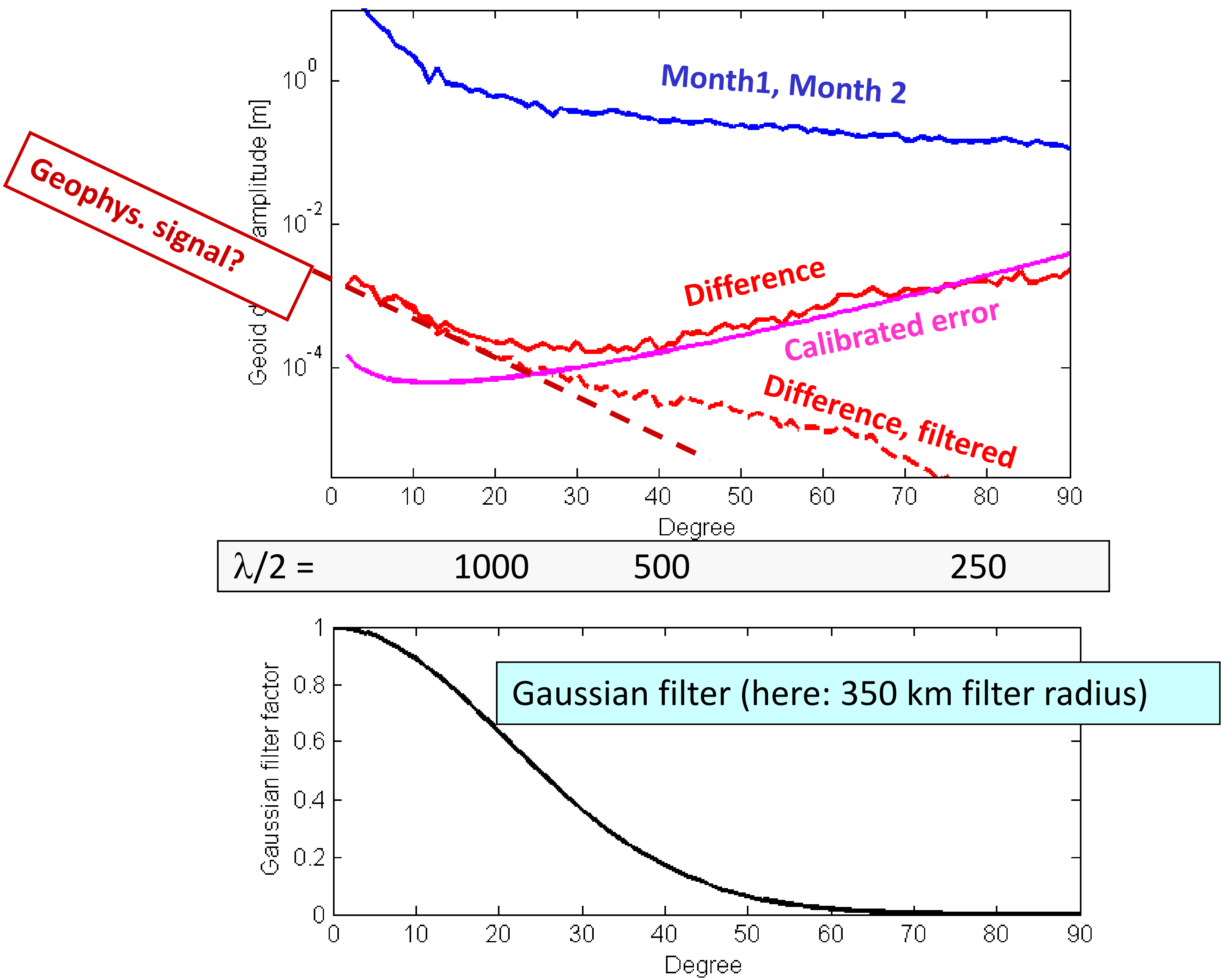
Signal and noise in time-variable GRACE solutions



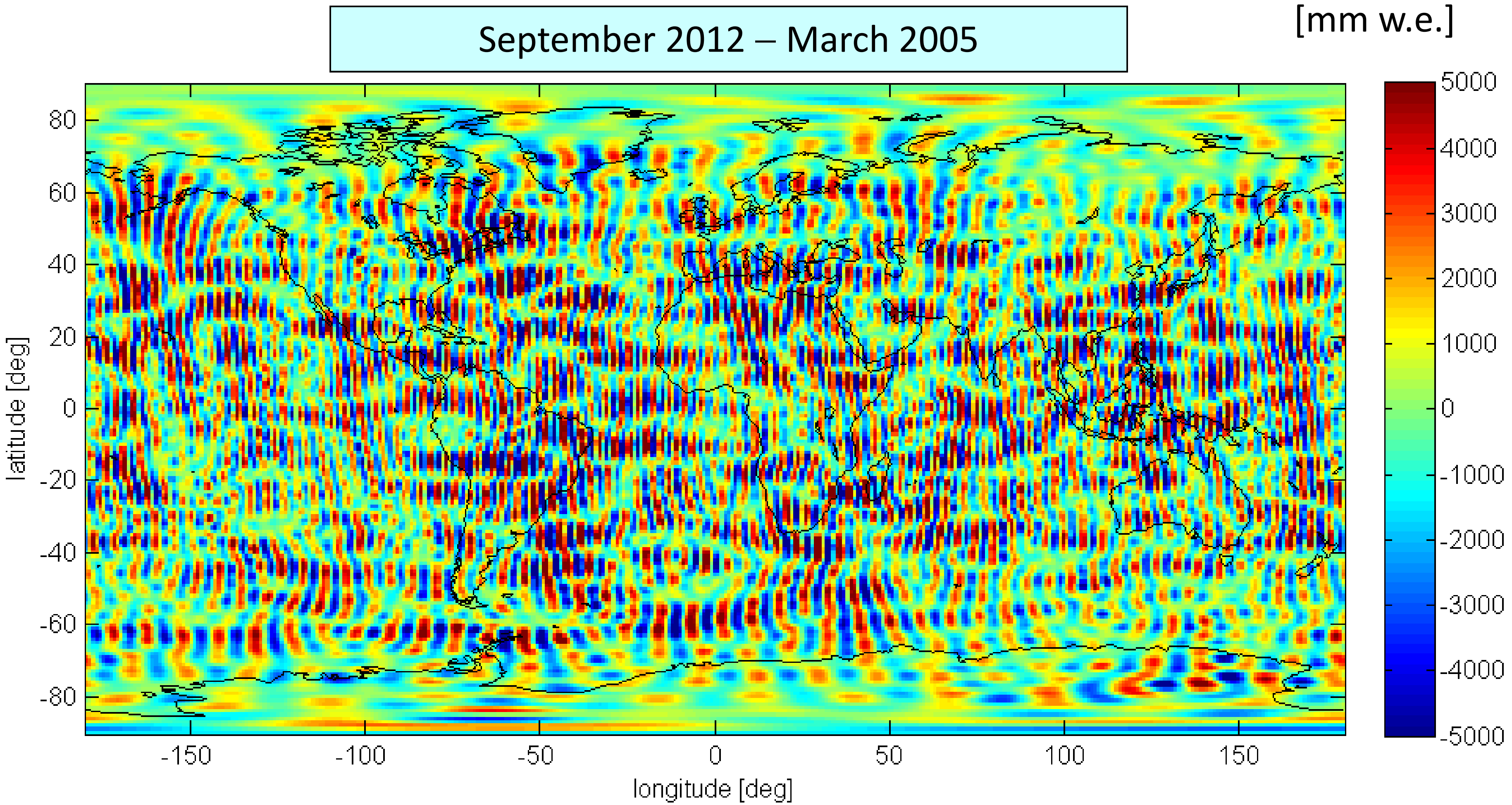
→ Errors dominate the difference!

λ/2 =	1000	500	250

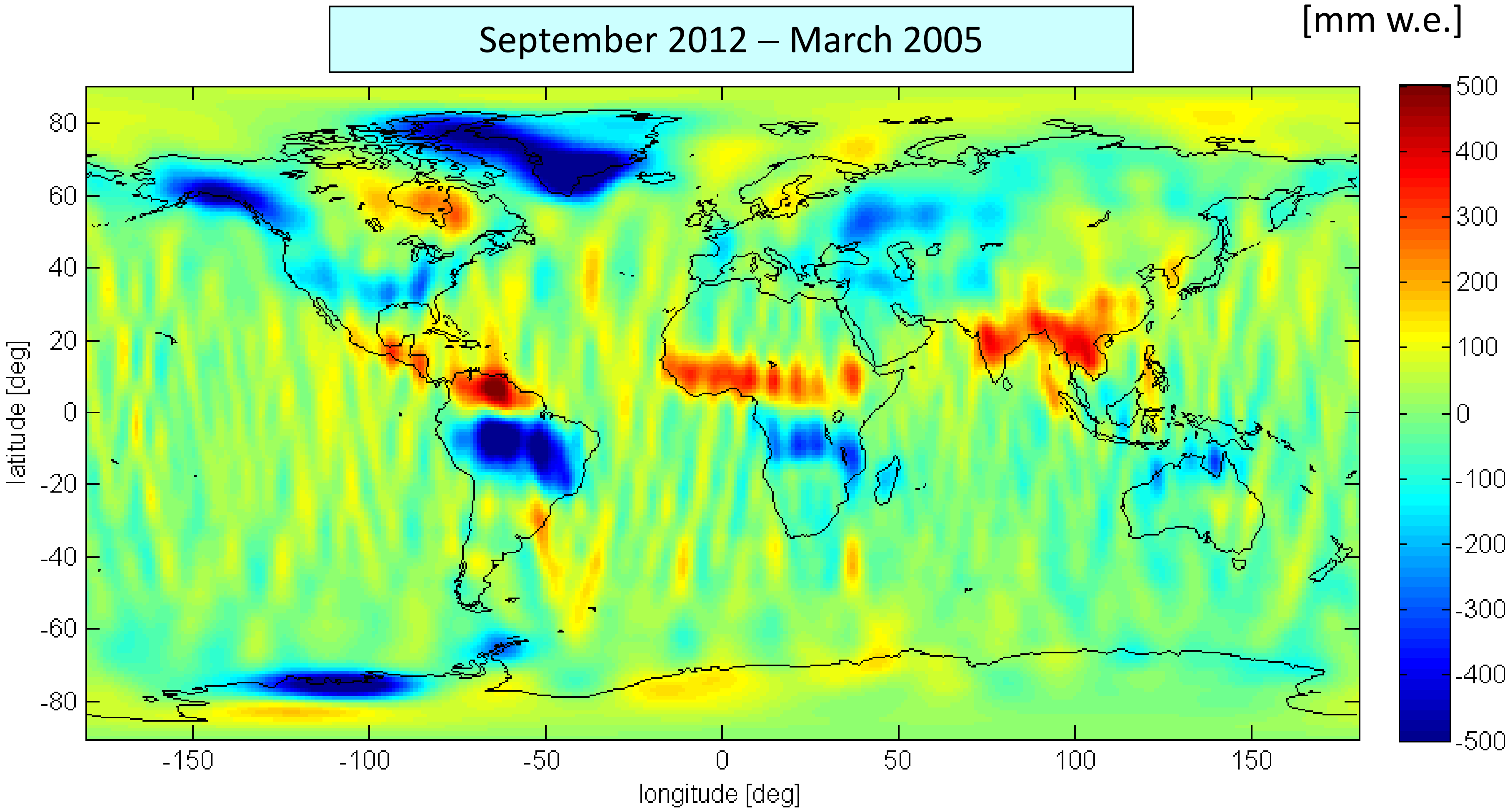
Signal and noise in time-variable GRACE solutions



Monthly solution difference: without filtering



Monthly solution difference: after filtering

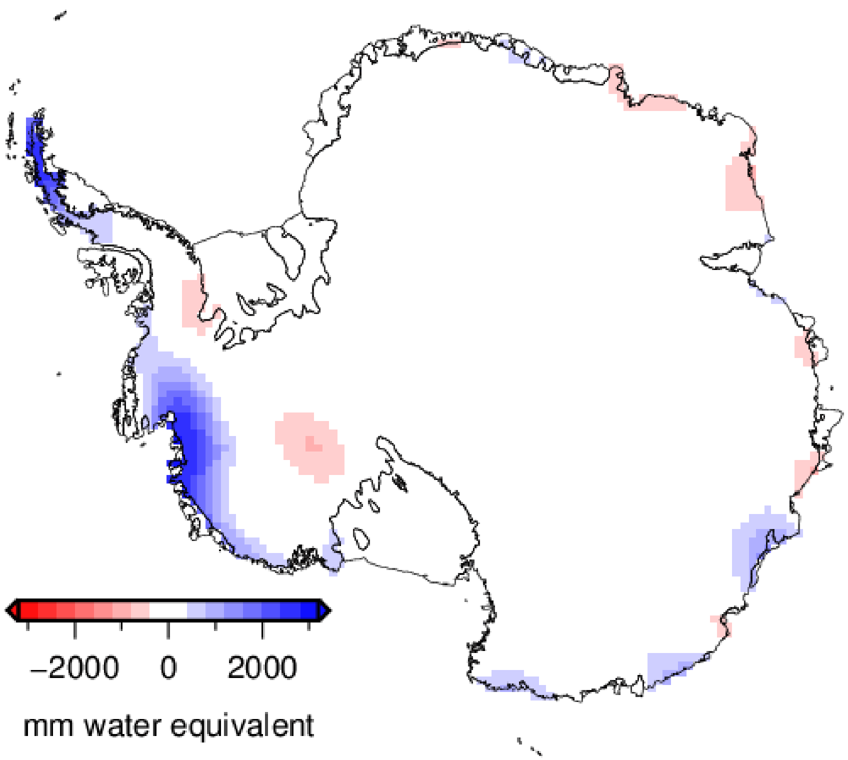


Examples of advanced Level-3 products

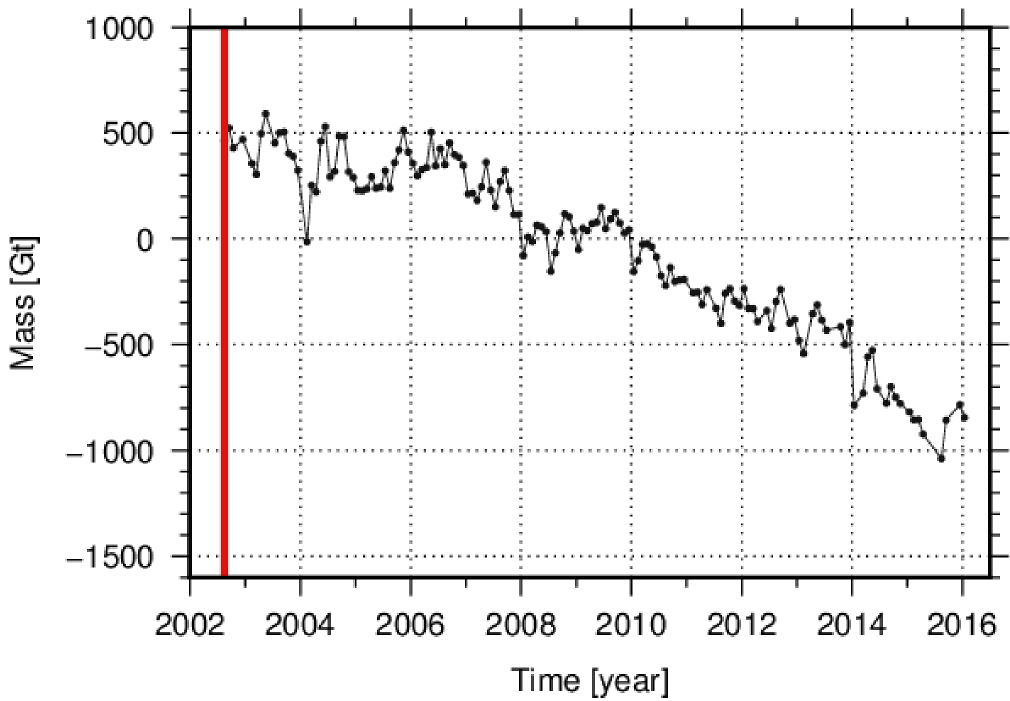
(from ESA Climate Change Initiative project)

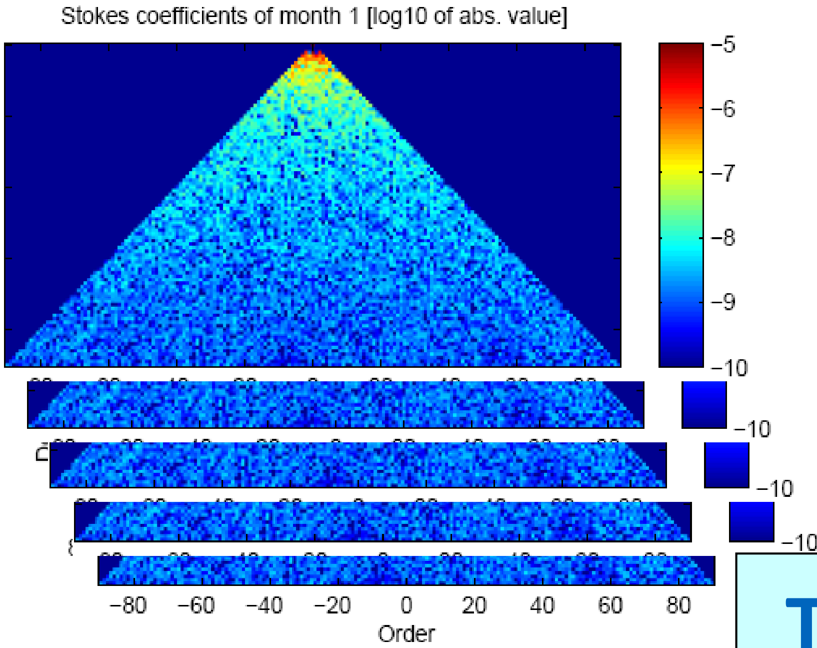
Interactive data portal: https://data1.geo.tu-dresden.de

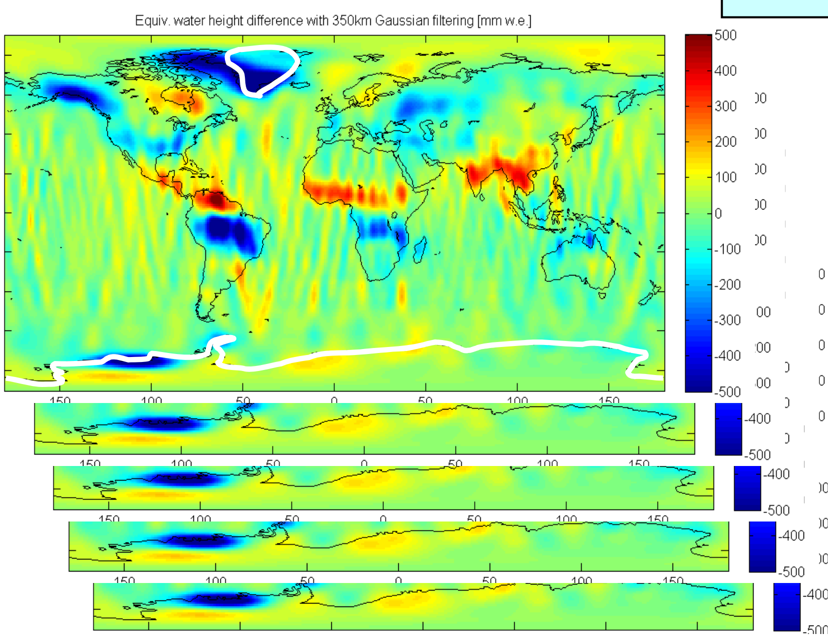
Gridded product



Basin-integrated mass change

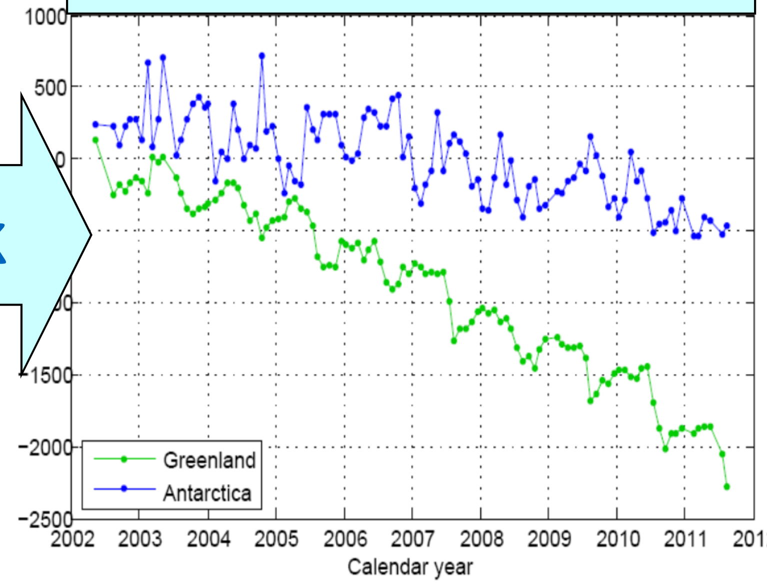




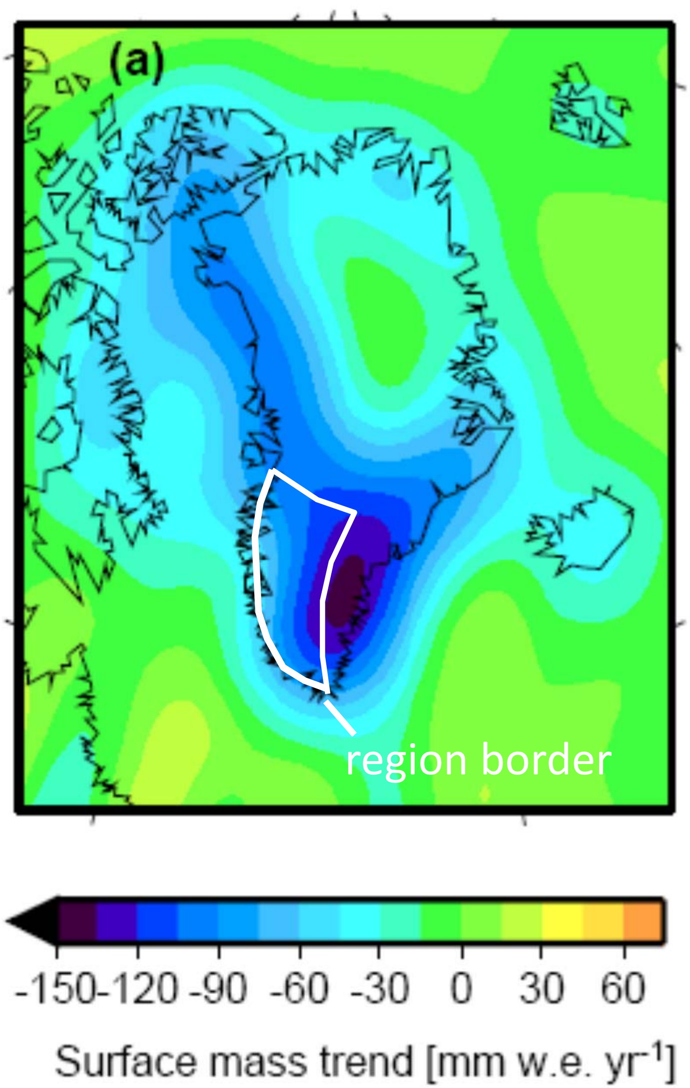


The task

Mass change [Gt]
integrated over a region



Regional integration: Short tour



Surface mass density [mm w.e., or kg/m^2], integrated over a target region gives **Mass changes.**

But:

We have to smooth
in order to dampen **GRACE errors**

Smoothed signal does not allow precise spatial discrimination

Integration will include some mass effects that originate *from outside* the target region
→ **leakage-in**

… and will not precisely capture the mass effects *from inside* the target region
→ **leakage-out**

Modifying the region function is a possibility to reduce leakage

Longer tour: integrated mass change

Surface mass density [mm w.e., or kg/m²], integrated over a target region gives **Mass changes.**

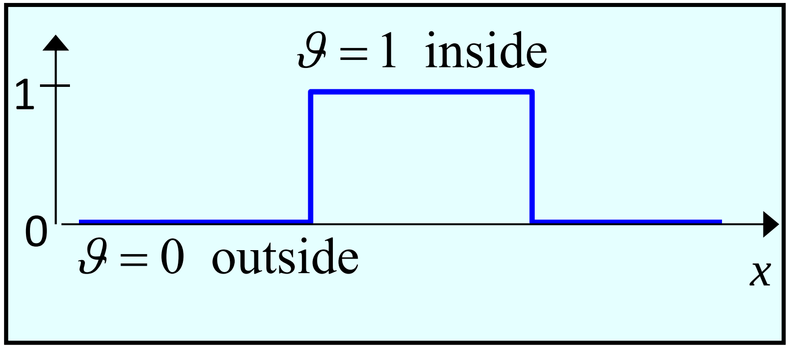
$$\Delta m(t) = \iint_{\text{Region}} \Delta\kappa(\lambda,\phi,t)\, R^2 d\Phi$$

Surface mass density

Same, as a global integral:

$$\Delta m(t) = \iint_{\text{Global}} \vartheta(\lambda,\phi)\, \Delta\kappa(\lambda,\phi,t)\, R^2 d\Phi$$

Region function



The same can be expressed in the spherical harmonic domain:
(by spherical harmonic expansion of both functions and using orthogonality relations)

$$\Delta m(t) = 4\pi R^2 \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \vartheta_{nm}\, \Delta\kappa_{nm}(t)$$

Spherical harmonic Coefficients

Spherical harmonic Coefficients

→ **would need full spectrum of $\Delta\kappa_{nm}$**

Longer tour: integrated mass change *estimates*

$$\Delta m(t) = 4\pi R^2 \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \vartheta_{nm} \; \Delta\kappa_{nm}(t)$$

Intuitive estimation approach:

dampen the poorly determined parts,
e.g. by Gaussian filter factors

$$\widehat{\Delta m}(t) = 4\pi R^2 \sum_{n=0}^{n_{\max}} \sum_{m=-n}^{n} \vartheta_{nm} \; w_n \; \Delta\kappa_{nm}^{\text{sat}}(t)$$

Interpretation 1: Filtering of the GRACE fields

Spatial domain:

$$\widehat{\Delta m}(t) = \iint_{\text{Global}} \vartheta(\lambda,\phi) \, \Delta\tilde{\kappa}^{\text{sat}}(\lambda,\phi,t) \, R^2 d\Phi$$

Longer tour: integrated mass change *estimates*

$$\Delta m(t) = 4\pi R^2 \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \vartheta_{nm} \, \Delta\kappa_{nm}(t)$$

Intuitive estimation approach:

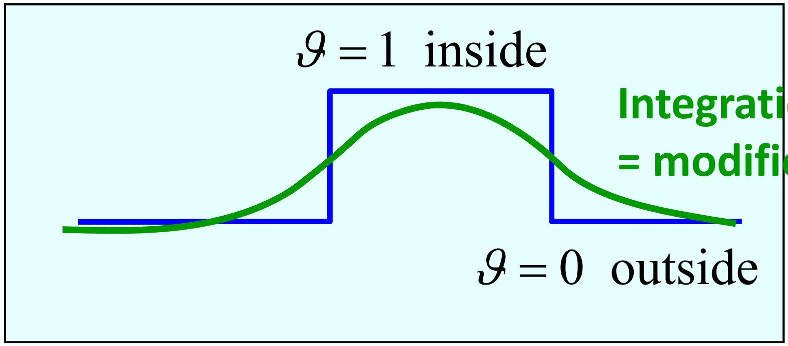
dampen the poorly determined parts, e.g. by Gaussian filter factors

$$\widehat{\Delta m}(t) = 4\pi R^2 \sum_{n=0}^{n_{\max}} \sum_{m=-n}^{n} \vartheta_{nm} \, w_n \, \Delta\kappa_{nm}^{\text{sat}}(t)$$

Interpretation 2: Modification of the region function (while keeping GRACE fields unchanged)

Spatial domain:

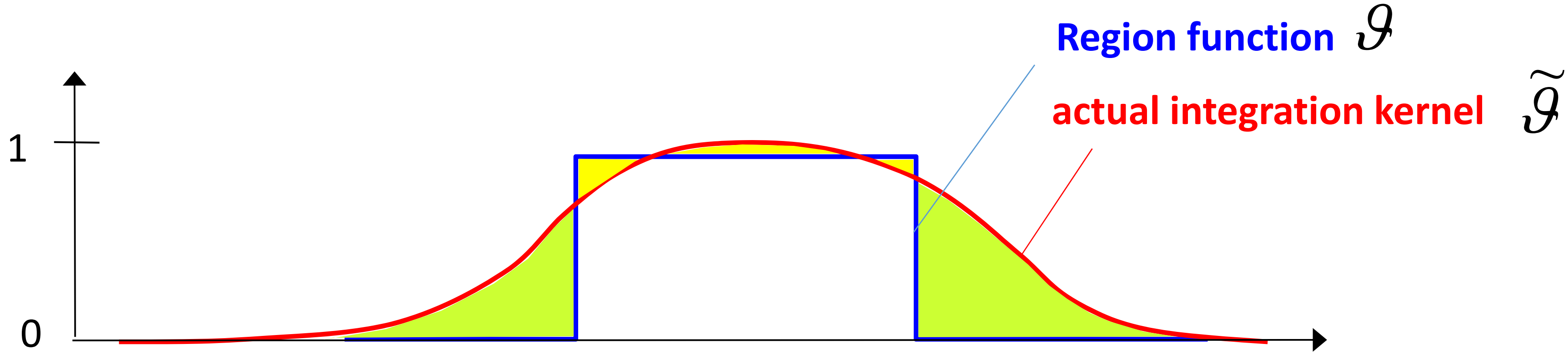
$$\widehat{\Delta m}(t) = \iint_{\text{Global}} \tilde{\vartheta}(\lambda,\phi) \, \Delta\kappa^{\text{sat}}(\lambda,\phi,t) \, R^2 d\Phi$$



Integration kernel = modified region function

Leakage effects: another illustration

$\tilde{\vartheta} \neq \vartheta$ → Leakage error



Signal inside the region is integrated with weight $\neq 1$ → Leakage out

Signal outside is included with weight $\neq 0$ → Leakage in

Assessment of leakage is done by
- inspection of the integration kernel
- simulations with synthetic signals (with known “truth”)

The problem of separating superimposed signals

Gravity field observations allow no vertical discrimination of the underlying mass changes.

To isolate ice mass changes, we have to reduce

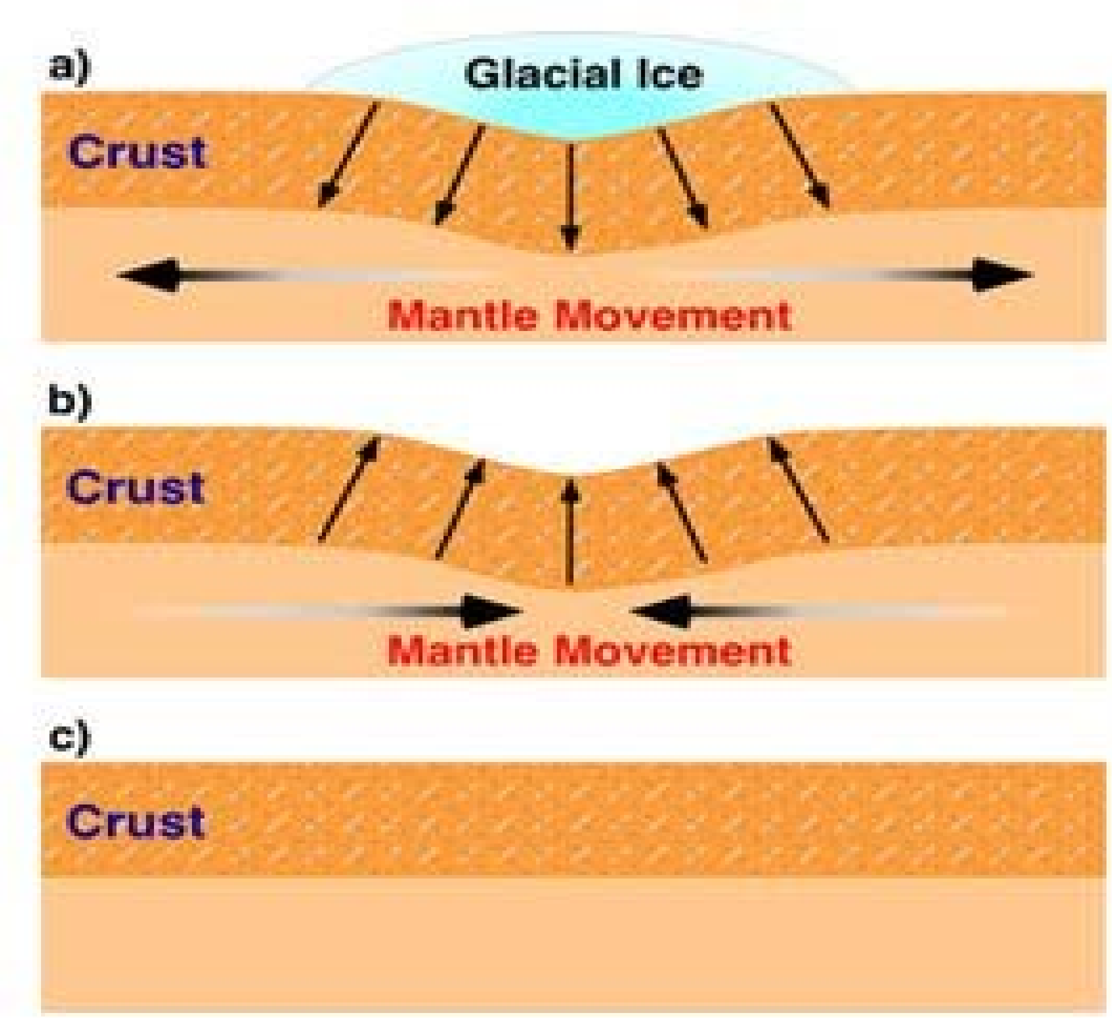
a) Atmospheric mass changes
b) Solid Earth mass displacements due to GIA.

a) is done within GRACE processing based on ECMWF* operational analysis data. The accuracy of related long-term trends is debatable.

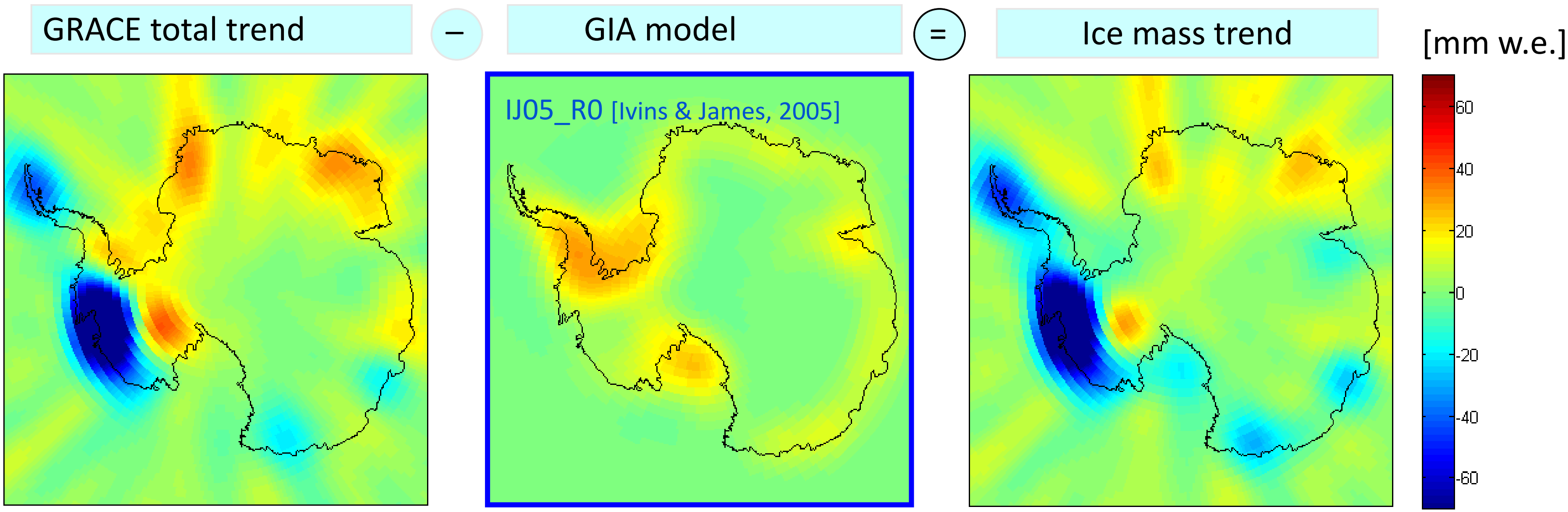
b) Is done by users, usually based on GIA models. The uncertainty of those models is the prime error source for GRACE mass balance estimates in Antarctica!

*European Centre for Medium-range Weather Forecasts

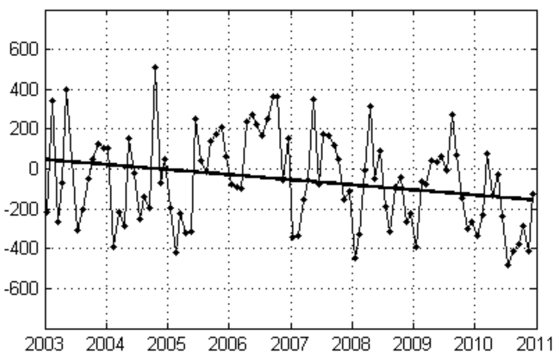
Glacial Isostatic Adjustment (GIA)
(see today afternoon)



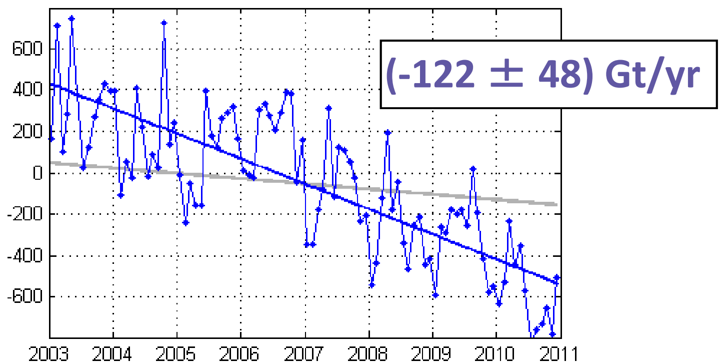
The importance of GIA correction



Mass change [Gt]



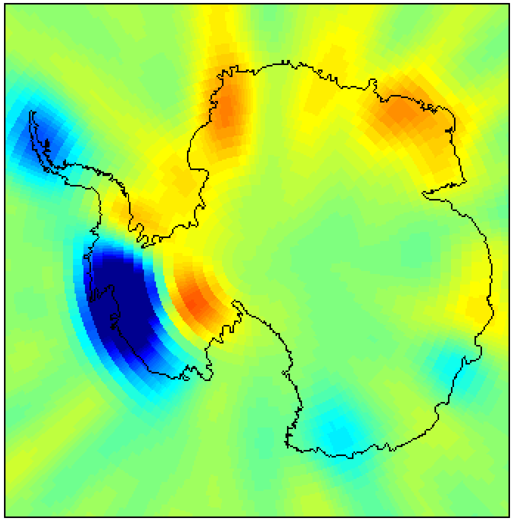
Mass change [Gt]

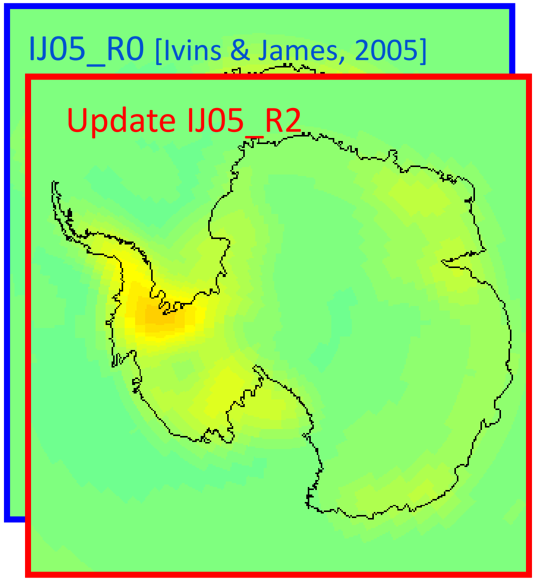


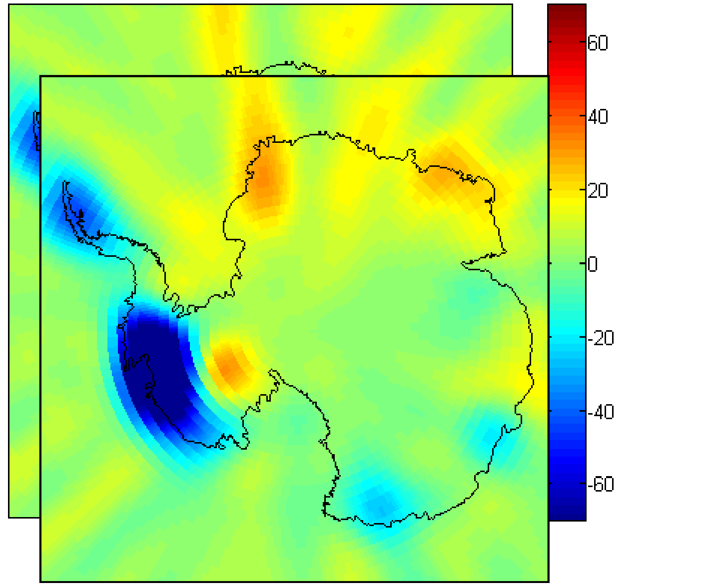
[Horwath & Dietrich 2009, *Geophys. J. Int.*, updated]

The importance of GIA correction

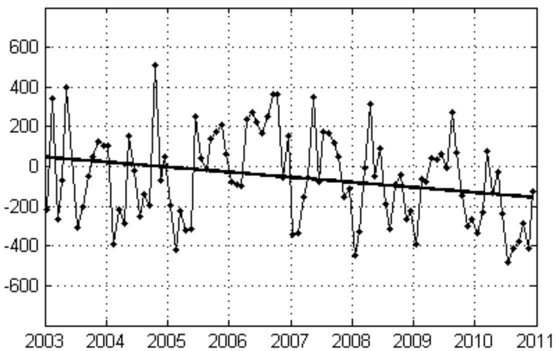
GRACE total trend – GIA model = Ice mass trend





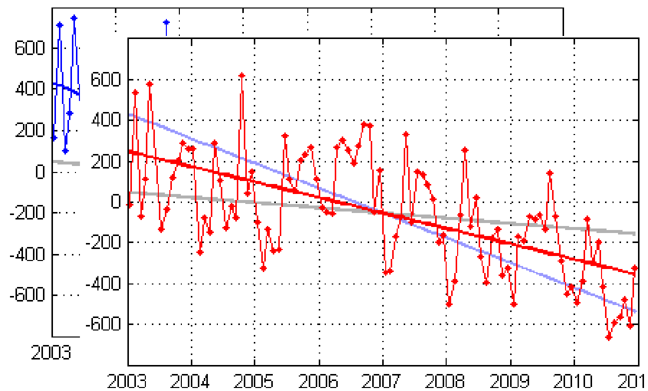


Mass change [Gt]



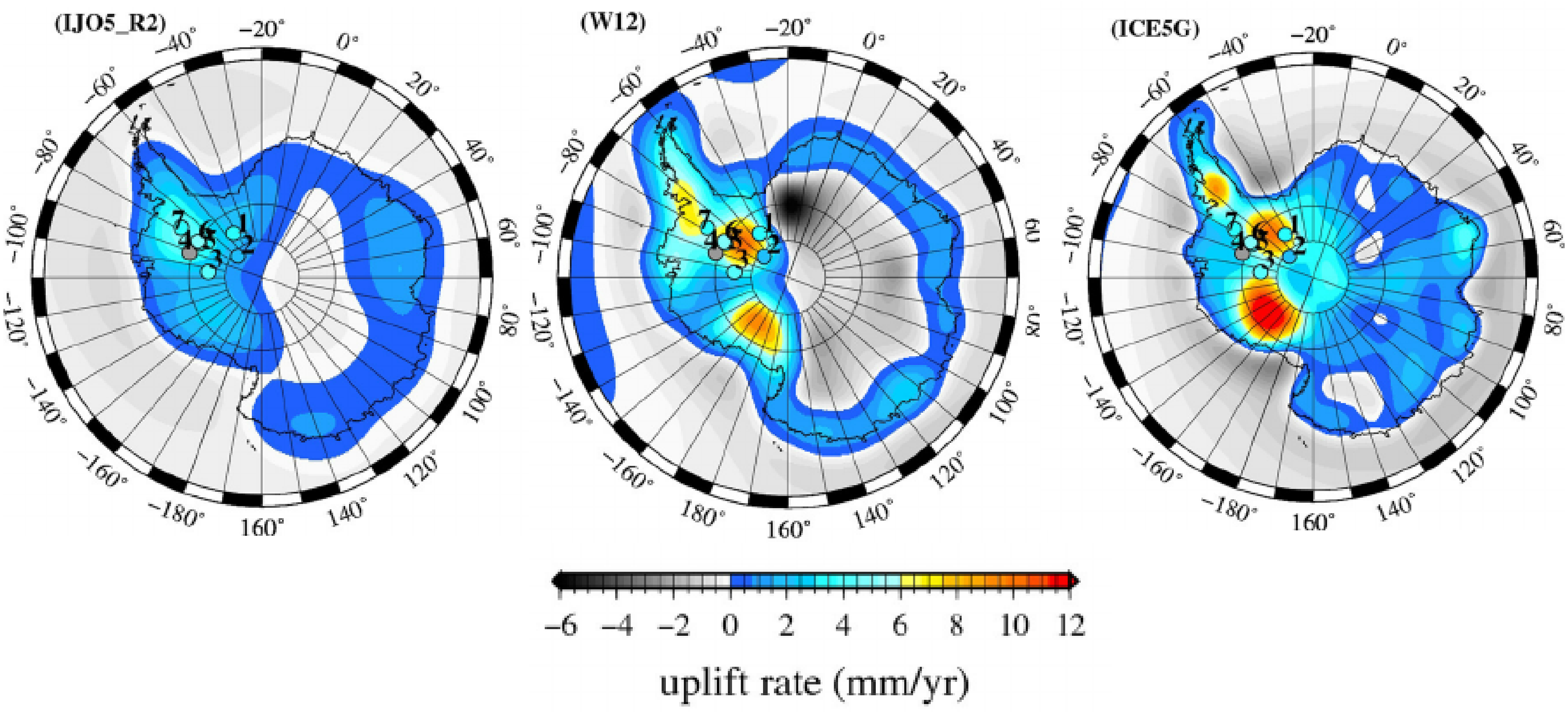
[Ivins et al. 2013]

Mass change [Gt]



GIA models differ substantially

three GIA models



[Bradley et al. 2015]

Summary on GRACE mass balance estimates

Simple principle:
Gravity field changes
→ changes in surface mass [kg/m²]
→ integrate over an area to get changes in mass [kg]

Note:
Other conceptual approaches exist: mascon approaches / forward modeling approaches.
However, the underlying core mathematical mechanisms are similar.

Error sources are:

- GRACE solution errors, or in other words, reduced sensitivity to small spatial scales
- Leakage errors

} Two sides of the same coin; Conflicting minimization goals

- Errors in separating superimposed signals: GIA information is crucial (and uncertain)

} Call for sensor combination

Contents

Principles

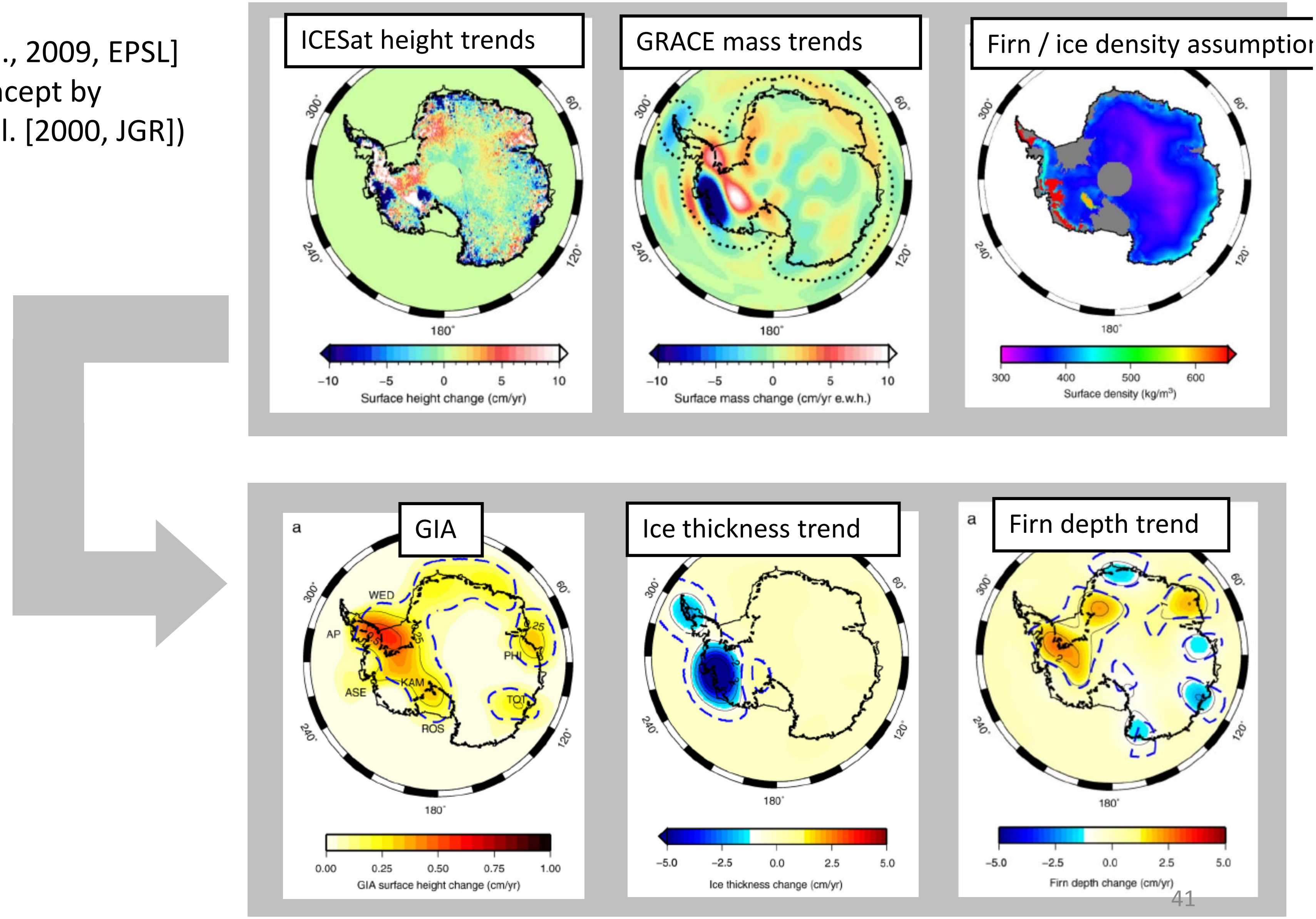
Earth system processes manifest themselves in geodetic parameters – generally in more than one (geometric, gravimetric, earth orientation)

From a single type of geodetic observation, only part of the Earth system signal may be captured. Usually such partial signal may not be distinguished from signals of other processes.

→ combine all relevant geodetic techniques.

Combining GRACE and altimetry to resolve ice mass change and GIA

[Riva et al., 2009, EPSL]
(Basic concept by
Wahr et al. [2000, JGR])



Combining GRACE and altimetry: some details

Mass changes from GRACE

$$\dot{m}_{GRACE} = \dot{m}_{GIA} + \dot{m}_{surf}$$

Corrected for elastic effect

Height changes from ICESat

$$\dot{h}_{ICESat} = \dot{h}_{GIA} + \dot{h}_{surf} + \dot{h}_{ela}$$

Including elastic effects $\approx -0.015 * \dot{h}_{ICESat}$

$$\dot{h}'_{ICESat} = \dot{h}_{ICESat} - \dot{h}_{ela}$$

$$\dot{h}'_{ICESat} = \dot{h}_{ICESat} * 1.015$$

Links between geometry and mass:

$$\dot{m}_{GIA} = \dot{h}_{GIA} * \rho_{rock}$$

$$\dot{m}_{surf} = \dot{h}_{surf} * \rho_{surf}$$

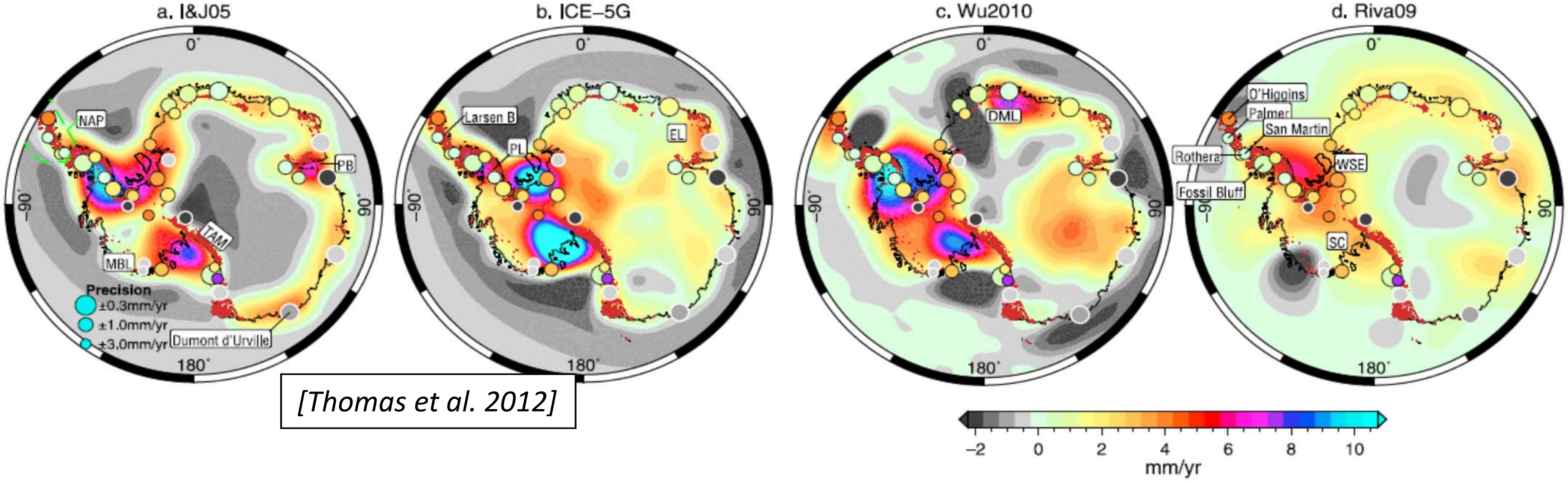
Together:

$$\dot{h}_{GIA} = \frac{\dot{m}_{GRACE} - \rho_{surf} * \dot{h}'_{ICESat}}{\rho_{rock} - \rho_{surf}}$$

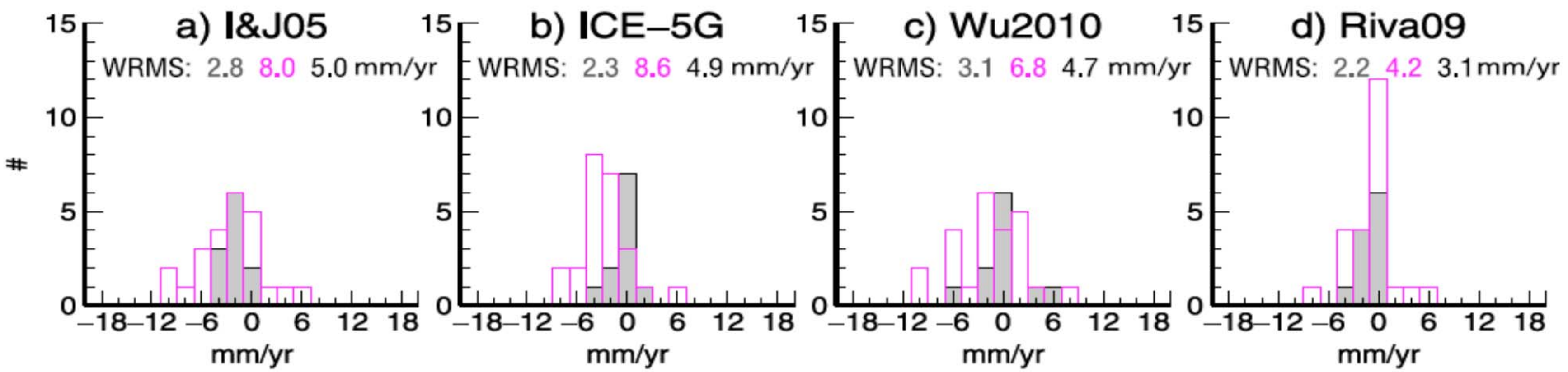
Validating GIA solutions by GPS vertical uplift rates

Geophysical GIA models

GRACE + altimetry solution

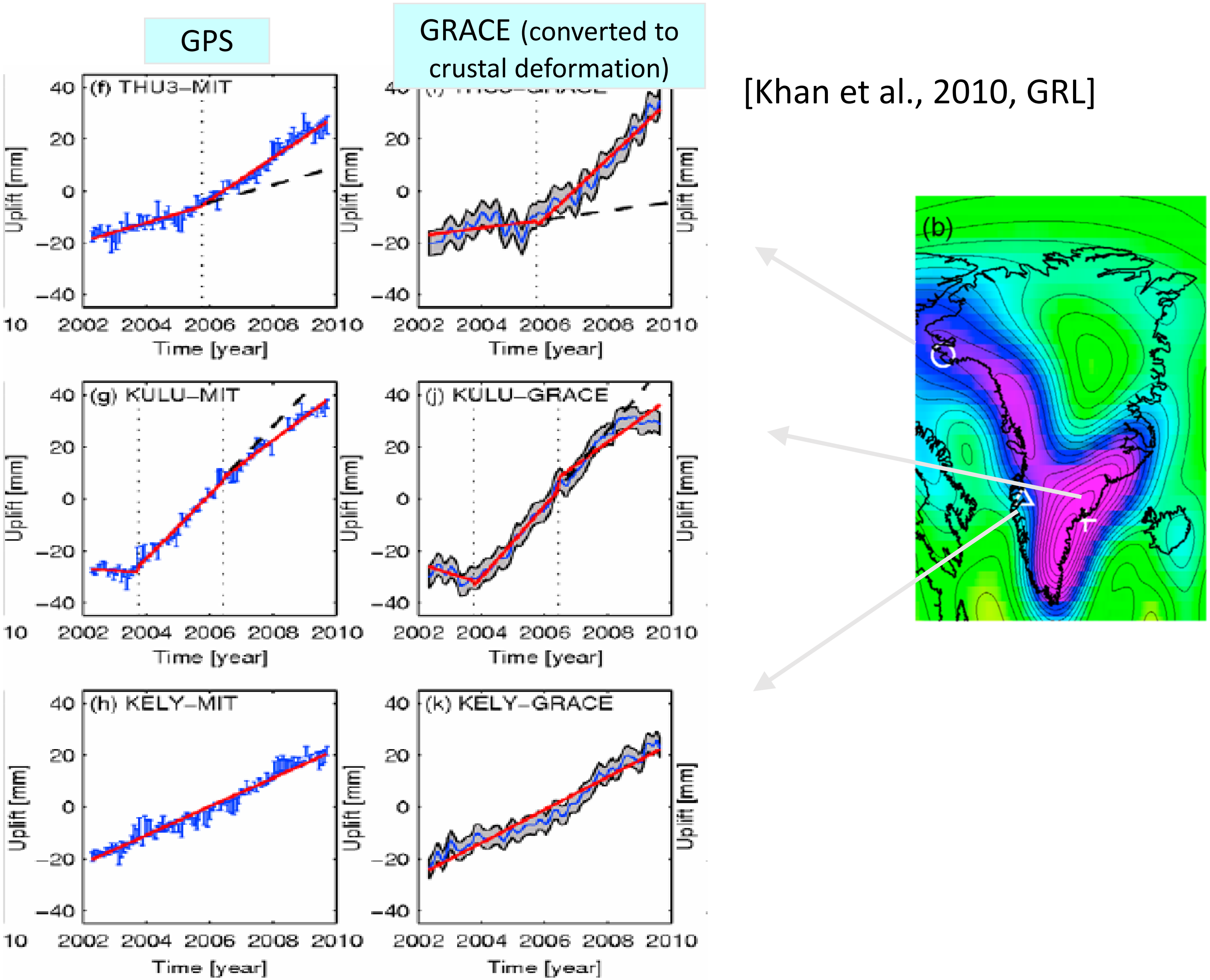


[Thomas et al. 2012]



→ **"GRACE + Altimetry" gives a better description of GIA than GIA models do**

Combination of GRACE with GPS



[Khan et al., 2010, GRL]

GPS on ice surface to constrain elevation trends

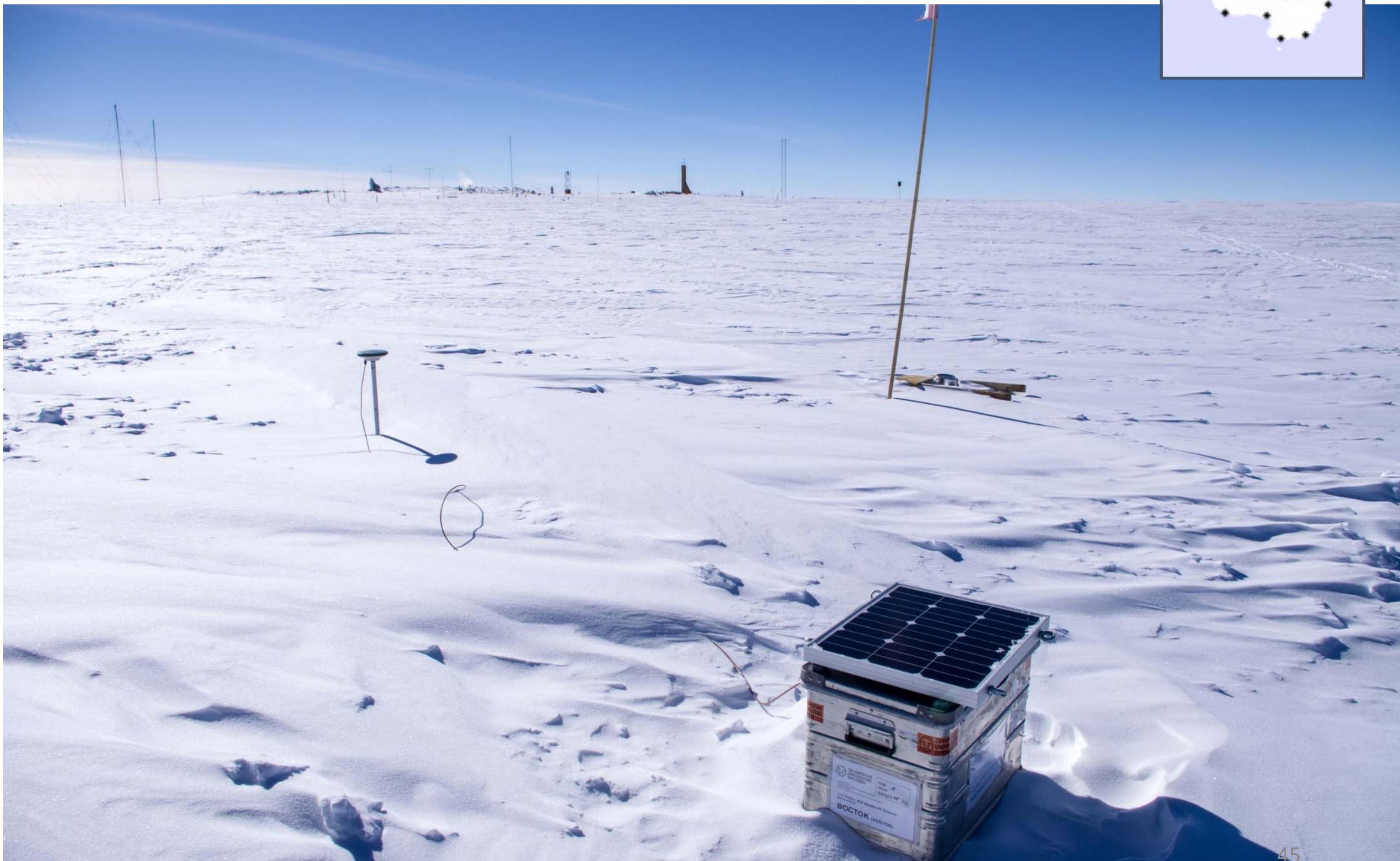


Foto: Martin Lindner, TU Dresden, Institut für Planetare Geodäsie

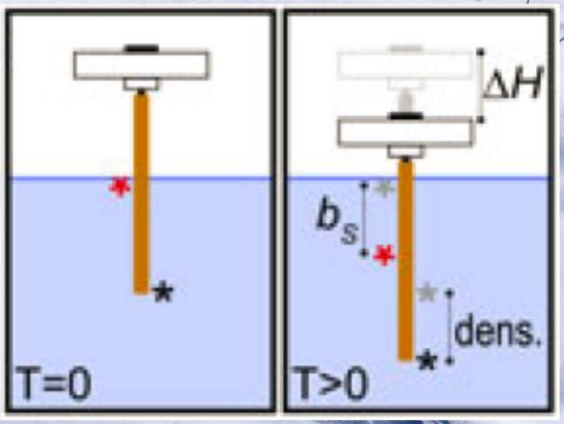
GPS on ice surface to constrain elevation trends

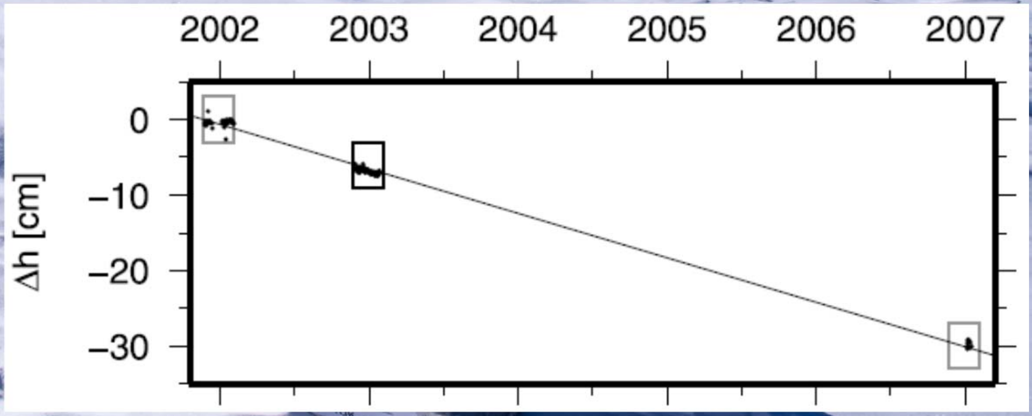
Elevation trend of the marker 62.1 ± 4.9 mm/yr

Annual growth of firn layer above the marker 62.4 ± 0.9 mm/yr

(from 200-year mean accumulation rate and observed snow density at the surface)

→ Height change rate of the surface 0.3 ± 4.9 mm/yr





[Richter et al. 2008, 2014]

Foto: Martin Lindner, TU Dresden, Institut für Planetare Geodäsie

Conclusions and outlook

GRACE satellite gravimetry, by its direct sensitivity to mass changes, has revolutionized our knowledge on ice sheet changes.

Challenges consist in

a) the limited resolution, manifested in GRACE errors in high degrees; their dampening induces leakage.

b) the insensitivity / reduced sensitivity to degree 1 (“geocenter variations”) and the degree 2, order 0 (“Earth flattening term”) – not covered in this lecture.

c) the separation of superimposed signals, in particular ice mass changes and GIA. This challenge calls for the combination of different sensors and modeling.

The exercise before lunch will familiarize you with aspects of (a) and (c).

EGSIEM Autumn School, September 2017, Potsdam

Martin Horwath, TU Dresden, Martin.Horwath@tu-dresden.de

Andreas Groh, TU Dresden

Instructions for the

Exercise on the combination of satellite data

1 Objectives

This practical demonstrates one possibility to combine different satellite data sets. In particular, GRACE-derived trends in surface mass and surface height trends inferred from ICESat satellite laser altimetry data are combined in order to derive GIA-induced crustal deformations over the Antarctic Ice Sheet. For this purpose, the approach by Riva et al. (2009) is implemented.

The exercise is divided into three parts:

1. **Model visualisation**

   A model describing the density of ongoing surface mass changes of the Antarctic Ice Sheet (i.e. firn/ice density model) as well as a simple model of the the Earth's mantle density are load and visualised. In addition, three different GIA models are compared in terms of their corresponding surface mass change and vertical crustal deformation rate.

2. **Preparation of satellite data**

   Gridded surface height trends from ICESat (prepared by L. Schröder) are given on a 5km x 5km polar-stereographic grid and are down-sampled to a spatial resolution of 50km x 50km. The linear trend in surface mass over the same period (2003-03 – 2009-10) is derived from monthly GRACE solutions of release ITSG-Grace2016 (Klinger et al, 2016).

3. **GIA-induced crustal deformations from GRACE and ICESat**

   In this step, you will implement the approach by Riva et al. (2009) and combine both satellite data sets and the density models in order to derive an estimate for the GIA-induced vertical crustal deformation. The combination approach is applied to different versions of the input data (i.e. using different filters). The resulting GIA estimates are compared to the predictions from the GIA models.

2 Data sets

All data sets and tools required to complete the practical are provided and are located in the `Data\GRACE`, `Data\Altimetry`, `Data\General` and `Tools` directories. The following data sets are used during the exercise:

1. Three different glacial isostatic adjustment models are provided (in the spherical harmonic domain). Namely: IJ05_R2 (Ivins et al., 2013), W12a (Whitehouse et al., 2012) and ICE-6G (Peltier et al., 2015).
2. A firn-ice density [kg/m³] mask according to McMillan et al. (2014).
3. A model for the Earth's mantle density [kg/m³] (Riva et al., 2009).
4. Surface height trends [m/yr] over the Antarctic Ice Sheet resulting from a repeat track analysis of ICESat laser altimetry data (prepared by L. Schröder). The data set is provided as a netcdf file and is given in polar-stereographic coordinates [m] with a spatial resolution of 5km x 5km.
5. GRACE monthly solutions of release ITSG-Grace2016 (Klinger et al., 2016). The solutions are freely available from: https://www.tugraz.at/institute/ifg/downloads/gravity-field-models/itsg-grace2016/.
6. Spherical harmonic coefficients of degree one need to be added to the GRACE monthly solutions. Coefficients derived by the method of Swenson et al. (2008) can be obtained from: ftp://podaac.jpl.nasa.gov/allData/tellus/L2/degree_1/.
7. The spherical harmonic coefficient of degree 2 and order 0 has to be replaced, e.g. by an estimated derived from satellite laser ranging (SLR) observations (Cheng et al., 2013). This data set is available from: ftp://podaac.jpl.nasa.gov/allData/grace/docs/.
8. Elastic Load Love Numbers (LLN), describing the Earth’s elastic response on a surface loads (Farrell, 1972) are required to perform the conversion between Stokes coefficients and coefficients of the equivalent water height (EWH).

3 Course of the exercise

The central Matlab script `Exercise_DataCombination.m` contains all required steps to load and visualise the input data. It is your task to go through the script and run it step by step. Whenever input from your side is needed an error message will prompt you to provide input, e.g. it is your task to implement the combination approach.

You will find several questions/tasks within the script, which need to be answered. Whenever results are generated within the script you should output and carefully study them. Ask yourself what causes visible phenomena or the differences revealed by an intercomparison.

At the end of the script you have the opportunity to save all your results in a *.mat file (binary) and to save all the figure generated so far.

The central directory of the practical contains the following files and subdirectories:

`Exercise_Data_combination.m`	- the central Matlab script
`Data\GRACE`	- data required to derive trends in surface mass
`Data\Altimetry`	- ICESat altimetry data
`Data\General`	- auxiliary data
`Tools`	- required Matlab tools
`Figures`	- directory for storing the generated figures

4 References

Cheng, M., Tapley, B. D., & Ries, J. C. (2013). Deceleration in the Earth's oblateness. J. Geophys. Res. Solid Earth, 118(2), 740–747.

Farrell, W. E. (1972). Deformation of the Earth by Surface Loads. Rev. Geophys. Space Phys., 10(3), 761–797.

Gunter, B. C., O. Didova, R. E. M. Riva, S. R. M. Ligtenberg, J. T. M. Lenaerts, M. A. King, M. R. van den Broeke, and T. Urban (2014). Empirical estimation of present-day Antarctic glacial isostatic adjustment and ice mass change, The Cryosphere, 8, 743–760.

Ivins, E. R., James, T. S., Wahr, J., O. Schrama, E. J., Landerer, F. W., & Simon, K. M., 2013. Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *Antarctic contribution to sea level rise observed by GRACE with improved GIA correction*, 118(6), 3126–3141.

Klinger, B., Mayer-Gürr, T., Behzadpour, S., Ellmer, M., Kvas, A., & Zehentner, N. (2016). The new ITSG-Grace2016 release, EGU General Assembly 2016, Vienna, Austria, 17/04/16 - 22/04/16, DOI: 10.13140/RG.2.1.1856.7280.

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A., & Wingham, D. (2014). Increased ice losses from Antarctica detected by CryoSat-2. *Geophys. Res. Lett.*, *41*(11), 3899–3905.

Peltier, W. R., Argus, D. F., & Drummond, R. (2015). Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model: Global Glacial Isostatic Adjustment. J. Geophys. Res. Solid Earth, 120(1), 450–487.

Riva, R. E. M., Gunter, B. C., Urban, T. J., Vermeersen, B. L. A., Lindenbergh, R. C., Helsen, M. M., Bamber, J. L., van den Broeke, M. R., and Schutz, B. E. (2009). Glacial isostatic adjustment over Antarctica from combined ICESat and GRACE satellite data. Earth Planet. Sc. Lett., 288, 516–523.

Swenson, S., Chambers, D., & Wahr, J. (2008). Estimating geocenter variations from a combination of GRACE and ocean model output. J. Geophys. Res., B113, B08410.

Whitehouse, P. L., Bentley, M. J., Milne, G. A., King, M. A., & Thomas, I. D. (2012). A new glacial isostatic adjustment model for Antarctica: calibrated and tested using observations of relative sea-level change and present-day uplift rates. Geophys. J. Int., 190(3), 1464–1482.

EGSIEM Autumn School, September 2017, Potsdam

Martin Horwath, TU Dresden, Martin.Horwath@tu-dresden.de

Andreas Groh, TU Dresden

Instructions for the

Exercise on ice mass balance estimates from GRACE

Objectives

In this practical we utilise GRACE monthly gravity field solutions to infer mass change time series for the Antarctic Ice Sheet (AIS) and selected drainage basins. The time series are compared with alternative GRACE-derived products.

The drainage basins to be considered during the practical are shown in the figure. In addition, basin aggregation for the Antarctic Peninsula (basin 29: 24, 27, 28), East Antarctica (basin 30: 2-17), West Antarctica (basin 31: 1, 18-23) and the entire Antarctic Ice Sheet (basin 32) can be studied. For the sake of clarity your investigations should first be focussed on the entire AIS (basin 32) and one smaller basin (e.g. Basin 22)

.

The practical is divided into three parts:

1. **GRACE-observed global mass change signals in space domain and spherical harmonic domain**

   We use a time series monthly GRACE solutions (release ITSG-Grace2016, Klinger et al, 2016) to analyse global mass variation signals. This part may build on experience from the Tuesday morning exercise.

2. **Regionally integrated mass change time series from GRACE monthly solutions**

   The regional integration approach, in combination with a Gaussian filter, is implemented in the spherical harmonic domain in order to derive mass change time series from GRACE monthly solutions on basin scale. The inferred time series are corrected for solid Earth mass changes due to glacial isostatic adjustment (GIA) using a GIA model. By using different Gaussian filter radii, the effect of filtering on the mass change estimates is studied. Finally, the mass change time series are analysed and the corresponding contributions to changes in global mean sea level are derived.

3. **Intercomparison with alternative GRACE results and independent data**

   In this part, the inferred mass change time series and the mass balance estimates are compared with the Gravimetric Mass Balance (GMB) products derived within the ESA Climate Change Initiative (CCI) project on the Antarctic Ice Sheet (AIS_cci).

Differences between both data sets are used to conclude on limitations of the method applied in the practical. Possible modifications to overcome these limitations are demonstrated.

Data sets

All data sets and tools required to complete the practical are provided and are located in the `Data\GRACE`, `Data\General` and `Tools` directories. Whenever a data set needs to be obtained in the course of the exercise, this is explicitly stated. The following data sets are used during the exercise:

1. GRACE monthly solutions of release ITSG-Grace2016 (Klinger et al., 2016). The solutions are freely available from: https://www.tugraz.at/institute/ifg/downloads/gravity-field-models/itsg-grace2016/.
2. Spherical harmonic coefficients of degree one need to be added to the GRACE monthly solutions. Coefficients derived by the method of Swenson et al. (2008) can be obtained from: ftp://podaac.jpl.nasa.gov/allData/tellus/L2/degree_1/.
3. The spherical harmonic coefficient of degree 2 and order 0 has to be replaced, e.g. by an estimated derived from satellite laser ranging (SLR) observations (Cheng et al., 2013). This data set is available from: ftp://podaac.jpl.nasa.gov/allData/grace/docs/.
4. Three different glacial isostatic adjustment models are provided (in the spherical harmonic domain). Namely: IJ05_R2 (Ivins et al., 2013), W12a (Whitehouse et al., 2012) and ICE-6G (Peltier et al., 2015).
5. Elastic Load Love Numbers (LLN), describing the Earth's elastic response on a surface loads (Farrell, 1972) are required to perform the conversion between Stokes coefficients and coefficients of the equivalent water height (EWH).
6. The provided basins outlines, basin areas and region functions (given in the spherical harmonic domain) are based on the definitions of Zwally et al. (2012), which are available from: http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php.

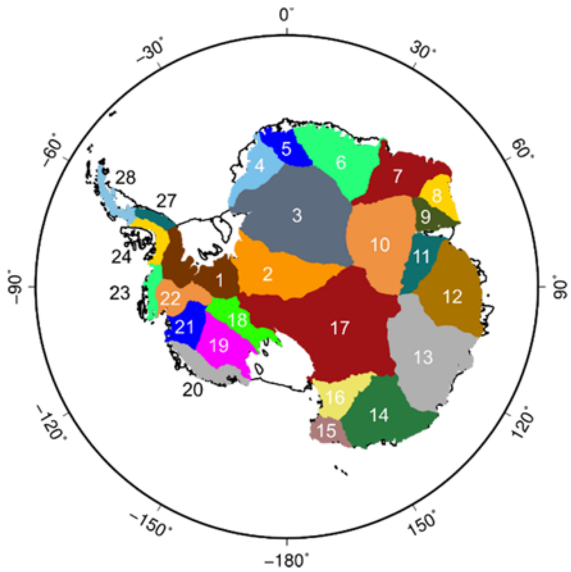


Figure: Drainage basins of the Antarctic Ice Sheet. In addition, the following basin numbers apply:
29: Antarctic Peninsula;
30: East Antarctica;
31: West Antarctica;
32: Entire Antarctic Ice Sheet

7. The GMB basin products and the GMB basin mass balance estimates generated by TU Dresden within the AIS_cci project need to be **downloaded** by each participant. After registration the products can be downloaded from https://data1.geo.tu-dresden.de/ais_gmb/. Both unpacked files need to be stored in the Data\GRACE directory.

1 Course of the exercise

Nearly all steps of the exercise are already included in the central Matlab script `Exercise_IceMassBalance.m`. It is your task to go through the script and run it step by step. Comments, describing the purpose of the individual step, are added throughout the script.

You will find several questions/tasks within the script, which need to be answered. Whenever results are generated within the script you should output and study them. Ask yourself about the causes of visible phenomena or for the differences revealed by an intercomparison.Discuss with other students and tutors.

At the end of the script you have the opportunity to save all your results in a *.mat file (binary) and to save all the figure generated so far.

The central directory of the practical contains the following files and subdirectories:

`Exercise_GRACE.m`	- the central Matlab script
`Data\GRACE`	- all input data
`Data\General`	- auxiliary data
`Tools`	- required Matlab tools
`Figures`	- directory for storing the generated figures

2 References

Cheng, M., Tapley, B. D., & Ries, J. C. (2013). Deceleration in the Earth's oblateness. J. Geophys. Res. Solid Earth, 118(2), 740–747.

Farrell, W. E. (1972). Deformation of the Earth by Surface Loads. Rev. Geophys. Space Phys., 10(3), 761–797.

Ivins, E. R., James, T. S., Wahr, J., O. Schrama, E. J., Landerer, F. W., & Simon, K. M., 2013. Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *Antarctic contribution to sea level rise observed by GRACE with improved GIA correction*, 118(6), 3126–3141.

Klinger, B., Mayer-Gürr, T., Behzadpour, S., Ellmer, M., Kvas, A., & Zehentner, N. (2016). The new ITSG-Grace2016 release, EGU General Assembly 2016, Vienna, Austria, 17/04/16 - 22/04/16, DOI: 10.13140/RG.2.1.1856.7280.

Peltier, W. R., Argus, D. F., & Drummond, R. (2015). Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model: Global Glacial Isostatic Adjustment. J. Geophys. Res. Solid Earth, 120(1), 450–487.

Swenson, S., Chambers, D., & Wahr, J. (2008). Estimating geocenter variations from a combination of GRACE and ocean model output. J. Geophys. Res., B113, B08410.

Van Wessem et al. (2014). Improved representation of East Antarctica surface mass balance in a regional climate model. J. Glac., 60(222), 761-770, doi: 10.3189/2014JoG14J051.

Whitehouse, P. L., Bentley, M. J., Milne, G. A., King, M. A., & Thomas, I. D. (2012). A new glacial isostatic adjustment model for Antarctica: calibrated and tested using observations of relative sea-level change and present-day uplift rates. Geophys. J. Int., 190(3), 1464–1482.

Zwally, J. H., Giovinetto, M. B., Beckley, M. A. & Saba, J. L., 2012. Antarctic and Greenland Drainage Systems. *GSFC Cryospheric Sciences Laboratory at* http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php.