WP1100: Requirements Analysis Progress Report

NGGM Science Team:
DEOS, Department of Earth Observation and Space Systems, TU Delft
IAPG, InstitutfürAstronomische und PhysikalischeGeodäsie, TU München
GIS, Institute of Geodesy, Universität Stuttgart
ULUX, University of Luxembourg

Introduction

- Mass transport in the Earth System
  - Acts over spatial scales from 10 km to 1000's km
  - Acts over temporal scales from sub-daily, seasonal, to long-term trends
  - Acts over the entire globe
  - Includes changes in
    - the Solid-Earth
    - oceans
    - cryosphere
    - continental water
    - atmosphere (not considered here)

Outline

- What are the rough spatial and temporal characteristics of each of the mass transport systems?
- What is the current status of satellite gravimetry with respect to these space, time, geographical distribution, etc.?
- What are the problems with aliasing and signal separation that limit our ability to interpret satellite gravimetry results?
- What are the remaining scientific questions, and how do we parameterize a NGGM to optimize our chances of addressing these questions?

Introduction

- Goal is to provide mission designers with enough information to design and build an NGGM
- parameters to be defined include
    - accuracy
    - spatial resolution
    - spatial coverage
    - temporal resolution
    - mission lifetime
- trade-offs exist between these parameters (to be discussed later)

Accuracy

- accuracy of observed gravity must be sufficient to observe the process of interest
- amplitude of observation errors << amplitude of mass transport signal
- amplitudes usually defined in terms of geoid height or thickness of an equivalent layer of water

Accuracy requirement of mass changes expressed as the thickness of a thin layer of water (mm). Values in the form 0.5 (0.1) indicate a minimum useful accuracy, and a desired or target accuracy.

Application	**mm H_2O**
Hydrologic basin total water change	20(10)
Glacier mass loss	2(1)
Ice sheet mass loss	20(5)
Oceanic gyers spin up or down	4(1)
Global Sea-level rise; thermostatic/eustatic	1(0.3)
Glacial Isostatic Adjustment	0.5(0.2)

Spatial Resolution

- mass transport in the Earth System spans a wide range of spatial scales
  - degree 1 ($\lambda \approx 20{,}000$ km): seasonal variations in environmental surface masses
  - degree ($\lambda \approx 10$ km): volcanoes, earthquake mass displacement, glaciers, soil moisture, ocean currents, etc.

Temporal Resolution

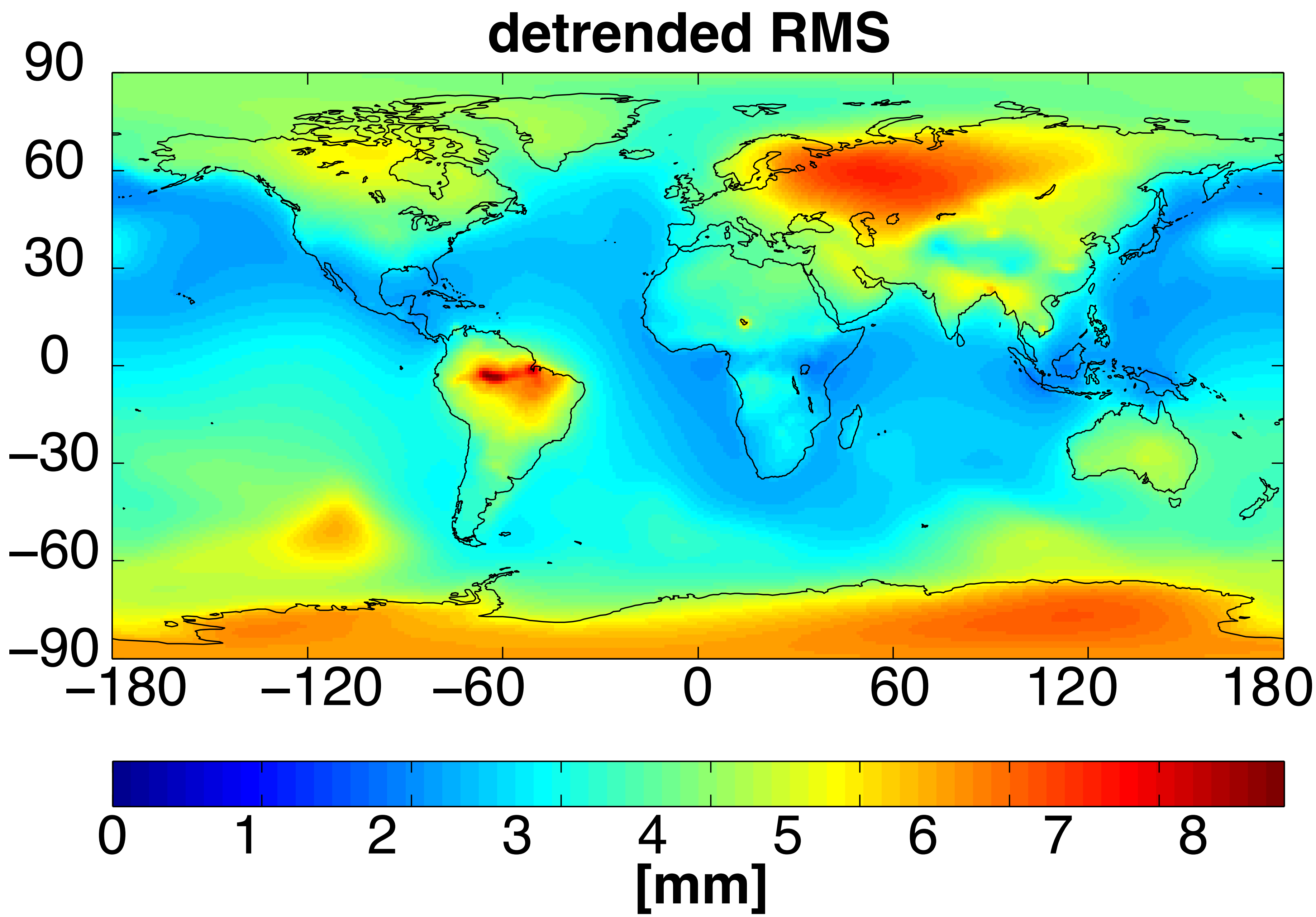
- Different mass transport processes show a very different behavior in the time domain
  - atmosphere: predominantly takes place with periods between several hours, semi-diurnal, diurnal, fortnightly, annual etc.
  - solid Earth: mostly linear trends within the time interval of a few years to 100's of years.
  - hydrosphere:
    - hours (ocean tides), seasonal
    - long term trends due to basin scale mass changes, sea level rise, etc.
  - ice
    - seasonal, interannual, long term trends
- temporal resolution, must be sufficient to capture most of the spectrum of the target processes
- important when considering nuisance parameters

Temporal Coverage

- in terms of verifying long-term trends, the scientific value of a mission is proportional to its duration
- global change and solid earth processes, these are primarily characterized by long-term trends (besides earthquakes)
- must be considered in mission design

Spatial Coverage

- mass transport occurs at the poles (ice mass change) and at the equator



MTS AOHIS model with trends removed for 1995

For the remaining discussions...

- Focus on the temporal and spatial characteristics of the signals

Current Status of Satellite Gravimetry

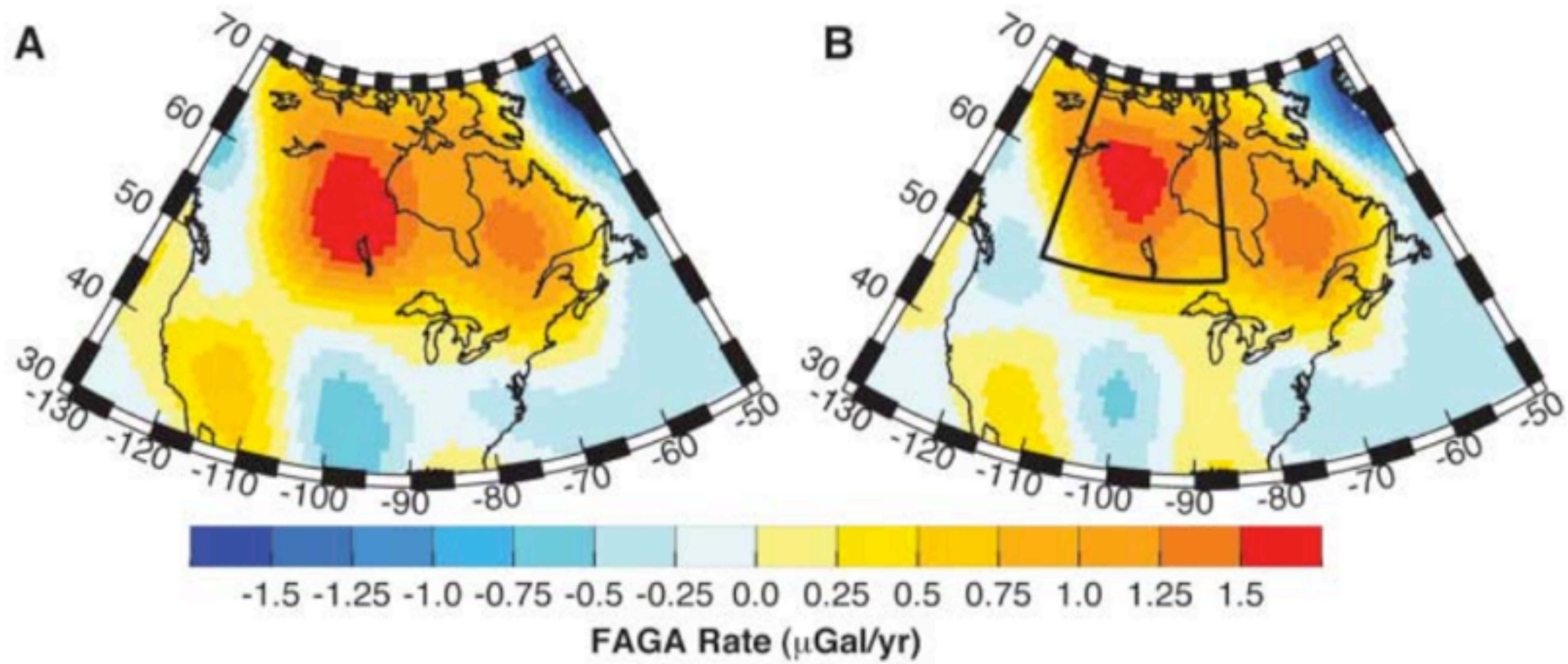
- Only discuss TVG, however bear in mind that any TVG mission will also generate improvements in the static gravity field
- Best TVG mission to date, GRACE
- For every paper mentioned here, there is usually a minimum of one additional paper on exactly the same topic

GRACE Solid-Earth

- GIA
  - 1 - 2 mm/yr geoid signal (1-2 cm H_2O)
  - $\lambda \approx 500$ km
  - $T \approx$ 100-10,000 years
  - signal found in the mid- to high-latitudes with global impact
- co- and post-seismic deformation
  - sub-mm to mm geoid ($\leq$ 1 cm H_2O)
  - $\lambda \approx$ 10-200 km
  - $T \approx$ instantaneous to decades; maybe secular (build up of strain)
  - earthquake zones
- volcanoes
  - sub-mm geoid (< 1 cm H_2O)
  - $\lambda \approx$ 10-50 km
  - $T \approx$ instantaneous to secular
  - earthquake zones

GRACE Solid-Earth

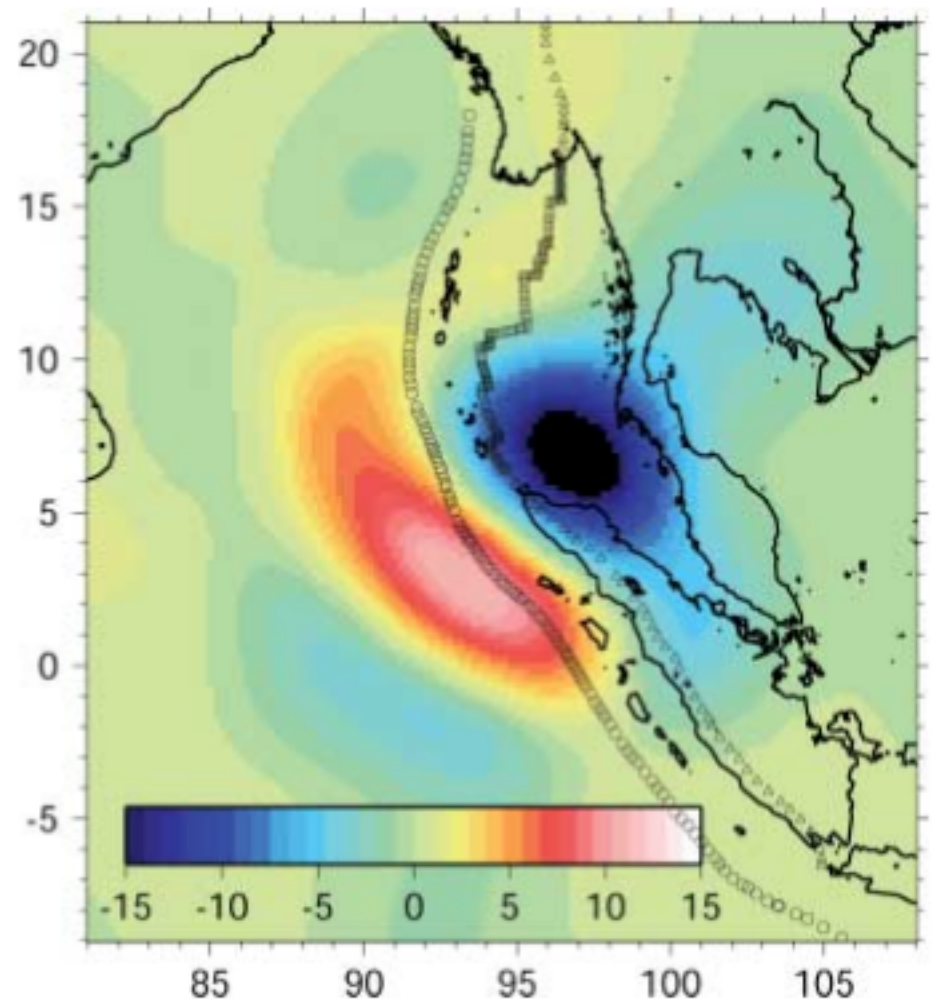
- Free-air gravity trend over Canada derived from GRACE
- CSR RL01; l ≤ 70; 500 km Gaussian smoothing, destriping => geoid heights on 1° x 1° grid; separation using GLDAS
- isolated GIA signal from the mantle convection process
- GIA few thousand years << convective flow

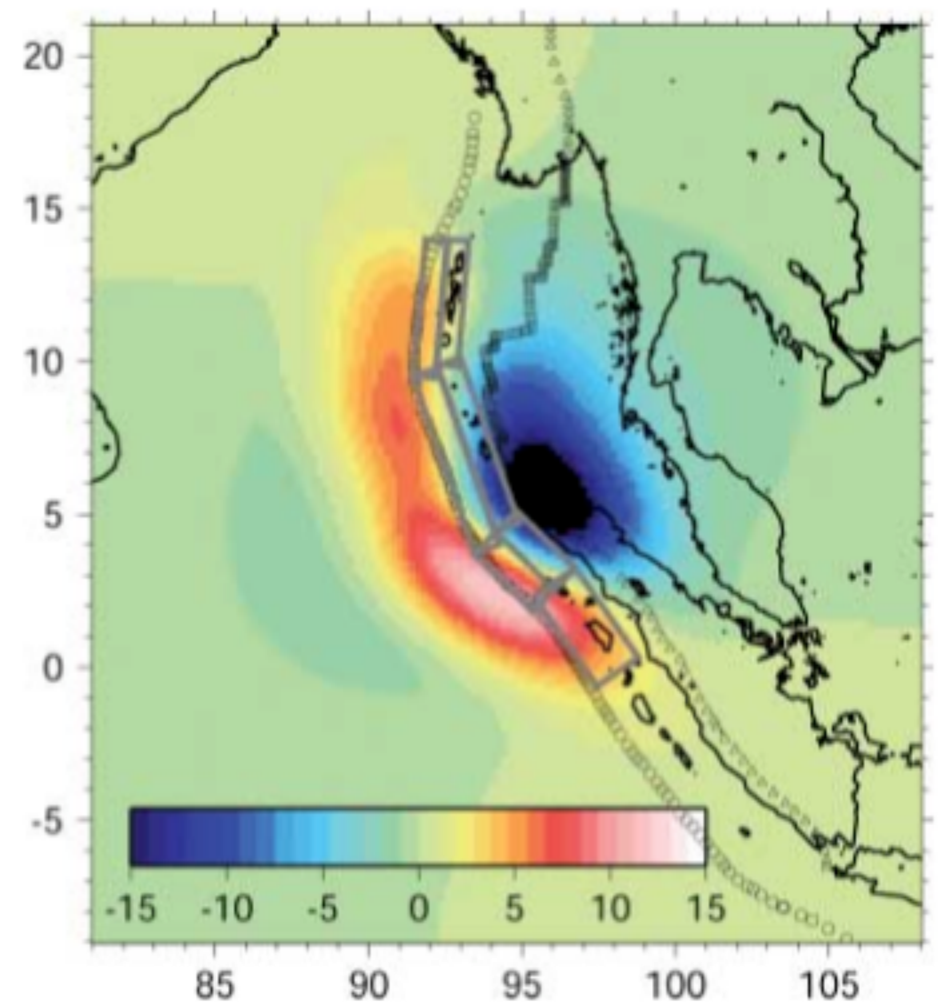


"GRACE gravity data constrain ancient ice geometries and continental dynamics over Laurentia", Tamisiea et. al. Science 2007

GRACE Solid-Earth

- Sumatra-Andaman 9.1 earthquake detection with KBR SST
- coseismic deformation
- best fit dislocation model: roughly equal contributions of vertical displacement and dilatation effects
- observations of crustal dilatation resulting from an undersea earthquake





units μGals

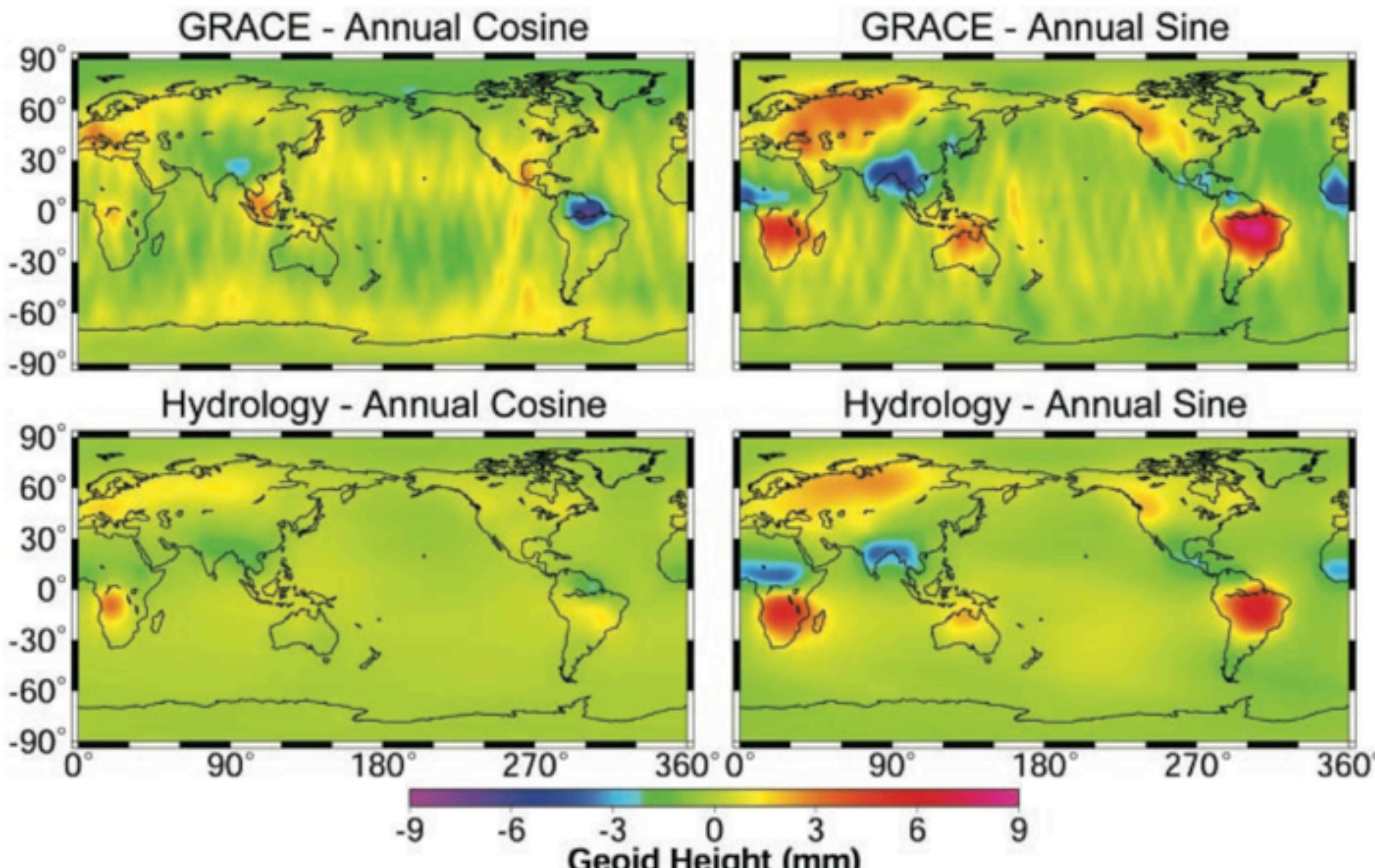
"Crustal dilatation observed by GRACE after the 2004 Sumatra-Andaman earthquake", Han et al., Science, 2006

GRACE Hydrology

- snow, precipitation, groundwater, soil moisture, evapotranspiration
  - 2-6 cm geoid (20 - 60 cm H_2O)
  - $\lambda \approx$ 10-1000's km
  - $T \approx$ hourly to seasonal to secular
  - continental land masses

GRACE Hydrology

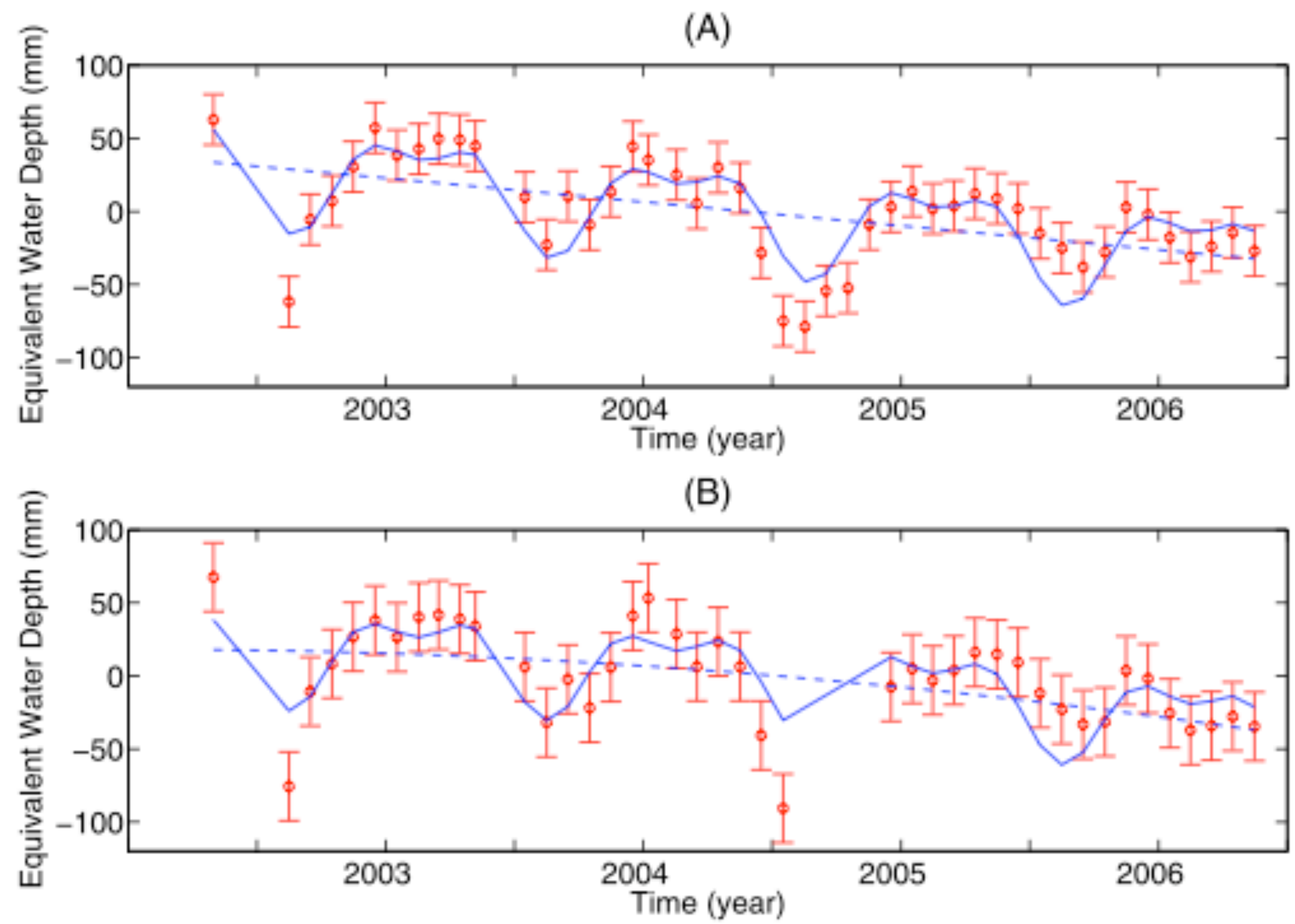
- Early on, there was a focus on extracting the seasonal long wavelength signal in the continental water storage
- 14 fields; no degree 2 coefficients; down weighted the higher degrees, 400 km smoothing radius
- 2002 solutions can resolve spatial scales of 1000 km; 2003 solutions down to 400 km



"GRACE measurements of mass variability in the Earth System", Tapley et al., Science, 2004

GRACE Hydrology

- Basin Analyses: Congo
- 46 months; CSR RL01; $l \leq 70$; C20 from SLR; 600 km averaging kernel
- trend + seasonal evident
- trend independent of size of the averaging kernel
- estimated R - E using a model of precipitation
- trend = -17 ± 12 mm/yr
- 4 years insufficient to conclude that the trend is secular



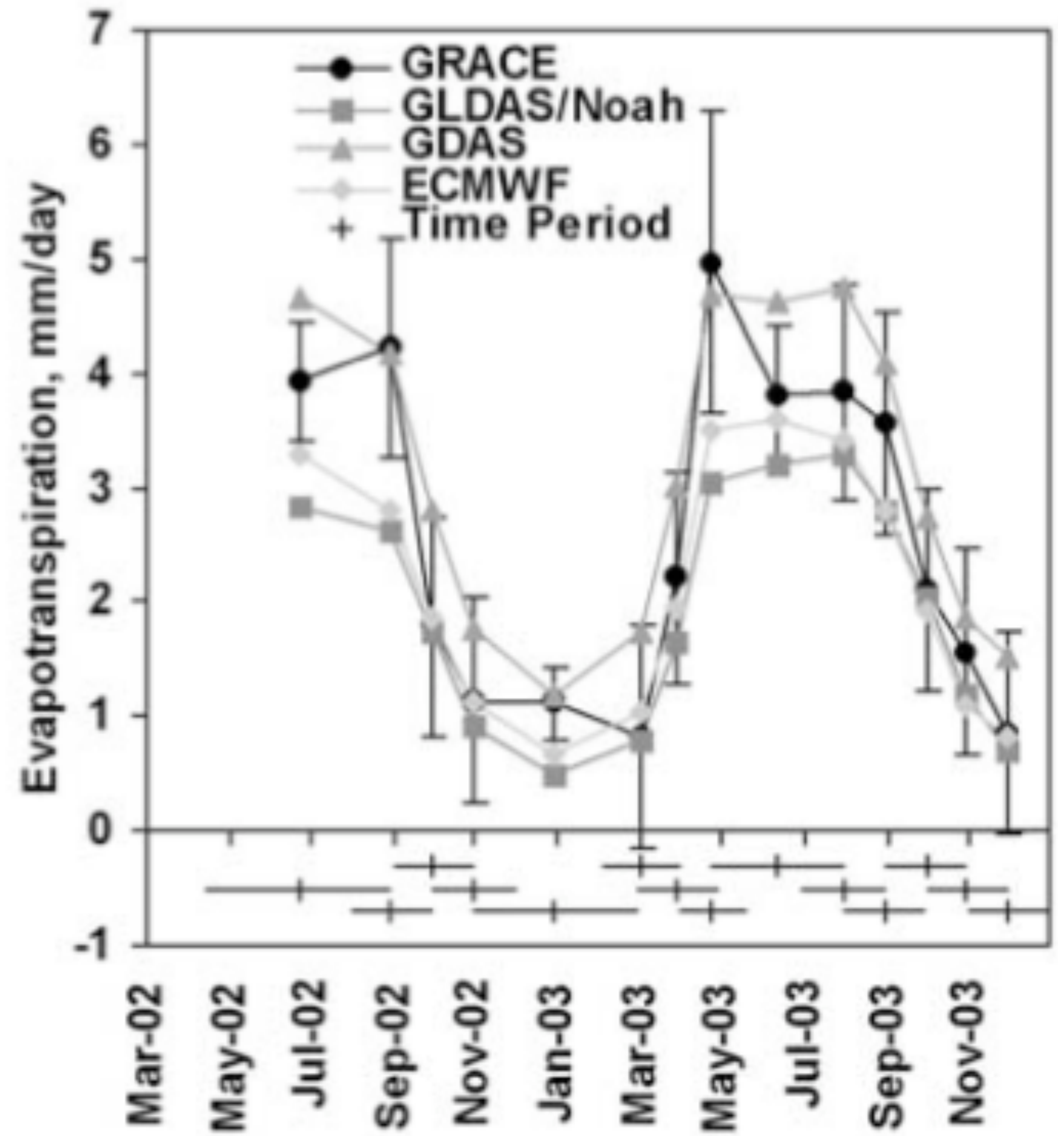
A) constrained
B) unconstrained

"Land water storage within the Congo Basin inferred from GRACE satellite gravity data", Crowley et al., GRL, 2006.

GRACE Hydrology

- Evapotranspiration difficult to measure on regional scales
- $ET = P - Q - \Delta S$
- P and Q are pretty reliable; ΔS missing over most of the globe
- ΔS closely approximates the storage change observed by GRACE
- compared with numerical models
- averaging radii had little effect

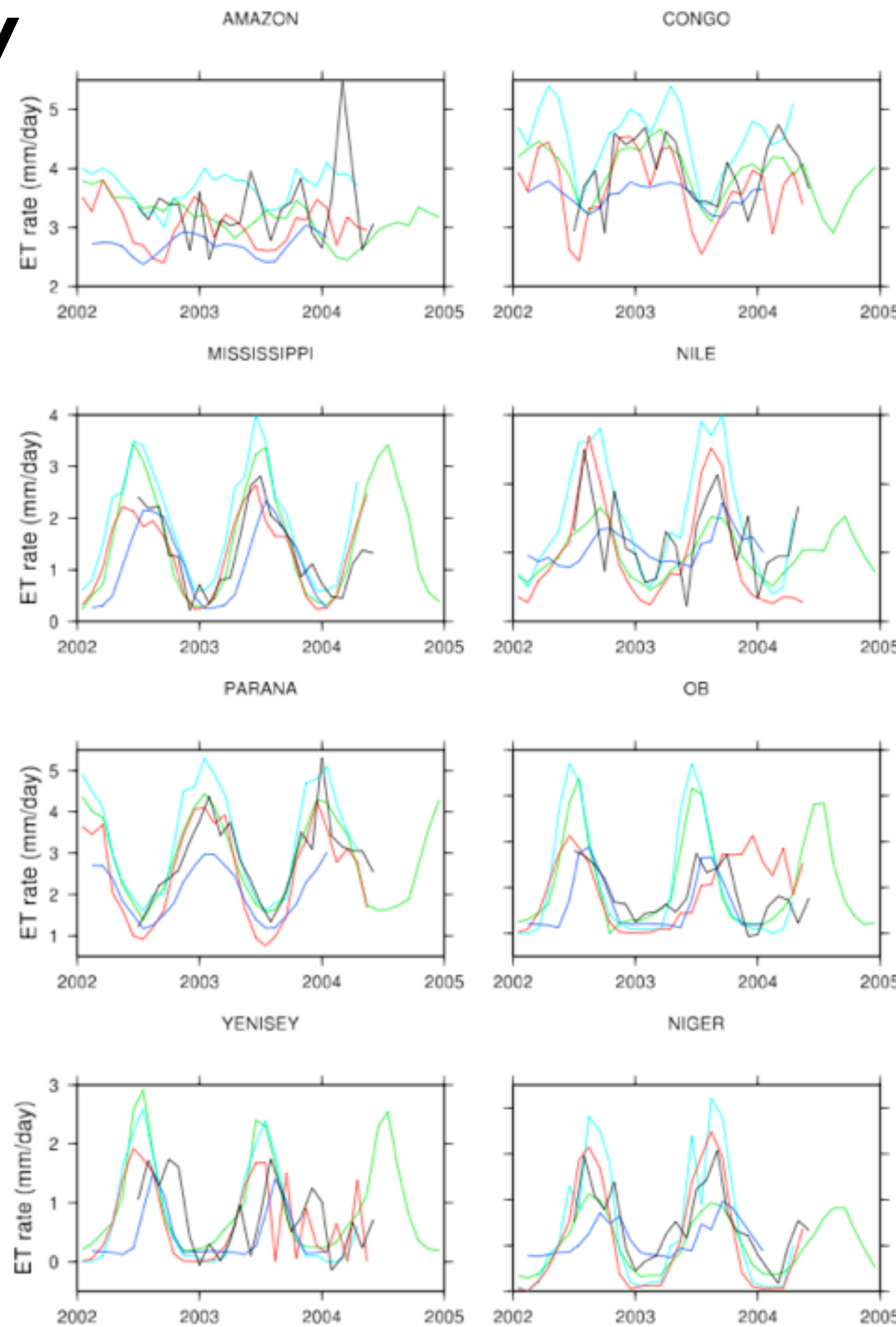
Mississippi River Basin



"Basin scale estimates of evapotranspiration using GRACE and other observations", Rodell et al., GRL, 2004.

GRACE Hydrology

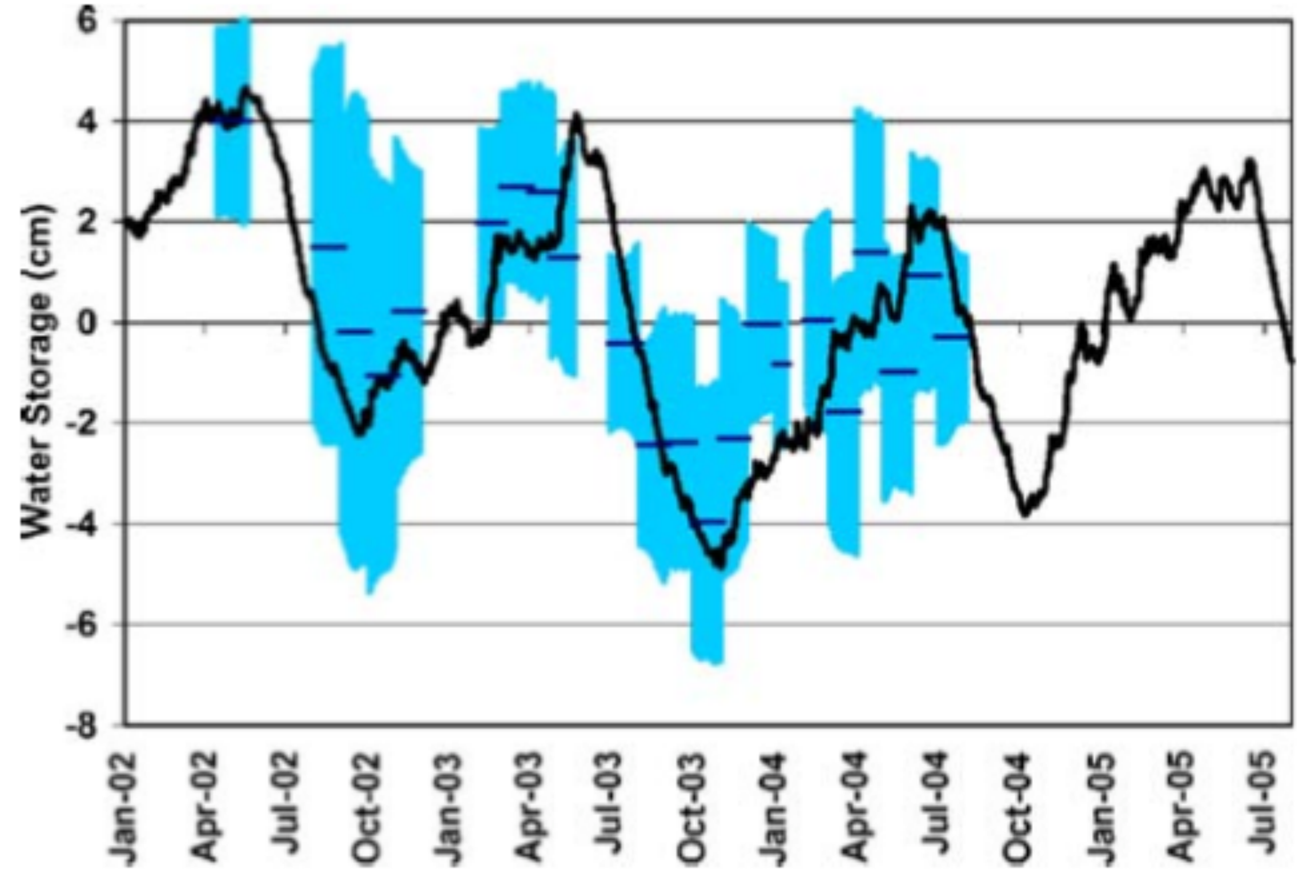
- Evapotranspiration for 16 global basins (only 8 shown)
- GRACE compared with WGHM, GLDAS, LAD, Orchidee
- GPCC precipitation
- runoff from LAD and WGHM

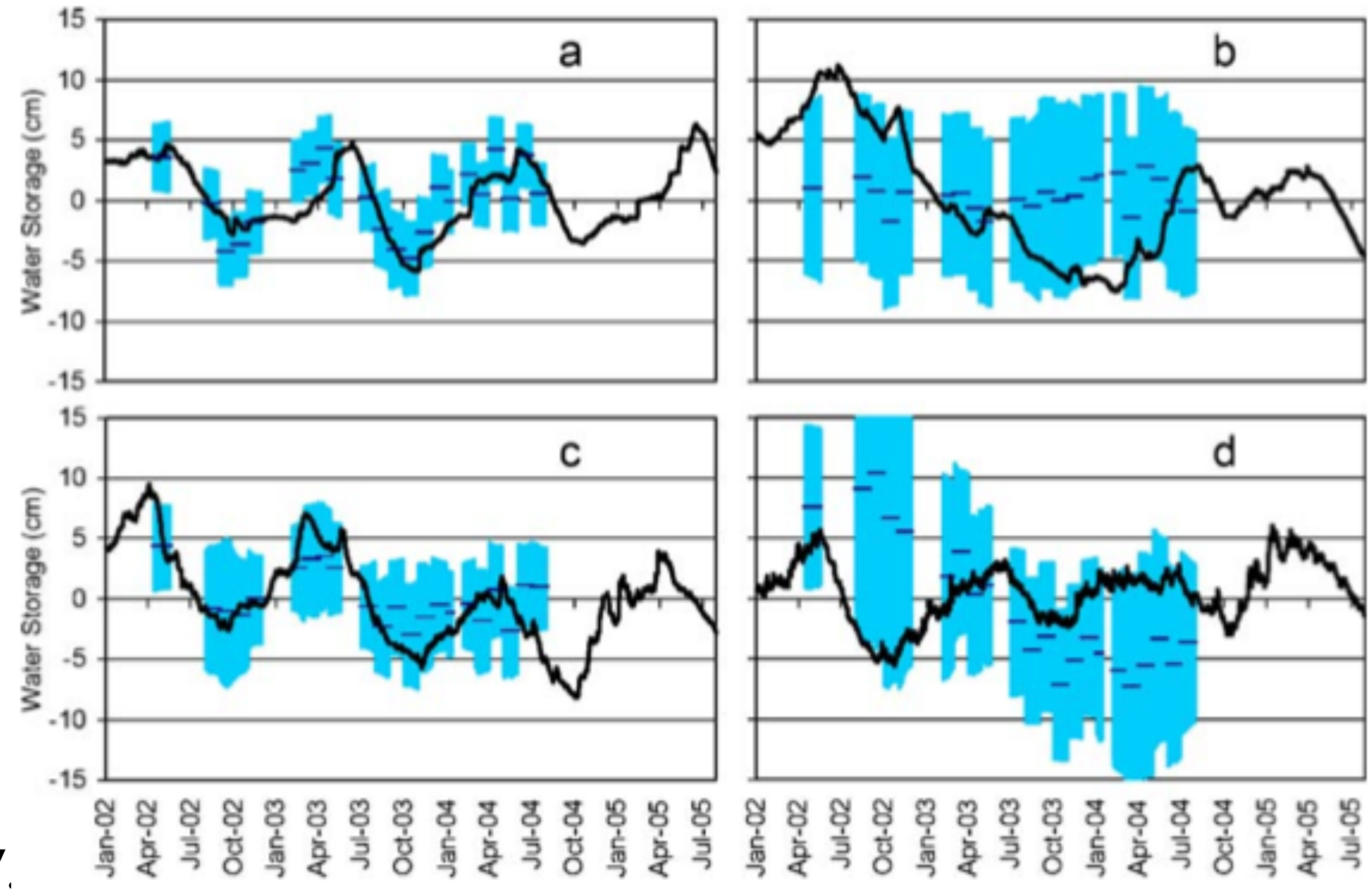


"Time variations of the regional evapotranspiration rate from Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry", Ramillien et al., WRR, 2006.

GRACE Hydrology

- Groundwater storage
- $\Delta GW = \Delta TWS - (\Delta SM - \Delta SME)$
- 3-hourly SM and SWE from GLDAS averaged to the GRACE solutions
- compared with GW wells
- works for Mississippi Basin and the 4 sub-basins

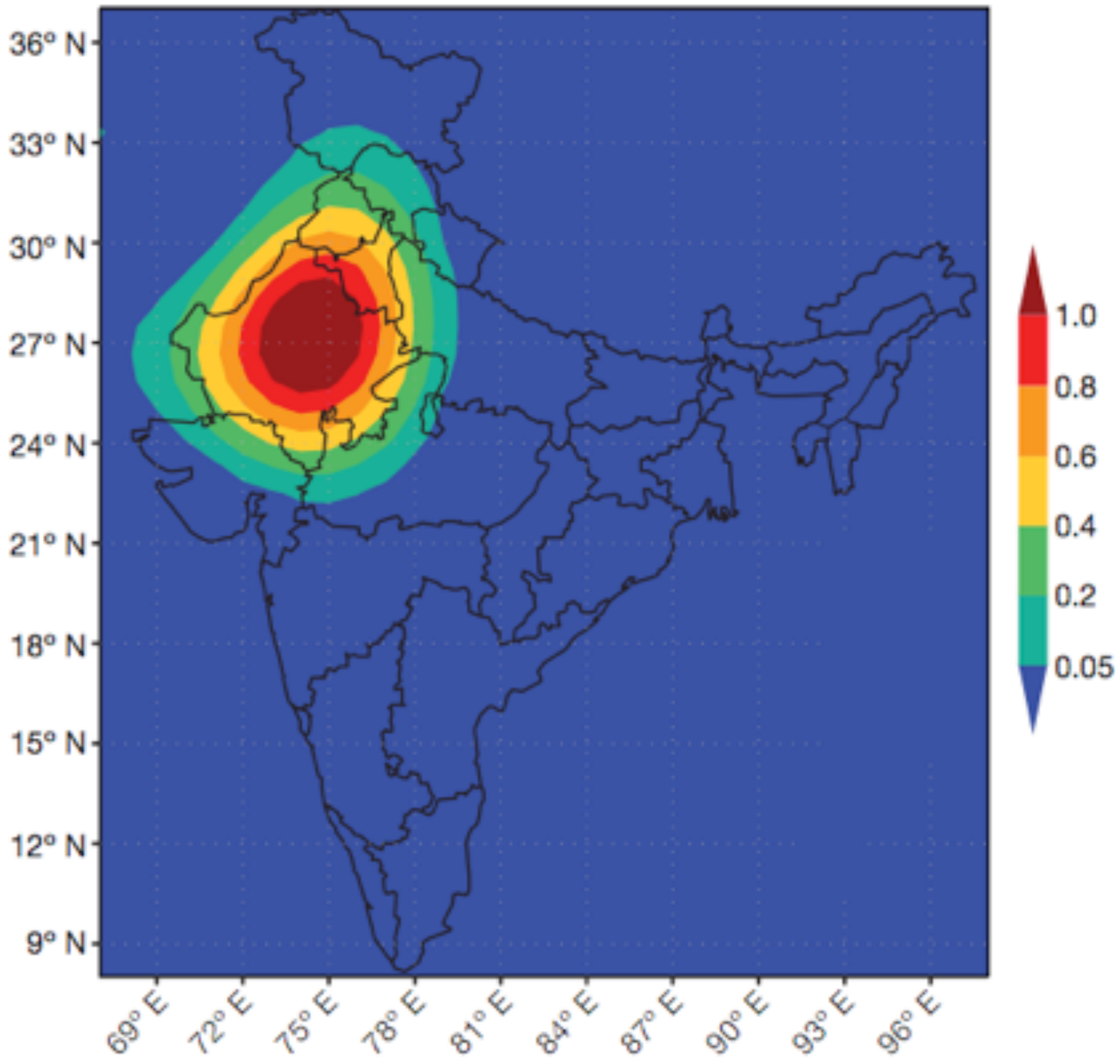


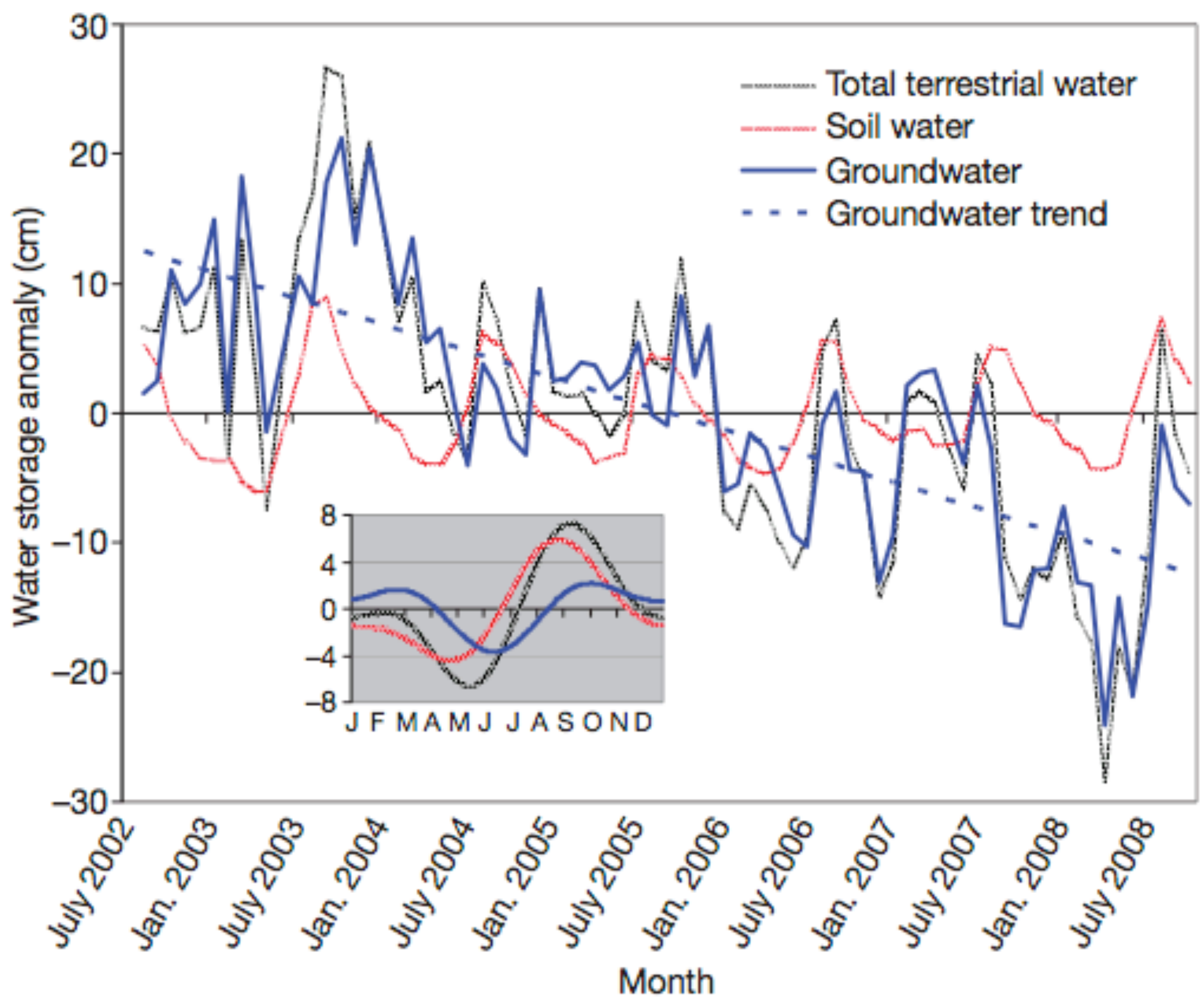


"Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE", Rodell et al., Hydrogeology J., 2007.

GRACE Hydrology

- Groundwater storage
- SW removed using GLDAS
- surface water considered but small





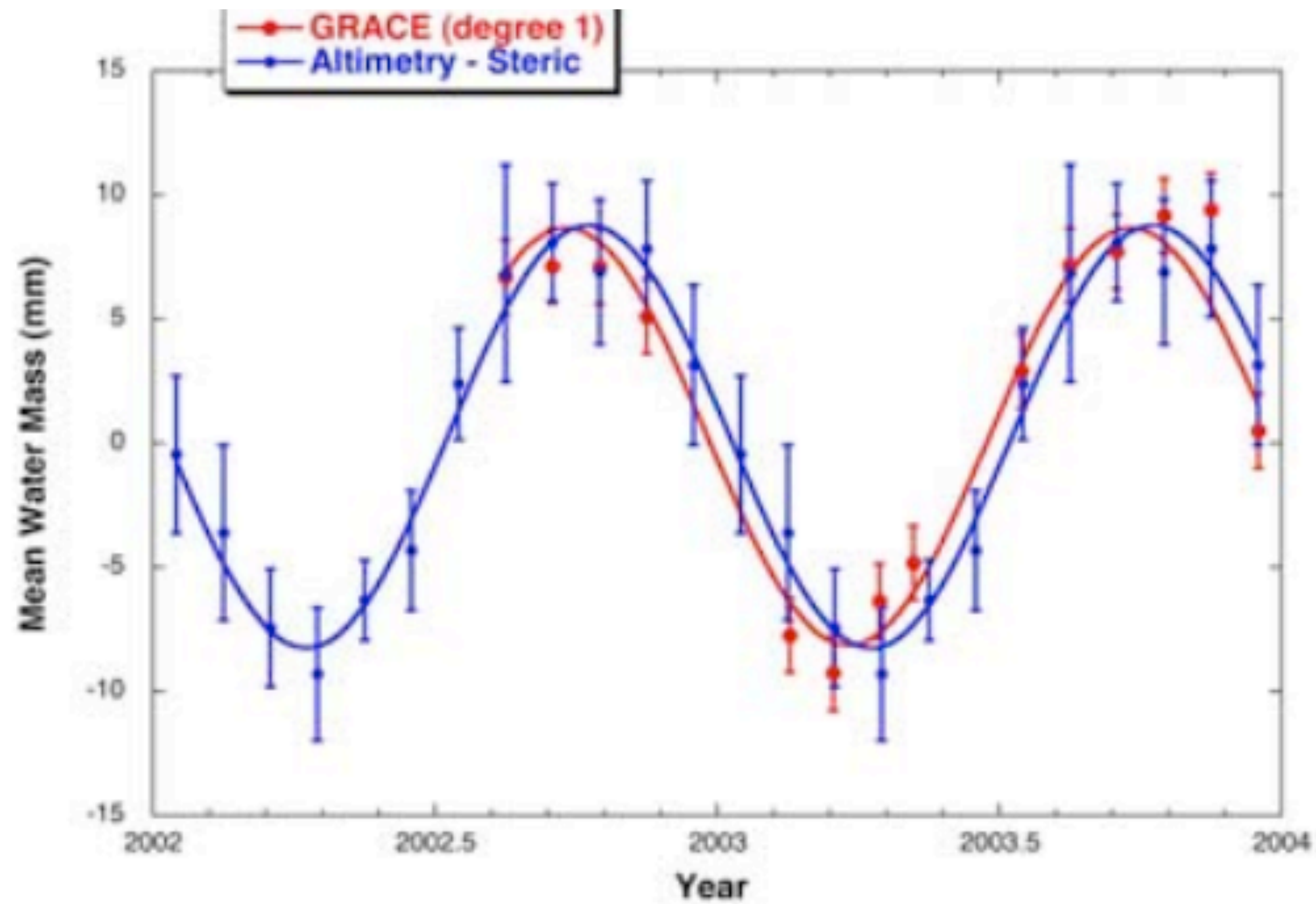
“Satellite-based estimates of groundwater depletion in India”, Rodell et al., Nature, 2009.

GRACE Oceans

- basin scale mass changes
  - 1 cm geoid (10 cm H_2O)
  - $\lambda \approx$ 1000-5000 km
  - T $\approx$ days, months, decades
  - ocean basins
- bottom currents
  - 0.1-1 mm geoid (0.1-1 cm H_2O)
  - $\lambda \approx$ 10-200 km
  - T $\approx$ days, months, decades
  - ocean basins, near steep topography
- global sea level
  - 0.1 mm/yr geoid (0.1 cm H_2O)
  - $\lambda \approx$ global to basin level
  - T $\approx$ interannual, secular
  - ocean basins

GRACE Oceans

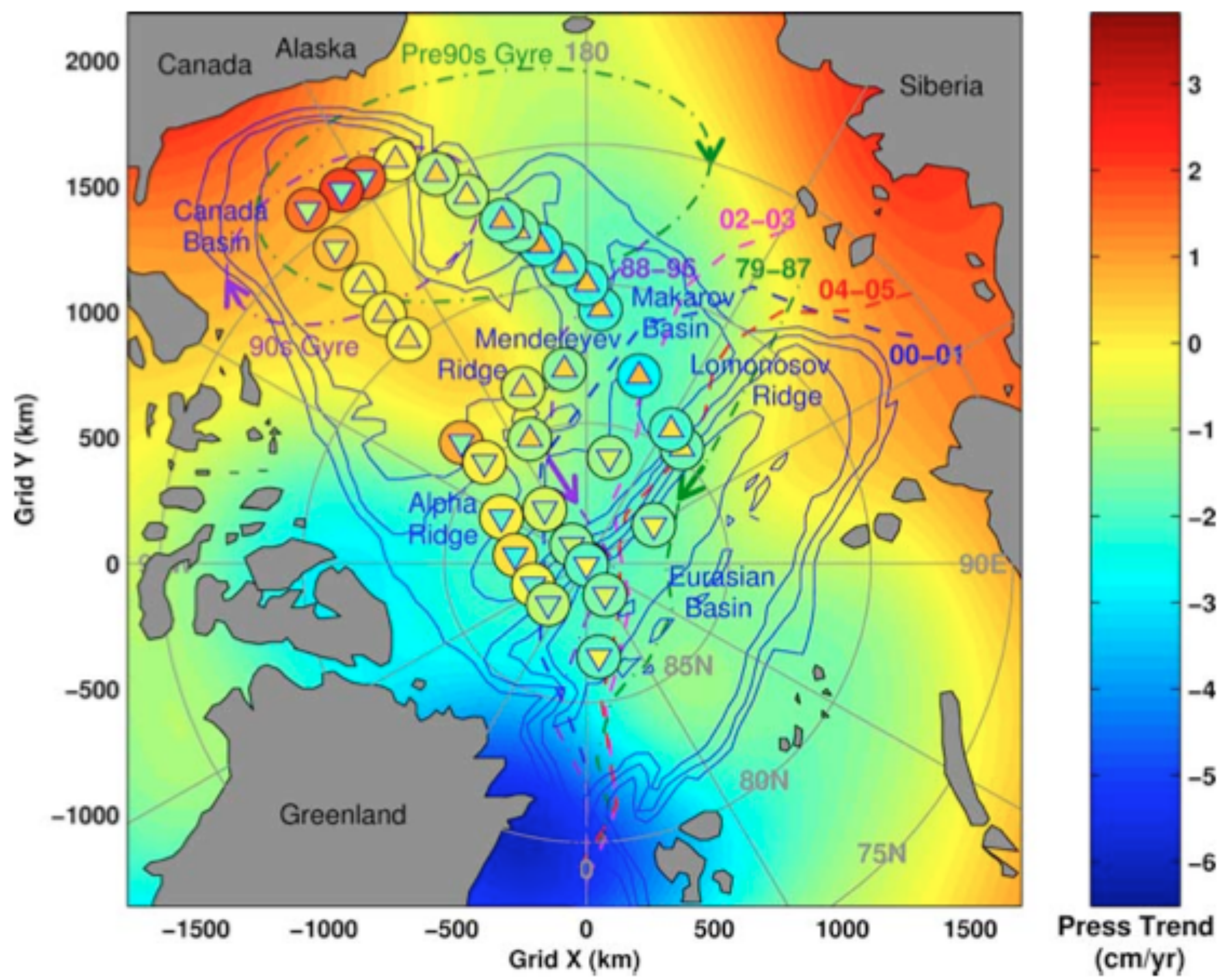
- Global ocean mass variations
- steric variation computed using the most recet world ocean atlas
- agreement between models improves when degree 1 from SLR geocenter is included



"Preliminary observations of global ocean mass variations with GRACE", Chambers et al., GRL, 2004.

GRACE Oceans

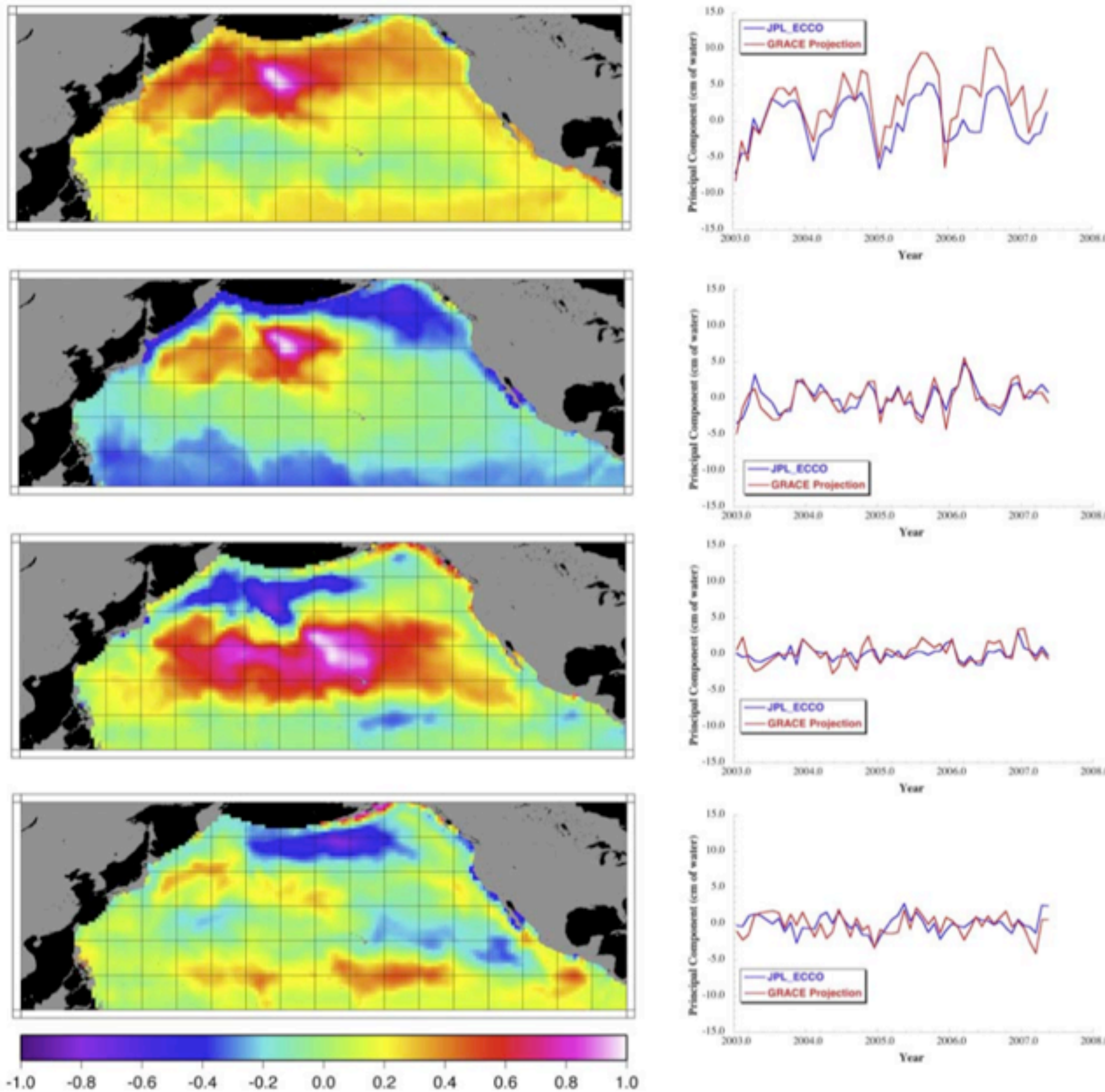
- Basin scale mass variations
  - Arctic: a comparison of GRACE ocean mass with the Arctic bottom pressure recorders
  - comparison with BPR trend results indicate a declining trend due to decreasing uper ocean salinities
  - distribution and magnitude indicates that the Arctic ocean is reverting from the cyclonic state characterizing the 1990's to the anticyclonic state prior to 1990



"Recent trends in Arctic Ocean mass distribution revealed by GRACE", Morison et al., GRL, 2007.

GRACE Oceans

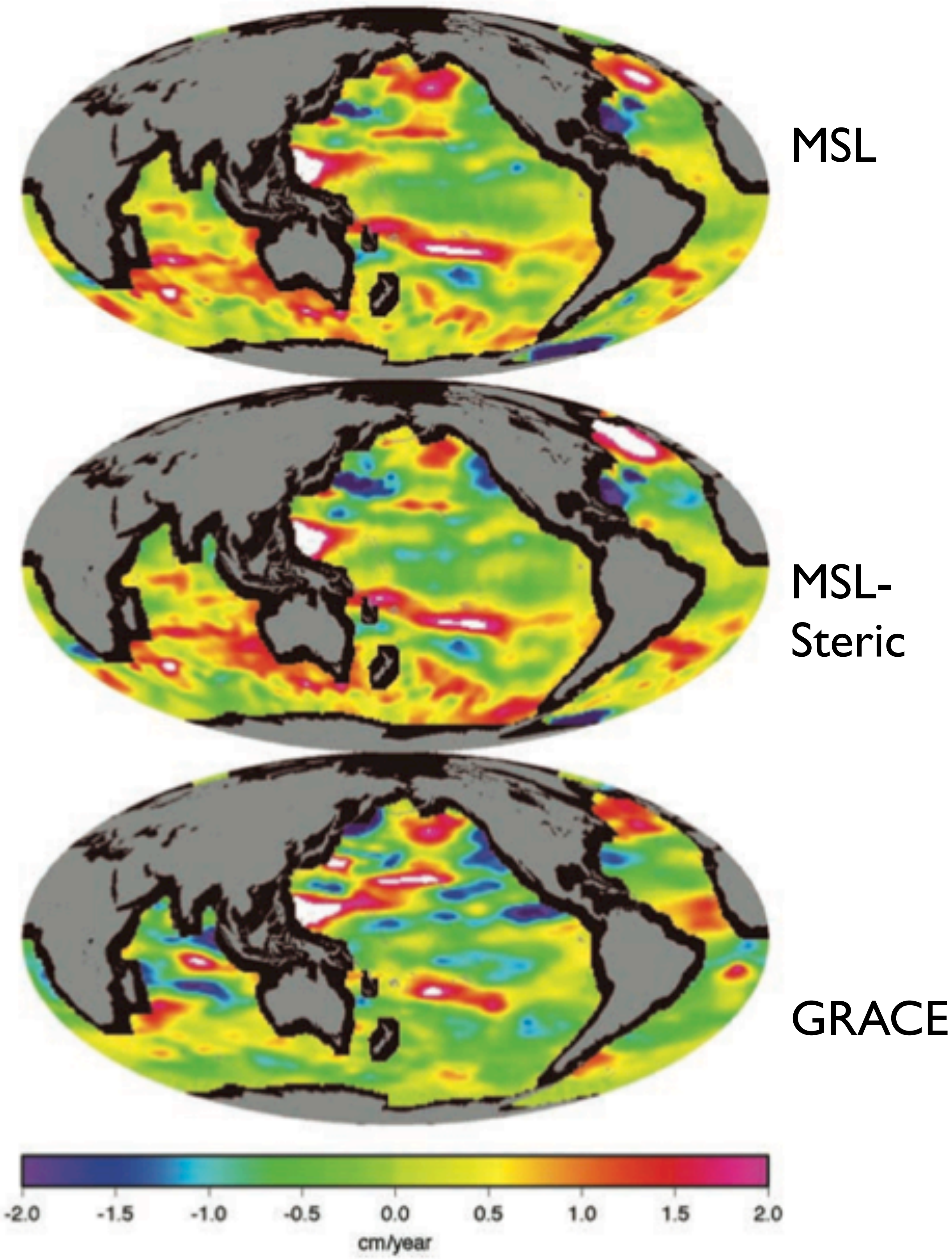
- Ocean bottom pressure



"Analysis of large-scale ocean bottom pressure variability in the North Pacific", Chambers and Willis, JGR, 2008.

GRACE Oceans

- ocean mass on even shorter scales
- GRACE = total ocean mass
- Jason-1 = Mean Sea Level
- Argo floats = temperature and salinity profiles => steric sea level
- GRACE = MSL - Steric
- lots of discrepancy in the southern oceans => problem seems to be with Jason
- seasonal variation due to the exchange of water from the lanc to the ocean



"Assessing the globally averaged sea level budget on seasonal to interannual timescales", Willis et al., GRL, 2008.

GRACE Oceans

- Ocean Circulation using the static geoid from GRACE and altimetry
  - North Atlantic: "Circulation of the North Atlantic Ocean from altimetry and the Gravity Recovery and Climate Experiment geoid", Jayne, JGR, 2006.
  - represents a substantial improvement over previous geoids
  - GRACE geoid is useful for estimating the mean circulation at a resolution of 300 km

GRACE Oceans

- Ocean Circulation using the static geoid from GRACE and altimetery
  - ACC: Antarctic Circumpolar Current Transport Variability during 2003–05 from GRACE", Zlotnicki et al., JPO, 2007.
  - comparison of GRACE with ECCO bottom pressure to investigate changes in the ACC along the Pacific sector, which is not sampled with BP data or tide gauges
  - complicated paper but...for the first time, demonstrated that variations in Earth's gravity field can be used to estimate transport variability in a major current

GRACE Oceans

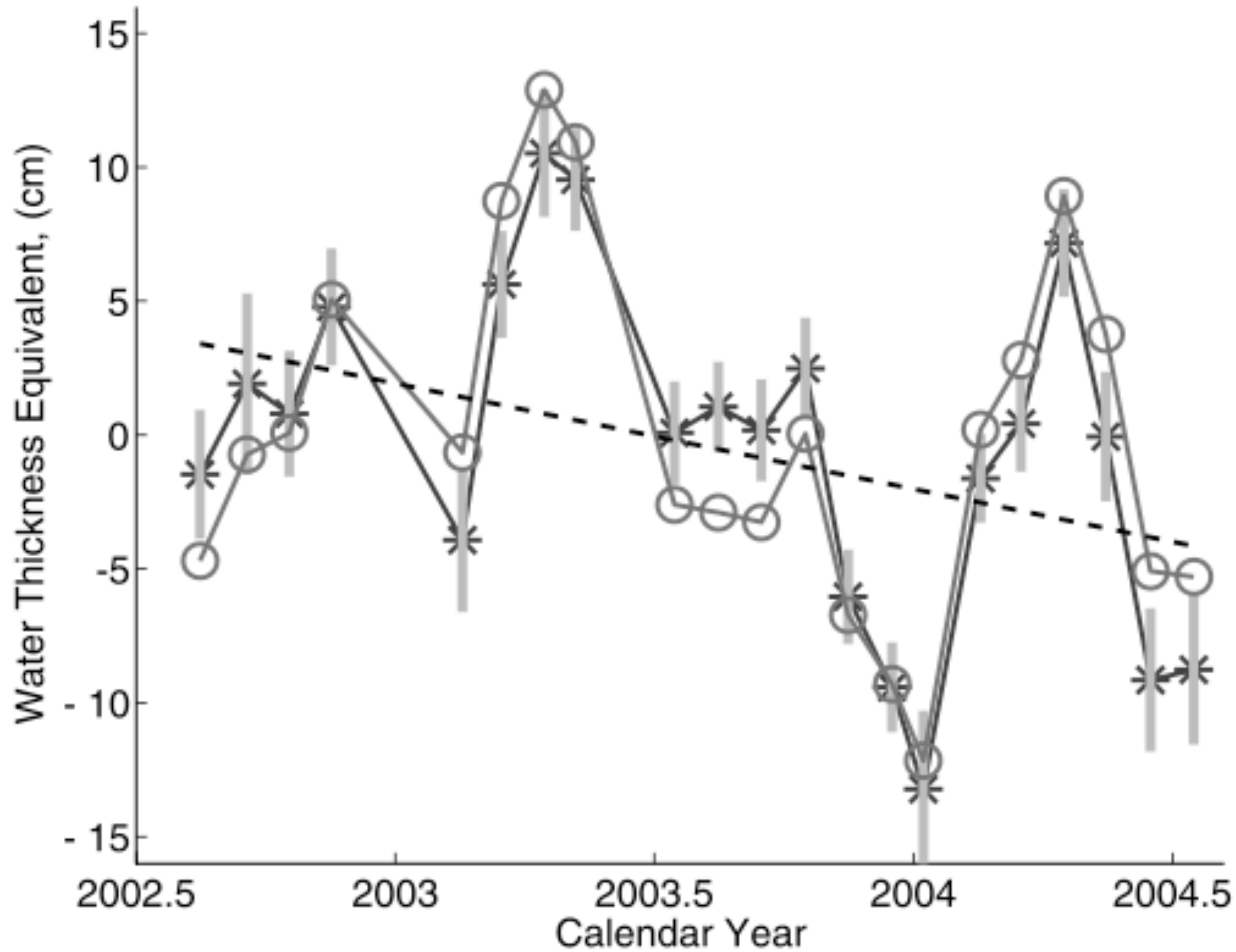
- Tides
  - k-band: “Ocean tidal solutions in Antarctica from GRACE inter-satellite tracking data”, Han et al., GRL, 2007.

GRACE Ice

- ice mass balance
  - < 0.01 mm/yr geoid (0.1 mm H_2O)
  - $\lambda \approx$ 100-1000 km
  - T $\approx$ seasonal, secular
  - ice sheets and glaciers

GRACE Ice

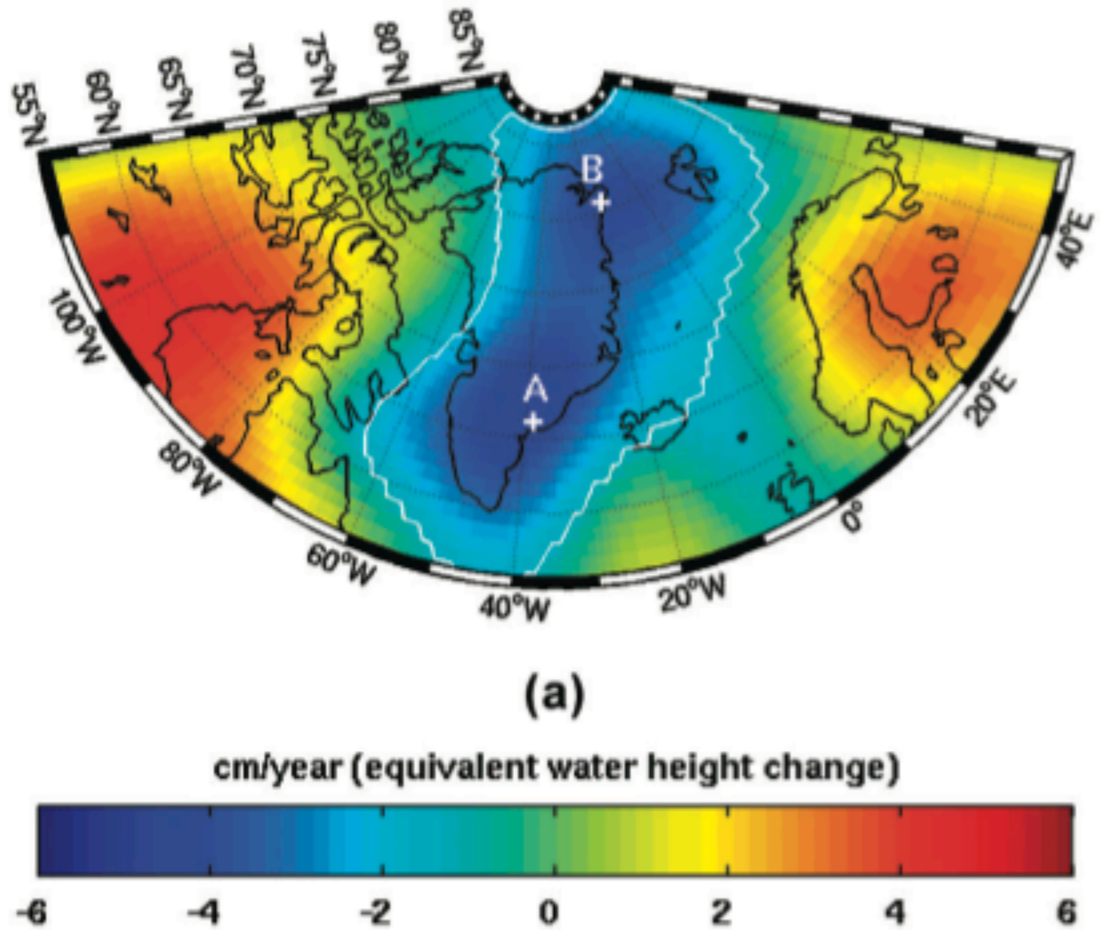
- Ice mass change trends Greenland, entire ice sheet



"Greenland mass balance from GRACE", Velicogna and Wahr, GRL, 2005.

GRACE Ice

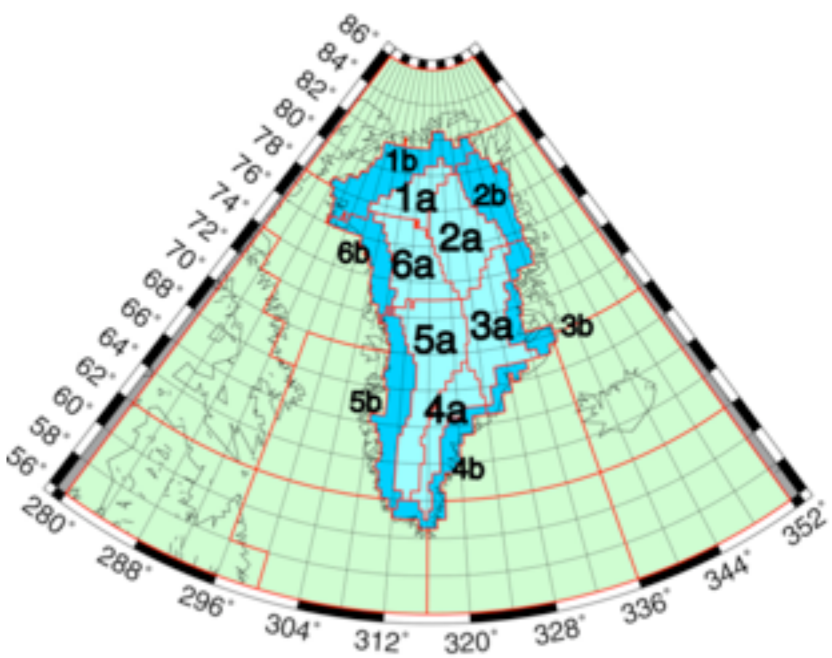
- Ice mass change trends North and South Greenland
- solution shows 2 regions of ice mass loss
    - southeast, where active ice flow and related ice loss observed using remote sensing
    - northeast, loss from Greenland + loss from Svalbard

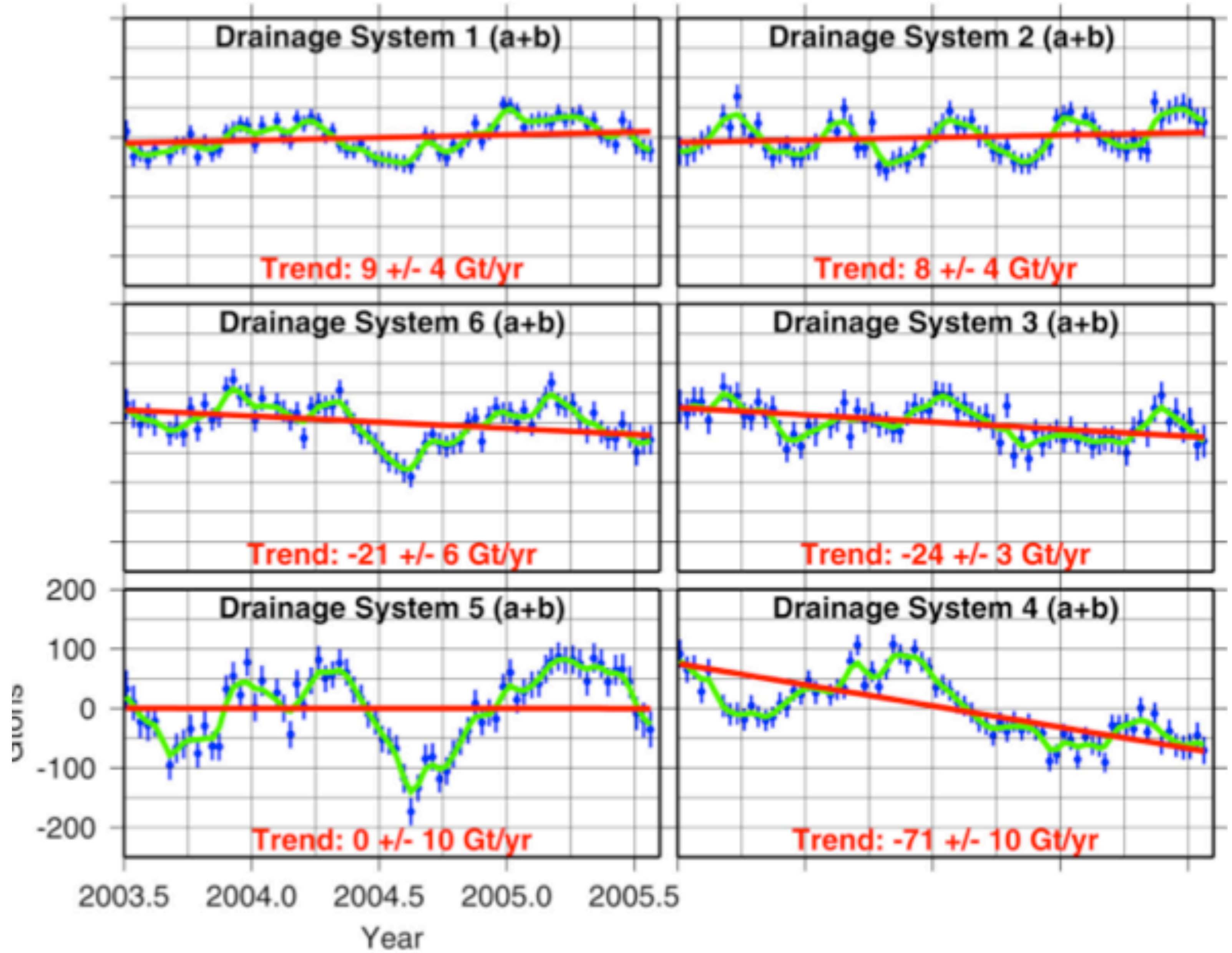


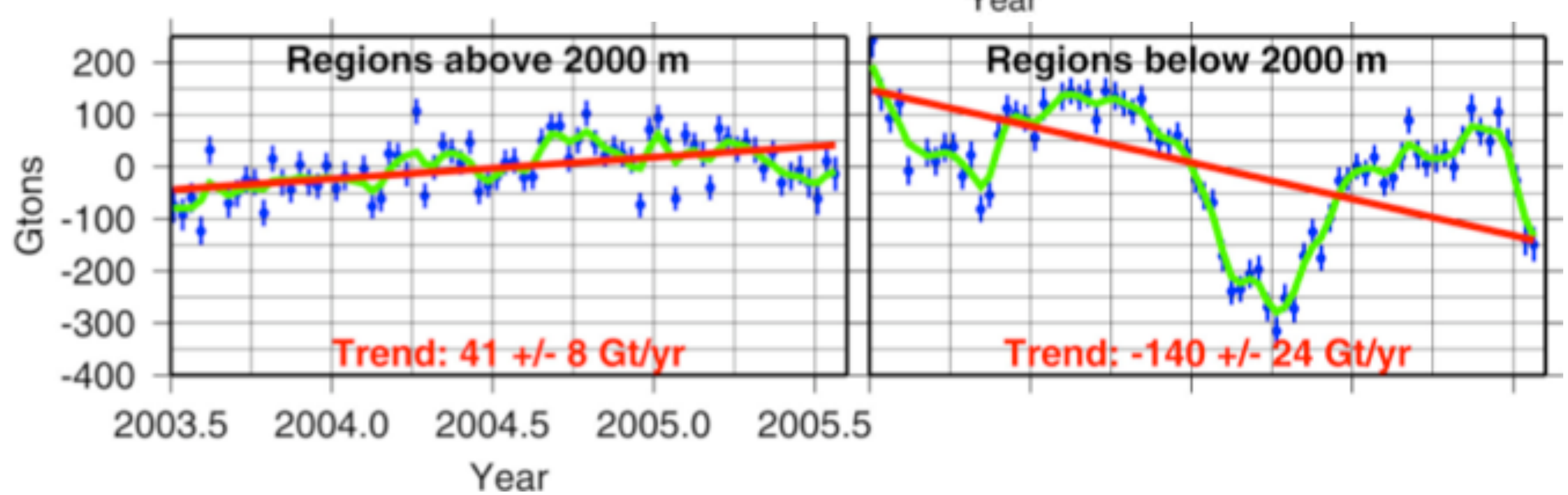
“Satellite gravity measurements confirm accelerated melting of Greenland Ice Sheet”, Chen et al., Science, 2006.

GRACE Ice

- Greenland basins
- 10 day solutions
- 300 km resolution



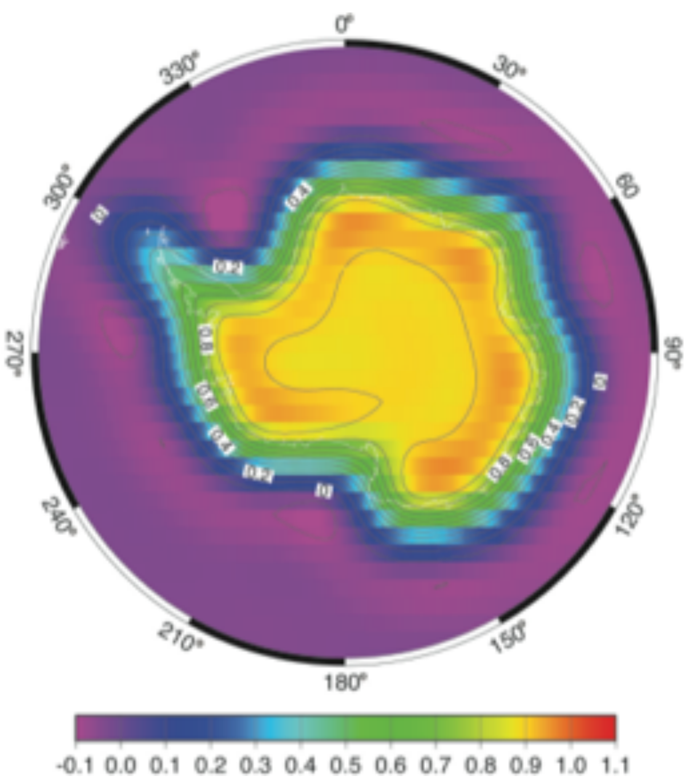


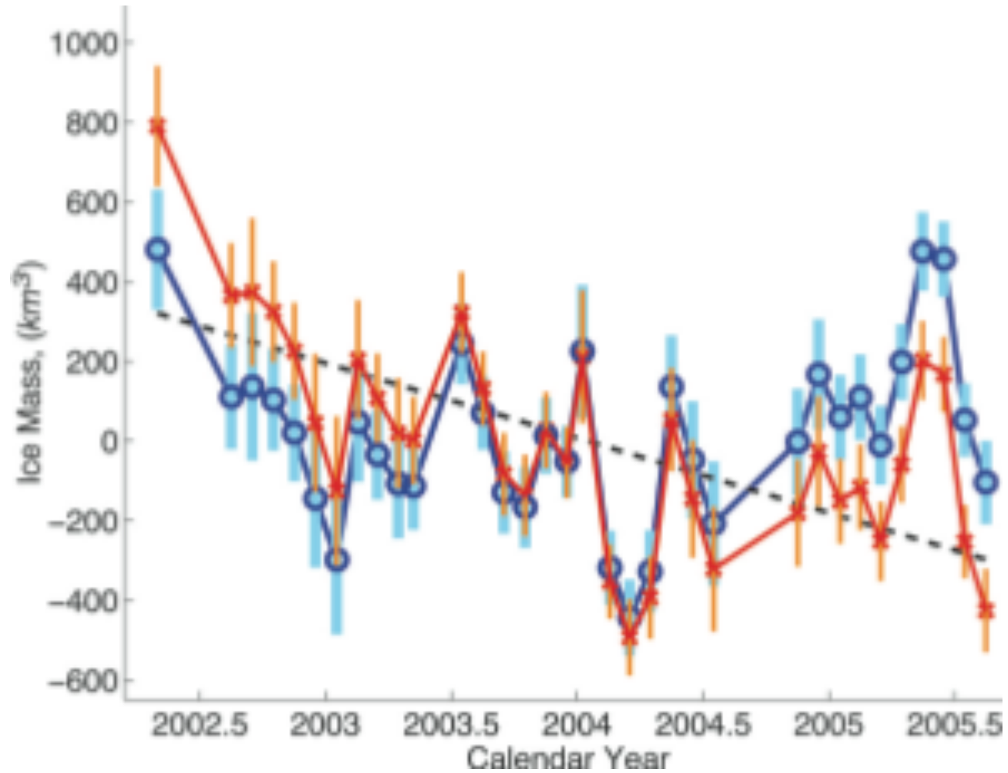


Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity Observations, Luthcke et al., Science, 2006.

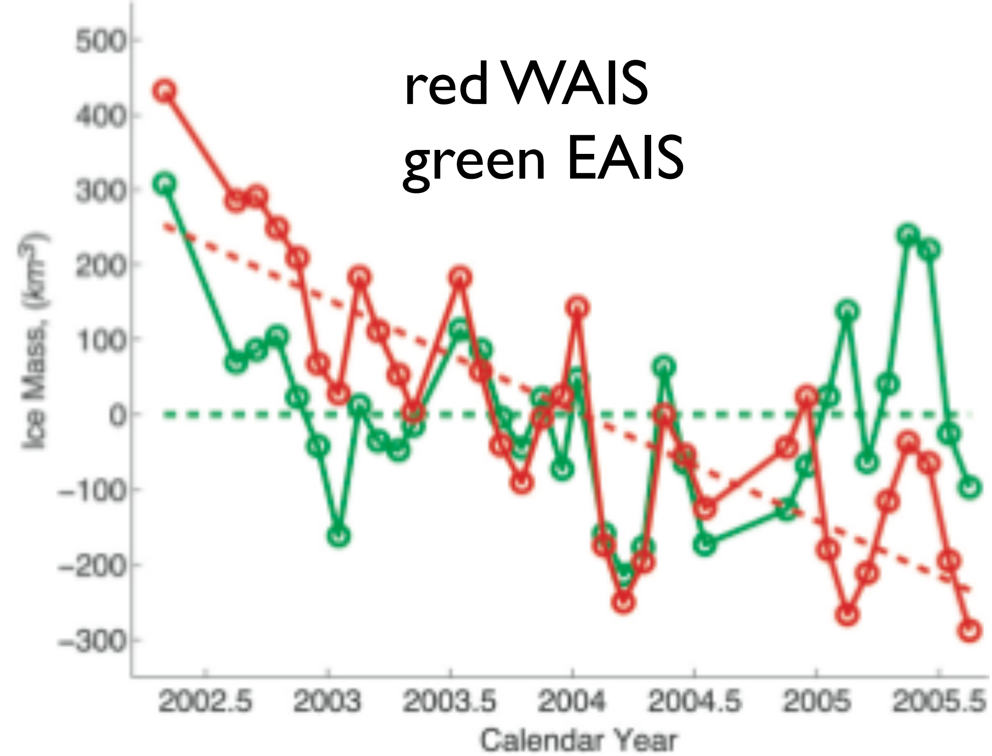
GRACE Ice

- Antarctica





All of Antarctica

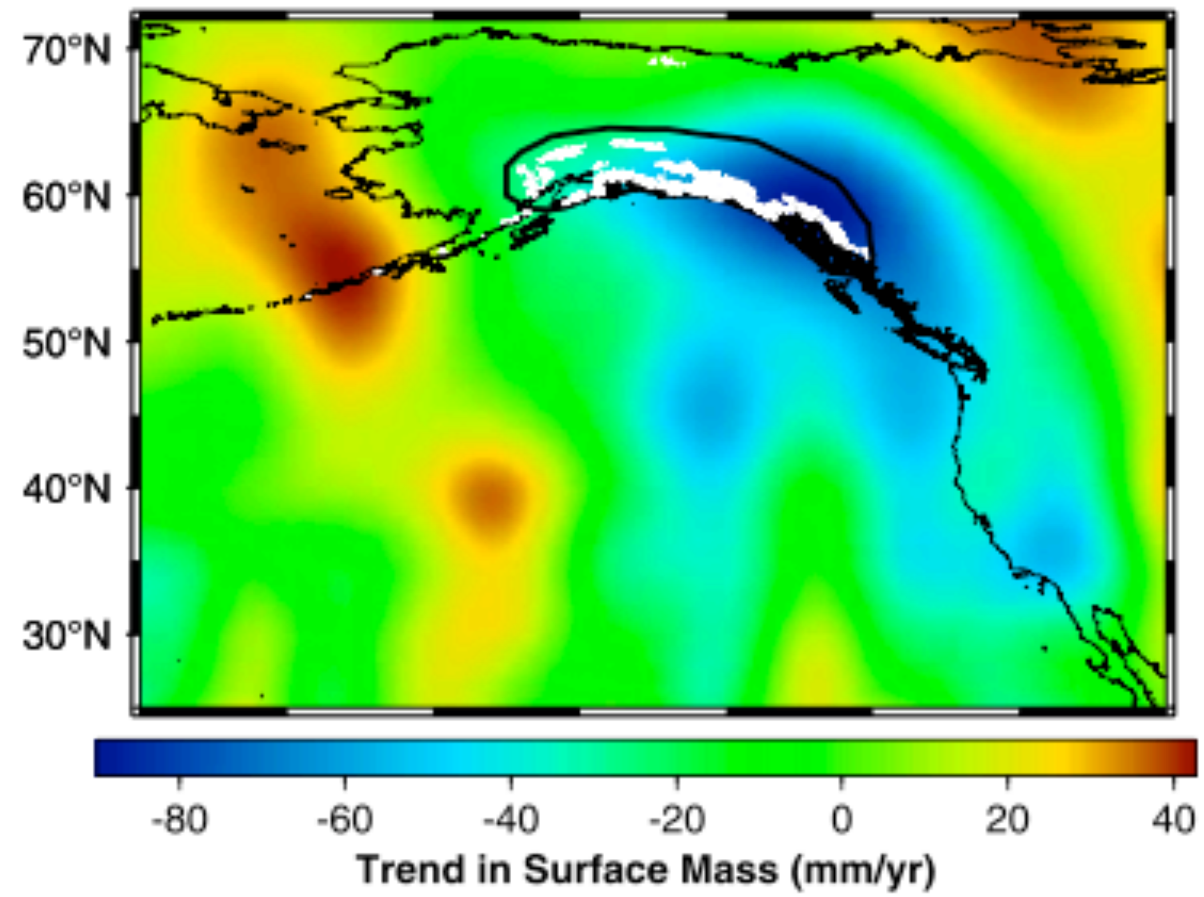


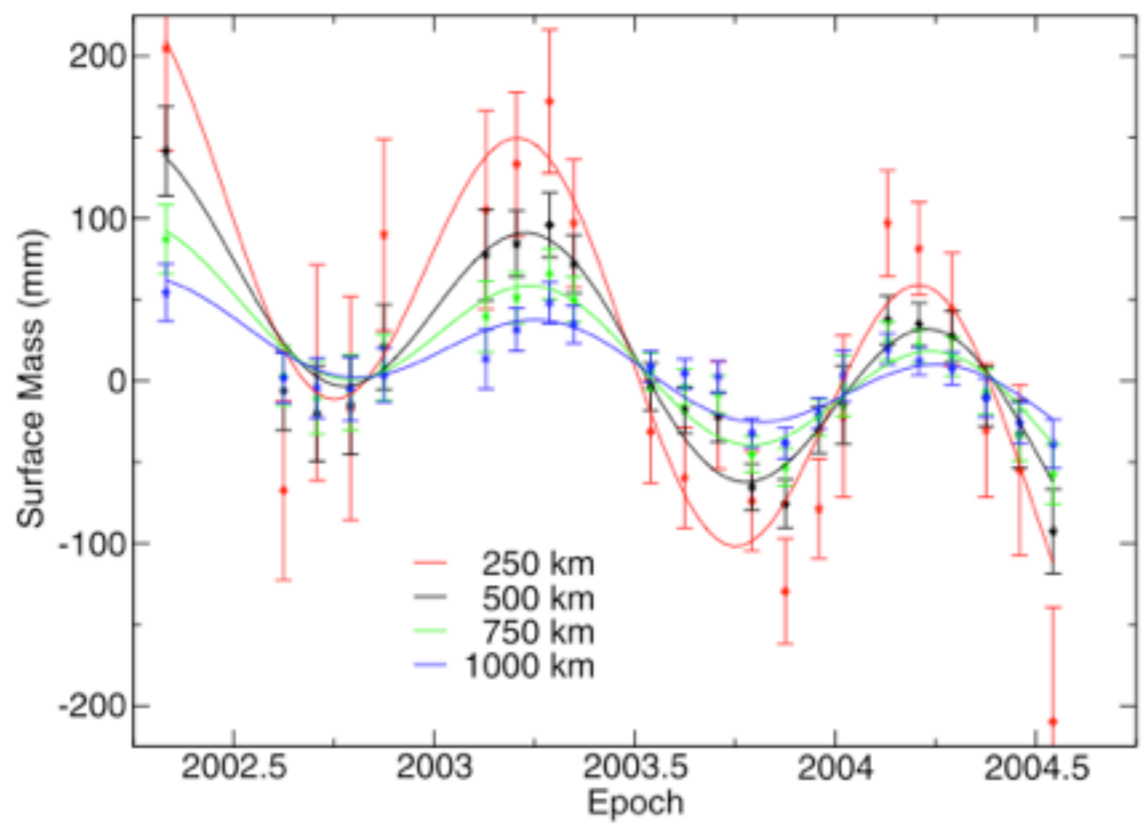
red WAIS
green EAIS

"Measurements of Time-Variable Gravity Show Mass Loss in Antarctica", Velicogna and Wahr, Science, 2006.

GRACE Ice

- Mountain glaciers
- Area of region 7.01 x 10^5 km^2; Area of Glaciers 0.87 x 10^5 km^2
- 2 > 1 > 70
- 500 km smoothing
- leakage modeled with ECCO and LaD World-Danube hydrology
- scale the amplitude of the smoothed results using forward model





"Constraining hydrological and cryospheric mass flux in southeastern Alaska using space-based gravity measurements", Tamisiea et al., GRL, 2005.

Summary GRACE

- Spherical Harmonics
  - information on mass change in all systems
    - down to scales of about 500 km optimisticaly
    - accuracy of 1 cm averaged over 600-700 km
    - at integrated monthly epochs
    - 7 years of observations so far; unknown mission lifetime
    - provides information all over the globe
    - with additional data, signals can be separated
- Mascons
  - smaller scales ~ 300 km
  - higher time resolution ~ 10 days

Summary GRACE: Disadvantages

- Spherical harmonics
  - aliasing
  - distortion - unique to GRACE?
  - temporal sampling is integrated over the month
  - separation problematic due to coarse temporal and spatial sampling
    - must always use additional models or data sets
    - finer resolution
- Mascons
  - processing requires highly specialized software
  - does not provide the same result as spherical harmonics

one more thing...

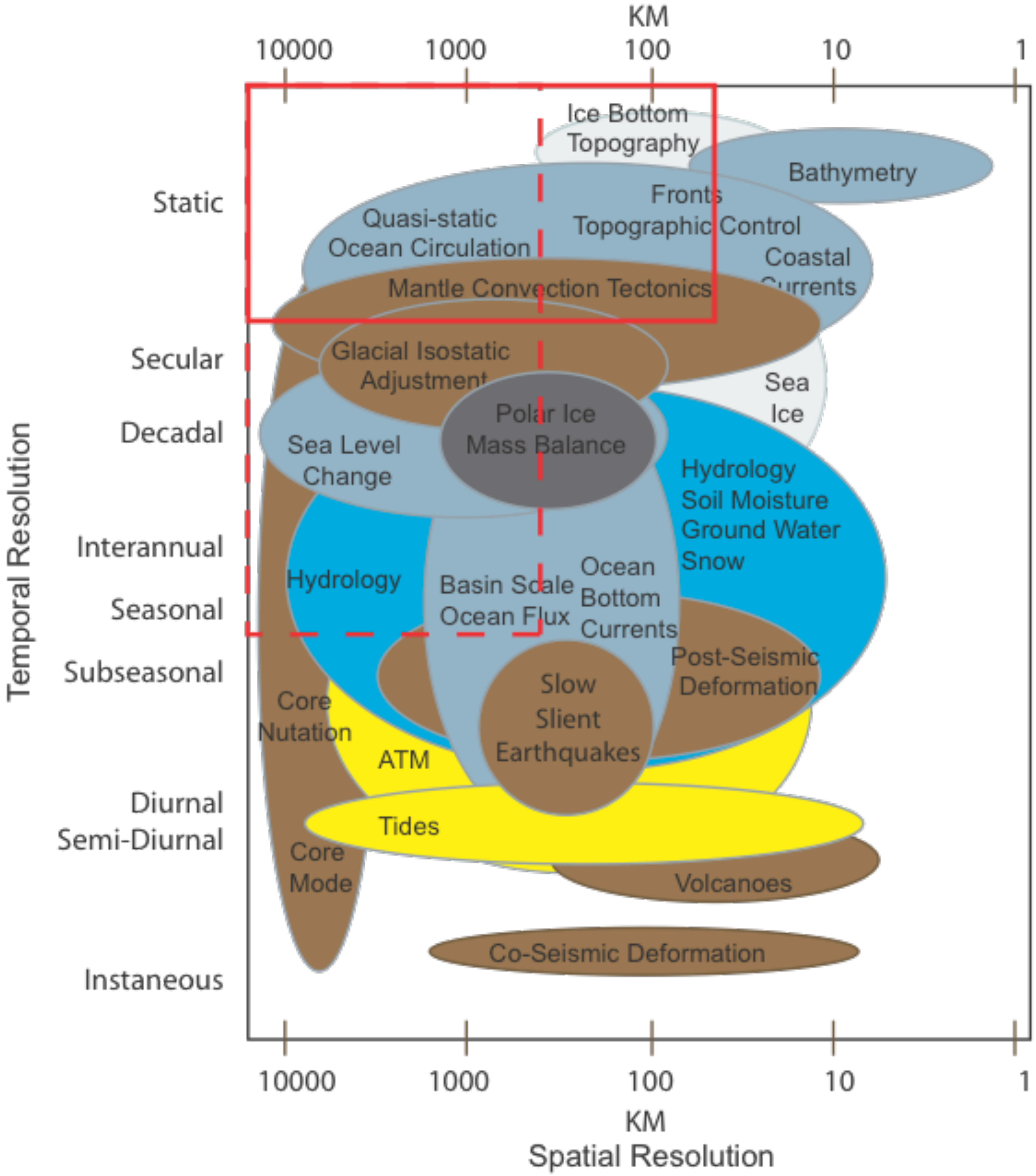
- Antarctic Example
  - Velicogna and Wahr (2006): -139 ± 73 Gt/yr [04/02 - 08/05]
  - Ramillien et al. (2006): -40 ± 36 Gt/yr [07/02 - 03/05]
  - Luthcke et al. (2007): -81 Gt/yr
  - Chen et al. (2008): -81 ± 17 Gt/yr [01/03 - 09/06]
  - Sasgen et al. (2007): 69 ± 4 Gt/yr
  - Horwath and Dietrich (2009): -109 ± 48 Gt/yr
- no fundamental contradiction; different values due to different time periods, but not the biggest problem
- differences in data analysis with their errors to be considered as a major cause

Signal and error in mass change inferences from GRACE: the case of Antarctica, Horwath and Dietrich, GJI, 2009.

Scientific Questions
versus
Mission Requirements

Mass Transport in the Earth System

- Components
  - ice
  - continental water
  - ocean mass
  - solid earth
- Mass transport happens on a wide range of spatial scales and temporal scales
- Mass transport that is important for characterizing global change occurs at the pole and the equator
- Mass transport associated with solid-Earth natural hazards, e.g. earthquakes and volcanoes, mostly in the low to mid latitudes
- Determination of trends is important for all components



yellow bubbles => background models
grey bubbles => static gravity

Rummel et al. (2003), Scientific objectives for Future Geopotential Missions, Technical Note, Version 6 from the ESA contract No: 16668/02/NL/MM "Enabling Observation Techniques for Future Solid Earth Missions".

What can be gained with an NGGM?

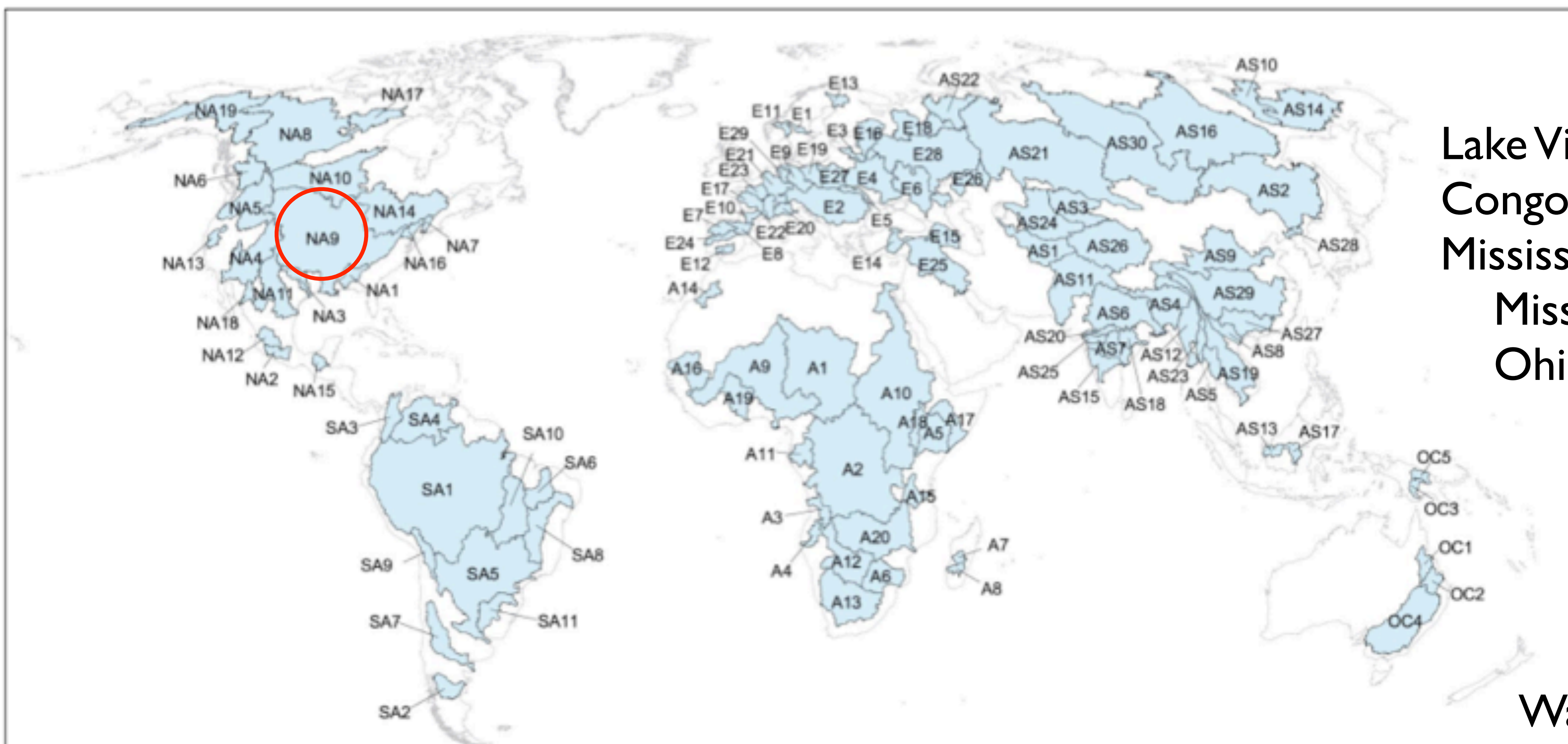
- Continental water storage
- Cryosphere
- Ocean mass
- Solid-Earth

- No prioritization at this point in the presentation

Continental Water Storage

- Determination of the change in surface water
  - lakes
  - reservoirs
  - wetlands
  - stream channels

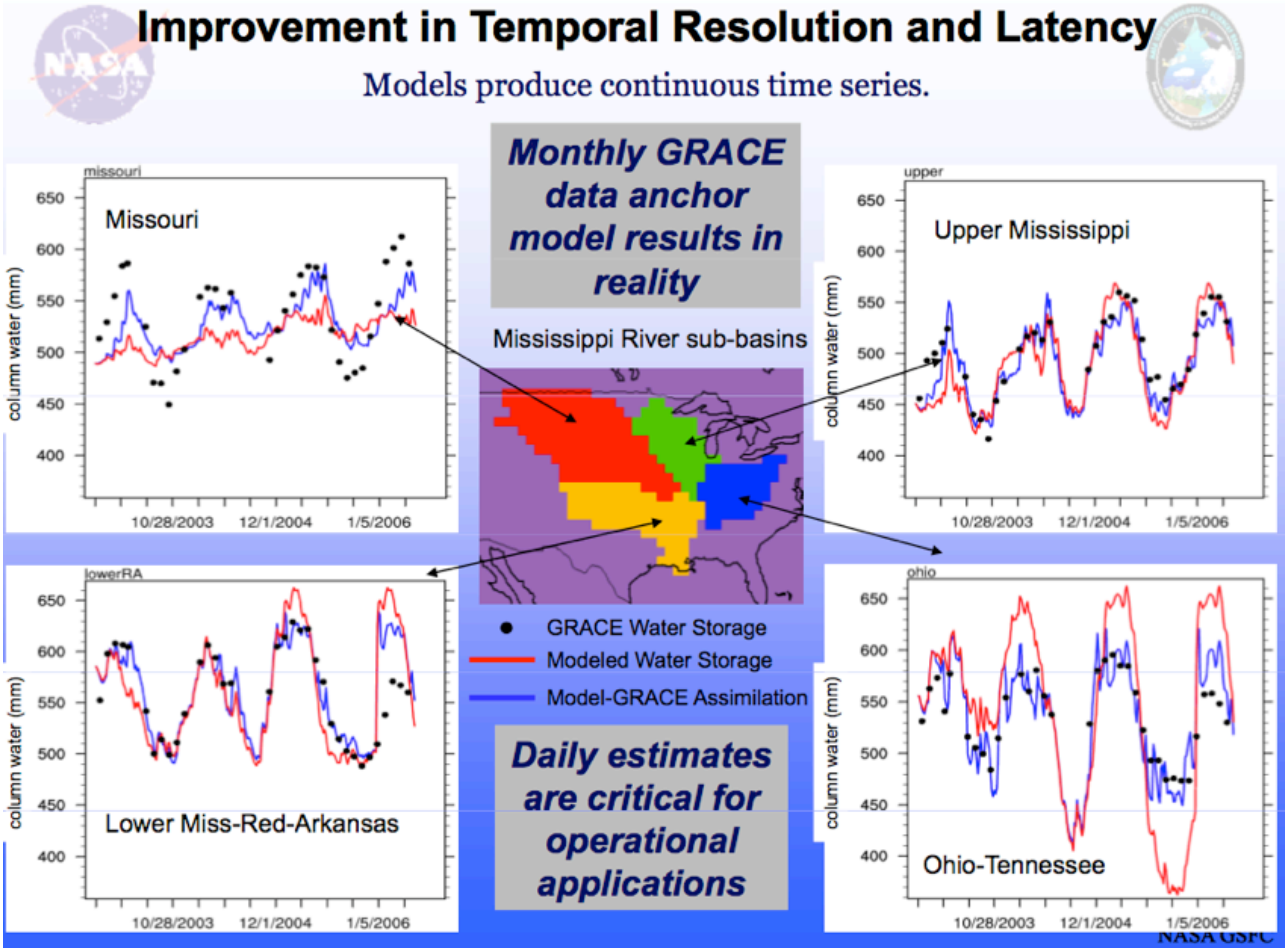
Major terms in the water cycle; representing ~ 0.01% of the total water in the hydrosphere



Lake Victoria 68,800 km^2
Congo 613,202 km^2
Mississippi 3,202,230 km^2
    Missouri 1,331,810 km^2
    Ohio 490,603 km^2

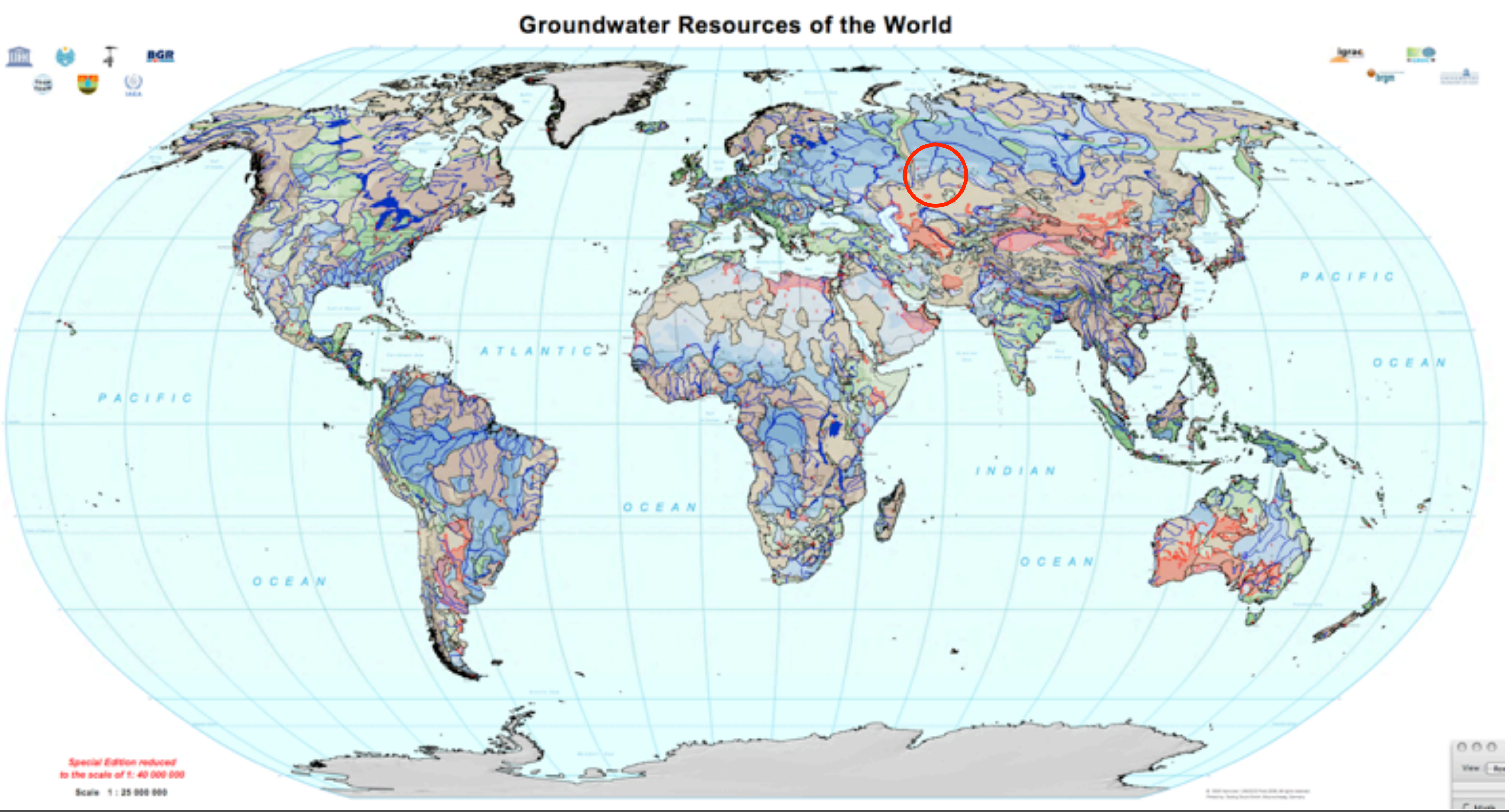
Water Resources eAtlas

Continental Water Storage



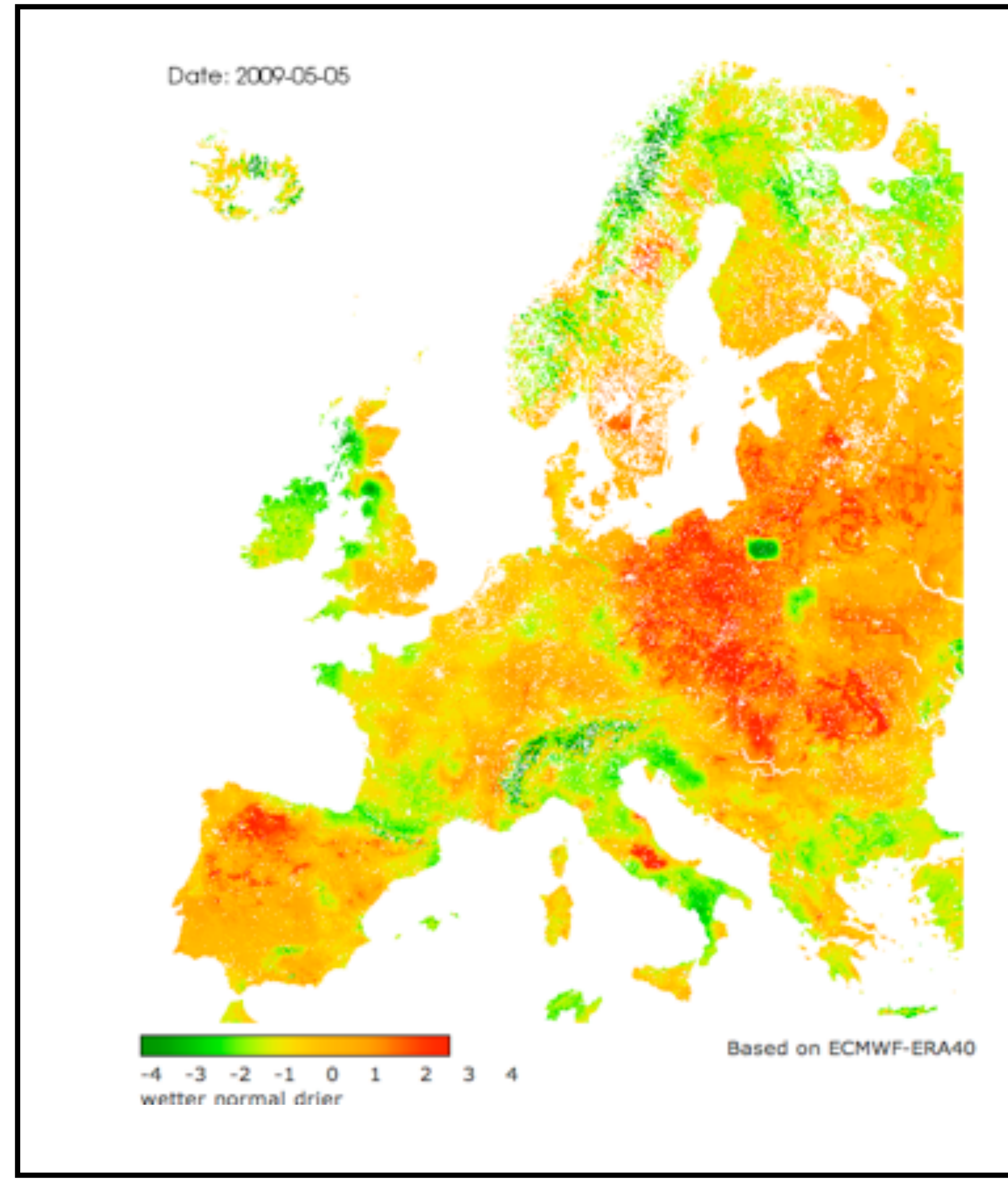
Continental Water Storage

- Groundwater storage
  - big component of the water cycle
  - trends required for analyzing
    - sinks of fresh water; drought analysis
    - global change



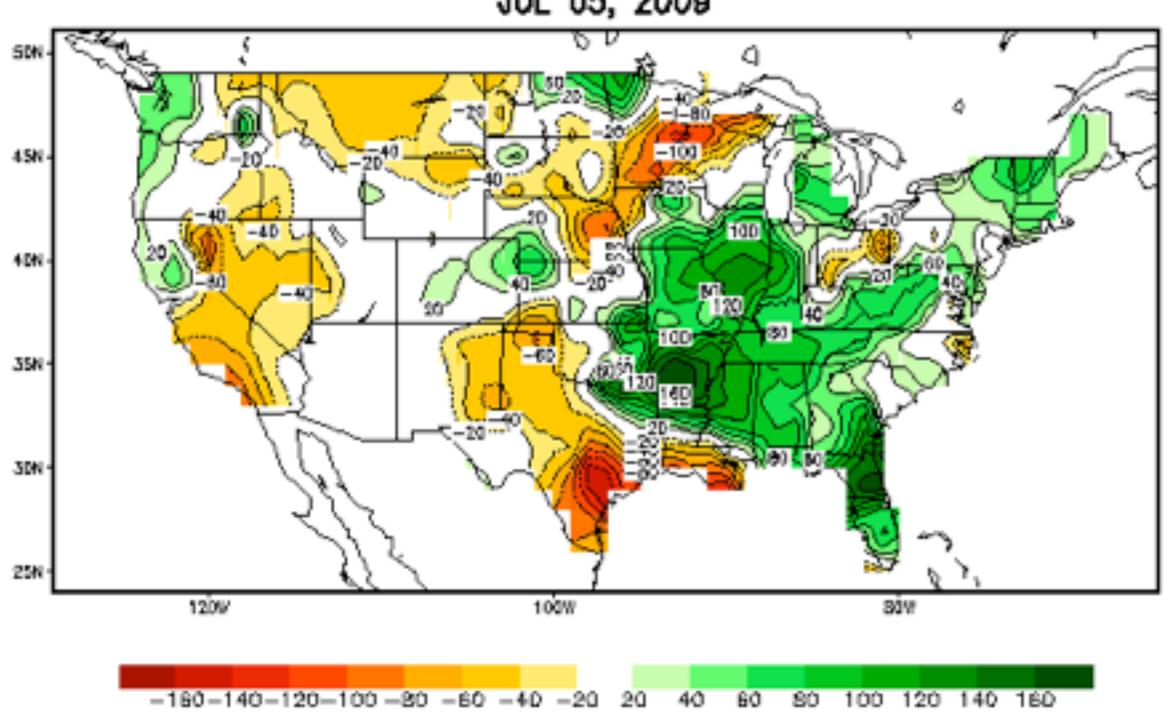
Continental Water Storage

- Soil moisture (200 - 800 km)
- critical to the physical processes governing energy and water exchanges at the land/air boundary
- Soil moisture controls the extent to which plants can exploit sunlight in photosynthesis and the effectiveness with which agriculture, forestry and freshwater resources can be developed.
- The importance of the soil moisture has resulted in a very large collection of numerical models all of which simulate soil moisture.



European Commission, Joint Research Center Institute for Environment and Sustainability

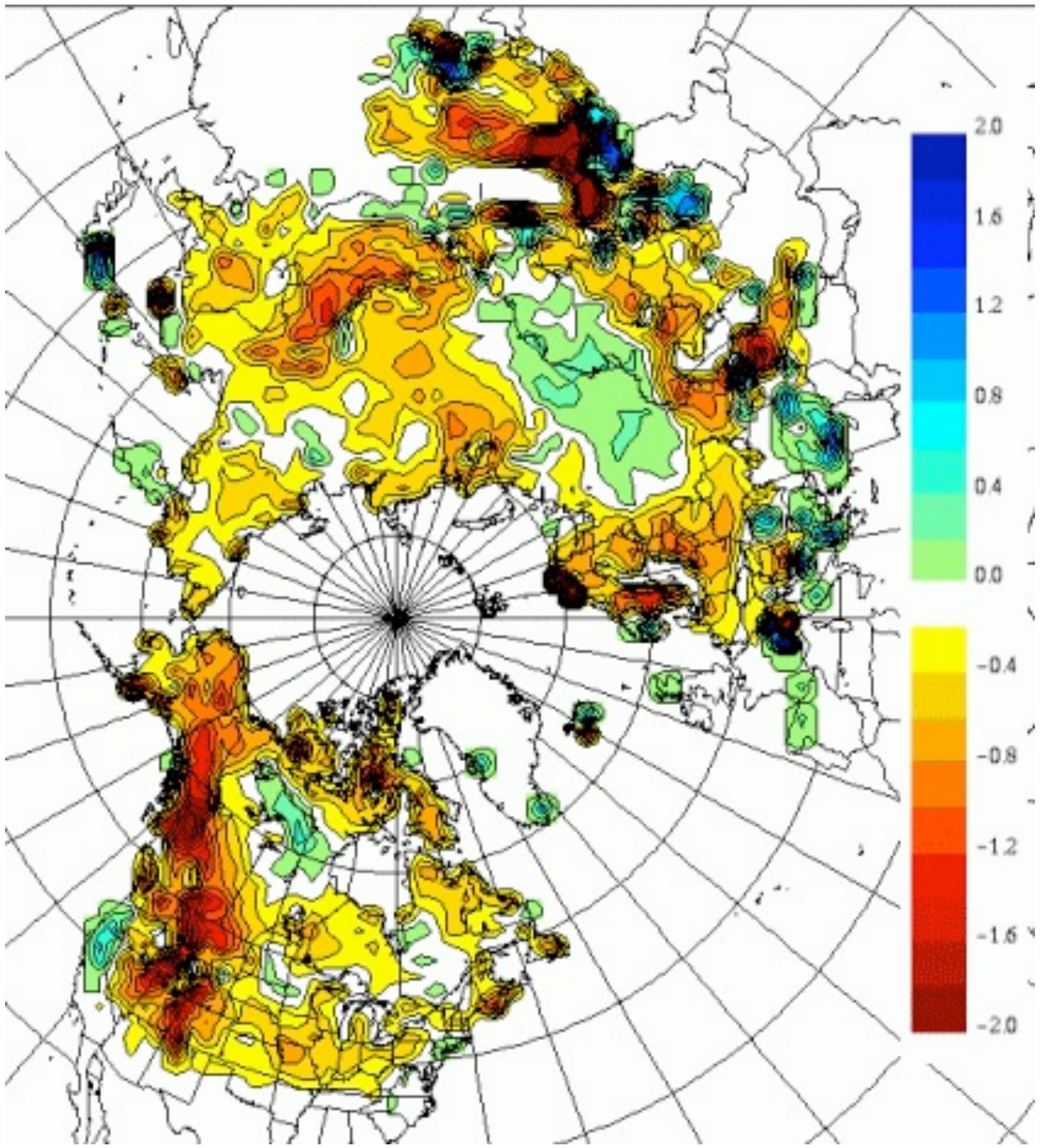
Calculated Soil Moisture Anomaly (mm)
JUL 05, 2009



National Weather Service
Climate Prediction Center

Continental Water Storage

- snow
  - affects circulation and climate on local to regional and global scales
  - very short scales in mountain ranges
  - challenge to be able to separate snow from other components of the water cycle



snow cover change 1972-1990; days per year of snow cover (CEOS)

Hydrology and Global Change

- Is the water cycle accelerating? Are floods increasing? Is drought increasing? In a warming climate we can expect more evaporation and thus more precipitation and runoff, i.e. bigger exchanges or more cycling of water in the water cycle. A future mission should enhance the spatial and temporal resolution of observations and provide the longer record required.
- What are the land contributions to global mean sea level rise? Currently these contributions to sea level rise are unclear [Church et al., 2001]. This question can be addressed by higher temporal and spatial resolution of the water-storage field over land.
- Are the observed trends real and are they representative of the long-term trends? Again any future mission must have a minimum decadal mission life to address this question.

Potential Outcomes for Continental Water Studies by improving Spatial Sampling

- processes act over spatial scales from 1 km to 1000's km
  - observation of mass change at the basin scale of medium size rivers
  - separation of the groundwater and soil moisture which have characteristically different spatial scales
  - observation of continental glacier melting and its effect on sea level
  - observation of mass change in reservoirs without the need to rely on in-situ observations or models for removing the effects of leakage
  - evapotranspiration and soil moisture at short scales at scales sufficient for managing water resources and agriculture

Potential Outcomes for Continental Water Studies by improving Temporal Sampling

- processes operate at hourly to weekly time scales
    - understanding of continental water transport at shorter time scales => important for understanding regional climate change
    - hydrological assessments required for managing water resources and agriculture

Potential Outcomes for Continental Water Studies by an Extended Mission Lifetime

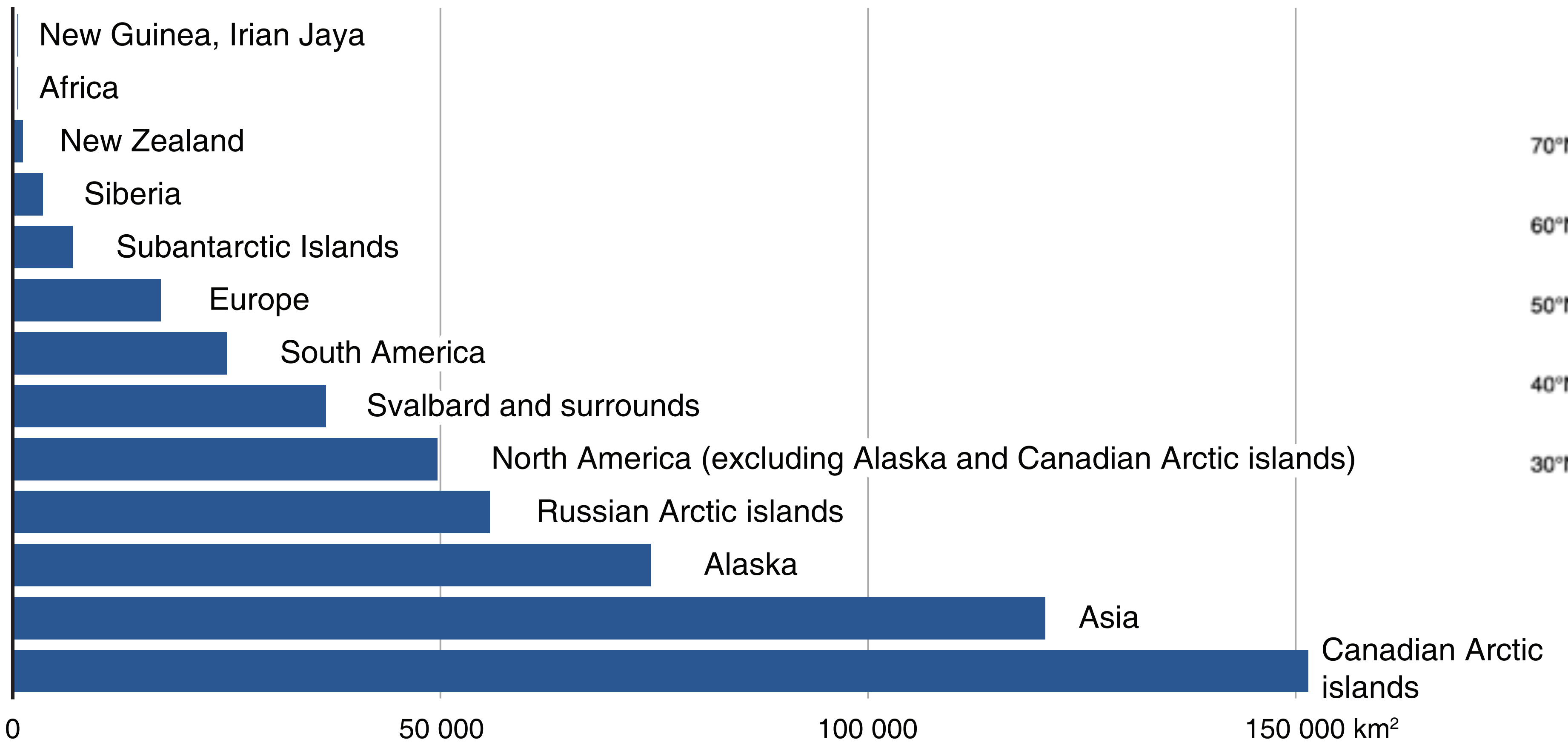
- a long mission lifetime, e.g. order of 10 years will allow for
  - a determination of the trends
    - in evapotranspiration
    - groundwater
    - droughts
    - soil moisture

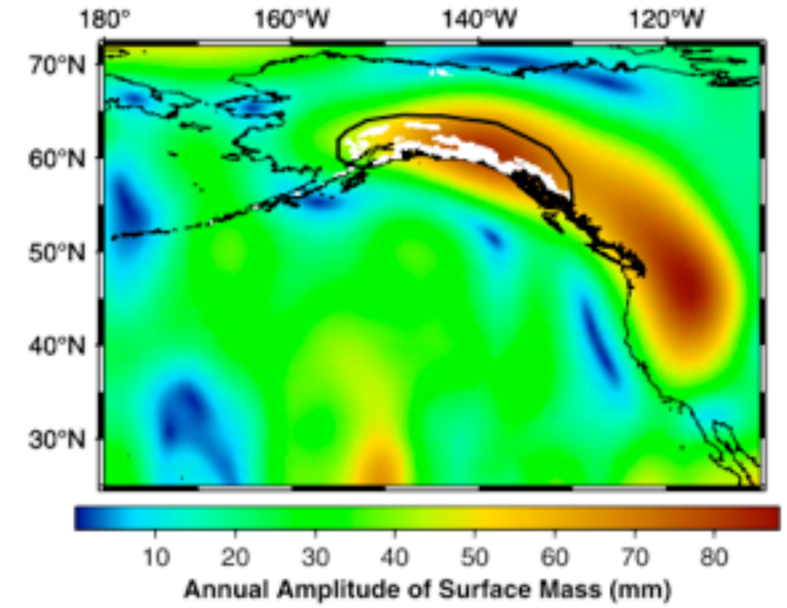
Ice

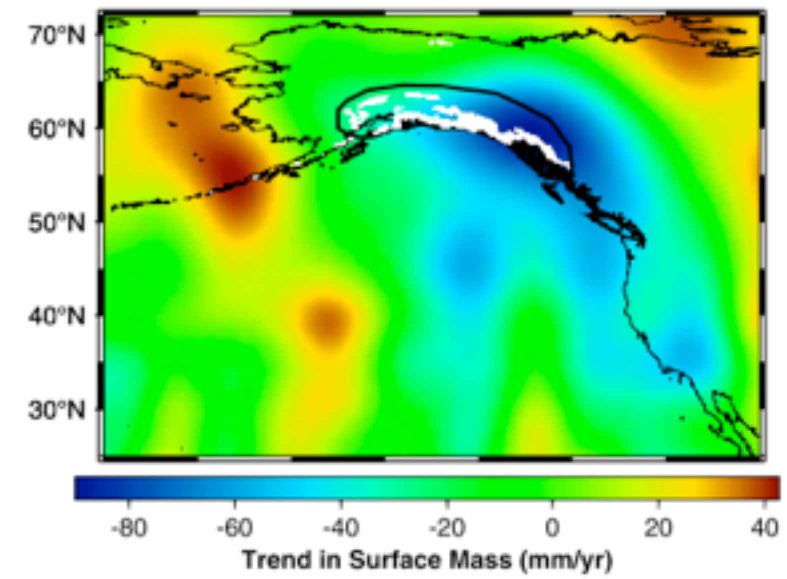
- Key Issues
  - mass balance of the ice sheets
  - contribution to sea level
  - NRC Panel on Climate Variability and Change:
    - “...accurate and high spatial sampling of ice mass change is essential for understanding their [ice sheets] contribution to sea-level rise.”
    - “...ongoing and frequent measurement of both land ice and sea ice will be needed to determine trends, update assessments, and test climate models.”
    - “Combining altimetry with a gravity measurement at a higher precision than GRACE would optimally measure change in ice sheet volume and mass and contribute directly to determining the ice sheet contribution to sea level.”

Ice

- Glaciers continental ice







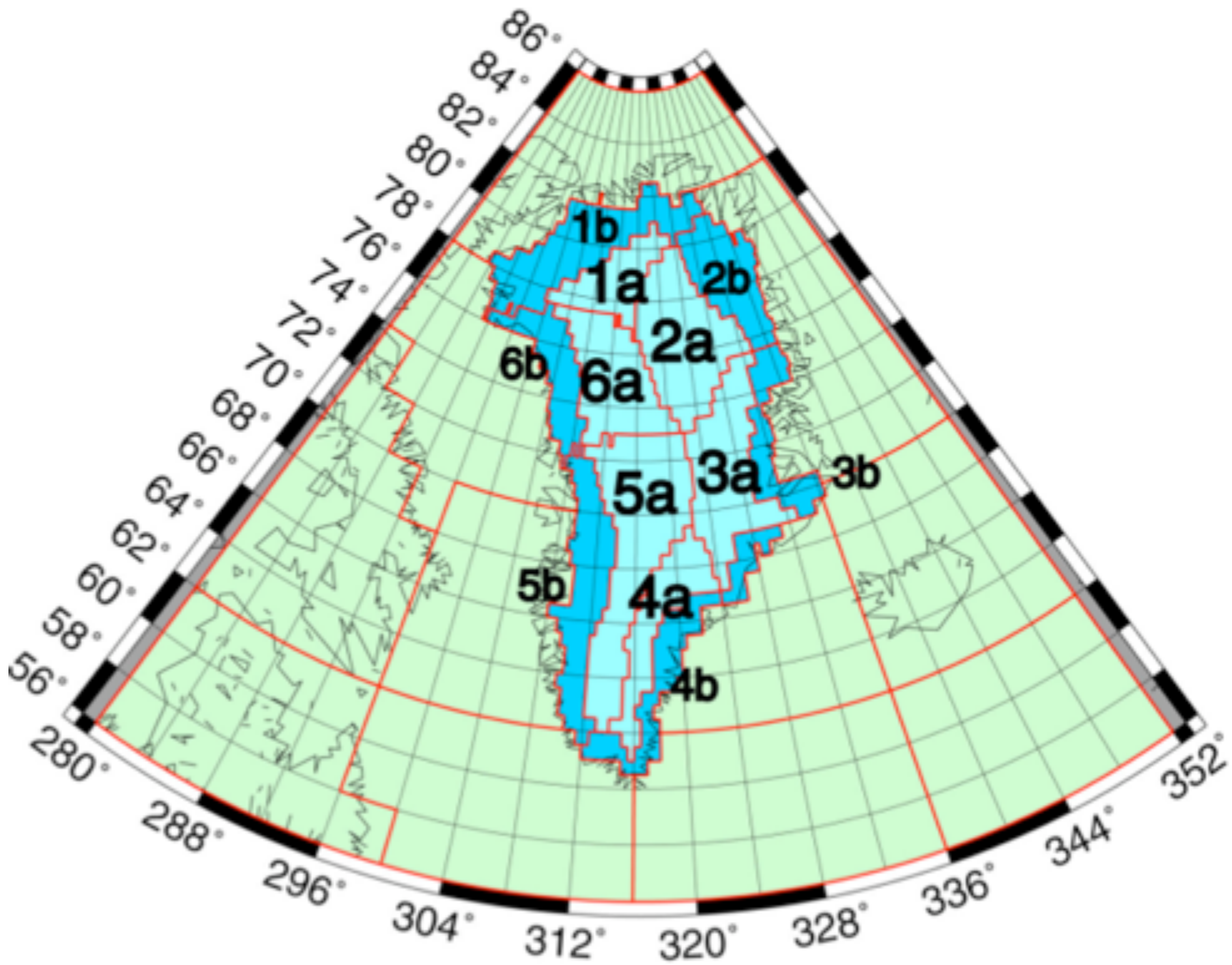
total area 7.01 x 10^5 km^2

area of ice 0.87 x 10^5 km^2

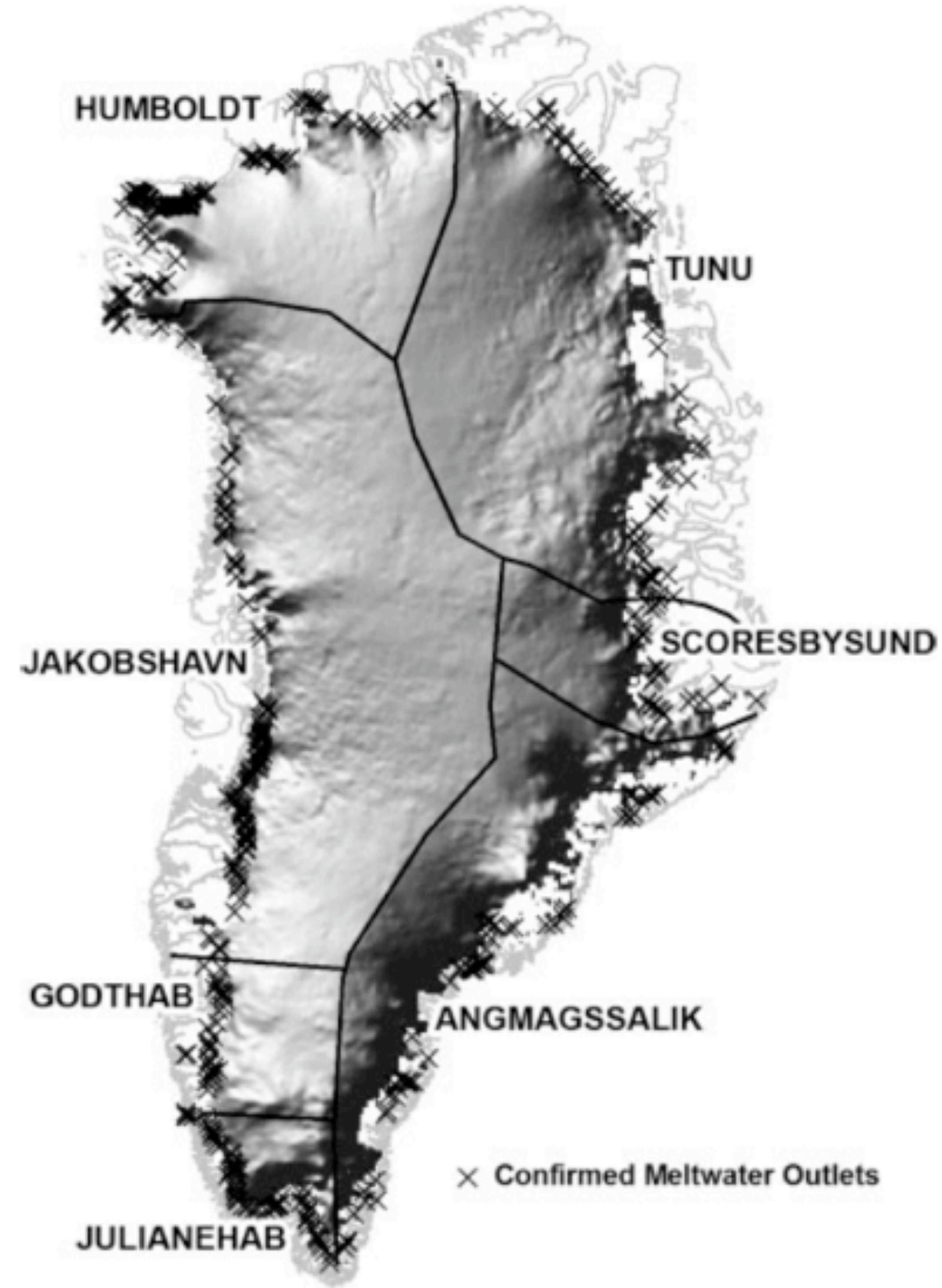
Overview of world glaciers and ice caps. (June 2007). In UNEP/GRID-Arendal Maps and Graphics Library. Retrieved 14:11, November 18, 2009 from http://maps.grida.no/go/graphic/overview-of-world-glaciers-and-ice-caps

Ice

- Ice sheets



Area between 340,000 and 66,000 km^2



Potential Outcomes for Ice Mass Studies by improving Spatial Sampling

- Ice mass varies at scales from 100 to 1000's km
  - an understanding of how glacier dynamics contribute to ice mass loss and sea level rise
  - separation of GIA from present day ice mass change
  - a distinction between ice mass changes over smaller regions => regional climate change analyses
  - a reduction in the uncertainty of the signal due to leakage of ocean mass signals

Potential Outcomes for Ice Mass Studies by Extending Mission Lifetime

- Longer time series
  - allow for the separation of GIA and present day mass change
  - establish trends in ice mass change; facilitates the detection of accelerations

Spatial Coverage Requirements for Ice

- most of the ice is located in the high latitudes
  - requires a mission that goes to these latitudes

Potential Outcomes for Ocean Mass Studies by improving Spatial Sampling

- ocean processes act over spatial scales from 10 km to global scales
- gravity is the only way to get ocean mass changes
  - improved analysis of current variability
  - improved analysis of bottom pressure, i.e. short scale mass variations
  - a reduction of leakage from hydrology and ice

Potential Outcomes for Ocean Mass Studies by Extending the Mission Lifetime

- determination of long term trends
  - with altimetry will improve models of mean dynamic topography at long wavelengths
  - with altimetry it might be possible to monitor the deep ocean circulation, measuring slow changes in density as water moves from basin to basin

Mission Requirements for Solid Earth

- higher spatial resolution will aid in the detection of more earthquakes
  - GRACE accuracy only allows us to observe earthquakes larger than magnitude 8
  - number of earthquakes observed increases exponentially with decreasing magnitude
  - understanding the mass change associated with earthquakes => improves our understanding of the earthquake cycle
- better observations of GIA at a global scale

Magnitude	**Average Annually**
8 and higher	1
7 - 7.9	17
6 - 6.9	134
5 - 5.9	1319
4 - 4.9	13,000 (estimated)
3 - 3.9	130,000 (estimated)
2 - 2.9	1,300,000 (estimated)

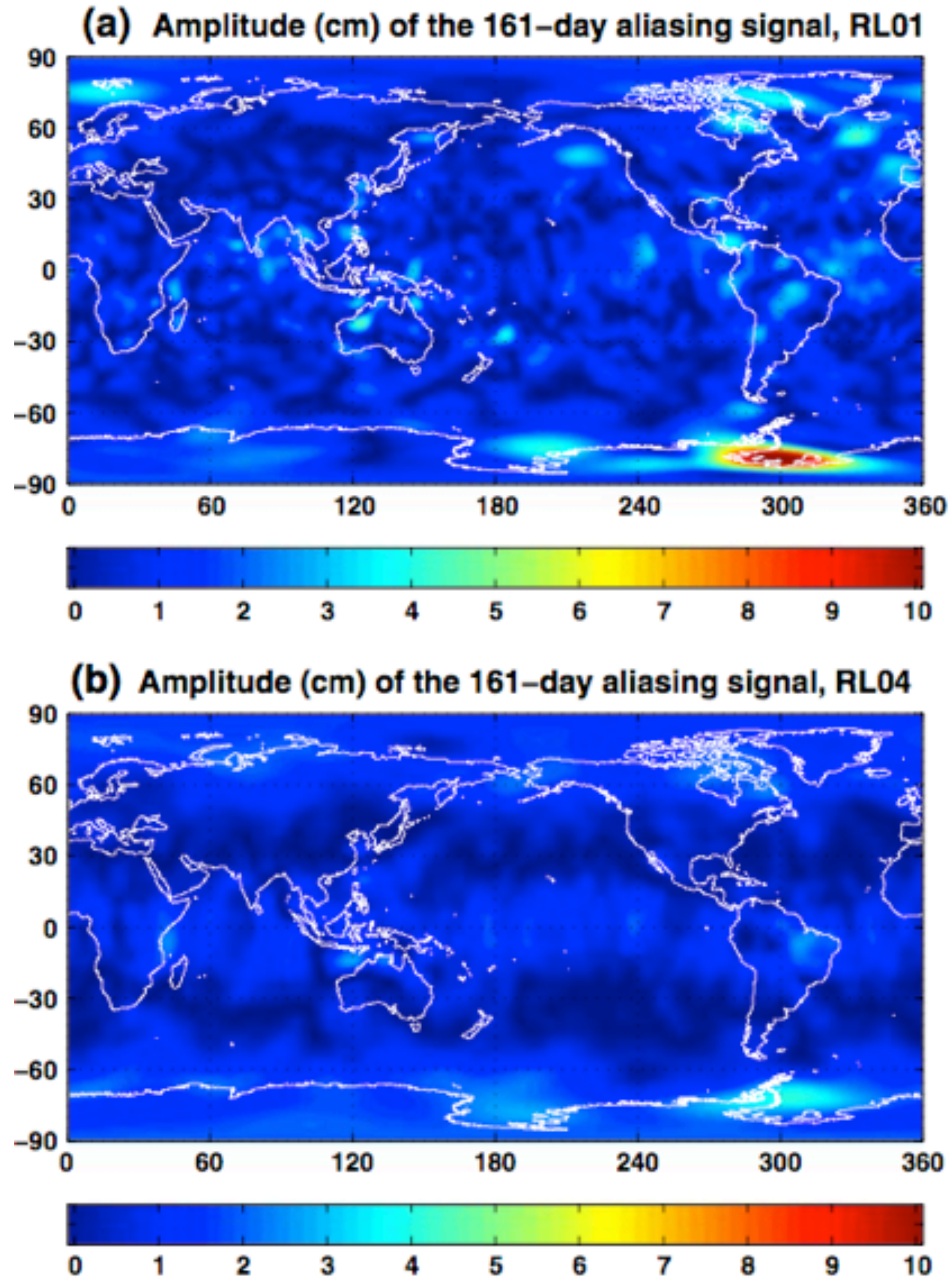
For all Mass Transports...

- an improvement in the spatial and temporal resolution of the NGGM will
  - allow for the observation of more classes of mass transport signals
  - aid in dealiasing
  - help separate the different signals
- all mass transport studies will benefit from an improvement in accuracy
- all mass transport studies will benefit from a long mission lifetime

Current Limitations: Aliasing and Background models

Aliasing

- Aliasing: mapping of signal from higher frequency onto lower frequency due to under sampling
- Caused by inadequate background models
  - atmosphere
  - ocean tides
- Improved recently, but there is still a long way to go

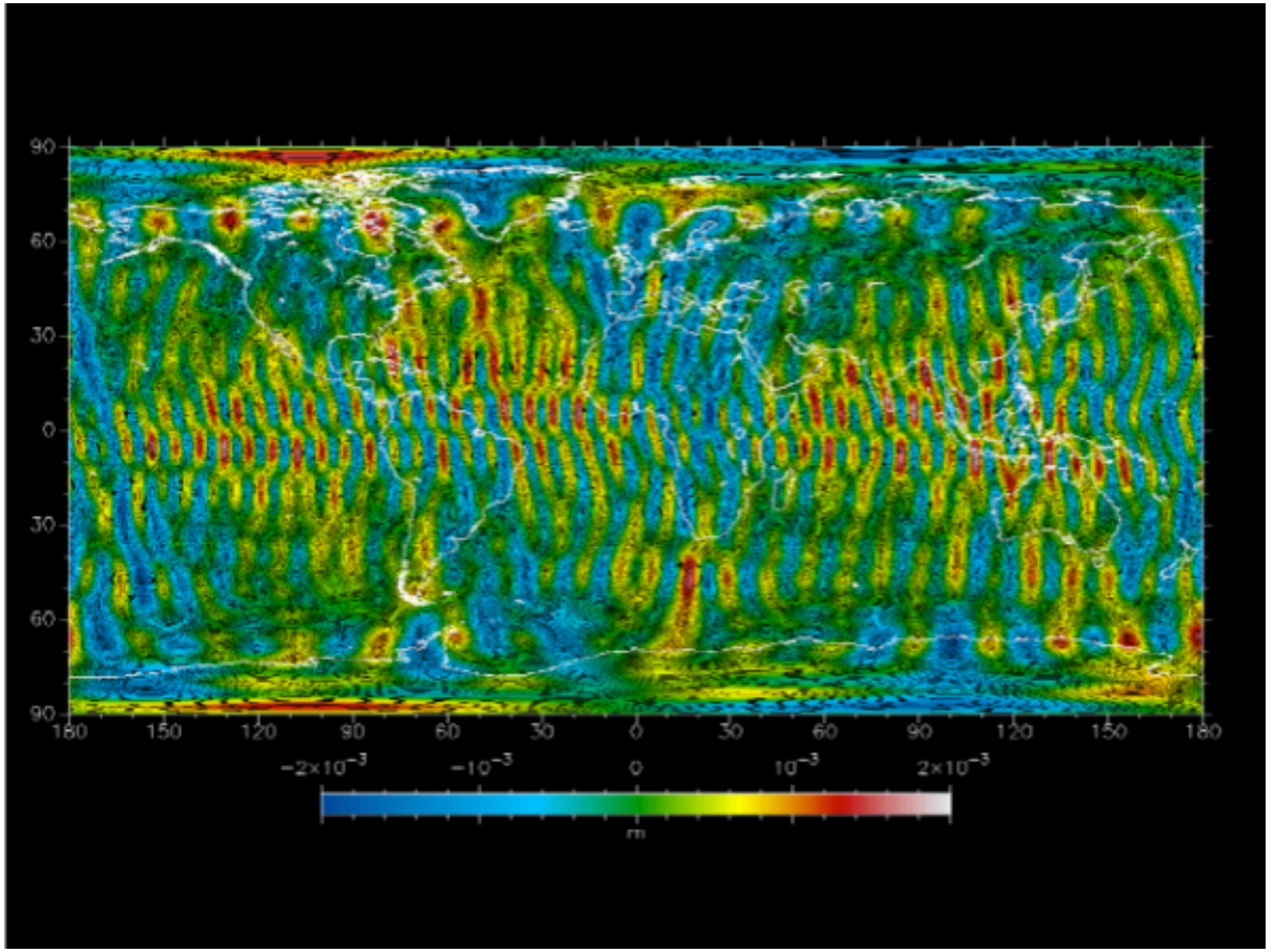


“S2 tide aliasing in GRACE time-variable gravity solutions”, Chen et al., J. Geod., 2008

Aliasing Errors

- Ocean tide: model errors
- Atmosphere: high frequency variations not captured; errors in the tidal model
- Nontidal oceanography
- Static gravity field models
  - Assume the l=2-200 part of EGM-96 represents the real static gravity field. If a 70x70 gravity field model is solved for, this leads to the aliasing of the l=71-200 part

Aliasing



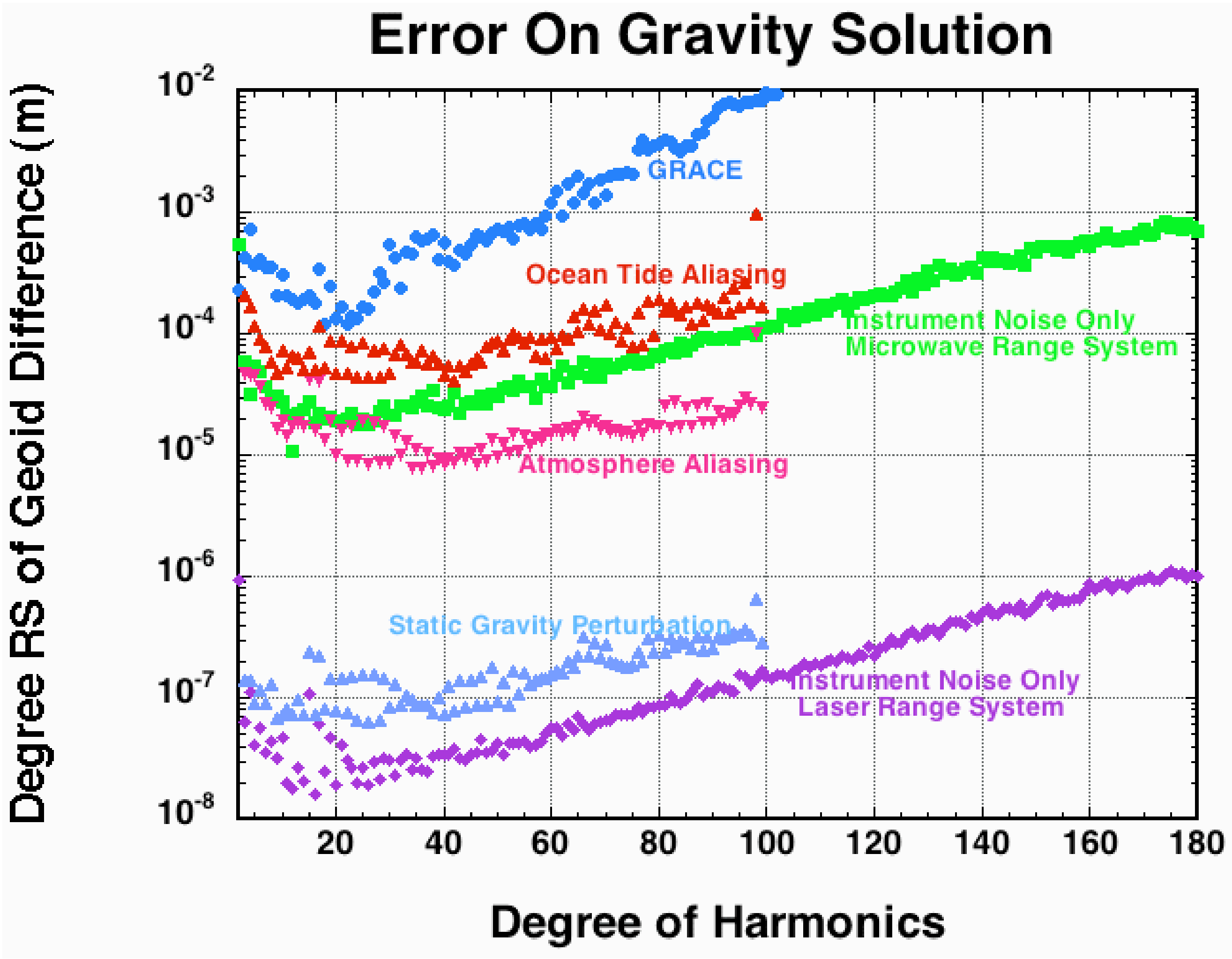
A simulation using comprehensive force models including a static gravity field (EGM96), tides (FES99), etc. We simulate GRACE range-rate observations using the same gravity field but using the GOT99.2b ocean tide model. The determined geoid is shown, which represents the error due to inadequacies in the tidal model.

Aliasing

- Careful review of the current GRACE error budget indicates that, to the best of our understanding, aliasing is not yet the limiting factor in gravity results from GRACE, and that improvement of systematic noise terms in a GRACE re-flight could gain improvements in the 3x - 10x range
    - Thermal control of spacecraft components
    - Attitude angular acceleration spectral control
    - Long term accelerometer noise (possibly partially thermal)
- After that, aliasing seems to dominate all measurement errors significantly

Aliasing Errors

- Simulation by Watkins for the "Earth Science Decadal Study Mission Concepts-Time Variable Gravity"
- Ocean tide errors: FES - GOT (all lines and complete to degree 90)
- Atmosphere errors: ECMWF - NCEP complete to degree 100



Ocean tide aliasing error is three orders of magnitude larger than the gravity recovery error caused by observation noise

Aliasing

- Aliasing seems to dominate all potentially improved measurement errors significantly
- There are no obvious forward modeling improvements that will change this
  - Tide models will improve at some level due to more altimetry and improved models but consensus indicates that the improvement won't be enough, due to baroclinic modes and other local variability)
  - Numerical weather forecasting models (a la ECMWF) will improve pressure modeling due primarily to GPS occultation assimilation
  - Nontidal ocean mass variability can be significant, even harder to model since not time/phase coherent

Aliasing Solutions (MTS)

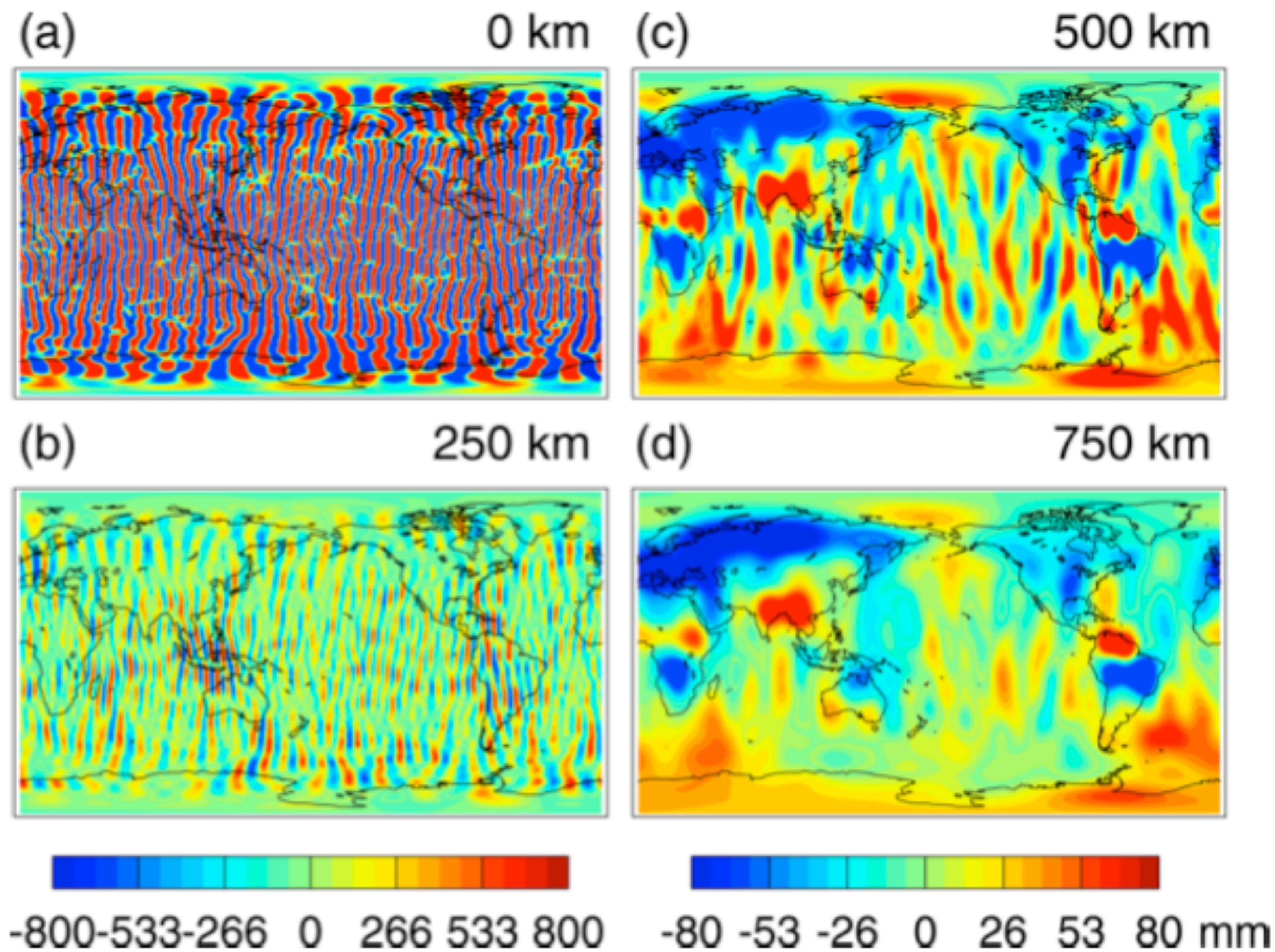
- Temporal filtering of the time variable gravity fields
  - band-pass filtering for the aliasing periods
  - high-pass filtering of scatter at short periods (T < 30-60 days); depends on signal of interest
  - aliasing periods should not coincide with characteristic periods of signals of interest
- Correct sampling of the tidal periods by choice of satellite constellation
  - temporal aliasing is reduced
  - tides can be estimated within the gravity adjustment
  - for a spatial resolution of l=50, 32-33 satellites are required depending on the inclination

Aliasing Solutions (MTS)

- Because the aliasing periods are known, the tides can be parameterized and estimated within the adjustment
  - huge system of equations and number of unknowns since time variable solutions are correlated with tides
  - find a mission, which separates the aliasing periods
    - low inclination, e.g. TOPEX
    - heterogeneous orbits, Bender type Mission
  - aliasing periods should not coincide with the periods of the signal to be recovered
  - due to remaining spatio-temporal aliasing (e.g. from static gravity field and the atmosphere) and correlations between the tidal signals and the signals of interest, the estimation and the reduction for tides may still be imperfect

Distortion

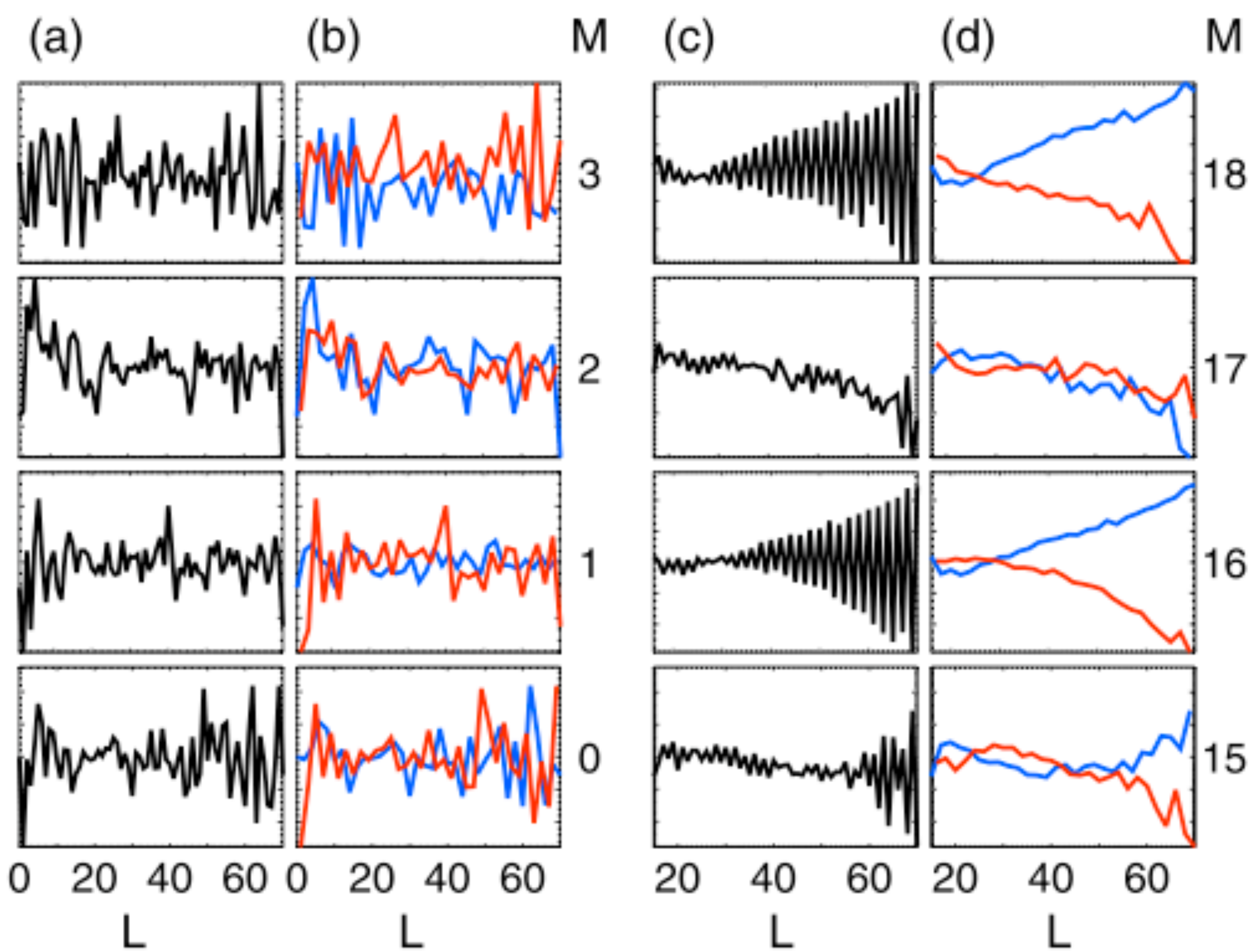
- Distortion (striations, stripes): geographic systematic effects resulting from the propagation of – errors in the observations due to – the sampling configuration (non-isotropy, (near-) polar orbit, resonances, inhomogeneous ground-track pattern, etc.)



"Post-processing removal of correlated errors in GRACE data", Swenson and Wahr, GRL, 2006.

Distortion

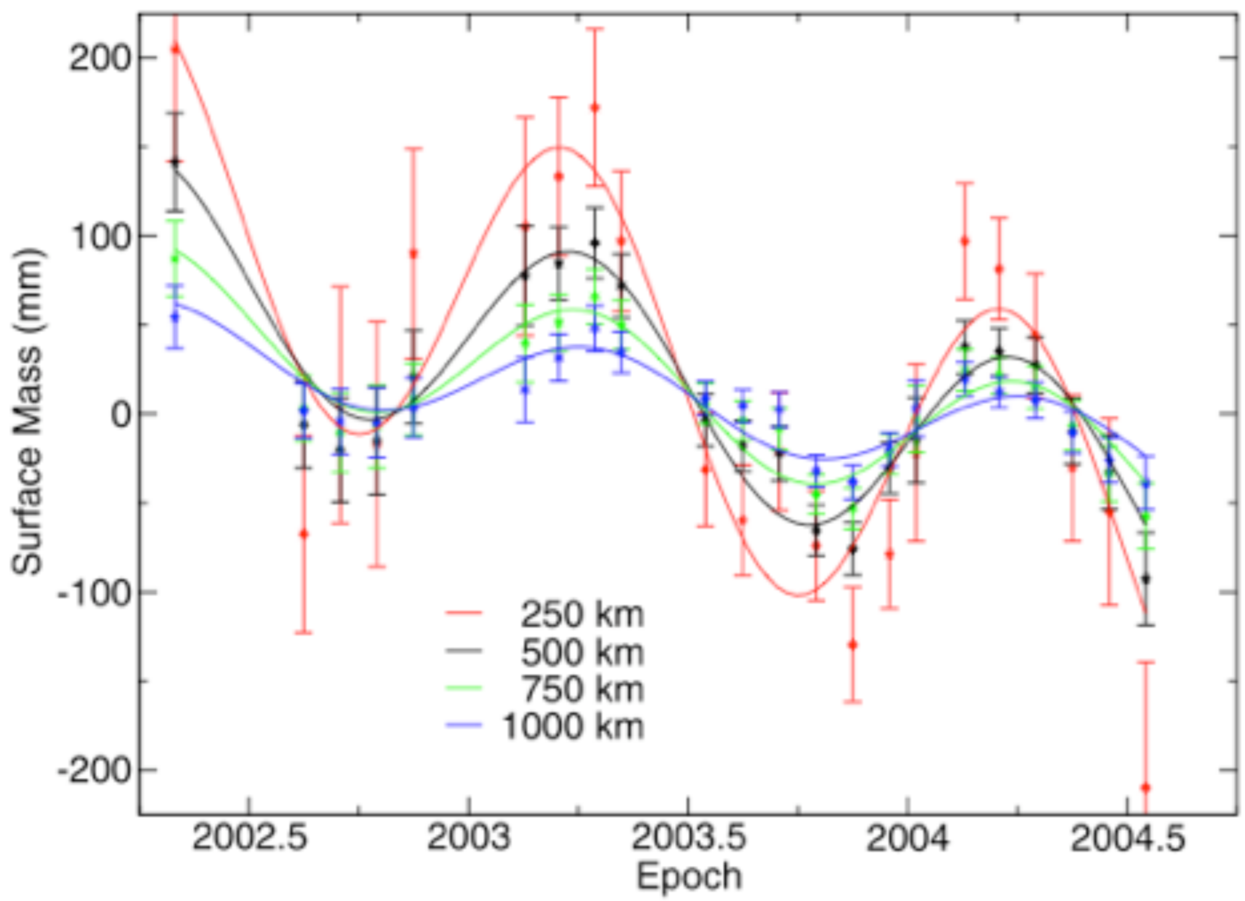
- caused by a systematic error which becomes evident at the resonances
- removed by fitting polynomial of degree 4 to l,m for m> 8



“Post-processing removal of correlated errors in GRACE data”, Swenson and Wahr, GRL, 2006.

Distortion

- Usually handled by spherical cap smoothing
- signal amplitude decreases with increasing smoothing radius
  - must rely on some kind of validation
  - demonstrate that amplitude of signal is independent of smoothing radius



"Constraining hydrological and cryospheric mass flux in southeastern Alaska using space-based gravity measurements", Tamisiea et al., GRL, 2005.

Separation of signals

- Separation: unravelling mass or gravity signal into its individual contributions from the superposition of all possible gravity effects that the measurement system intrinsically measures.

Separability

- Typically achieved by trying to model all gravity field sources except the one of interest
  - reasonable solution if the gravity signal of interest has a distinct temporal and spatial signature
  - problematic when the signal of interest "looks like" a nuisance signal, e.g. present day mass change versus GIA

Separability

- Solid-Earth
  - in general, SE signals have a characteristic temporal and spatial signature
  - removing other mass signals using models or filtering usually sufficient
- Oceans
  - separability hindered by the spatial sampling of GRACE (500-1000 km)
  - inaccuracies in contemporary numerical models of ocean circulation
  - the lack of direct observations (bottom pressure recorders)

Separability

- Ice
  - regions of present day ice mass change are also regions with GIA signal
    - to date, only models have been used to remove the GIA signal from GRACE observations
    - possible to use GNSS?
    - finer spatial sampling of gravity field would also help the separation
  - leakage of the ocean and hydrological signals into the ice signals
    - caused by the coarse resolution of GRACE
    - traditionally separated by forming averaging kernels to isolate the region of interest
    - mascon approach could also minimize leakage

Separability

- Ice
  - desirable to separate mass change signals due to global change from mass change signals due to glacier dynamics
    - impossible given the spatial resolution of GRACE

Separability

- Hydrology
  - problems here are the same as for Ice and the Solid Earth
  - usually handled using averaging kernels to limit the leakage effect
  - background models are also often used to remove signals that are not of interest (e.g. separating groundwater from soil moisture)

Priorities for NGGM

General Conclusions

- All systems of mass transport can be considered priorities
  - Ice
  - Continental water
  - Ocean mass
  - Solid Earth processes
- An improved understanding of these processes is important for scientific as well as societal reasons
- Any mission will be plagued by problems of aliasing
  - choice of mission parameters should allow for the mitigation of nuisance signals caused by poor background models

For all Mass Transports...

- an improvement in the spatial and temporal resolution of the NGGM will
  - allow for the observation of more classes of mass transport signals
  - aid in dealiasing
  - help separate the different signals
- all mass transport studies will benefit from an improvement in accuracy
- all mass transport studies will benefit from a long mission lifetime

Mass Transport Process	Observability: +, ++, or +++ (+++ easily observed with GRACE; ++ at the limit; + cannot be observed with GRACE)	Alternative techniques	Priority: +, ++, or +++ (more +, higher priority)	Rating
Solid Earth				
GIA	+++	GNSS, absolute gravimetry, levelling, etc. (measure surface deformations)	+++	++
Co-seismic deformation	++ (only the largest earthquakes are observable with GRACE)	Seismic data – globally; other techniques (GNSS, absolute gravimetry, levelling, etc.) – only in-land	+++	++
Post-seismic deformation	++	In the oceanic areas – no; In-land: GNSS, absolute gravimetry, levelling, etc.	+++	+++
Hydrology				
Ground water (antropogenic)	++	Only in-situ data (e.g. from hydrological wells)	+++	+++
Ground water (natural)	+++	in-situ data, hydrological models based on in situ and meteorological data	+++	++
Soil moisture	+++	In-situ data, microwave sensors, hydrological models, etc	+++	+
Snow cover	+++	Satellite altimetry (only volume, not mass); hydrological models	+++	++
Open water bodies	++/+	Satellite altimetry; in-situ data	+++	+
Ice				
Melting of ice sheets	+++	Satellite altimetry (only volume, not mass); INSAR (indirectly)	+++	+++
Melting of mountain glaciers	+	Satellite altimetry (only volume, not mass); INSAR (indirectly); in situ data	+++	+
Ocean				
Non-steric component of sea-level variations (seasonal and shorter time scales)	++	Combination of satellite altimetry and in-situ data	+++	+++
Non-steric component of long-term sea-level rise	+ (hardly separable from GIA)	Combination of satellite altimetry and in-situ data	+++	++

Priorities

- Characterization of the melting of ice sheets and continental ice
  - understanding global climate change and global sea level rise
  - satellite gravimetry is the only observation technique that allows ice mass balance to be quantified directly

Priorities

- Determination of the non-steric component of sea-level variations at seasonal and shorter time scales
  - important for climate change studies
  - currently measured with altimetry and models or observations of the steric component; problematic in the southern hemisphere
  - satellite gravimetry the only technique for measuring this quantity globally

Priorities

- ground water, soil moisture, snow, and surface water at higher spatial scales
  - important for climate change studies
  - important for understanding drought
  - important for managing fresh water stores
  - models may not be sufficient
  - in situ observations problematic when water stores cross boundaries

Priorities

- Post-seismic deformation
  - important for a better understanding of solid Earth hazards
  - satellite gravity is the only technique that can provide post-seismic deformation assessments in oceanic areas, where subduction zones are located and where the largest earthquakes occur