Geodetic Measurements of the Water Cycle

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University of Nevada, Reno
Statewide • Worldwide

IGCP 565 Project:

Developing the Global Geodetic Observing System Into a Monitoring System for the Global Water Cycle

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GROUP ON EARTH OBSERVATIONS

IGCP 565 Project:

Developing the Global Geodetic Observing System Into a Monitoring System for the Global Water Cycle

- Project Motivations, Objectives, Goals, and Approach
- Project Work Plan, Achievements, Challenges
- Plan for 2010 to 2012
- Geodesy4Water = GRACE or is there more?

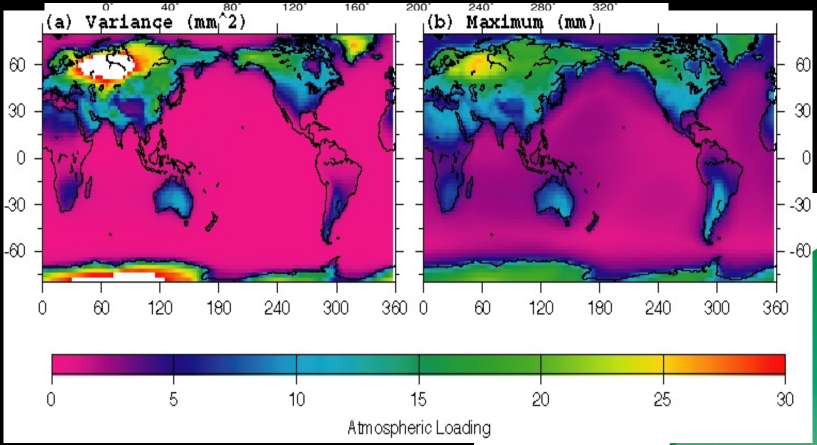
http://www.igcp565.org

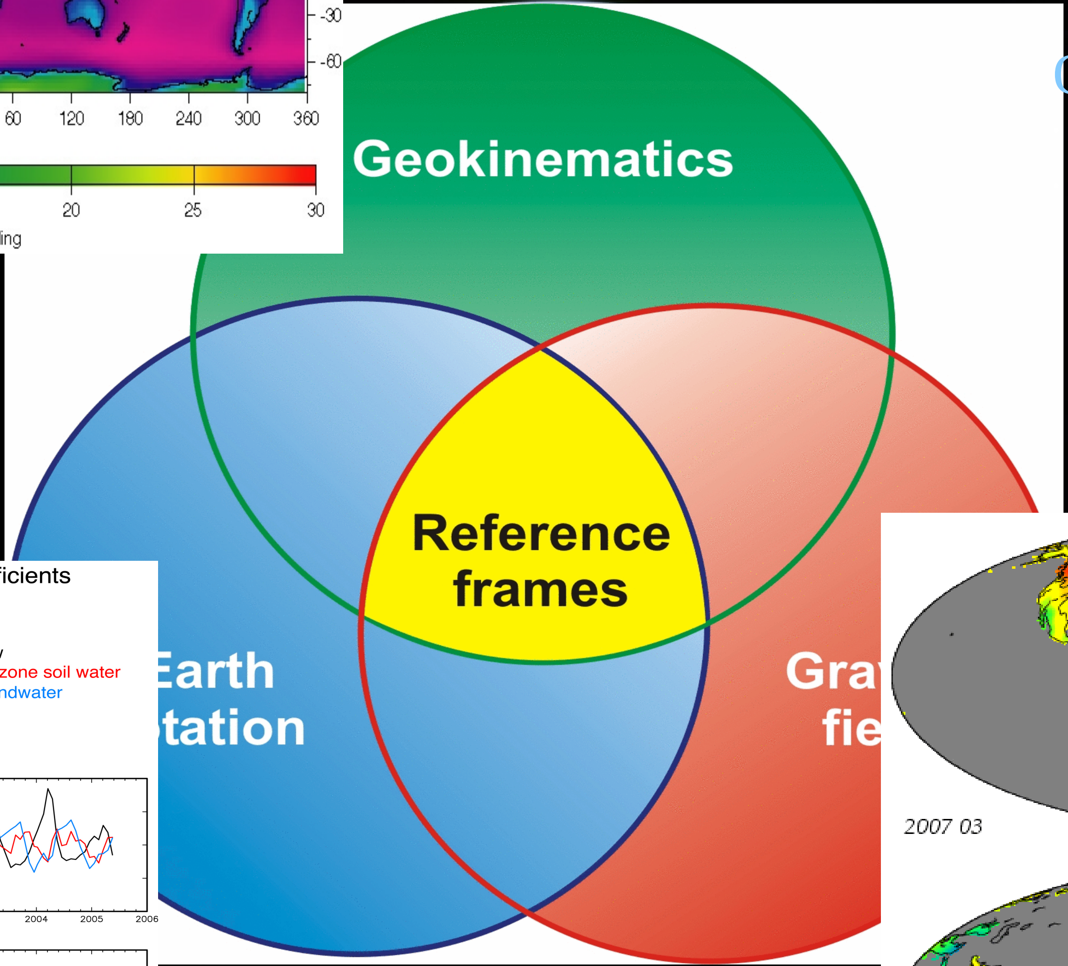
Societal Motivation

Science &Technology Motivation

The 'three pillars of geodesy':

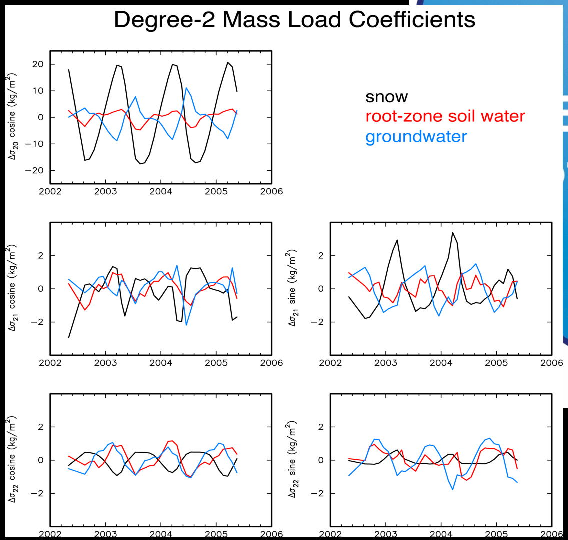
- Earth's Shape (Geokinematics)
- Earth's Gravity Field
  Earth Rotation

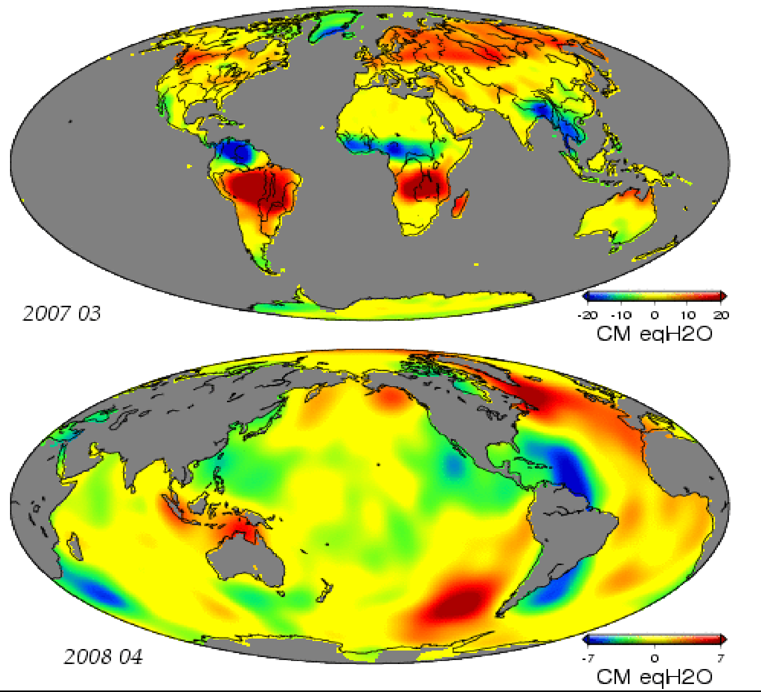




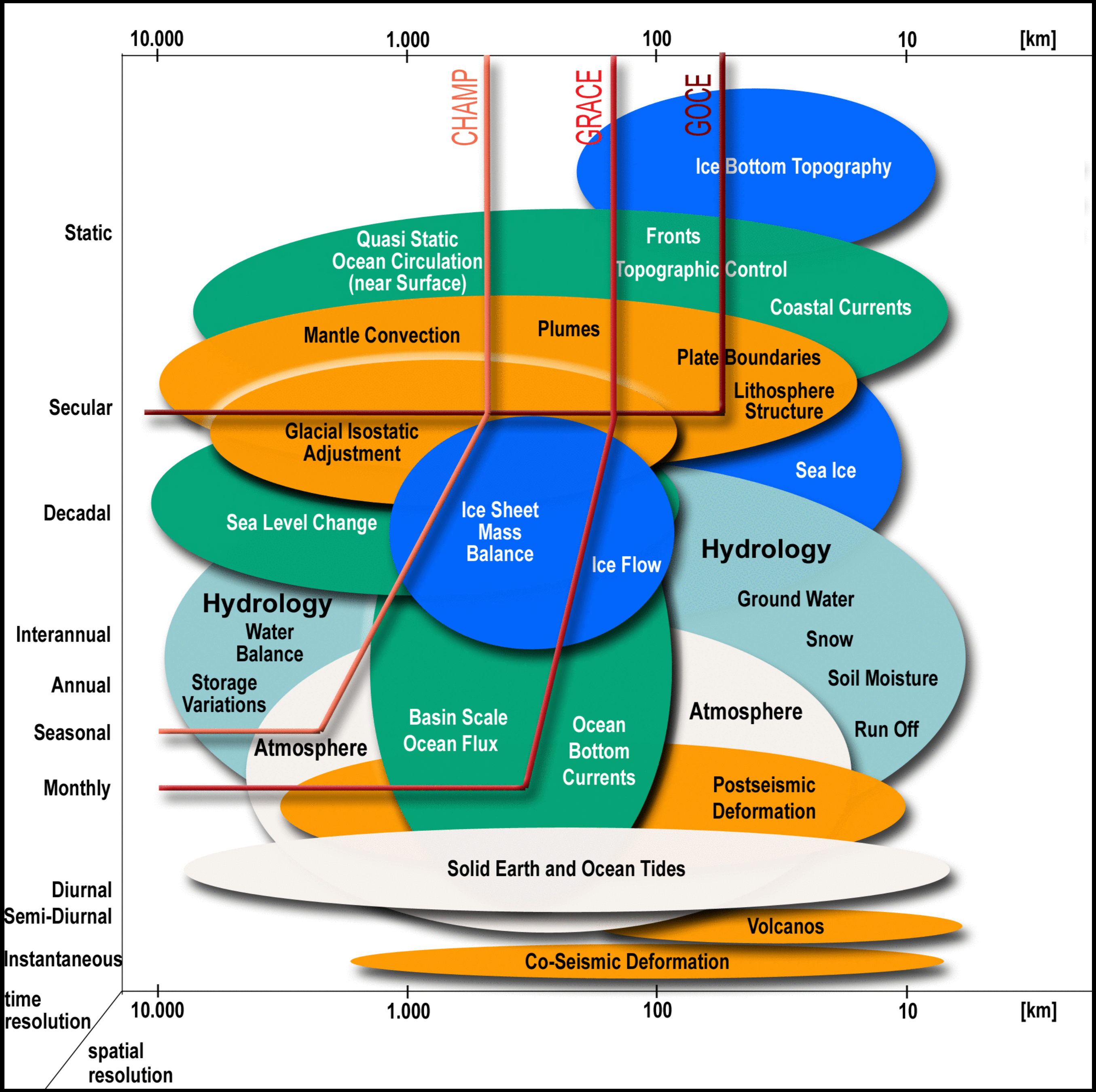
Output:

Reference Frame
Observations of the Shape, Gravitational Field and Rotation of the Earth

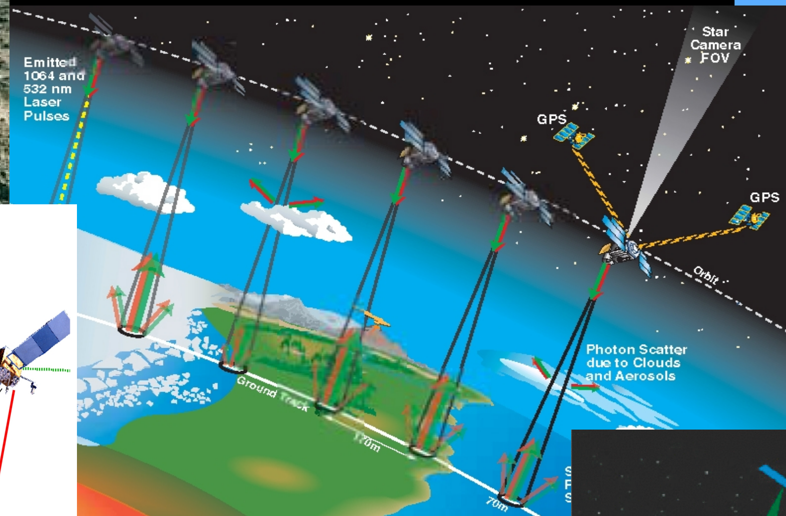


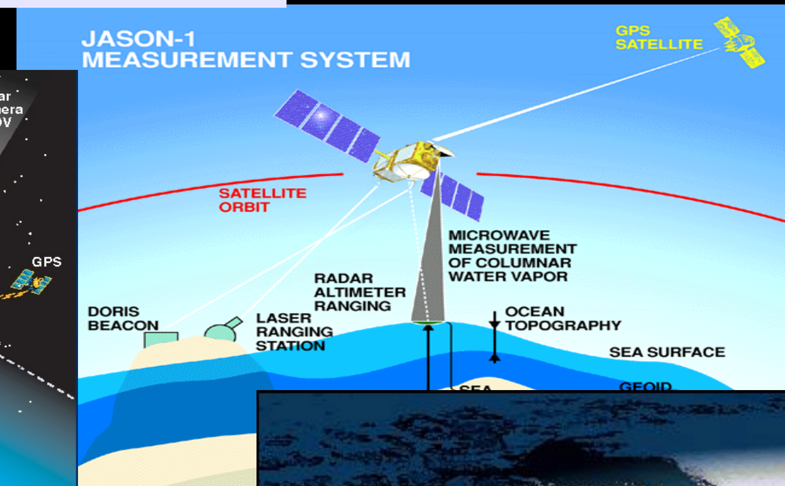


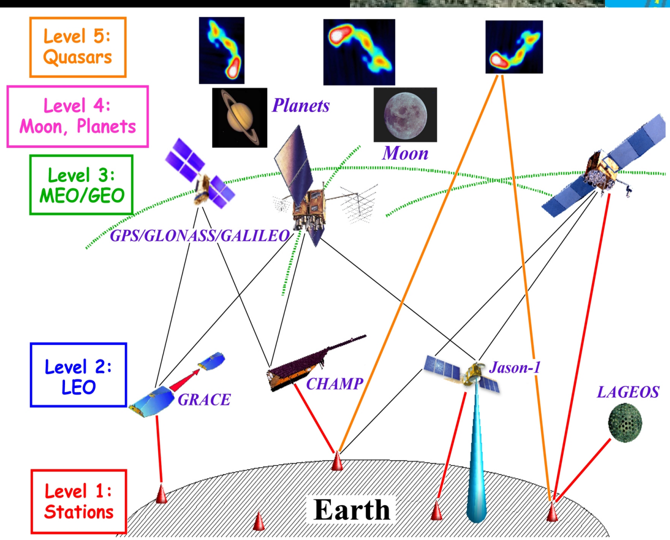
Science &Technology Motivation

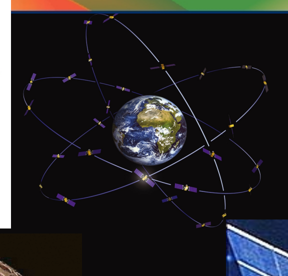


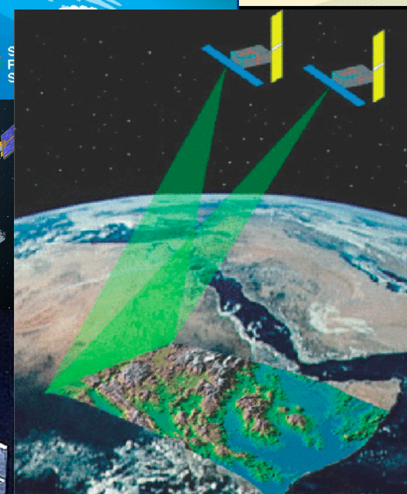
Science &Technology Motivation

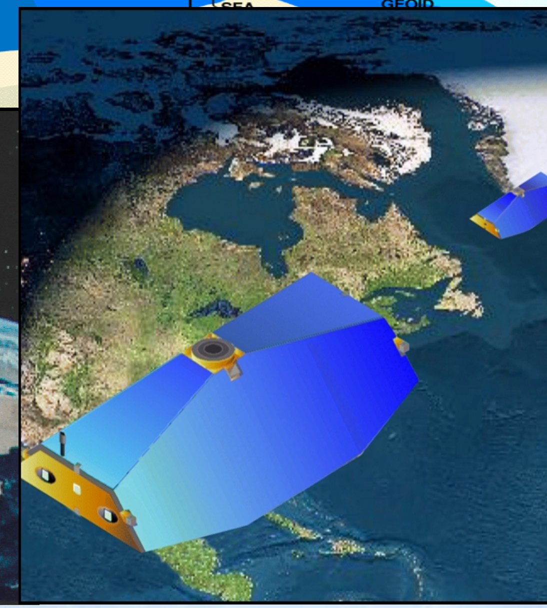


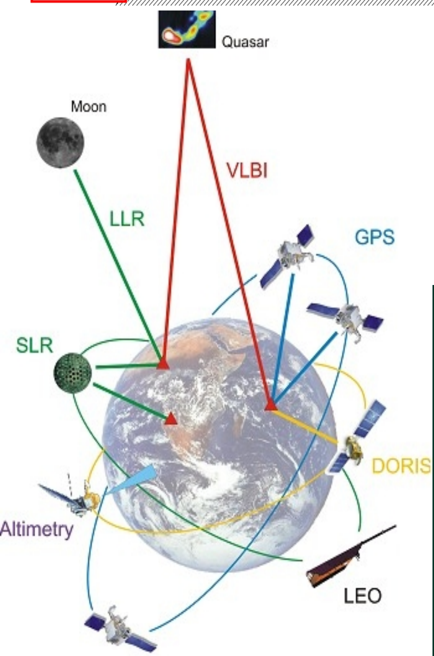


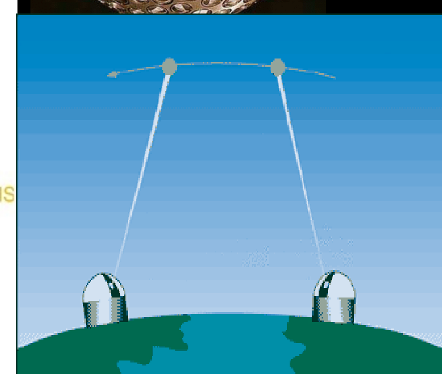


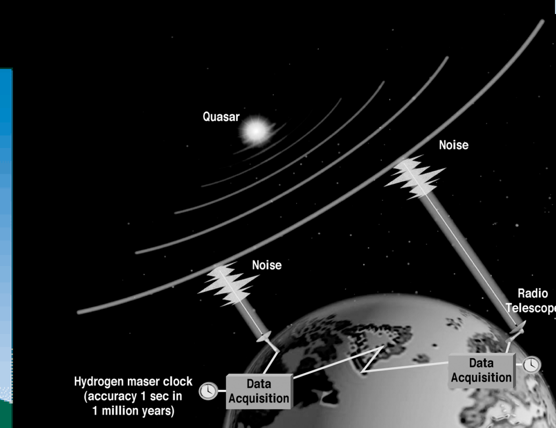




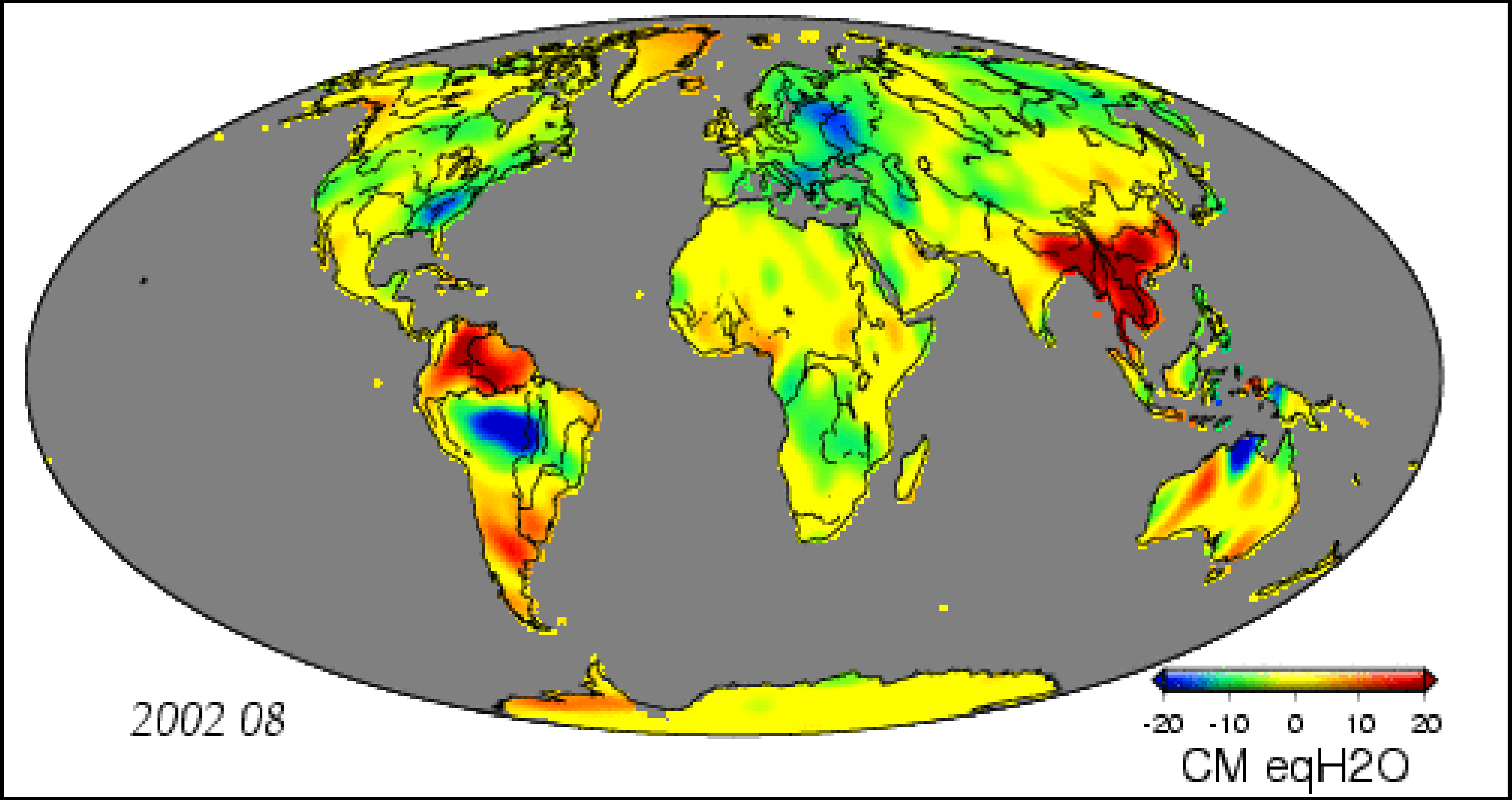






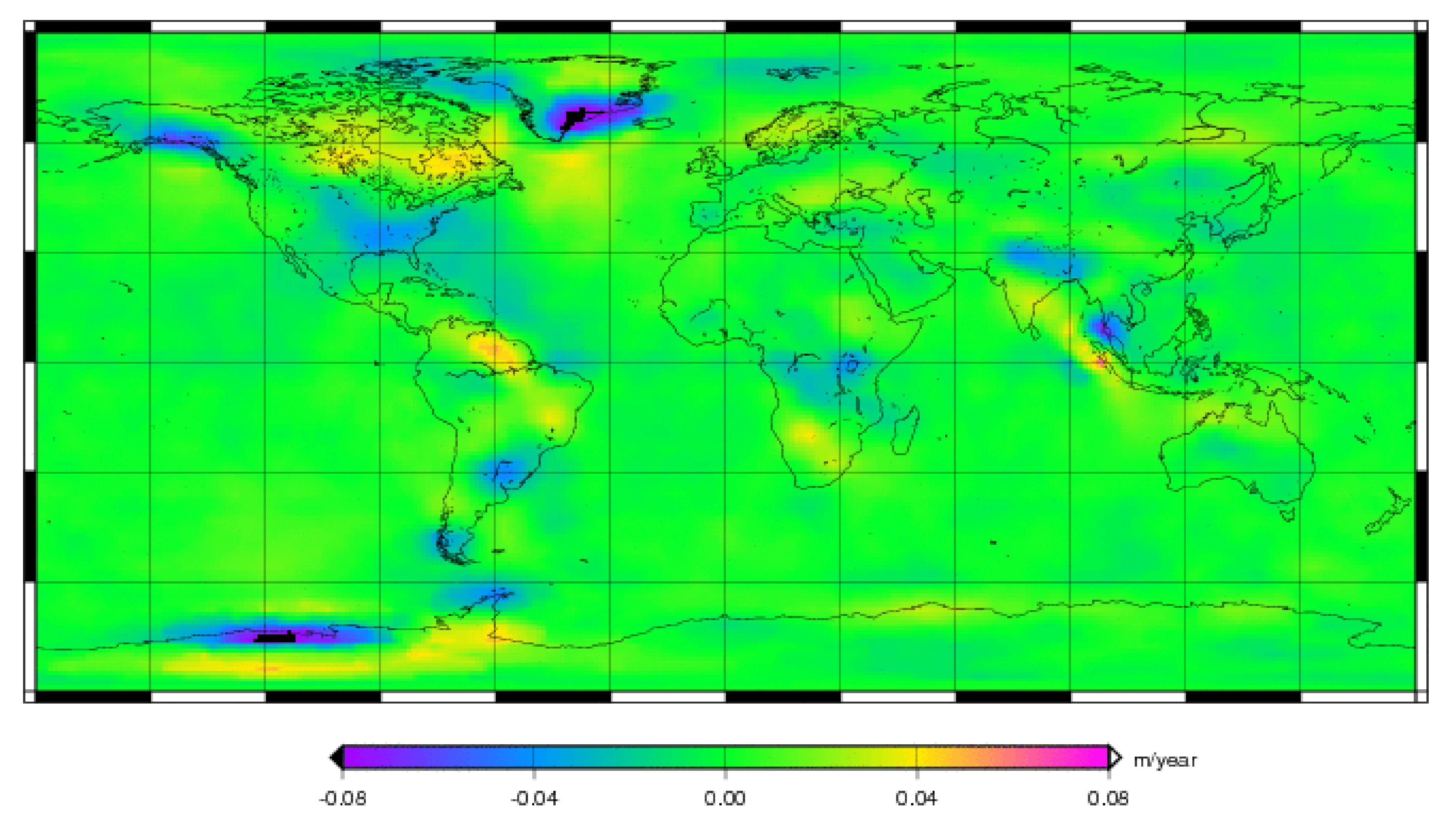


Science &Technology Motivation



http://grace.jpl.nasa.gov/information/

Science &Technology Motivation



JPL MASCON, secular trends 2003-2007, Watkins, 2008

IGCP 565 Project Objectives, Goals, and Approach

Objectives:

Develop GGOS into a monitoring for the global water cycle that:

- precisely records (water) mass movement through all components of the water cycle;
- detects significant changes in reservoir storage (groundwater, ice sheets, oceans, ...) and informs society about these changes;
- facilitates global and climate change science and research;
- supports regional water management.

Goals:

- Create a forum for experts from relevant disciplines to interact;
- Identify the challenges and develop a strategy to meet these;
- Develop regional products that can support societal applications, including water management;

Approach:

- Initiate, link, and coordinate relevant research projects;
- Organize a series of annual workshops;
- Interact with other relevant programs and initiatives.

Project Work Plan

Initiate and carry out relevant research projects:
- Extraction of the water cycle signals from geodetic observations
- Modeling of fingerprint of water cycle in geodetic observations
- Assimilation of geodetic observations in hydrological models.

A Series of Five Annual Work Shops:

2008: Science of geodetic monitoring of the hydrological cycle

2009: Ensuring continuous satellite gravity missions

2010: Determination of mass transports in the hydrological cycle from geodetic observations

2011: Integration of geodetic observations and products in models of the hydrological cycle

2012: Improving regional water management in Africa and Asia on the basis of geodetic water cycle monitoring

Achievements in 2008 and 2009

Presentation of Project at:

- IGWCO meeting (Geneva, Spring 2008);
- GEO UIC Meeting (Boulder, September 2008),
- UNESCO/UCI Symposium: (Irvine, 1-5 December 2008),
- GRACE Science Team Meeting (San Francisco, 12-13 December 2008)
- ISRSE33 (Stresa, Italy, May 2009),
- GRACE Science Team Meeting (Austin, November 5-6, 2009),
- GEO UIC Meeting (Washington, D.C., November 14, 2009).

Several proposals submitted:

- Purely geodesy: successful
- interdisciplinary: Reviewers' comments indicate a lack of acceptance of relevance of geodesy for hydrology

Achievements in 2008 and 2009

Workshop 1: “Science of geodetic monitoring of the hydrological cycle”

- San Francisco, December 11, 2008: 15 Participants from 5 countries:
- High-level presentations, all available at Workshop web page;
- Key conclusions summarized in a web-report

Workshop 2: Title changed from “Ensuring continuous satellite gravity missions” to “Towards a Roadmap for Future Satellite Gravity Missions”

- Graz, Austria, Sep. 30 – Oct. 2, 2009; 55 Participants from 12 countries
- Roadmap, declaration for GEO-VI, Strategic Target, all available at http://www.igcp565.org/workshop/Graz

Roadmap: Towards Future Satellite Gravity Missions

WHY GRAVITY?

Satellite gravity missions are a unique observational system for monitoring mass redistribution in the complete Earth system – no other sensors could do the same.

STRATEGIC TARGET

A multi-decade, continuous series of space-based observations of changes in the Earth's gravity field begun with the GRACE mission, and leading, before 2020, to satellite systems capable of global determination of changes in the Earth's gravity field from global down to regional spatial scales and on time scales of two weeks or shorter, as a contribution to an integrated, sustained operational observing system for mass redistribution, global change, and natural hazards, and in support of global water management, the understanding of climate variations, and the characterization and early detection of natural hazards.

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Project Meeting: “From Satellite Gravity Observations to Products”
- San Francisco, December 12-13, 2009, 9 participants from 4 continents
- Project review and detailed plans for the next three years

Challenges

Objectives:
Develop GGOS into a monitoring for the global water cycle that:
- precisely records (water) mass movement through all components of the water cycle;

For gravity, this is happening in the geodetic community, with a few (too few?) hydrologist involved. Integration of the “three pillars” is still not well enough developing.

- detects significant changes in reservoir storage (groundwater, ice sheets, oceans, ...) and informs society about these changes;

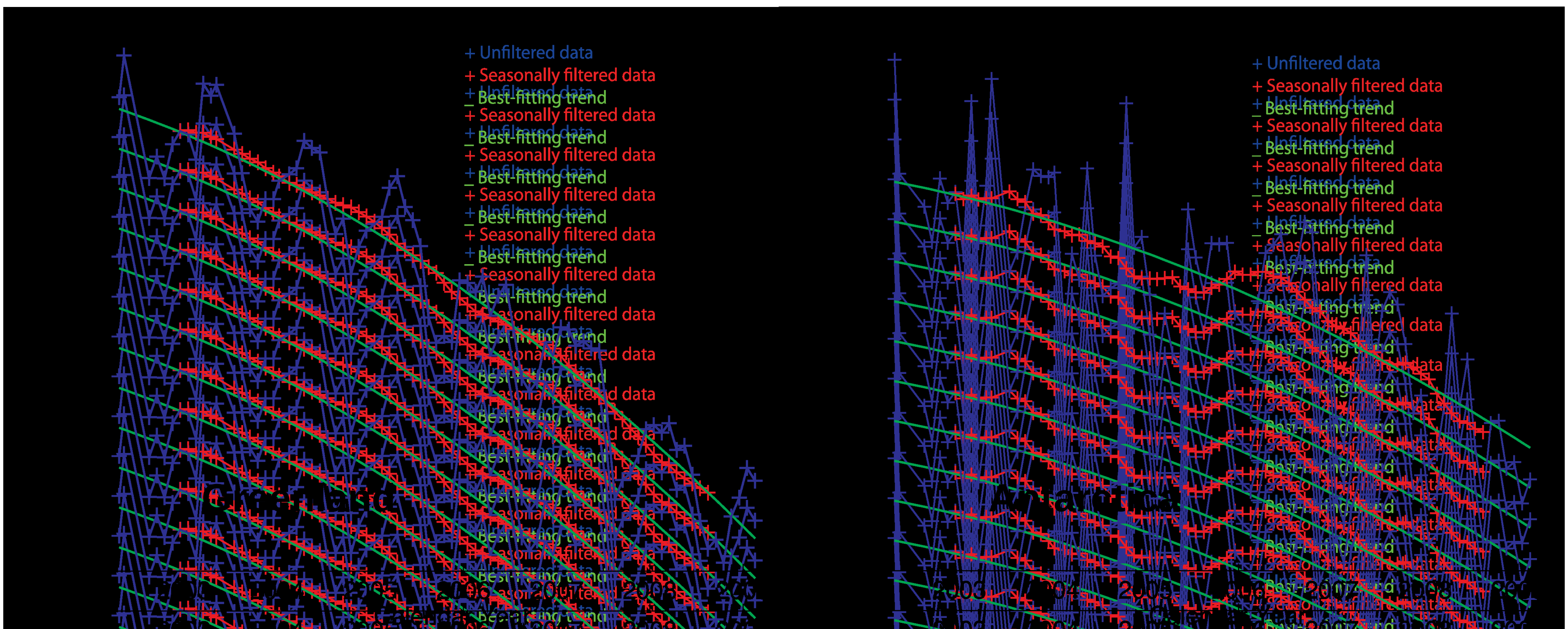
Based on gravity, we have a number of significant discoveries (see one-page stories), but information flow to society is limited;

GRACE Detects Accelerated Ice Mass Loss in Greenland and Antarctica

During the period of April 2002 to February 2009 the mass loss of the polar ice sheets was not constant but increased with time, implying that the ice sheets' contribution to sea level rise was increasing.

Greenland:
- mass loss increased from 137 Gt/yr in 2002–2003 to 286 Gt/yr in 2007–2009
- acceleration of -30 ± 11 Gt/yr^2 in 2002–2009.

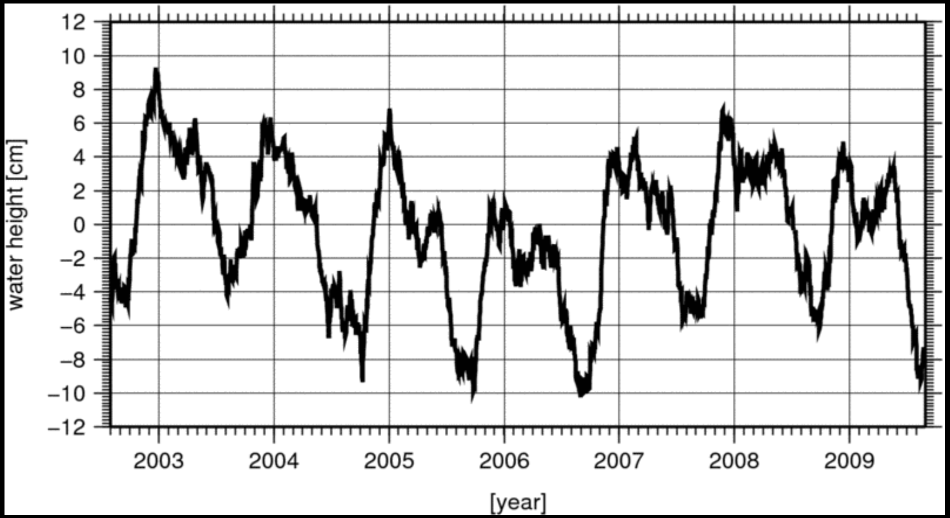
Antarctica:
- mass loss increased from 104 Gt/yr in 2002–2006 to 246 Gt/yr in 2006–2009
- acceleration of -26 ± 14 Gt/yr^2 in 2002–2009.



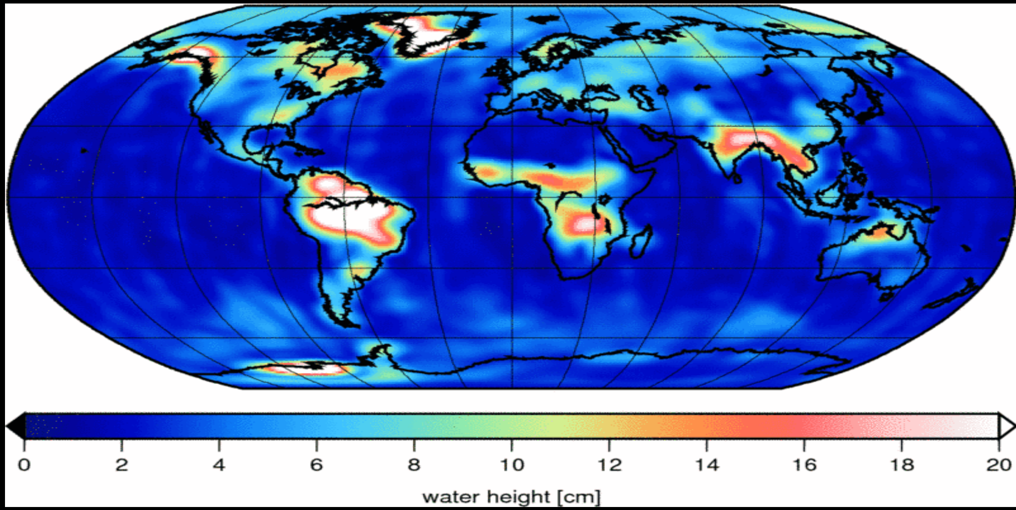
Velicogna, *GRL*,2009

Challenges

Daily Snapshots, ICT, Bonn

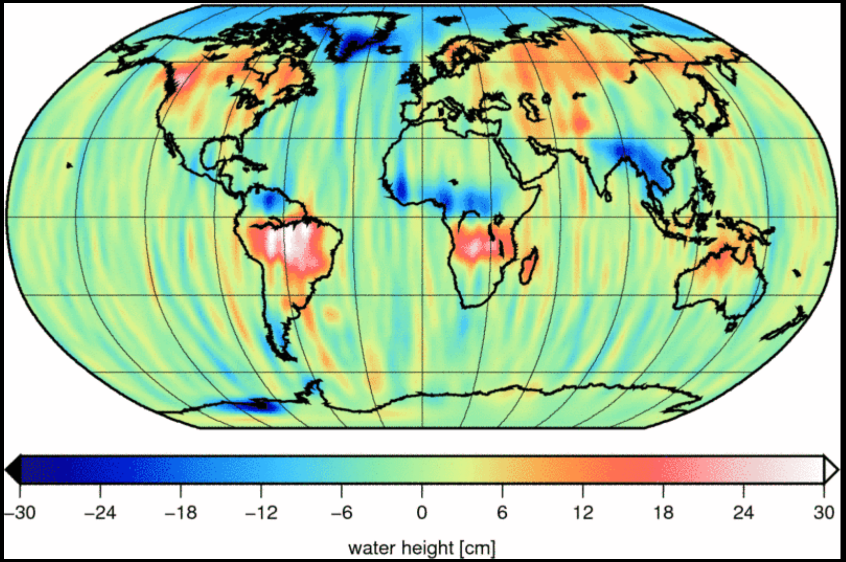


Daily estimates Congo Basin

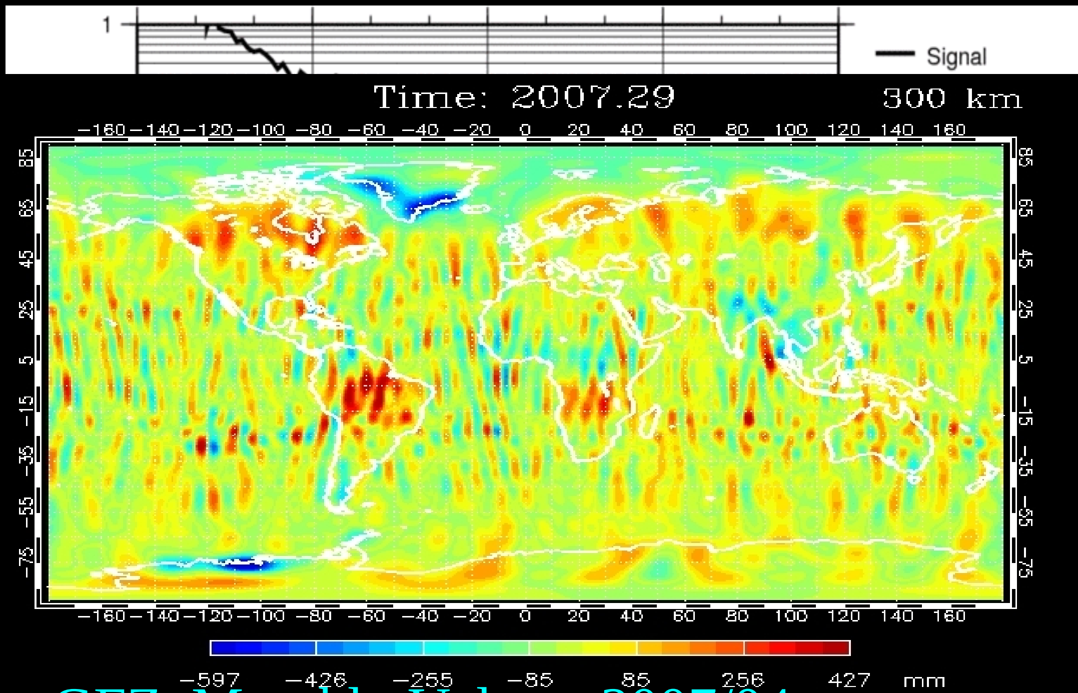


Standard Deviation, Kurtenbach et al., 2009

http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010



ICT, Monthly Values, 2007/04



GFZ, Monthly Values, 2007/04

Challenges

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Develop GGOS into a monitoring for the global water cycle that:
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For gravity, this is happening in the geodetic community, with a few (too few?) hydrologist involved. Integration of the “three pillars” is still not well enough developing.

- detects significant changes in reservoir storage (groundwater, ice sheets, oceans, ...) and informs society about these changes;
Based on gravity, we have a number of significant discoveries (see one-page stories), but information flow to society is limited;

- facilitates global and climate change science and research;
Is happening, but problems with data and product availability hampers progress;

- supports regional water management.
Very limited, partly because geodetic products are not easy to use and no “community”-validated products are available. Integrated products based on the three pillars are purely for research. Local studies are encouraging.

Challenges

Goals:

- Create a forum for experts from relevant disciplines to interact;

Limited success: Some hydrologist are participating in Project meetings and in geodetic meetings, but very few geodesists are joining hydrologists;

- Identify the challenges and develop a strategy to meet these;

Both the first and second workshop have made progress with identification, but the strategy to meet the challenges has not been developed fully. Some work went into proposals, and for gravity, the Roadmap details necessary steps. The strategy that would lead to useful products for water management still needs to be written.

- Develop regional products that can support societal applications, including water management;

Very little progress so far; but a better understanding of what is needed is developing.

Challenges

Approach:

- Initiate, link, and coordinate relevant research projects;

Initiation of new projects is slow; links and coordination needs to be improved;

- Organize a series of annual workshops;

Here the project is successful.

- Interact with other relevant programs and initiatives.

This has been slow initially, but plans for 2010 aim to improve the situation.

Plan for 2010 - 2012

2010:

Workshop 3:

- Originally: “Determination of mass transports in the hydrological cycle from geodetic observations”;
- Now: “Separation of hydrological and tectonic signals in geodetic observations”
- location: Reno, Nevada
- timing: October/November 2010
- Scope: focus on a few regions, e.g. South-West U.S., a region in East-Asia (Indonesia?), a region in Africa (Great Rift Valley)
- engage hydrological, geophysical, geodetic communities

Develop Concept/Roadmap for two test regions (South-West U.S. and Africa)

- integration of “three pillars” (particularly U.S. SW)
- validation: what independent data/models can be used?
- combination of geodetic observations with models

Plan for 2010 - 2012

2011:

Workshop 4:

- Title: “Integration of geodetic observations and products in models of the hydrological cycle”;
- location: Australia?
- timing: Co-located with IUGG (27 June - 08 July 2011)
- Scope: Methodology, demonstration, comparison of models, validation

2012:

Workshop 5:

- Title: “Improving regional water management in Africa and Asia on the basis of geodetic water cycle monitoring”;
- location: Africa
- timing: Late 2012

Geodesy4Water = GRACE?

$$\boldsymbol{u}(\boldsymbol{x},t) = \int_0^\infty \int_S \boldsymbol{G_u}(\boldsymbol{x},\boldsymbol{x}',\tau) L(\boldsymbol{x}',t-\tau)\mathrm{d}^2\boldsymbol{x}'\mathrm{d}\tau$$

$$\varphi(\boldsymbol{x},t) = \int_0^\infty \int_S G_\varphi(\boldsymbol{x},\boldsymbol{x}',\tau) L(\boldsymbol{x}',t-\tau)\mathrm{d}^2\boldsymbol{x}'\mathrm{d}\tau$$

$$\delta\Theta = \int_0^\infty \int_S G_\Theta(\boldsymbol{x},\boldsymbol{x}',\tau) L(\boldsymbol{x}',t-\tau)\mathrm{d}^2\boldsymbol{x}'\mathrm{d}\tau$$

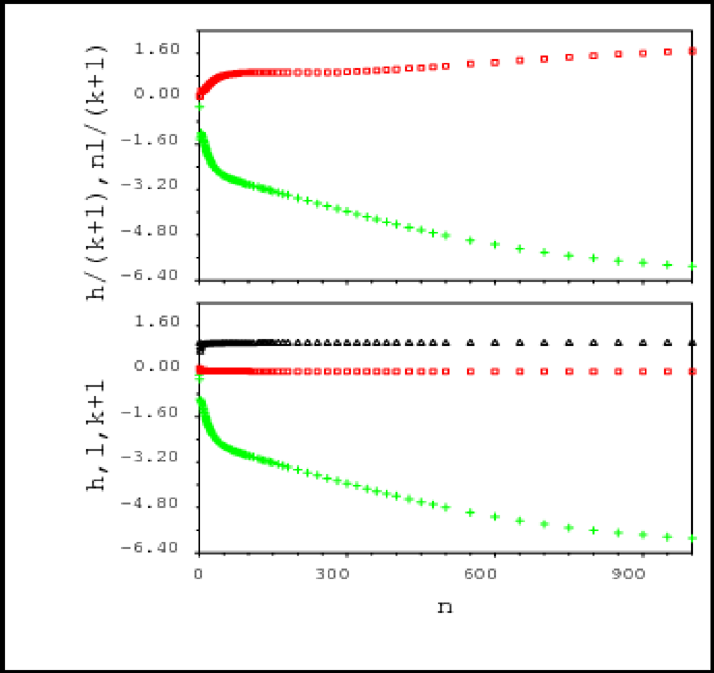
(Local) geodetic variables are inherently global and have memory ...

$$u_r(a,\vartheta,\phi) = \frac{M_\circ a}{M}\sum_{n=0}^{\infty} h_n' P_n(\cos\vartheta)$$

$$u_\vartheta(a,\vartheta,\phi) = \frac{M_\circ a}{M}\sum_{n=0}^{\infty} \ell_n' \frac{\partial}{\partial\vartheta} P_n(\cos\vartheta)$$

$$u_\phi(a,\vartheta,\phi) = 0$$

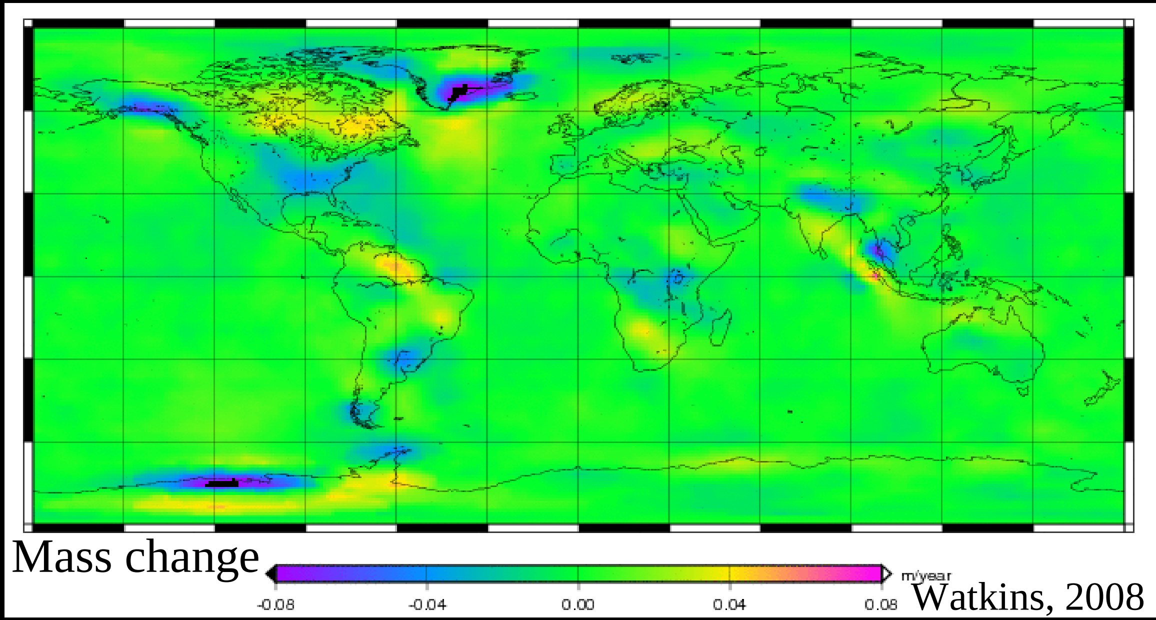
$$\varphi(a,\vartheta,\phi) = \frac{M_\circ G}{a}\sum_{n=0}^{\infty} (k_n'+1) P_n(\cos\vartheta)$$

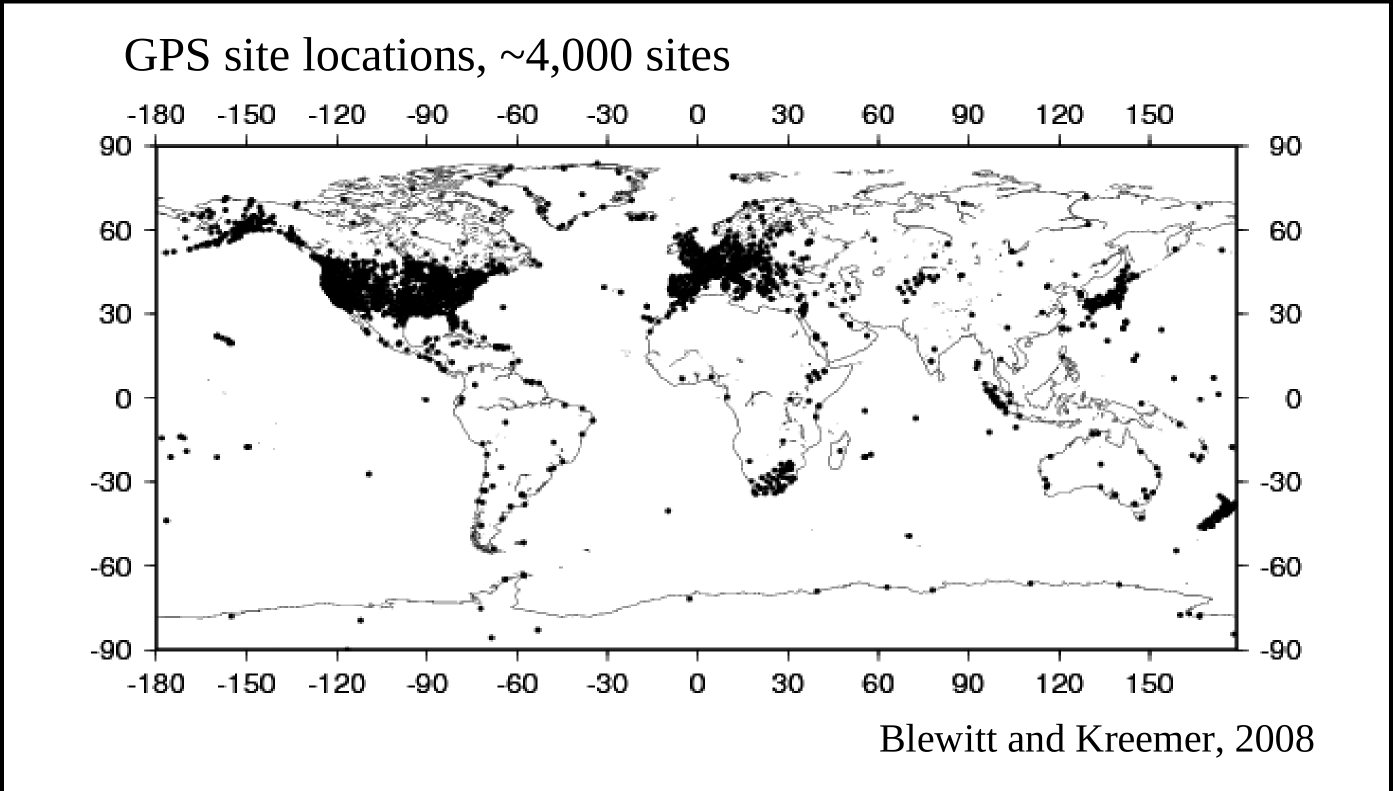


h: green
l: red
k: black

Small spatial scales: Vertical displacement is most sensitive

Geodesy4Water = GRACE?





Spatial gaps hamper integration of gravity and displacements

Validation of response functions, mass change models, ice sheet dynamics models:

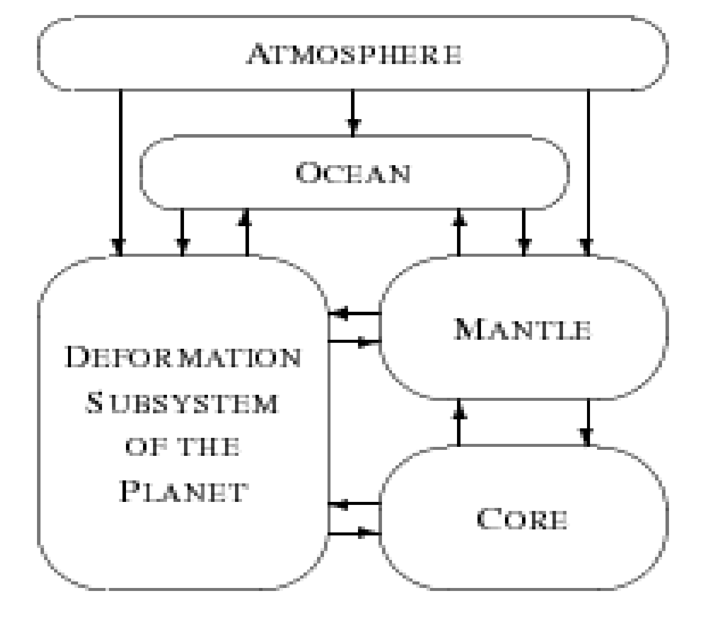
Increased observations (surface displacements, gravity, mass balance) in areas with large mass changes, in particular:

- Greenland;
- Svalbard;
- Antarctica and southern outh America .

Geodesy4Water = GRACE?

Two questions related to simulation/assimilation:
(1) What could be a framework for integrated model development?
(2) How good are our forward models?

Answer to (1):
- Modular model of independent modules coupled by boundary conditions and volume forces;
- Calibrated and validated for GRACE time



Problems:
- Boundary value problem for deformation and gravity field
- Spatial resolution: << 1 degree; high demands in terms of computer resources
- Temporal resolution: << 1 day
- Consistency of models and observations
- Mass conservation in the water cycle

Answer to (2):
- More complex ...

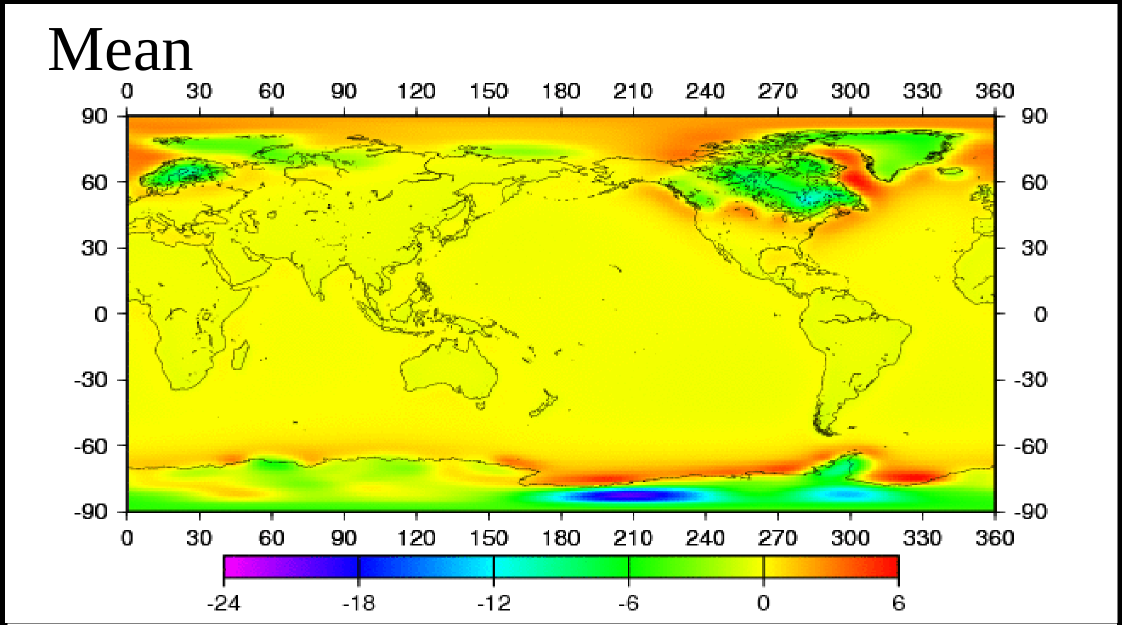
Geodesy4Water = GRACE?

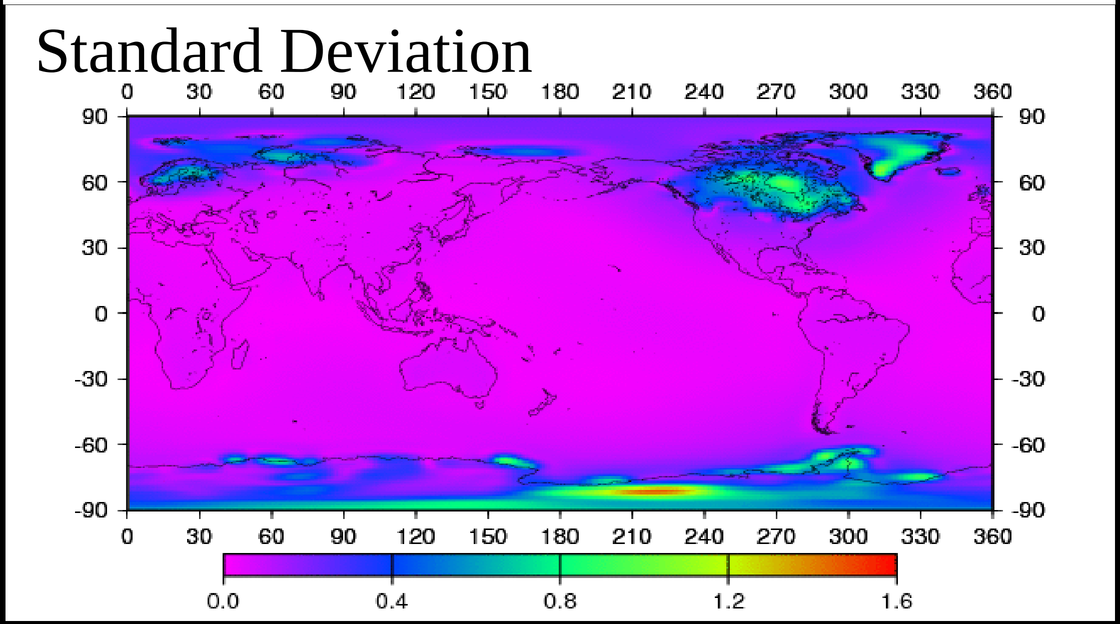
Some examples of problematic issues:

Module	Process	Status
atmosphere	loading	significant differences depending on pressure field, spatial resolution, ocean response
ocean	non-tidal loading	significant differences depending on ocean model
atmosphere	angular momentum	differences depending on meteorological model
cryosphere	Post-Mass Response	significant differences depending on ice history and Earth model
cryosphere	Co-Mass Response	significant differences depending on Earth model and approach

In most cases: Observation accuracy exceeds model accuracy

Geodesy4Water = GRACE?





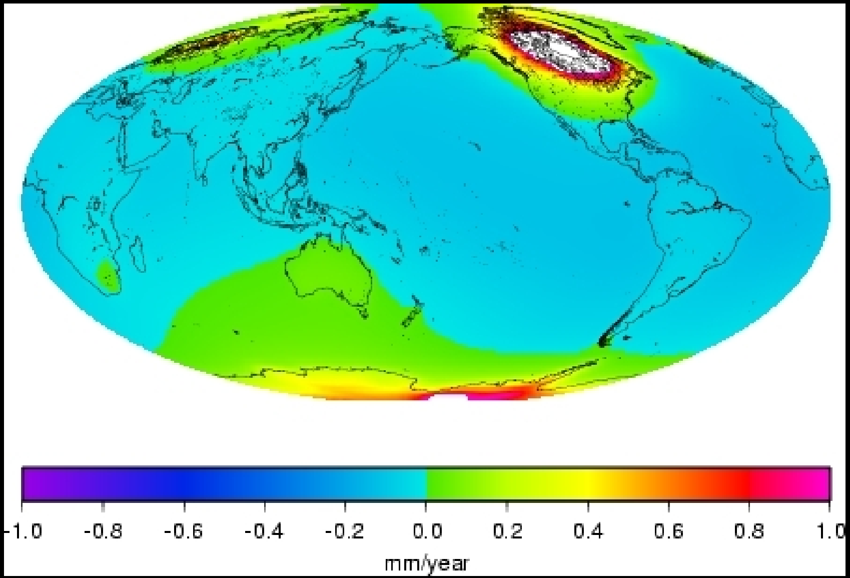
Post-Mass Response (PMR):

- 14 Local Sea Level trend predictions
- 3 groups
- ICE-3G and ICE-5G
- 10 different mantle viscosities

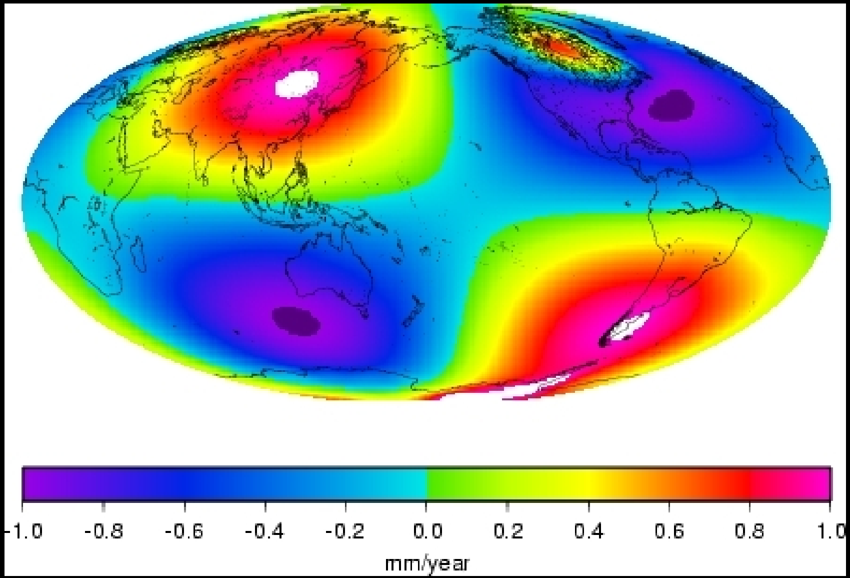
(all values in mm/yr)

In areas with large signals, standard deviation ~ 10%

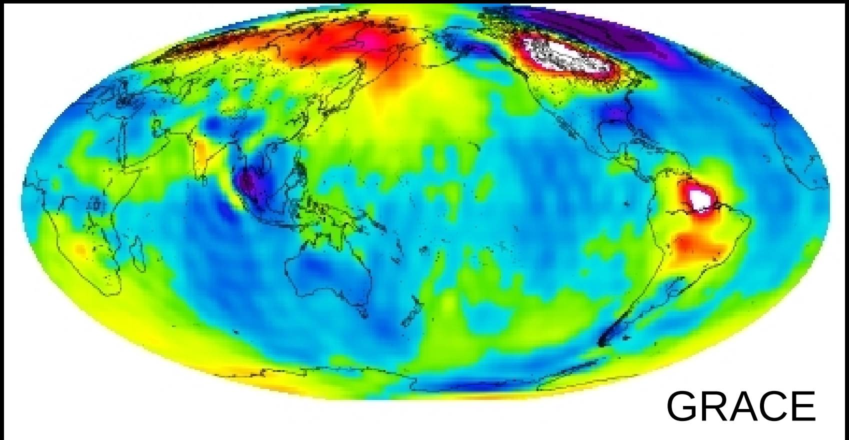
Geodesy4Water = GRACE?



Paulson et al., 2007



Peltier, 2004



Predicted geoid rates from different PGR models compared with observed rates from GRACE when no correction is applied

Chambers et al, 2009

Geodesy4Water = GRACE?

Co-Mass Response (CMR):

Significant differences in predicted Local Sea Level Fingerprints

Response calculated with PMR models have much small spatial variability than models based on an elastic loading approach

For Greenland:

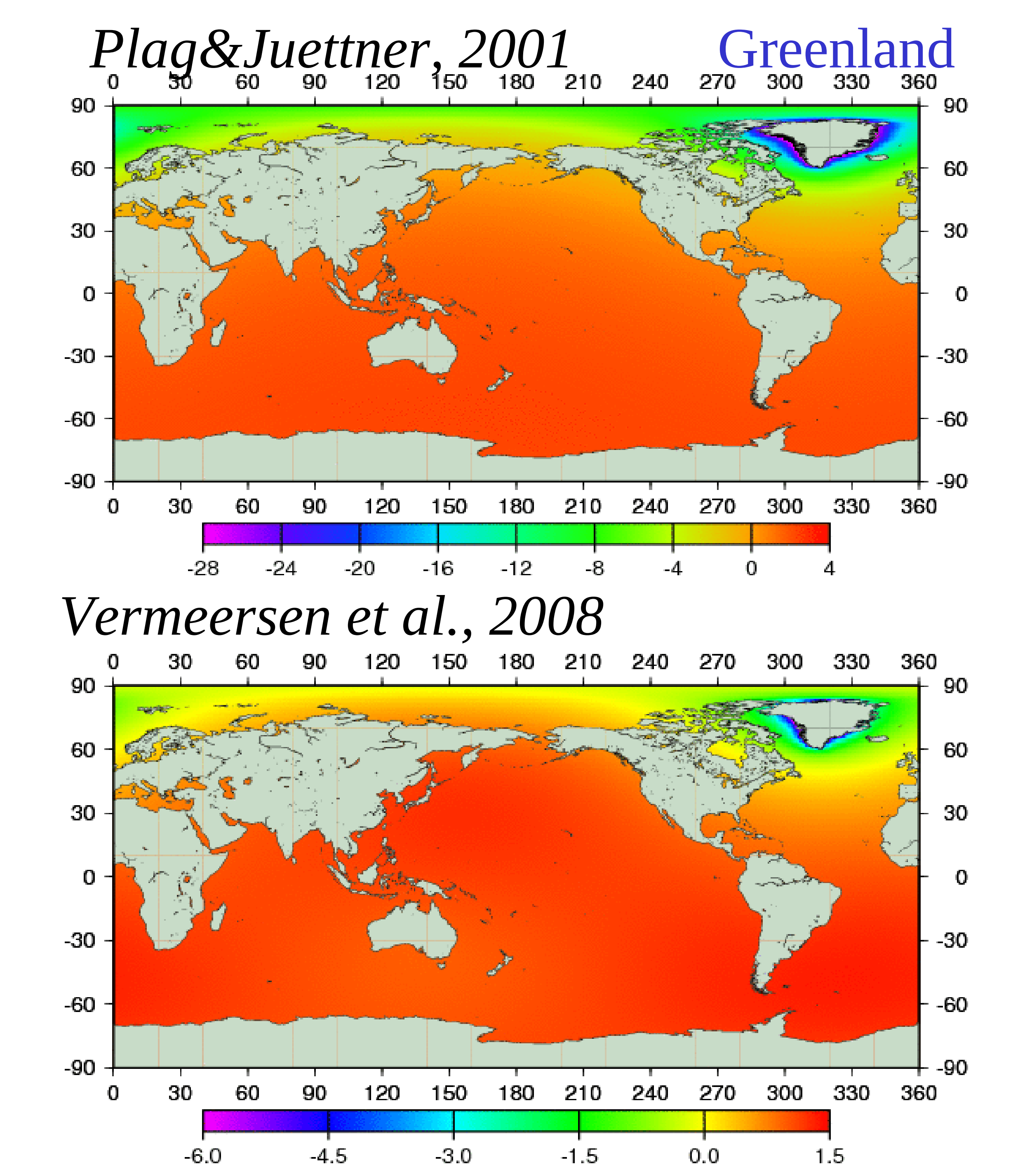
-6 to 1.4 versus

-25 to 3.0

Both models are currently not validated!

Svalbard observations:

-60 close to ice load



Conclusion (Towards Geodesy)

For higher spatial resolution, integration of gravity and displacements;

Observation accuracy exceeds model accuracy;

Large spatial gaps in displacements hamper full integration.

We need to improve/validate our forward models

We need to integrate the solid Earth into Earth system models

We need a whole-cycle (system) approach

We need a major community effort focusing on solid Earth modeling comparable to the efforts on climate modeling

PREDICTIONS:

Complexity of Water Cycle (= Earth System) renders reductionist approach inappropriate (in particular for sea level as output of the global water and energy cycle);

Emergence, based on observed characteristics: Earth observations are central.