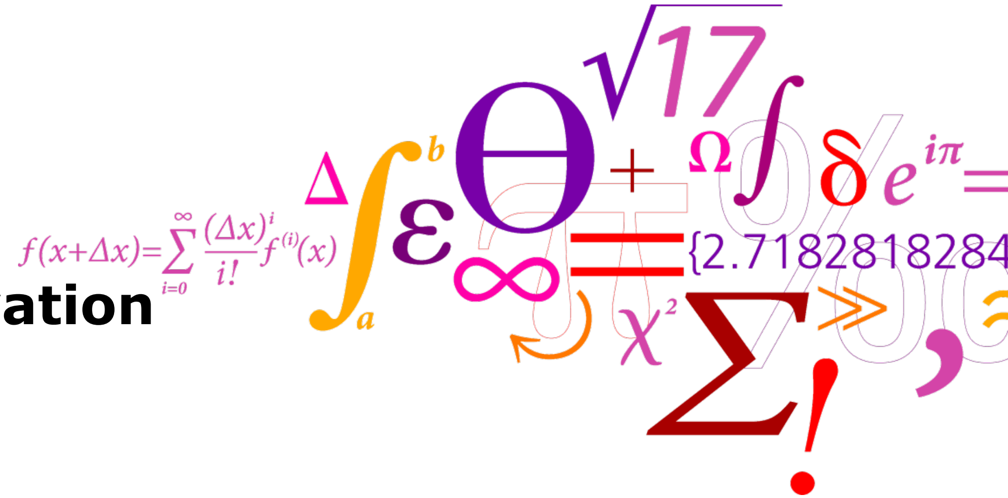
30552 – Lecture 13.

Putting Space Geodesy together -Gravity field and sea level change explained.

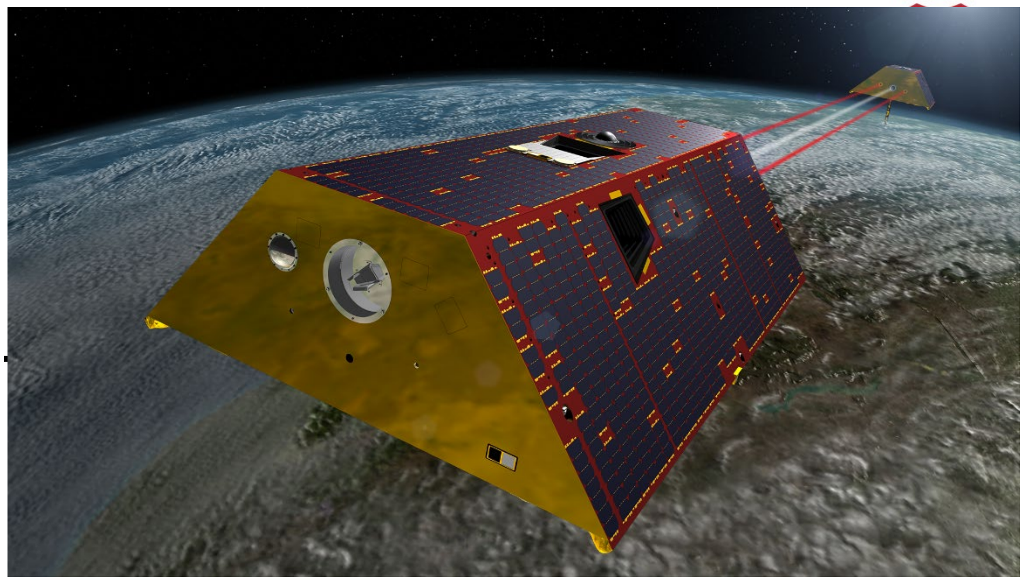
Prof Ole B. Andersen,
DTU Space,
Geodesy and Earth Observation

DTU Space
National Space Institute



Before we start:

If you feel ill, go home
Keep your distance to others
Wash or sanitize your hands
Disinfect table and chair
Respect guidelines and restrictions



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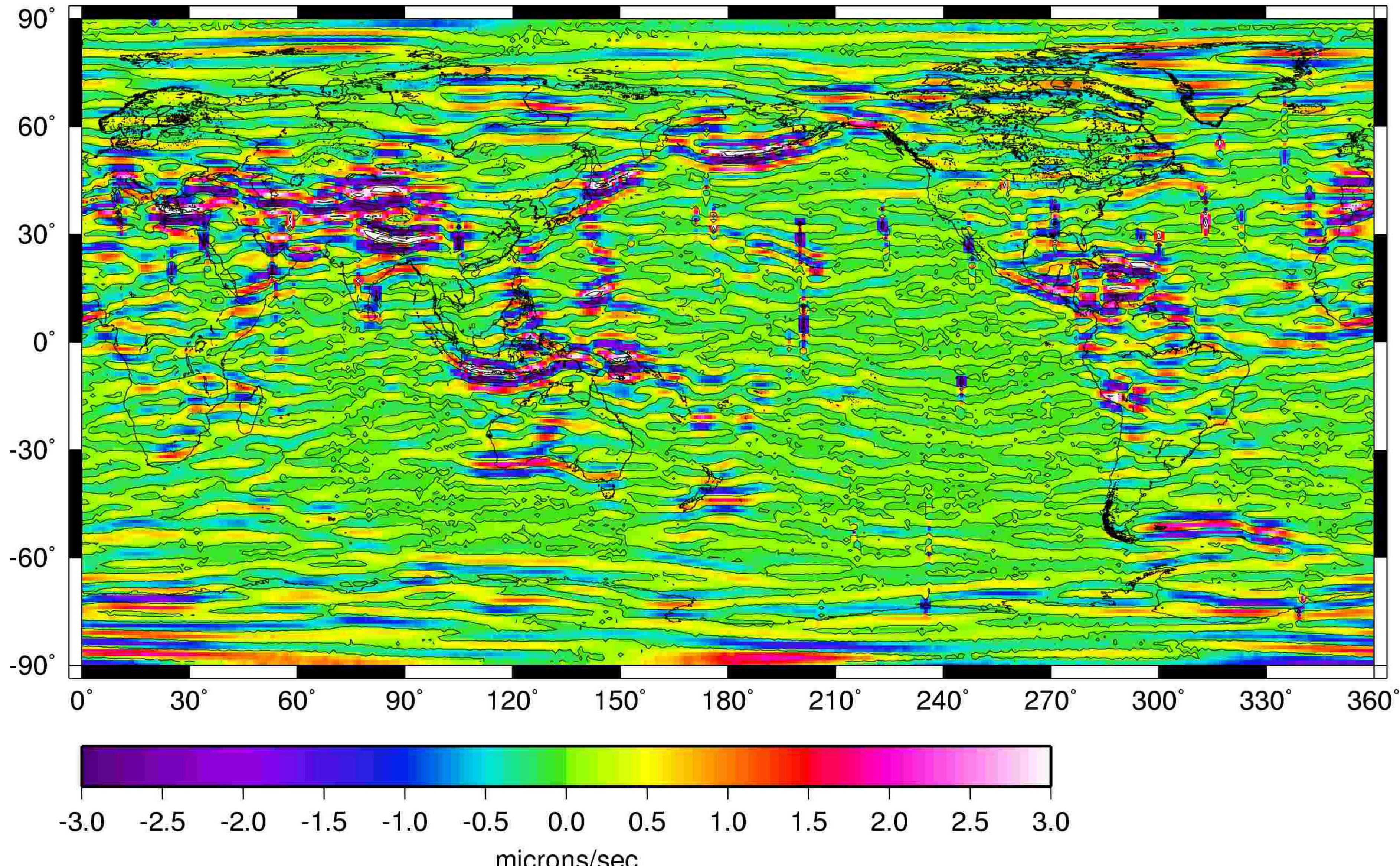
Repetition from last time:
GRACE satellite tracking and gravity.
Monthly solution (filtering limitations)
Mass movements in the Earth System
The water cycle
Equivalent water height
GRACE month fields.
GRACE discoveries.
Annual, Hydrology
Droughts and Earthquakes
Melting of the Ice caps + glaciers.

Sea level rise and closing the sea level budget.

The end +

GRACE - How it works


90˚
60˚
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270˚
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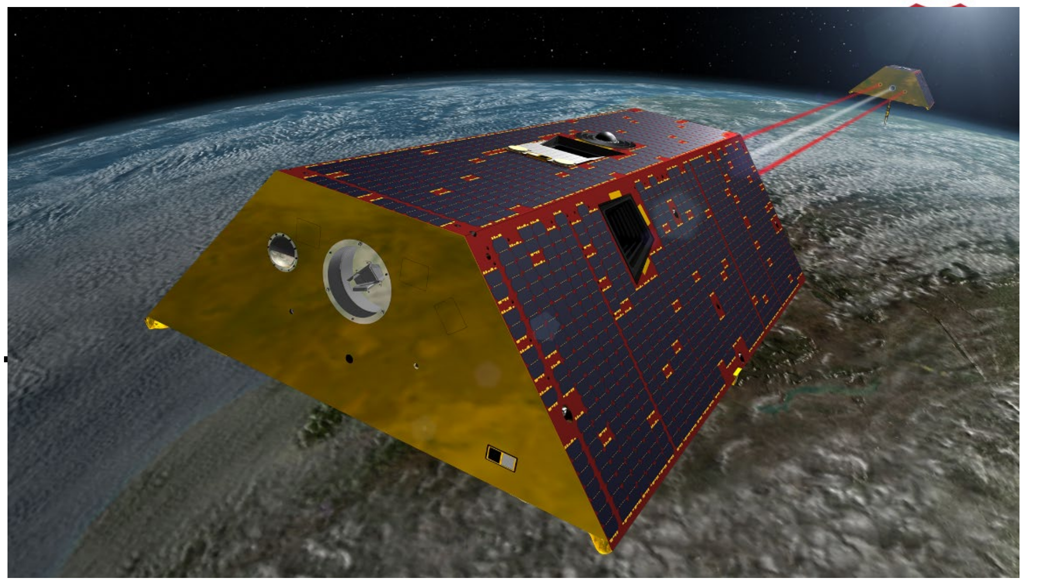
330˚
360˚
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
microns/sec

What did we learn.

- *We used ALL GRACE+GOCE+whatever observatioins to estimated global geopotential model.*
- *Geoid* $N = \frac{GM}{\gamma r} \sum_{n=2}^{\infty} 1 \sum_{m=0}^{n} P_{nm}(\sin\phi)[Cnm \cos m\lambda + Snm \sin m\lambda]$
- *Gravity* $\Delta g = \frac{GM}{r^2} \sum_{n=2}^{\infty} (n+1) \sum_{m=0}^{n} P_{nm}(\sin\phi)[Cnm \cos m\lambda + Snm \sin m\lambda]$

Today we will remove this from the GRACE observations and look at the residuals or the changes with time.

- *Geoid* $\Delta N = \frac{GM}{\gamma r} \sum_{n=2}^{\infty} 1 \sum_{m=0}^{n} P_{nm}(\sin\phi)[\Delta Cnm \cos m\lambda + \Delta Snm \sin m\lambda]$
- *Gravity* $\Delta (\Delta g) = \frac{GM}{r^2} \sum_{n=2}^{\infty} (n+1) \sum_{m=0}^{n} P_{nm}(\sin\phi)[\Delta Cnm \cos m\lambda + \Delta Snm \sin m\lambda]$



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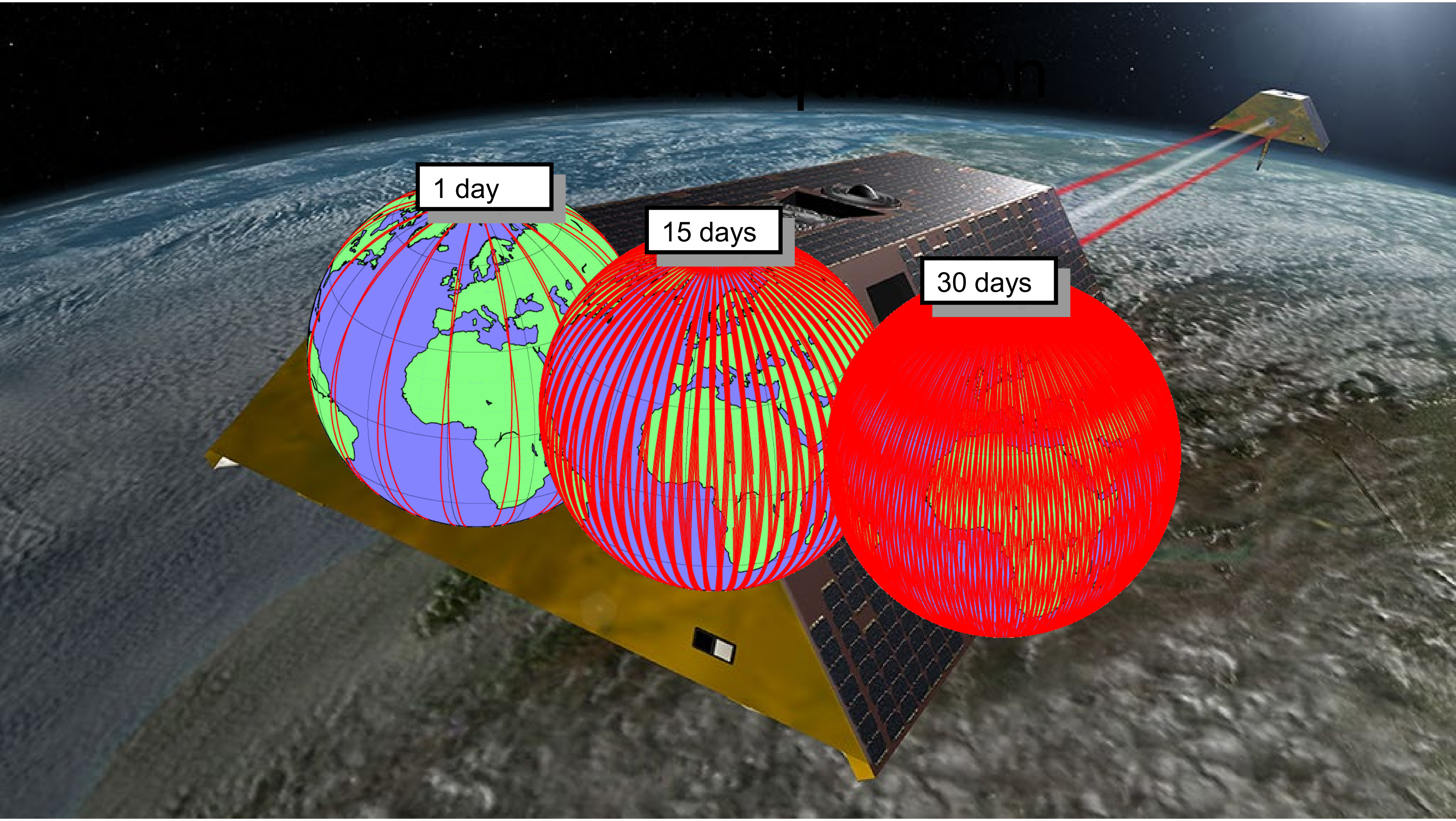
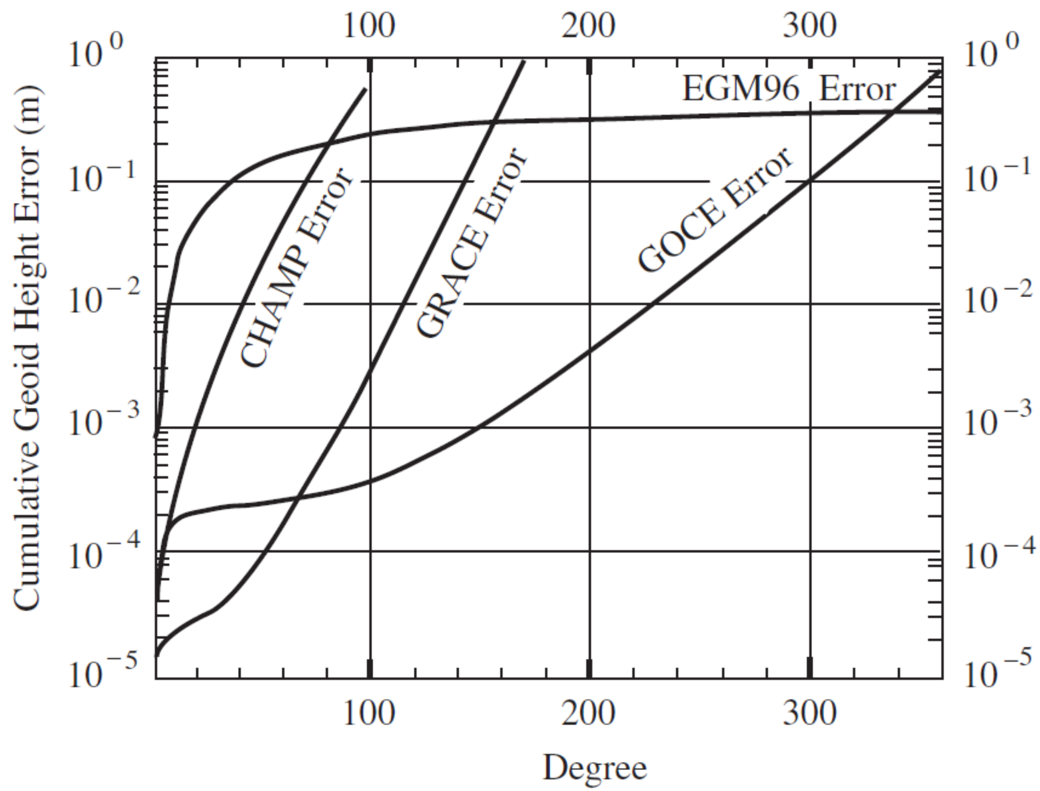

1 day
15 days
30 days

GRACE Limitation
Satellite to Satellite tracking.

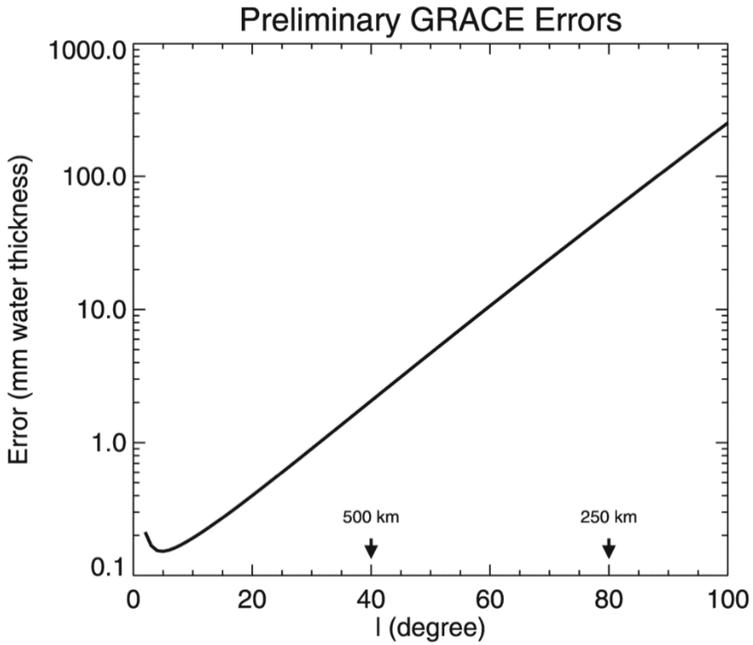


Limitation is degree and order 180 (200 km) using data from entire mission from one month it is less.

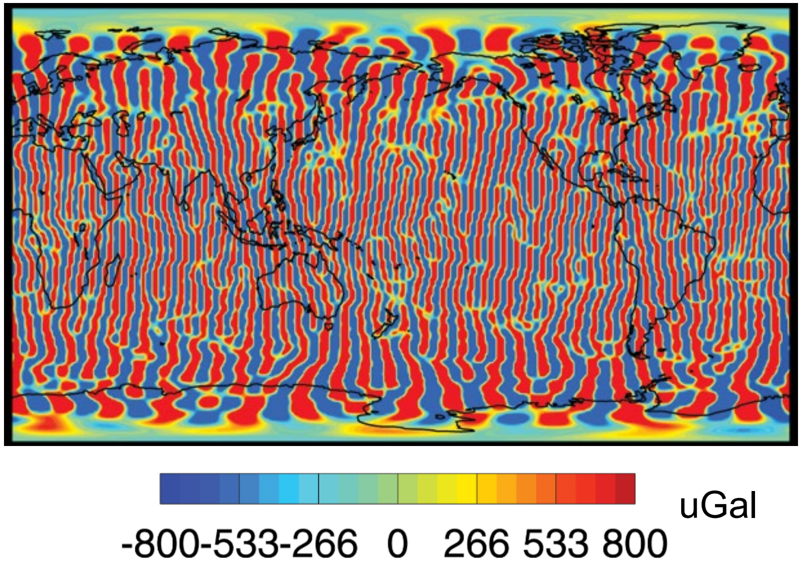
GRACE Errors

GRACE measurement error increases for high-degree, short-wavelength gravity coefficients.

Correlation between these errors results in longitudinal stripes in mapped anomaly fields.

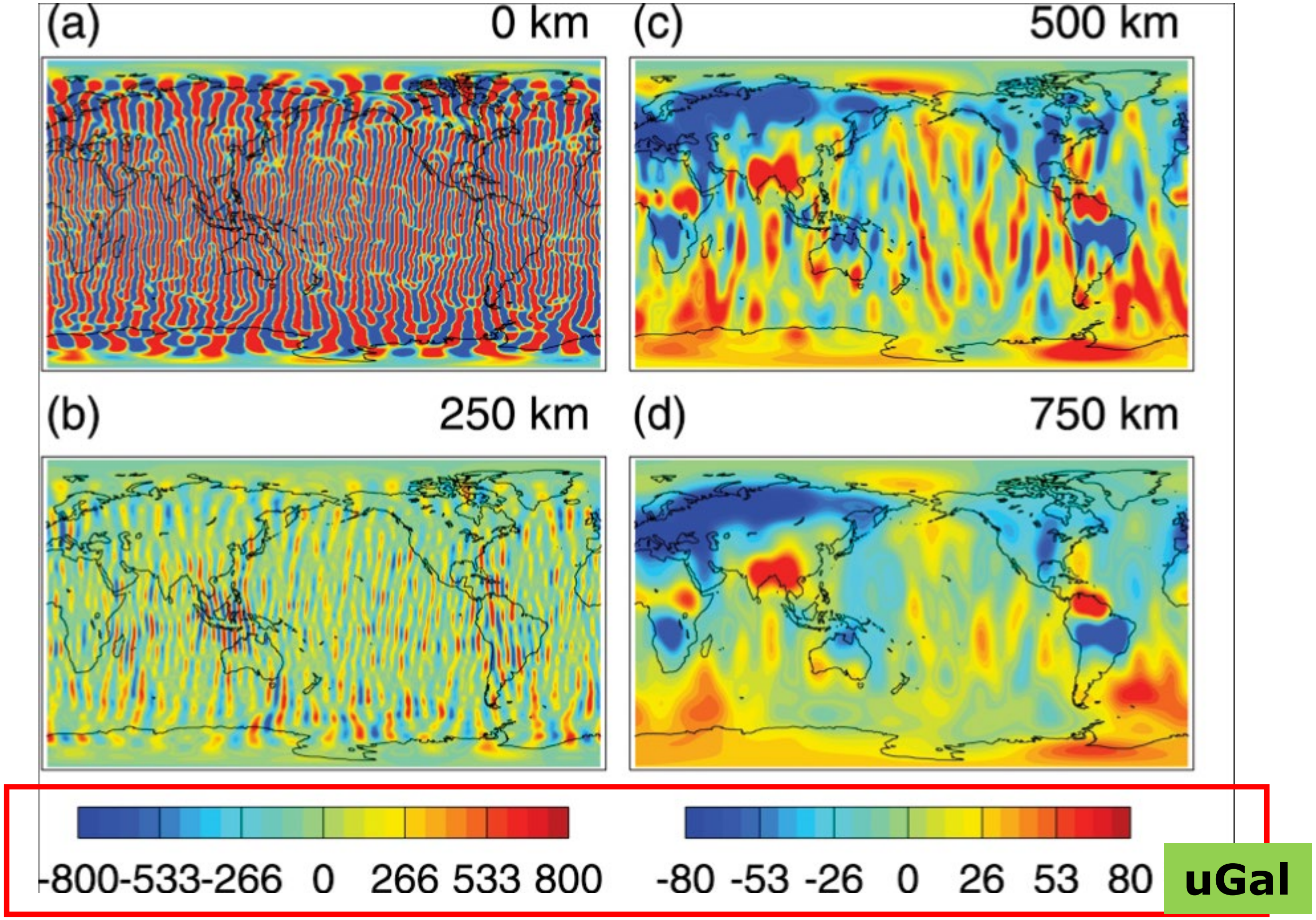


GRACE Unsmoothed mass anomaly



Estimates of the square root of the contribution to the variance of the inferred surface mass anomaly due to GRACE satellite measurement error.

Gaussian smoothing of GRACE mass anomaly maps



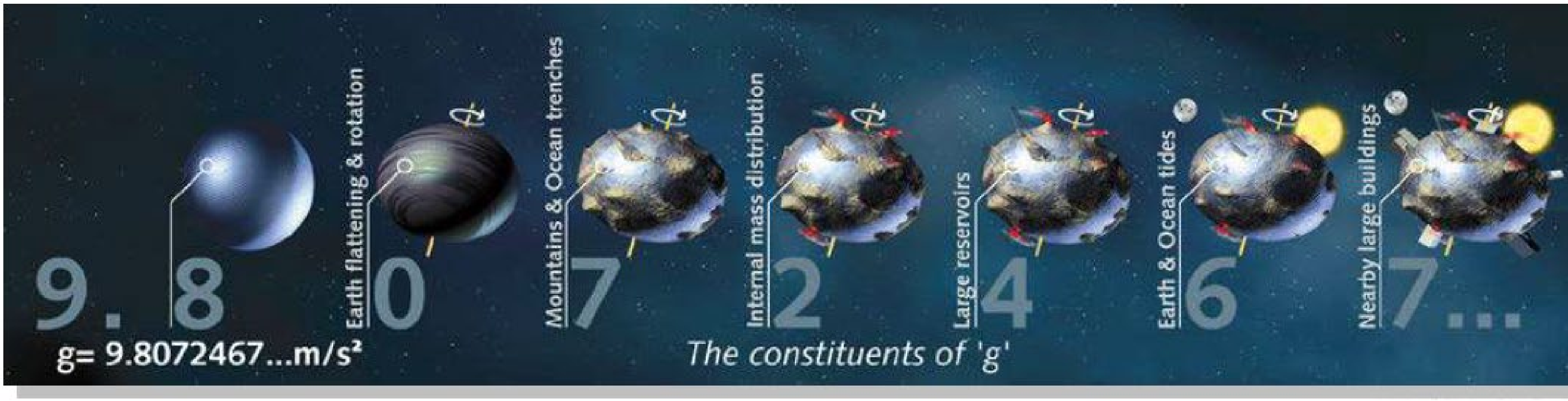
a. Unsmoothed

b. 250 km halfwidth

c. 500 km halfwidth

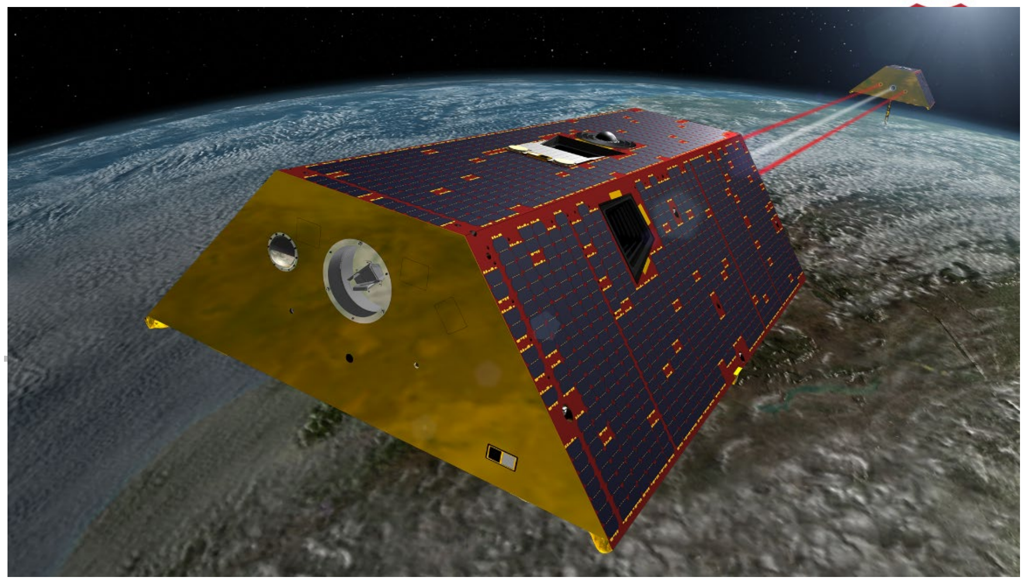
d. 750 km halfwidth

Small gravity field changes



1 gal = 1 cm/s2
1 mGal = 0.001 cm / s2
1 uGal = 0.000001 cm/s2

Changes to the 8^{th} digit of global gravity.



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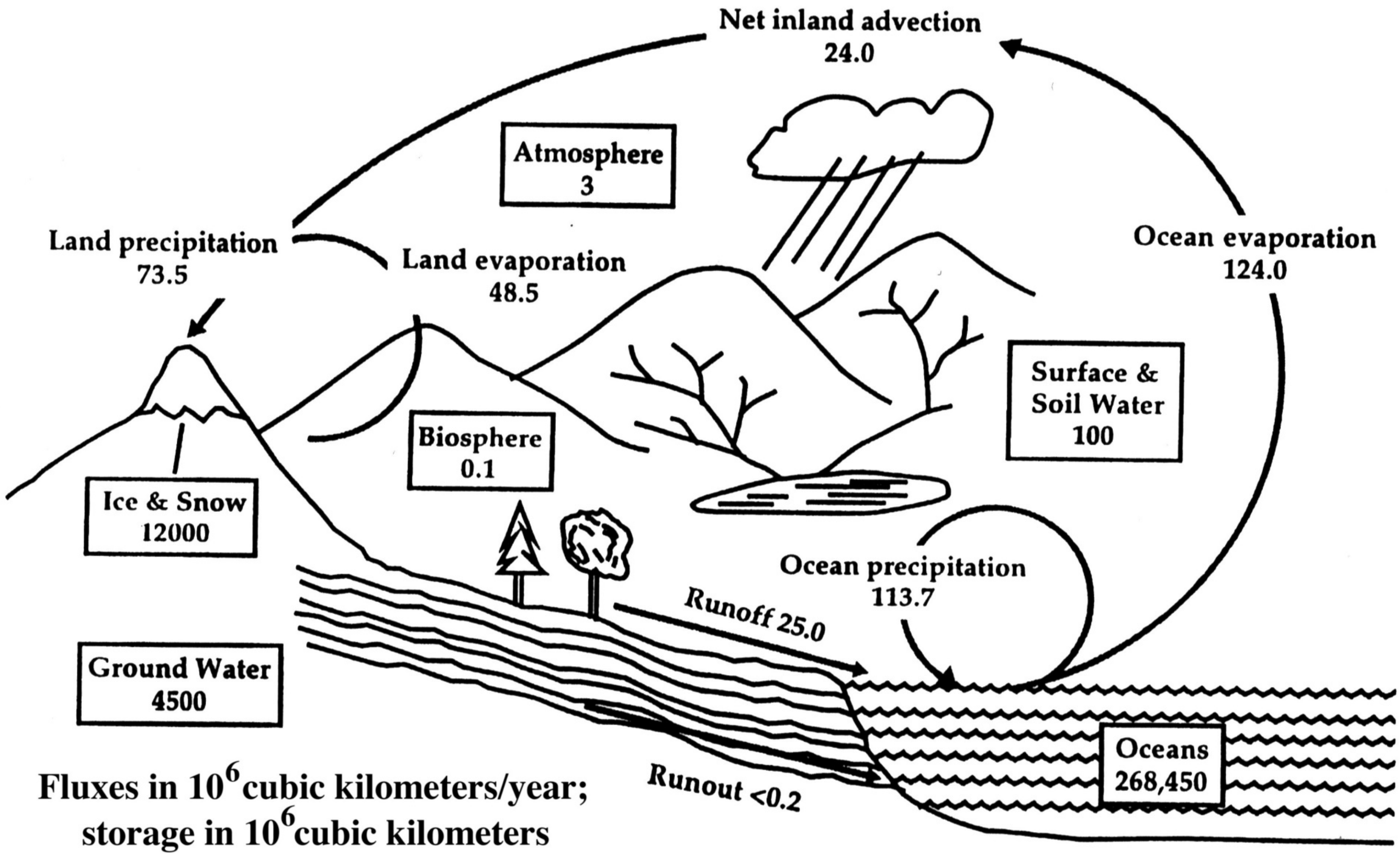
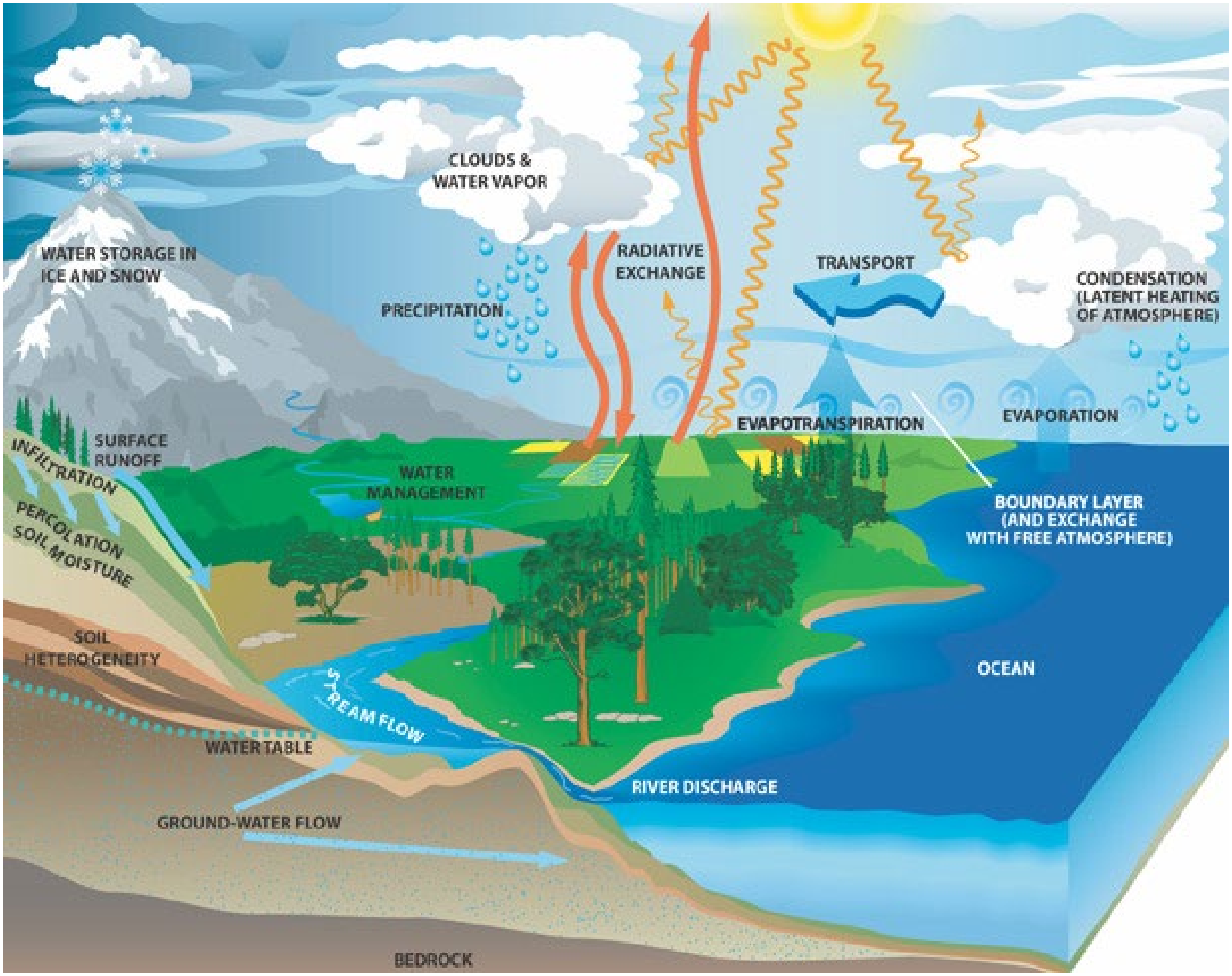
Mass in the Earth system which moves Water........
Where is the water?



The Global Water Cycle



is 6.67×10^{-11} N m^2 kg^{-2}

Equivalent water height. The Bouguer plate approximation

- Assuming you have an infinite plate of a material with density ρ
- And thickness H

$$\Delta g = 2 \pi G \rho H$$

G is the gravitational constant, $G = 6.67 \times 10^{-11}\ m^2\ s^{-2} kg^{-1}$

- Example
  - density of rock as $\rho = 2670\ kg/m^3$
  - density of water has $\rho = 1000.0\ kg/m^3$

So $2 \pi G = 4.191 \times 10^{-10}\ m^2\ s^{-2} kg^{-1}$ or 4.191×10^{-5} mGal $m^2\ kg^{-1}$

Using 1 Gal = 1cm/s2, 1 mGal = $1 \times 10^{-5}\ m/s^2$.

Equivalent water height
If we have a plate of water.

Inserting $\rho = 1000$ kg/m^3

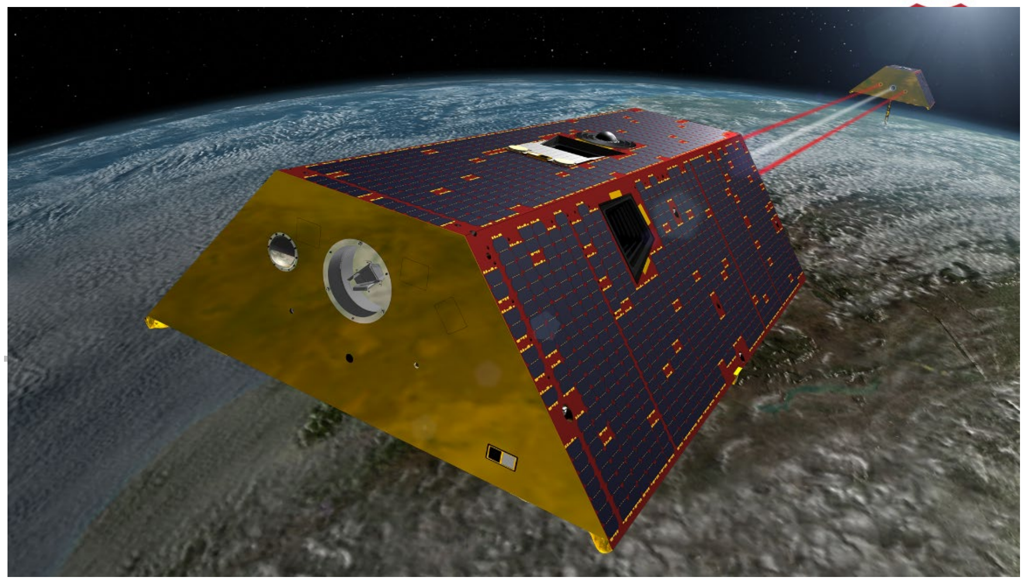
So Δg = 0.0419 mGal/meter(of water)
= 0.0419 uGal/mm(of water)
= 0.419 uGal/cm

$H = \Delta g / (2 \pi G \rho)$

2.4 cm (water)= 1 uGal (of gravity change)

Hence gravity changes are expressed in water height called

EWH (Equivalvent water height)



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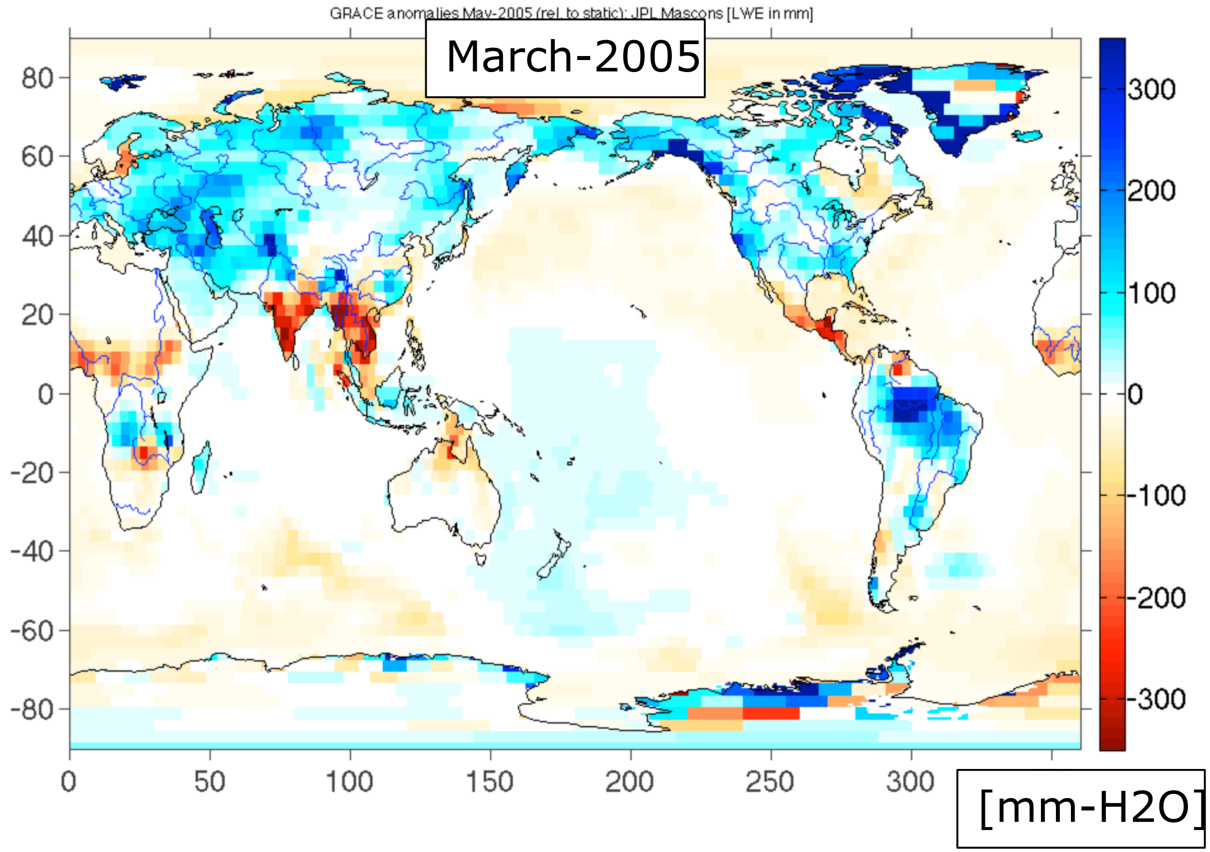
A typical GRACE month

The World According to GRACE (in May-2005, specifically):

- Monthly snapshot of near-surface mass variations (expressed in terms of **water height in millimeters** relative to the long-term average)
- Resolution: approx. 300km; Accuracy: 10-20 mm water height(depends on location)



Wet

More mass/water:
- Wet season ('winter')
- Above average

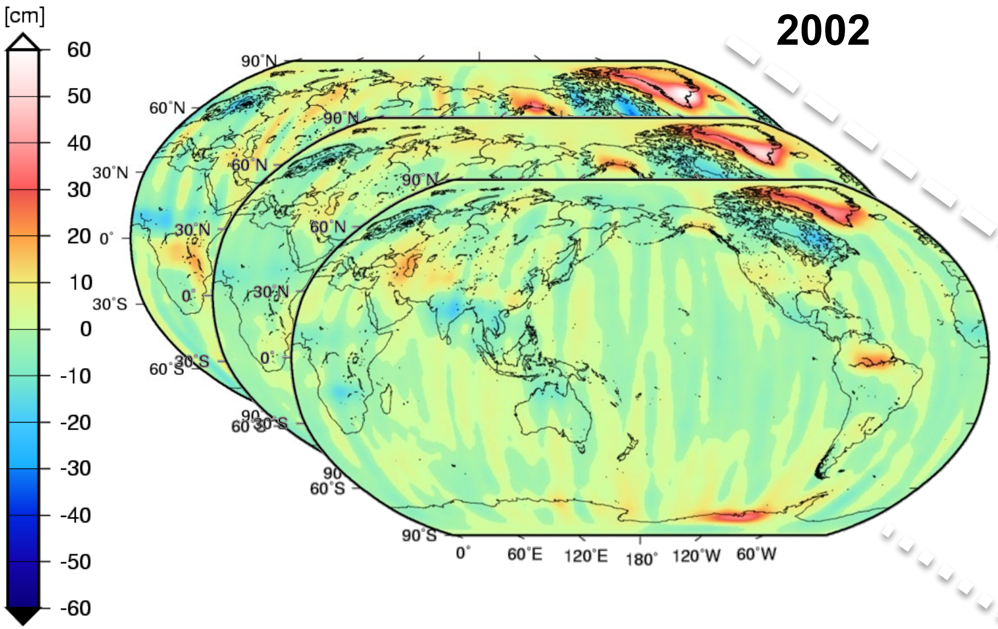
Normal

Relative to the long-term average
- 2004-2010
- 'static gravity field'

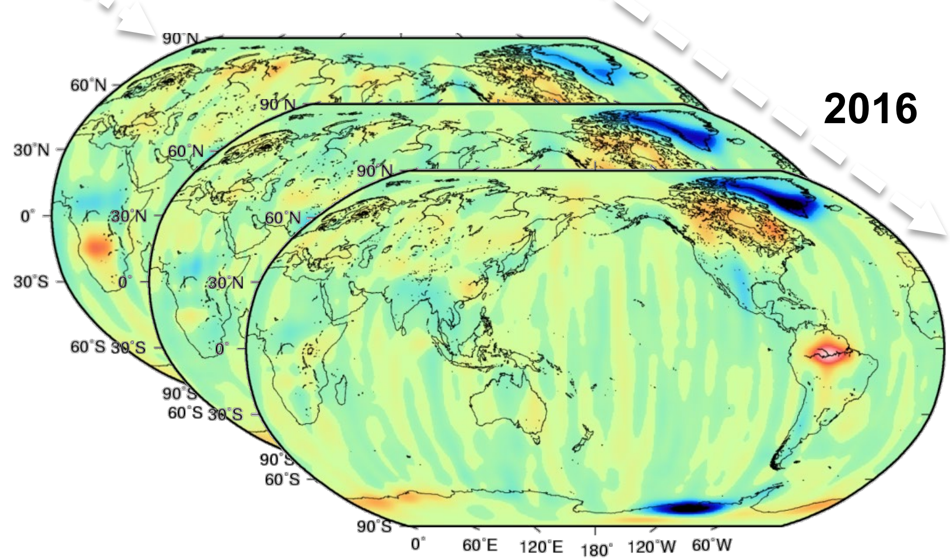
Dry

Less mass/water:
- Dry season
- Decreasing trends
- Groundwater use

Gravitational Mass Variations | GRACE – Challenges



- Integrated **temporal** variations of (**AOHIS**) :
  - Atmosphere (A)
  - Ocean (O)
  - **Hydrosphere (H)**
  - **Cryosphere (I)**
  - **Geosphere (S)**



Equivalent Water Thicknesses (**EWT**)

Background Modeling

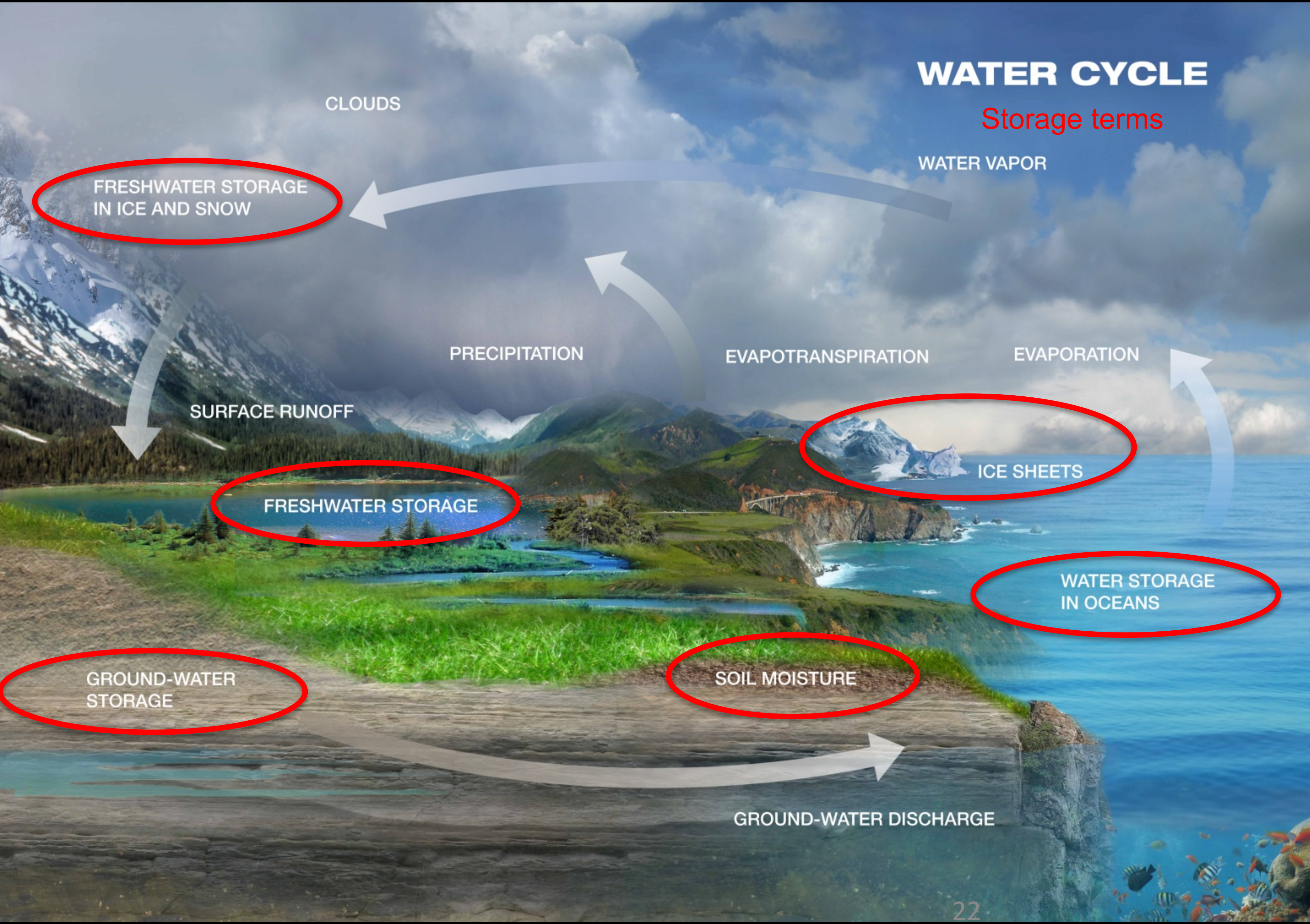
- During the processing of the GRACE data, the atmospheric and oceanic mass variations are modeled (usually using 3-6 hour fields from ECMWF and AOD1B models) in order to reduce temporal aliasing and remove the atmospheric mass variations. Depending on the science application, it may be necessary to restore the monthly mean of these fields. Therefore, the GRACE project provides these products for that purpose:

- GAA = Atmosphere only

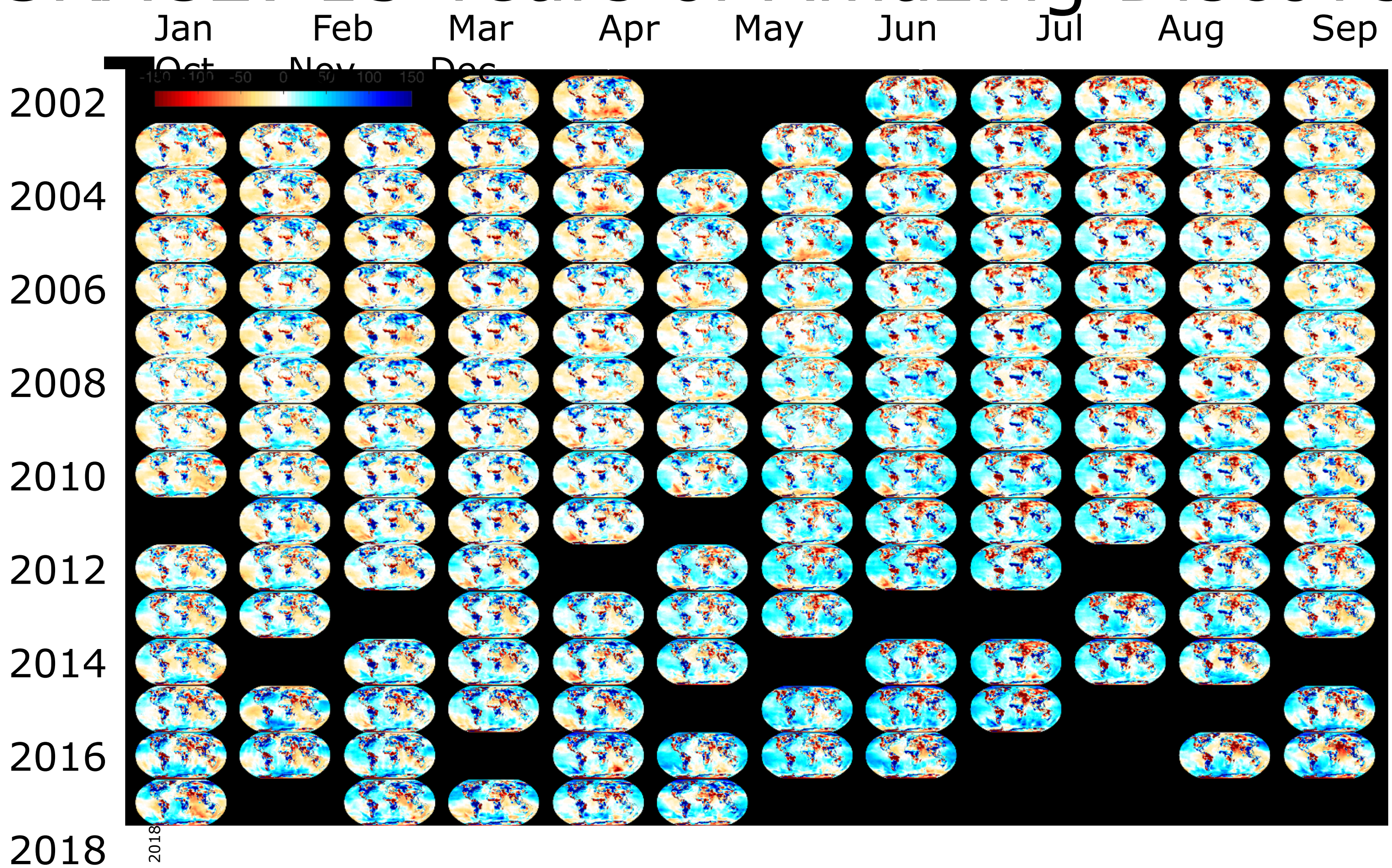
- GAB = Ocean only

- GAC = Atmosphere + ocean (Over the ocean, this is ocean bottom pressure)

- GAD = Ocean bottom pressure (GAC over ocean, 0 over land) This is the correct field to add for studying land hydrology. It should be nearly the same as GAC over the oceans.

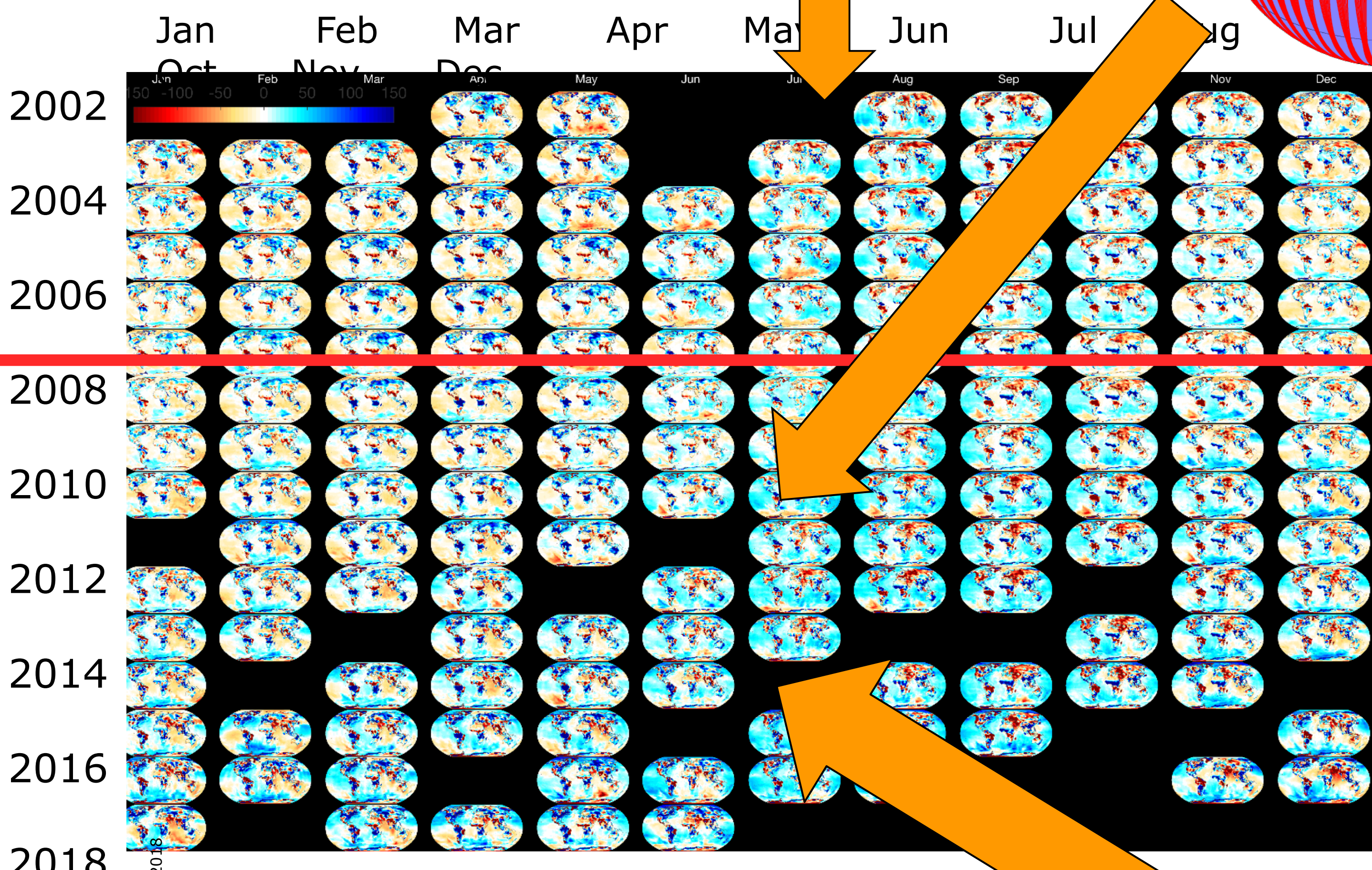

WATER CYCLE
Storage terms
CLOUDS
WATER VAPOR
FRESHWATER STORAGE
IN ICE AND SNOW
PRECIPITATION
EVAPOTRANSPIRATION
EVAPORATION
SURFACE RUNOFF
ICE SHEETS
FRESHWATER STORAGE
WATER STORAGE
IN OCEANS
GROUND-WATER
STORAGE
SOIL MOISTURE
GROUND-WATER DISCHARGE

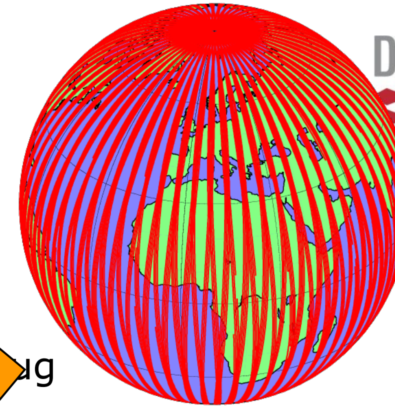
GRACE: 15 Years of Amazing Discoveries



What are the gaps?

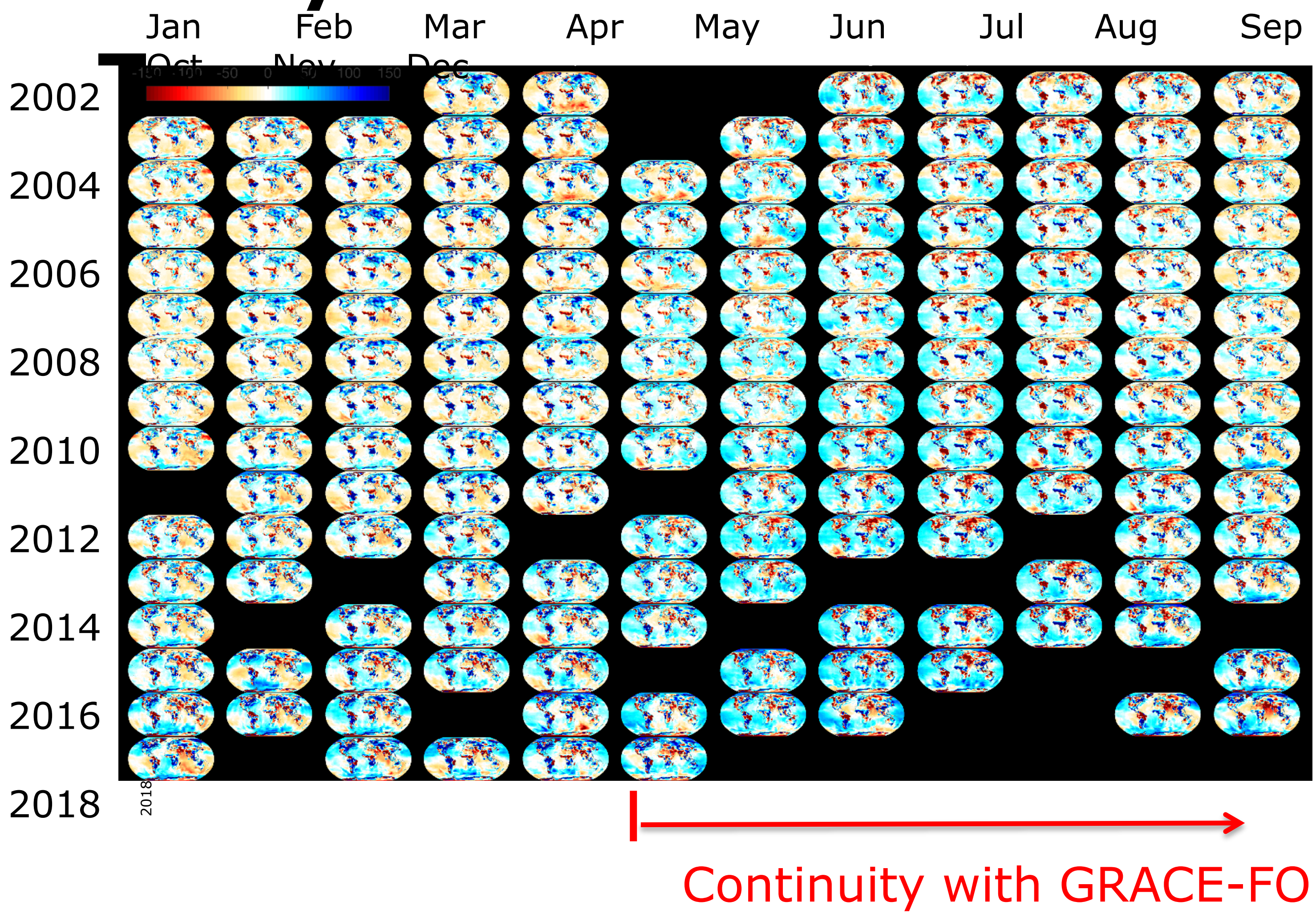
Recalibration
Shift of G1/G2



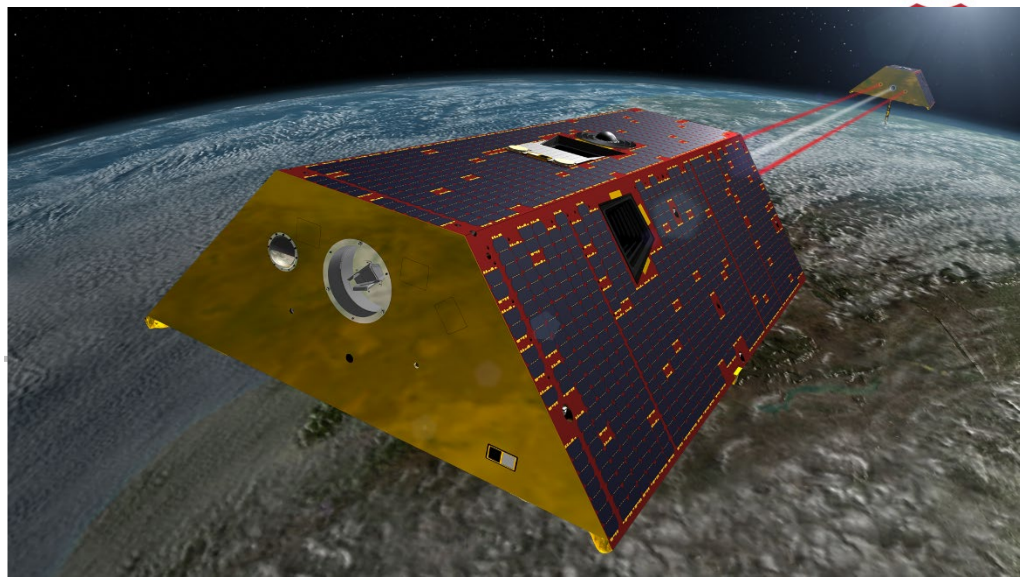


Battery degradation in G2 (4 our of 20 batteries dying)
Teperature lowering from 20 ° to 3°

Continuity – from GRACE to GRACE-FO



GRACE: Weight watching from Space



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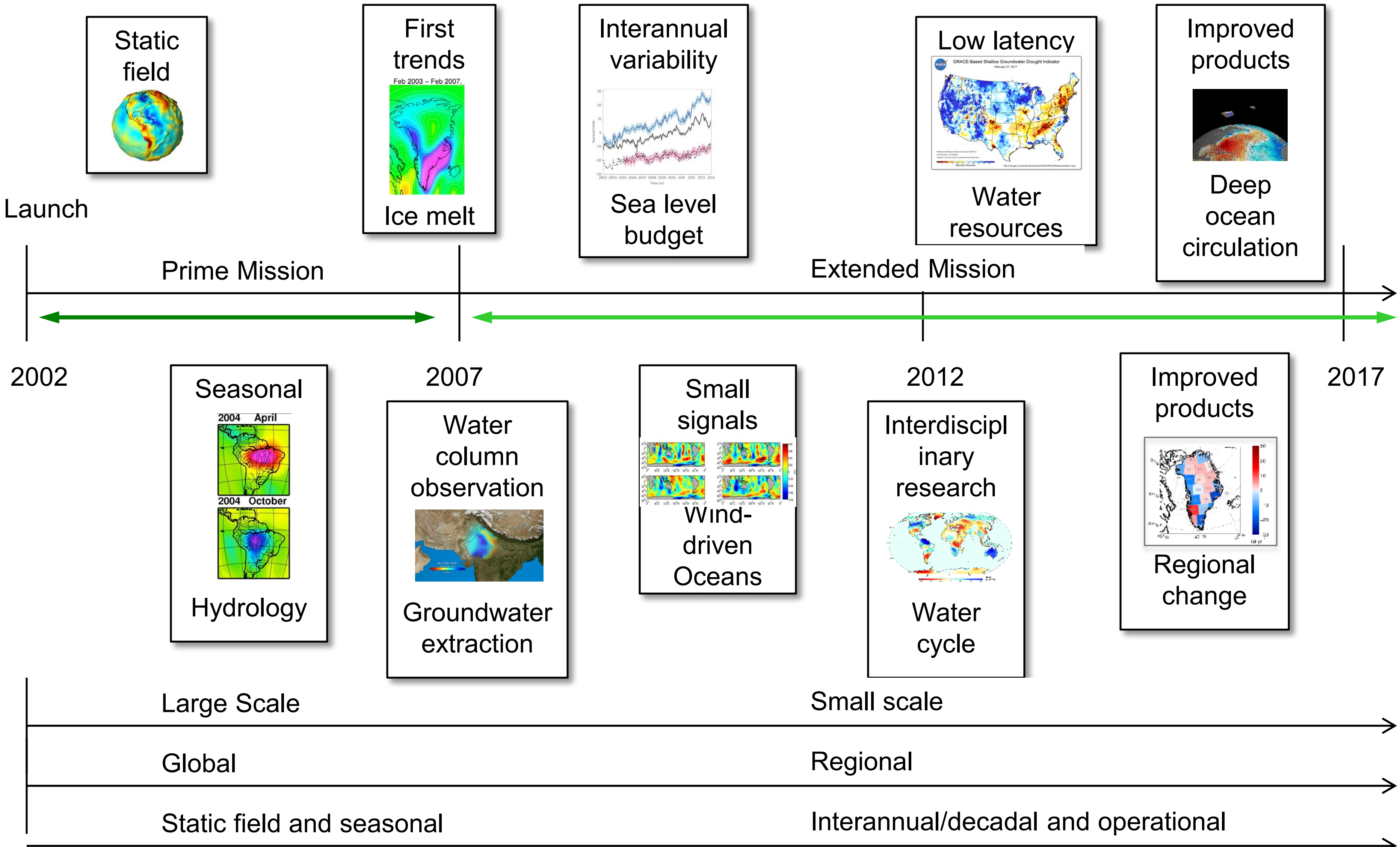
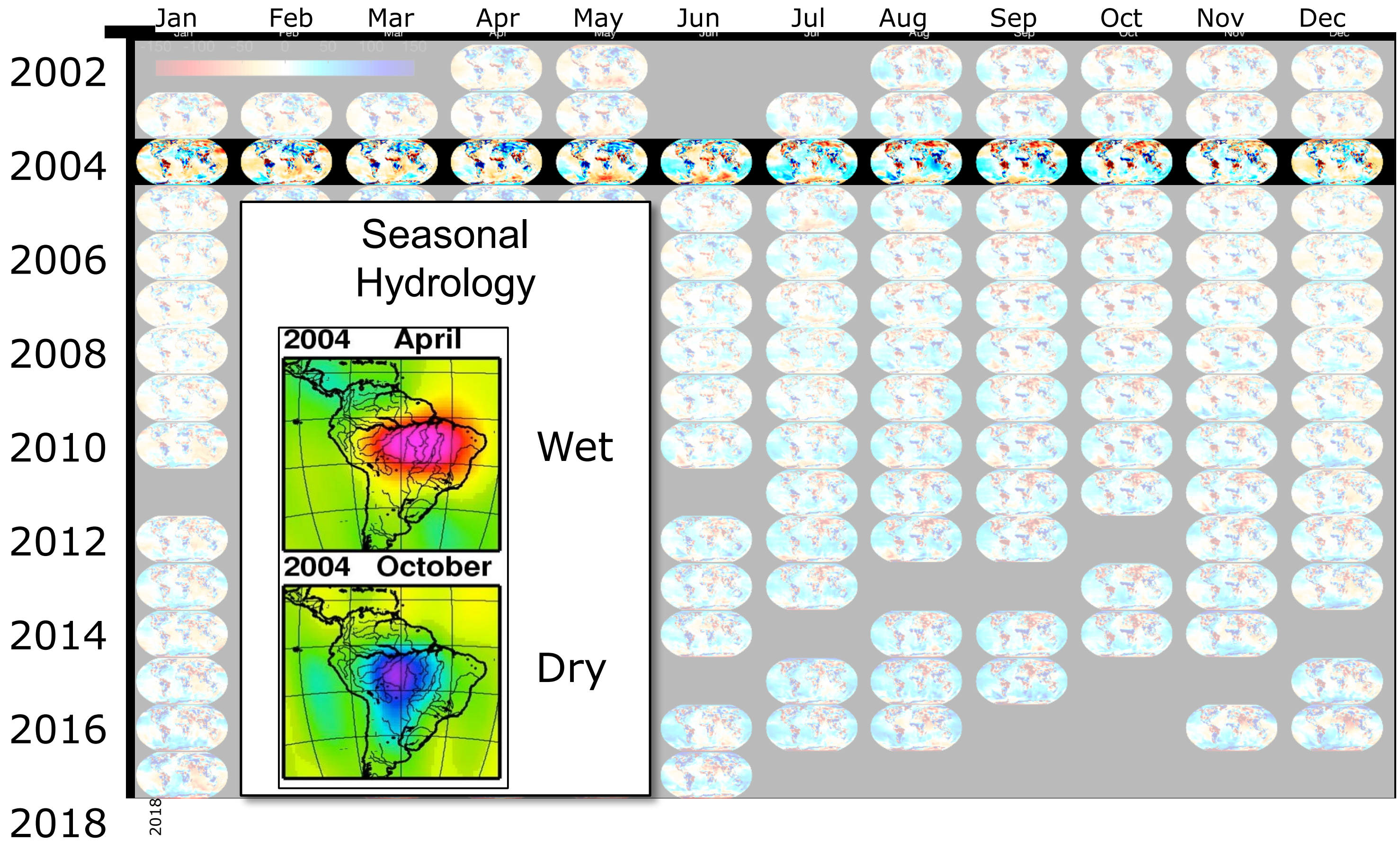
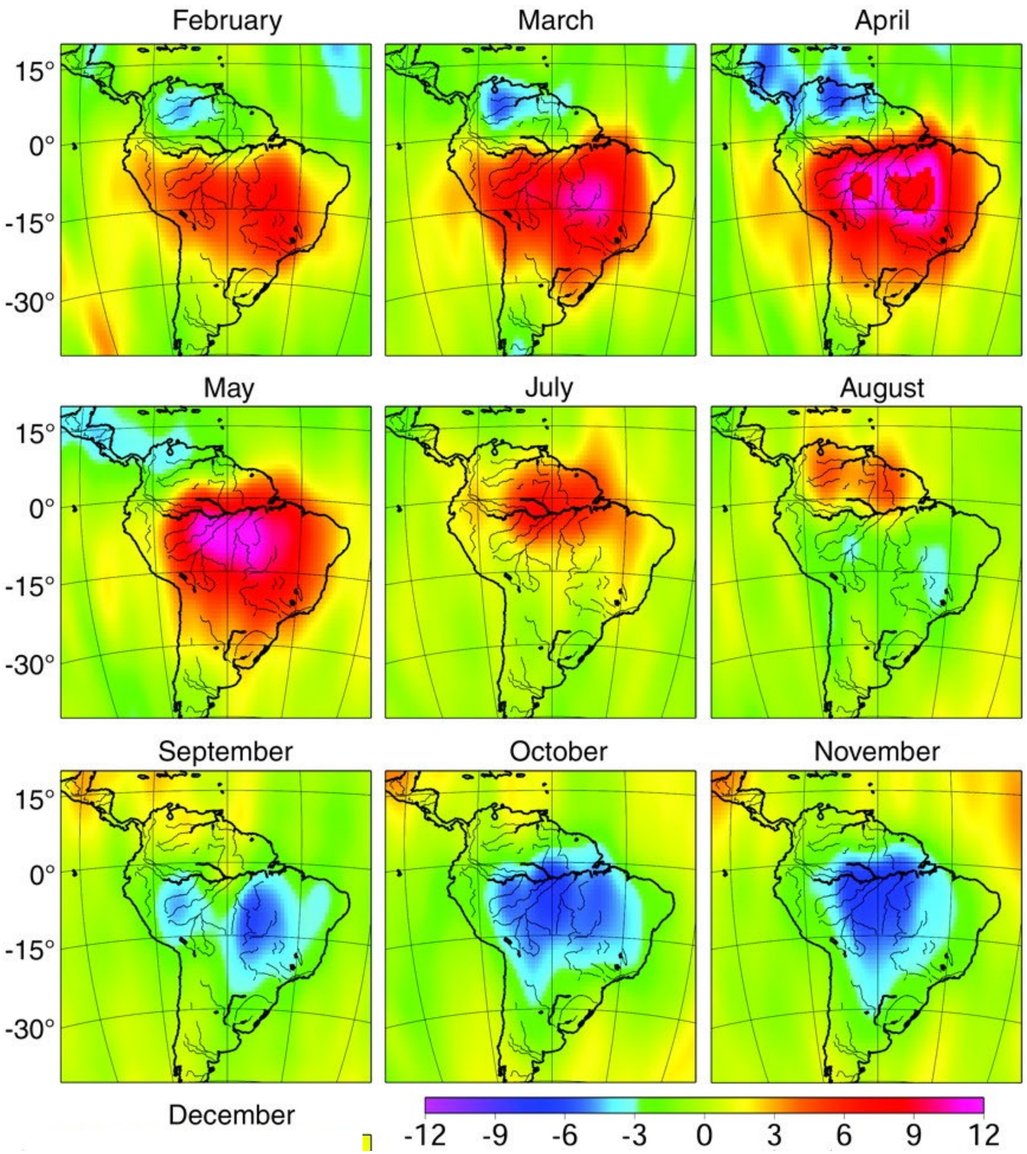
GRACE: Legacy of discoveries



GRACE: 15 Years of Amazing Discoveries

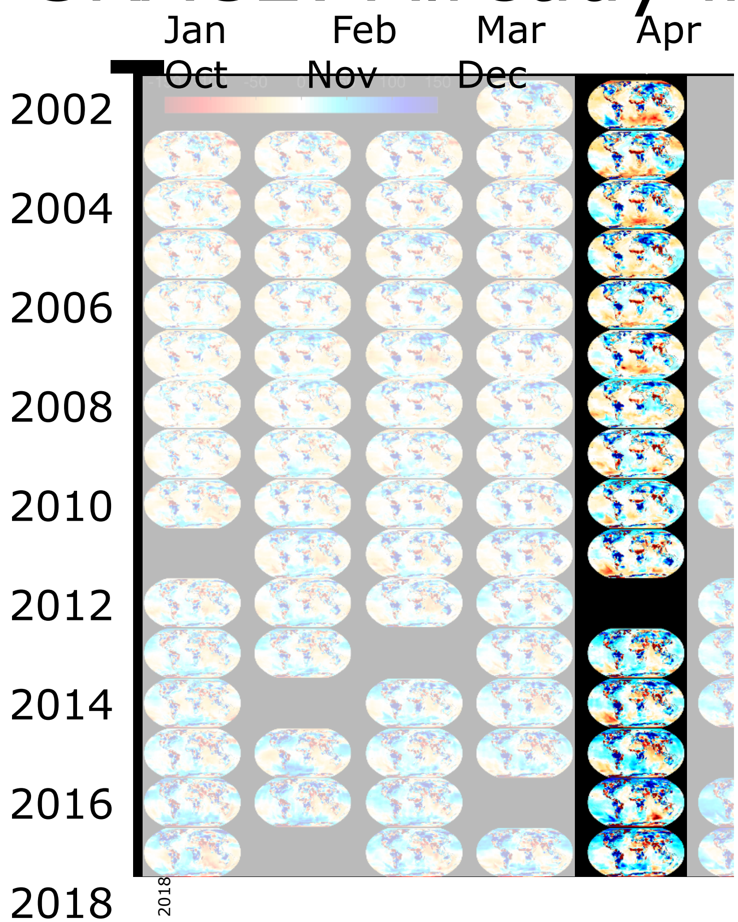


GRACE in the Amazon



Tapley et al., 2004

GRACE: Already in 2003 message clear



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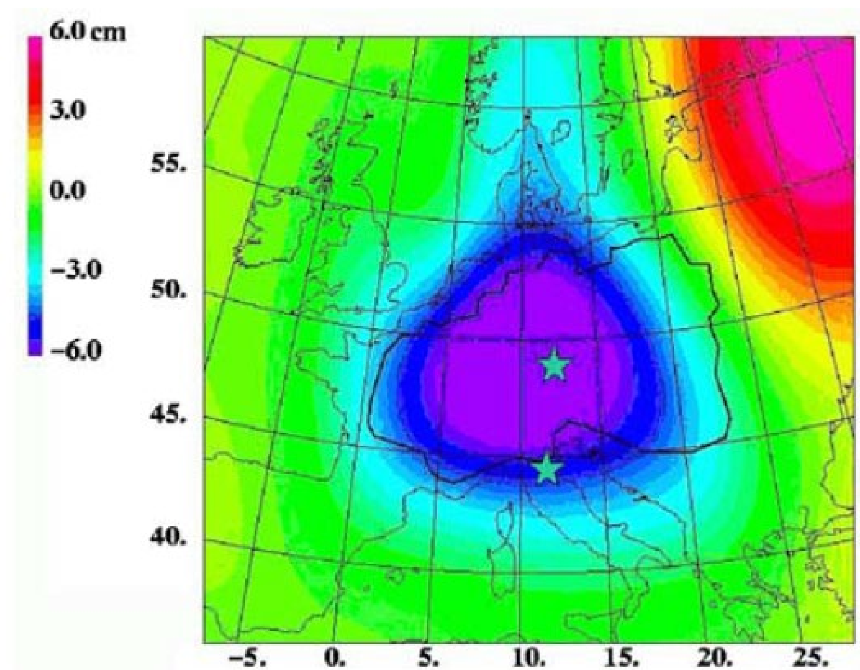
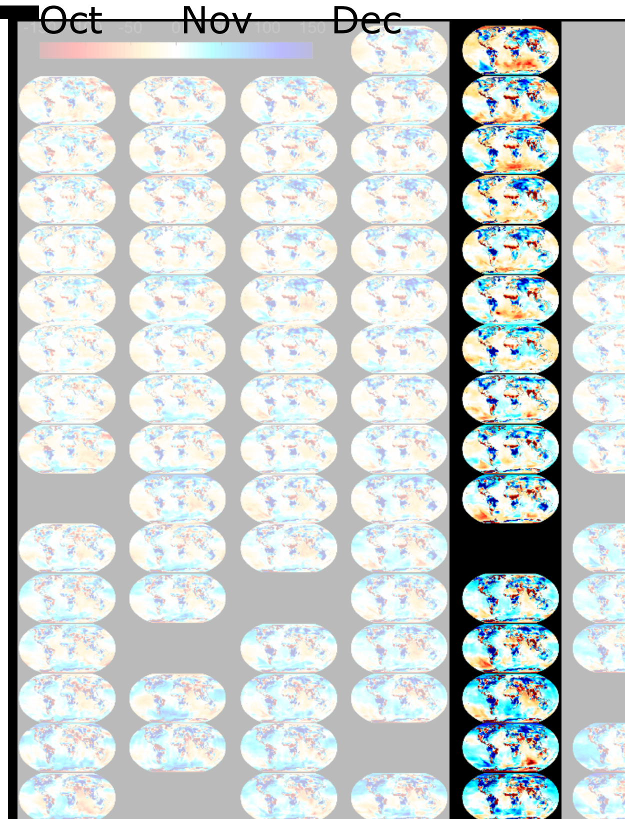
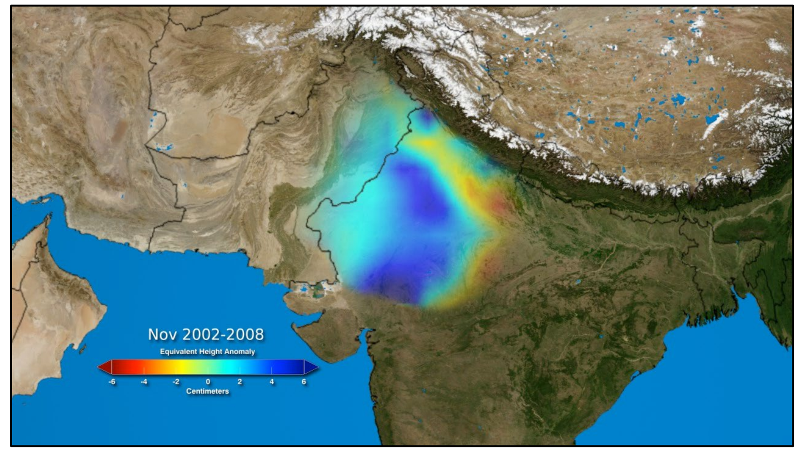


Figure 1. Linear inter-annual TWS trend in Europe from GRACE. Negative means less water in 2003 than 2002. The defined European drainage region is outlined in the figure along with the location of the Wettzell (Germany) and Medicina (Italy) superconducting gravity stations (stars).

GRACE: 15 Years of Amazing Discoveries

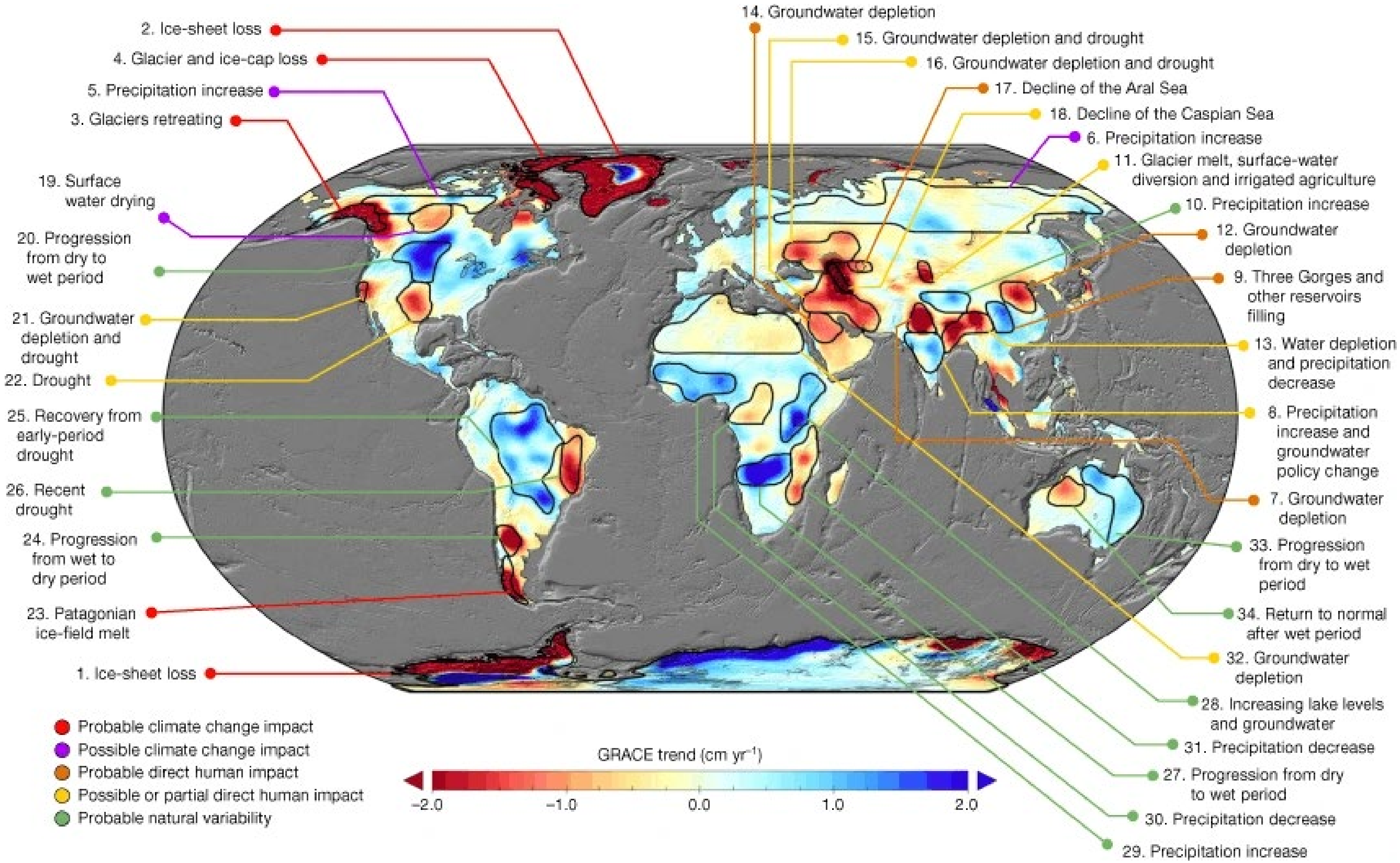


Long-term variations, trends & impacts

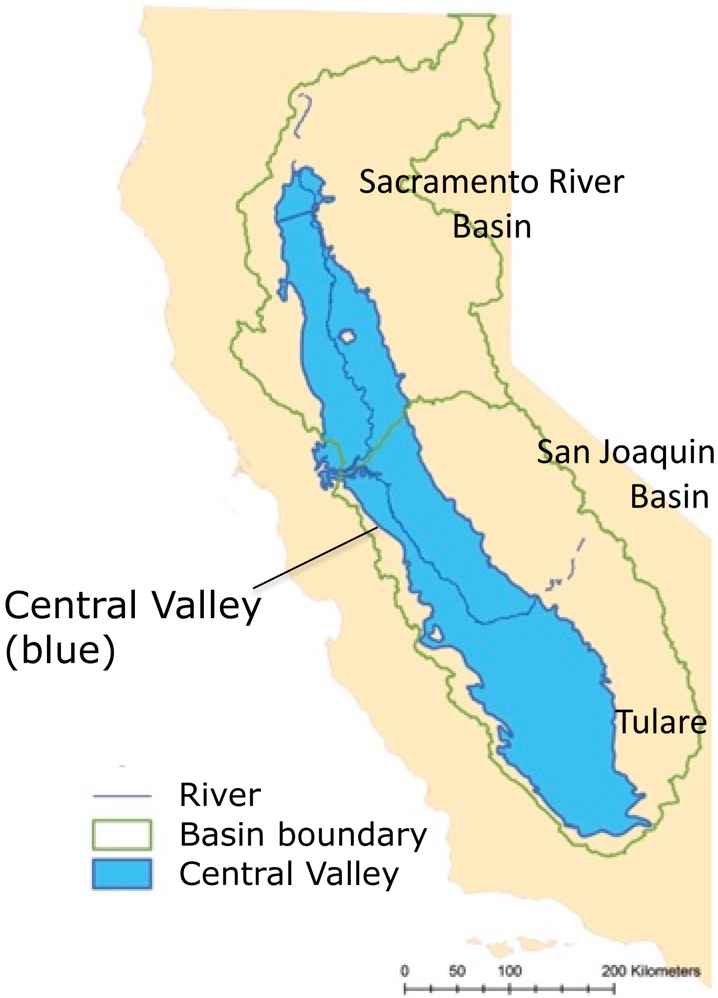


NW India Groundwater extraction

Global hydrological signals.



Local hydrological signals.
Groundwater depletion in California's Central Valley



Cover: Jay Famiglietti, NASA JPL, California Institute of
University of California, Irvine, after Famiglietti and Roc

EDITORIAL

Marcia McNutt, 2014

The drought you can't see

The Western Hemisphere is experiencing a drought of crisis proportions. In Central America, crops are failing, millions are in danger of starvation, and if the drought doesn't break soon, even vessels transiting the Panama Canal will need to lighten their loads, which will increase prices for goods transported globally. In the western United States, the drought-stricken region spans a vast area responsible for much of the nation's fruits, vegetables, and beef. As the drought's grip has tightened, water users have turned to tapping groundwater aquifers to make up the deficit for people, crops, livestock, and industry. But even when the rain does return, regreening the landscape and filling again the streams, lakes, and reservoirs, those aquifers will remain severely depleted. It is this underground drought we can't see that is enduring, worrisome, and in need of attention.

The Gravity Recovery And Climate Experiment (GRACE) satellites have provided a global look at groundwater depletion by monitoring small temporal changes in Earth's gravity field. GRACE confirmed massive losses of groundwater from the aquifer underlying California's agriculturally important Central Valley since the 1980s.* In the decade between 2003 and 2012, the drawdown was equivalent to the entire water storage volume of Lake Mead, the nation's largest surface reservoir.† The extraction of groundwater has caused wells to run dry and produced detectable regional uplift or rebound of the land due to water displacement (see Borsa *et al.*, p. 1587).

Underground reservoirs are a natural long-term water storage solution. Taking advantage of aquifers avoids the expense and environmental issues of dam construction. Unlike surface reservoirs, aquifers are not subject to evaporative loss, but under natural conditions they are only recharged slowly as excess precipitation percolates into the aquifer. In some cases, the average age of groundwater can be many thousands of years old, dating back to a time when the climate was wetter. But when water is withdrawn through pumping at prodigious rates, hydrologic processes are not sufficient to fully recharge the reservoirs, especially when land development has created impervious surfaces.

Forty years ago, the state of Arizona reached a critical juncture that called for action, with rapidly falling water tables, dry wells, subsiding land surface, and deteriorating water quality. Now, in the Tucson area for example, water from the Colorado River is used to artificially recharge the aquifers with excess water in wet years that can later be tapped during dry years. The statewide 1980 Groundwater Management Act guarantees that over a 10-year period, the aquifer cannot be overdrawn. The current crisis has prompted the legislature of California—the last state in the west without groundwater regulation—to pass a series of bills that establish state-level oversight of pumping from aquifers.

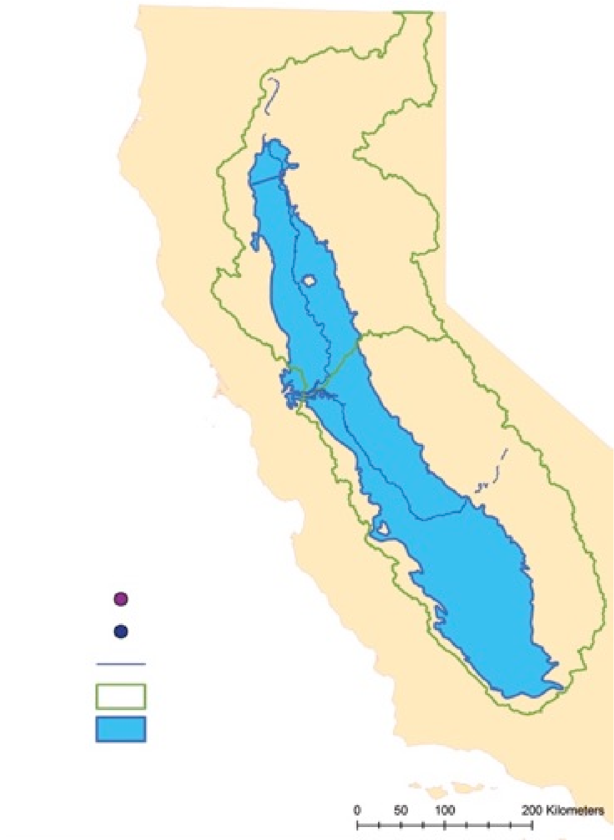
"It is high time we started managing our precious water supplies in harmony with the laws of nature."

Surface- and groundwater are all part of one coupled system, responding on different time scales to changes in precipitation. Five years ago when I was director of the U.S. Geological Survey (USGS), an Arizona congressman had some concerns about a USGS report on the impact of overpumping of groundwater on surface stream flows. The congressman declared, "You all should be aware that according to Arizona state law, surface water and groundwater flows are decoupled." Jim Leenhouts, the USGS associate director for the Arizona Water Science Center responded, without hesitation, "Thank you, congressman. Here at the USGS we follow the laws of nature, not the laws of man." It is high time we started managing our precious water supplies in harmony with the laws of nature.

– Marcia McNutt

*http://pubs.er.usgs.gov/publication/fs20093057. †J. S. Famiglietti, M. Rodell, *Science* **340**, 1300 (2013).

But if soil gets dry -> wildfires hard to control.



Gravity for Applications: Flood Forecasting

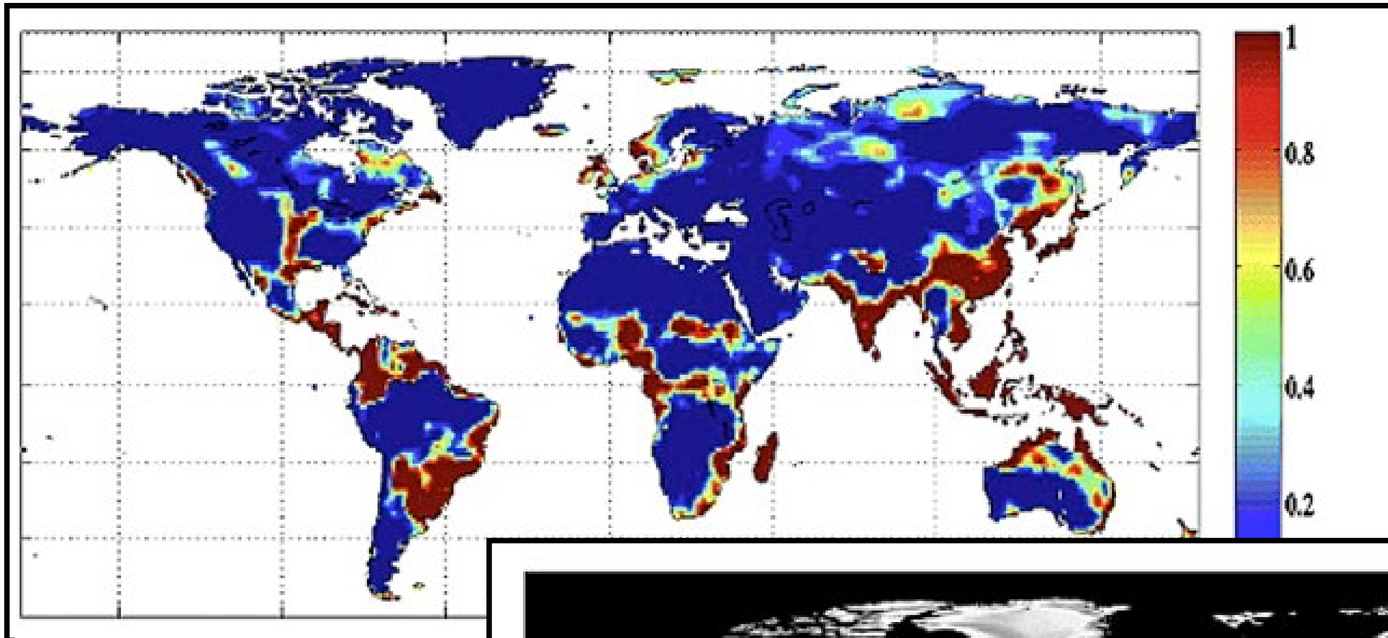
Is there an **indicator** that gives us an early warning sign for flooding?

Saturated soils

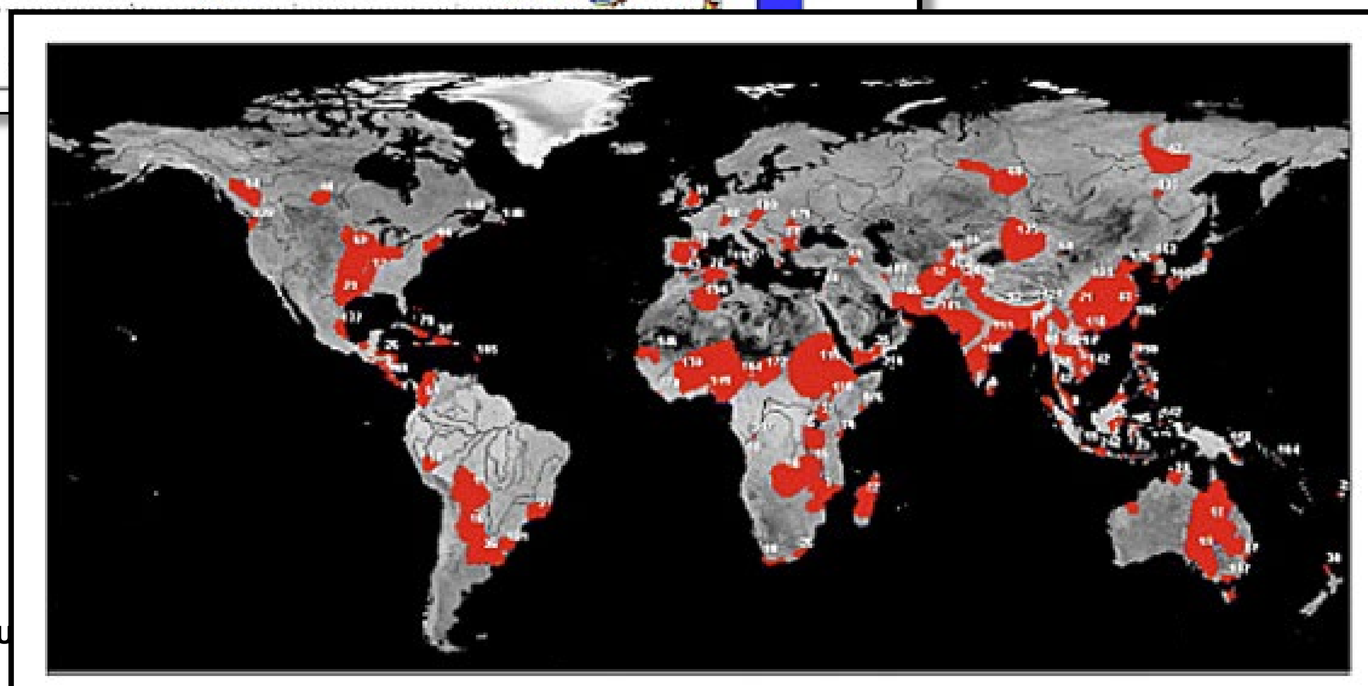
Danger of flooding

Goal: Flood indices for early warning before flood actually occurs

Gravity for Applications: Flood Forecasting



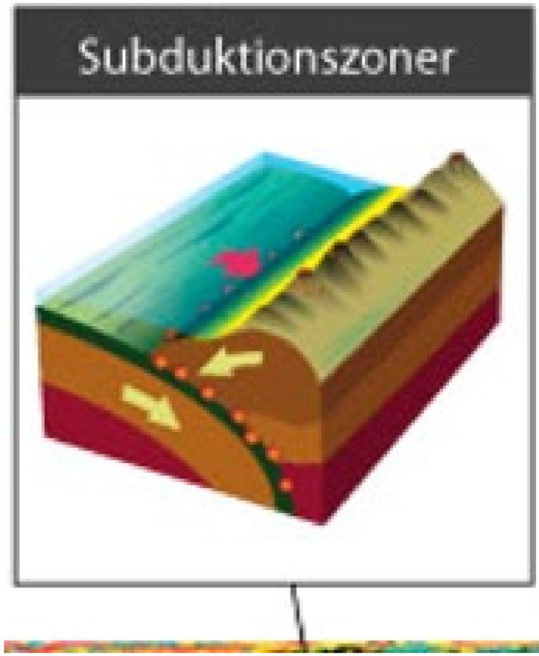
GRACE-derived flood index (May 2007)

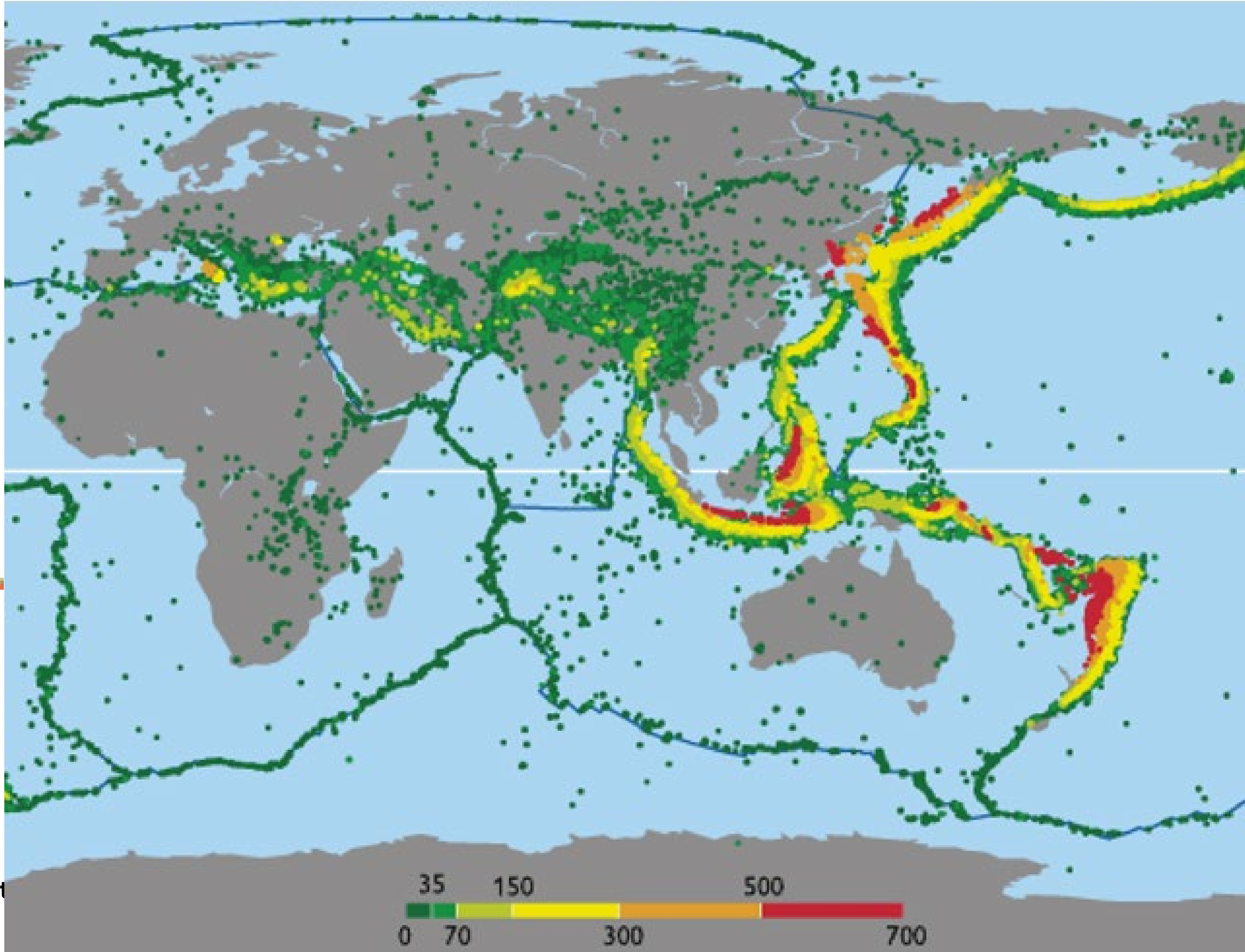


Floods that actually happened May 2007

Grace observes "Earthquakes"

Sumatra 2004 Earthquake where mass was shifted horizontally





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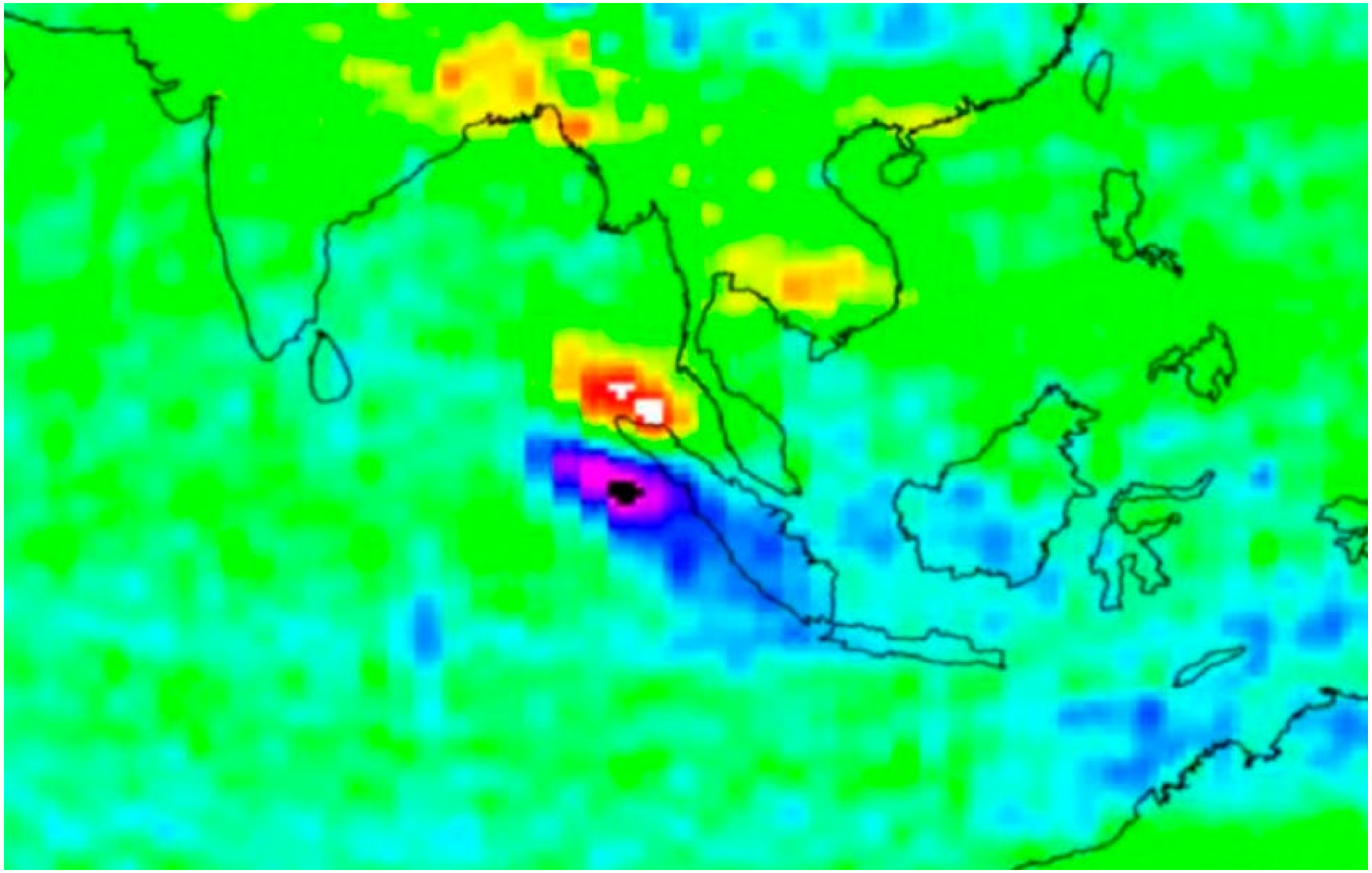

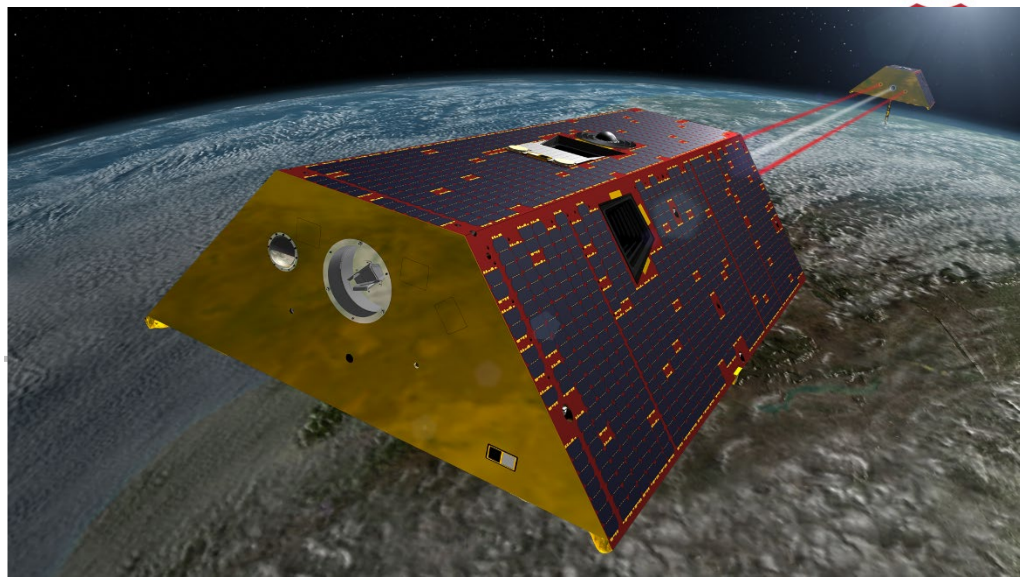

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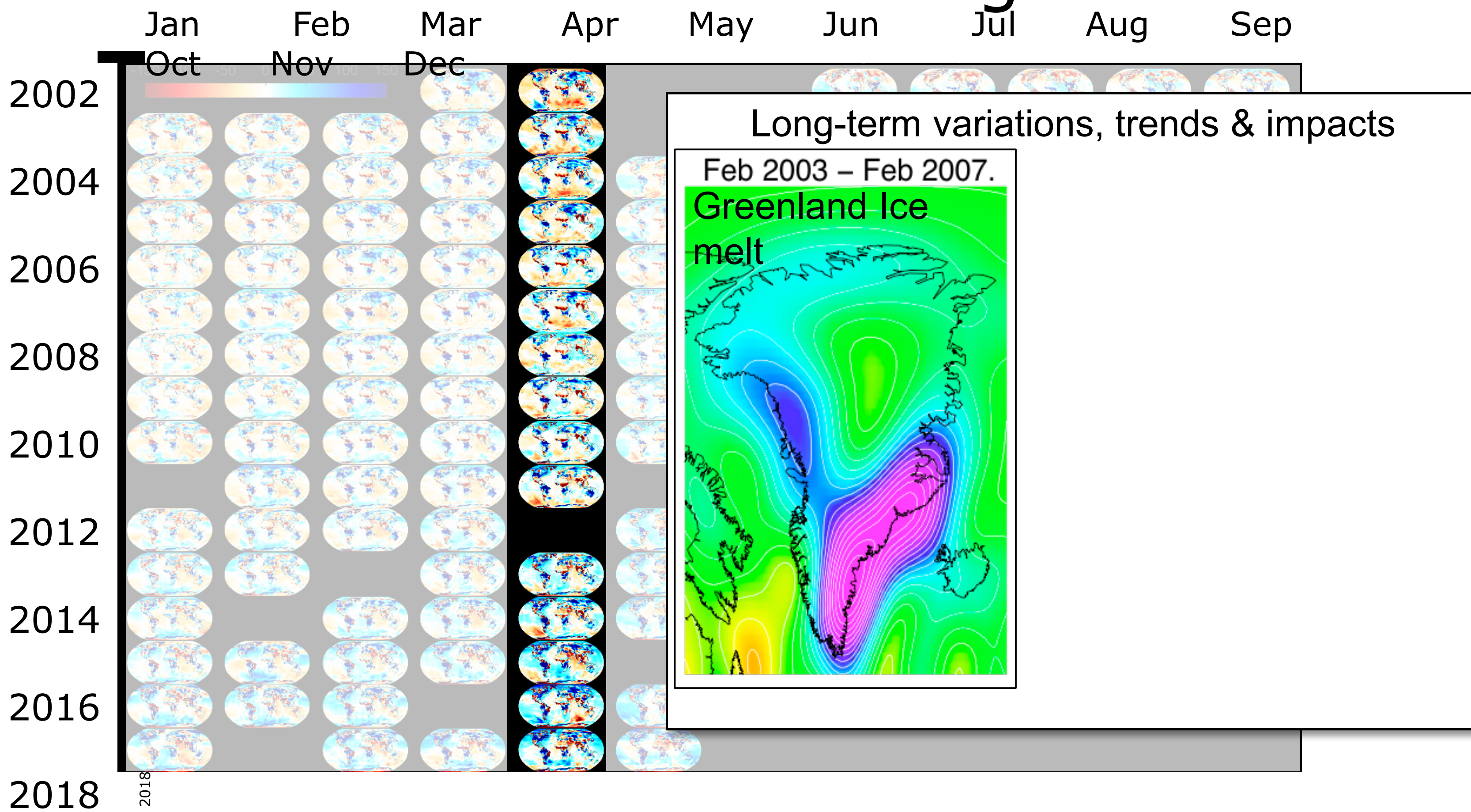
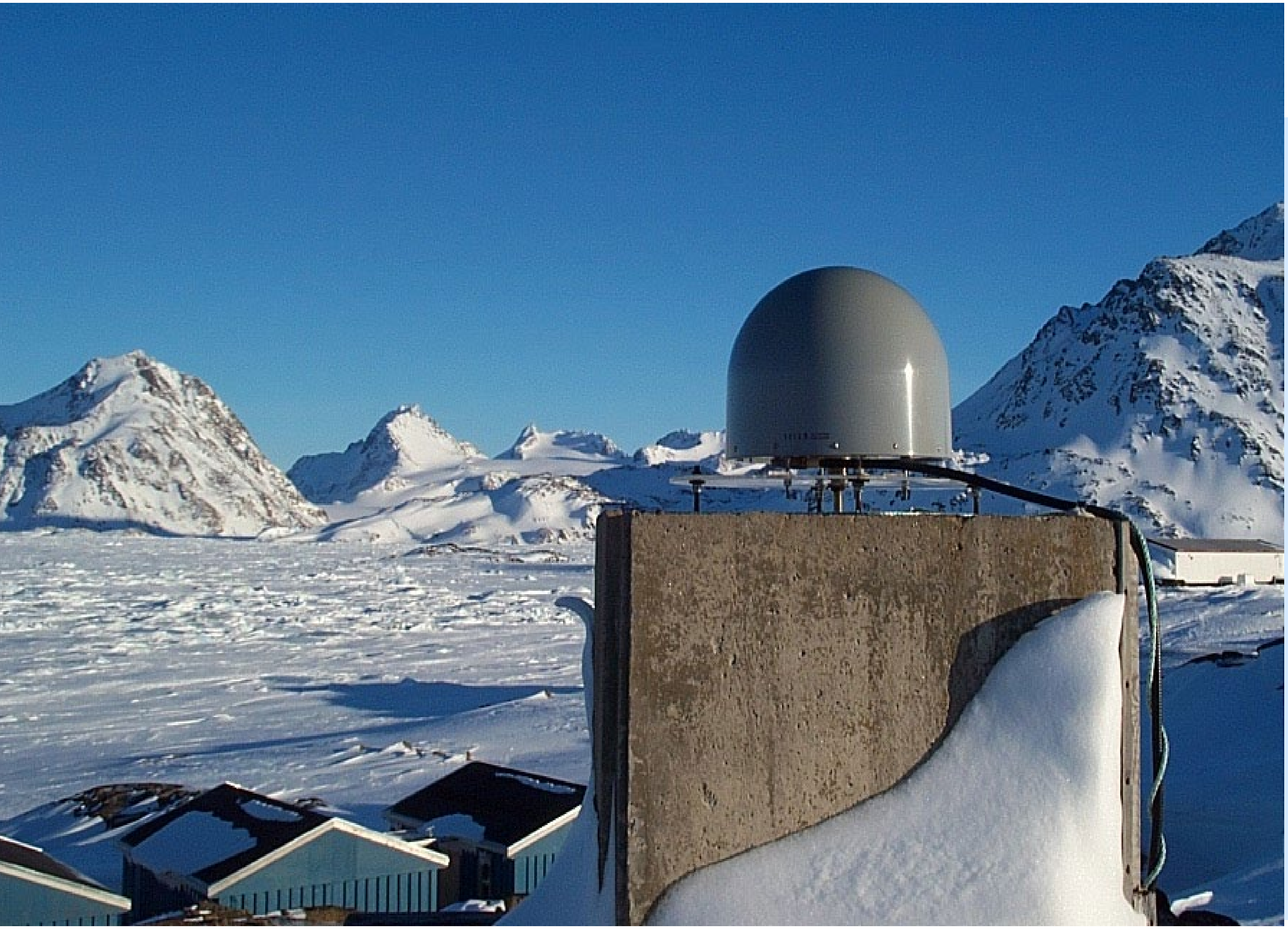
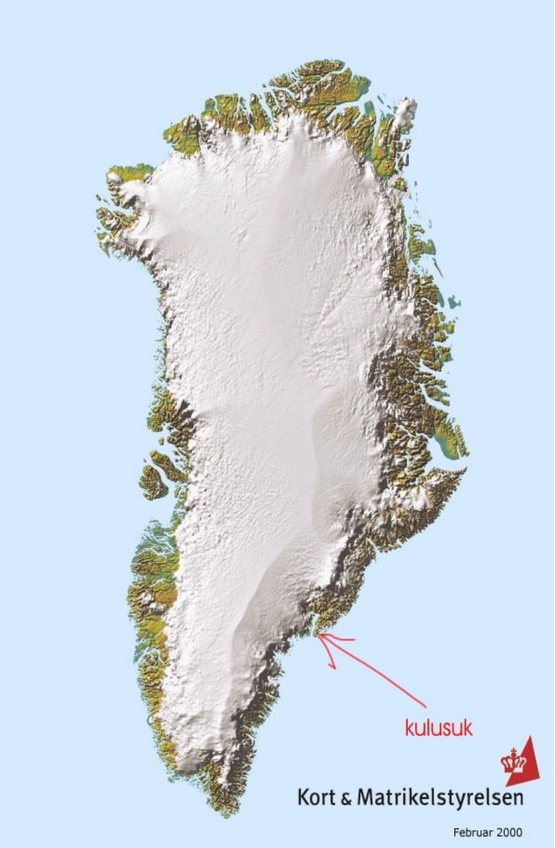
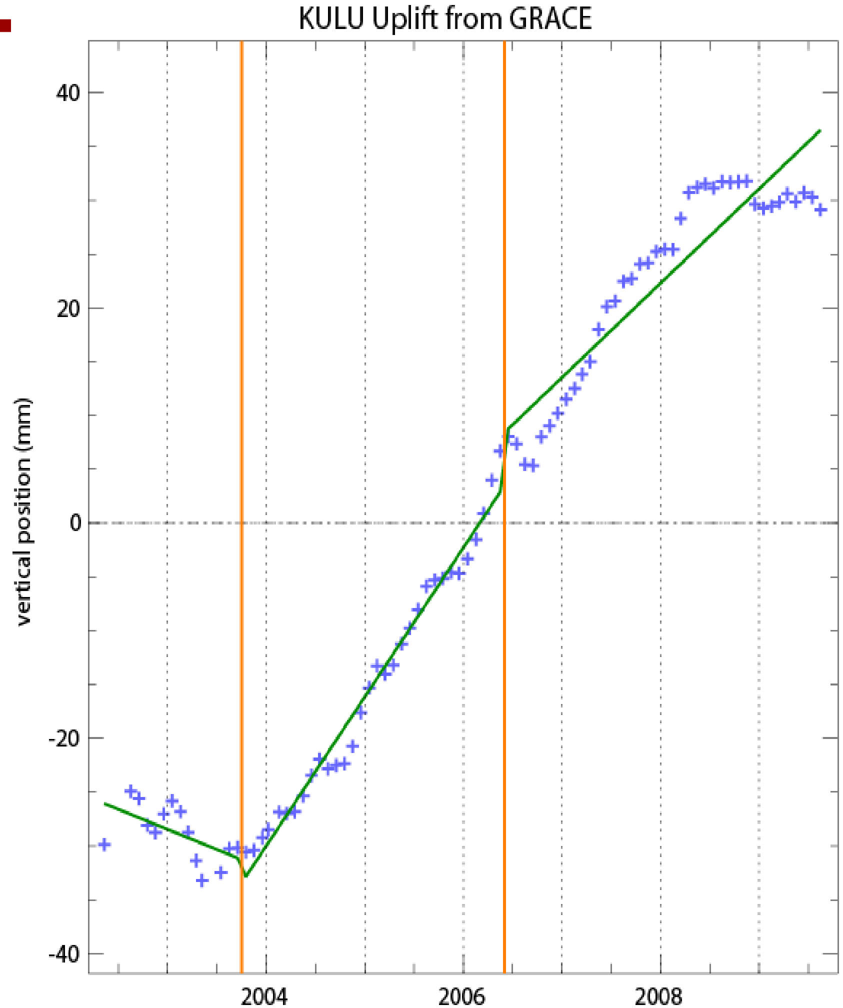


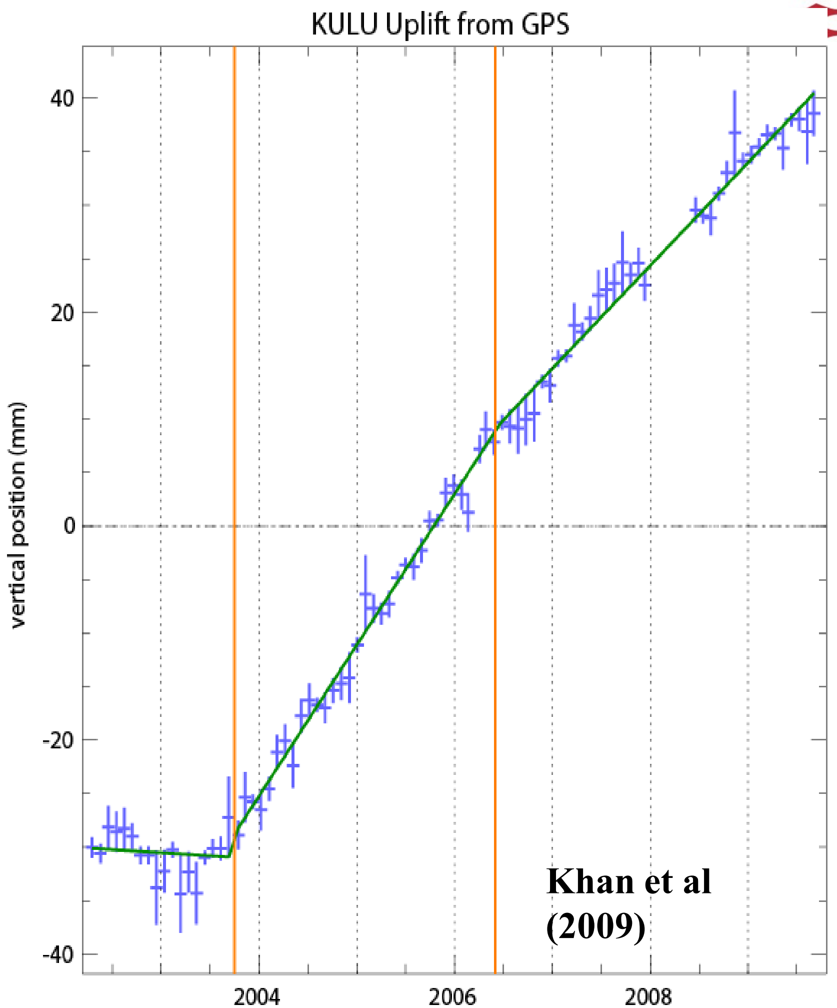
Present day Ice-unloading (PDIL / VLM Lecture)
Kulusuk GPS Site







Scaled GRACE predictions.



GPS observations

Both GRACE and GPS see a large increase in the trend in 2003/2004; and a smaller decrease in 2006/2007.

What is a GIGA TON of water.


Image Landsat / Copernicus
641 m
1995
Google Earth
40°46'29.10" N 74°03'19.11" W elev 2 m eye alt 1.98 km


400,000 Olympic
Swimming Pools
Image Landsat / Copernicus
Google Earth
641 m
1995

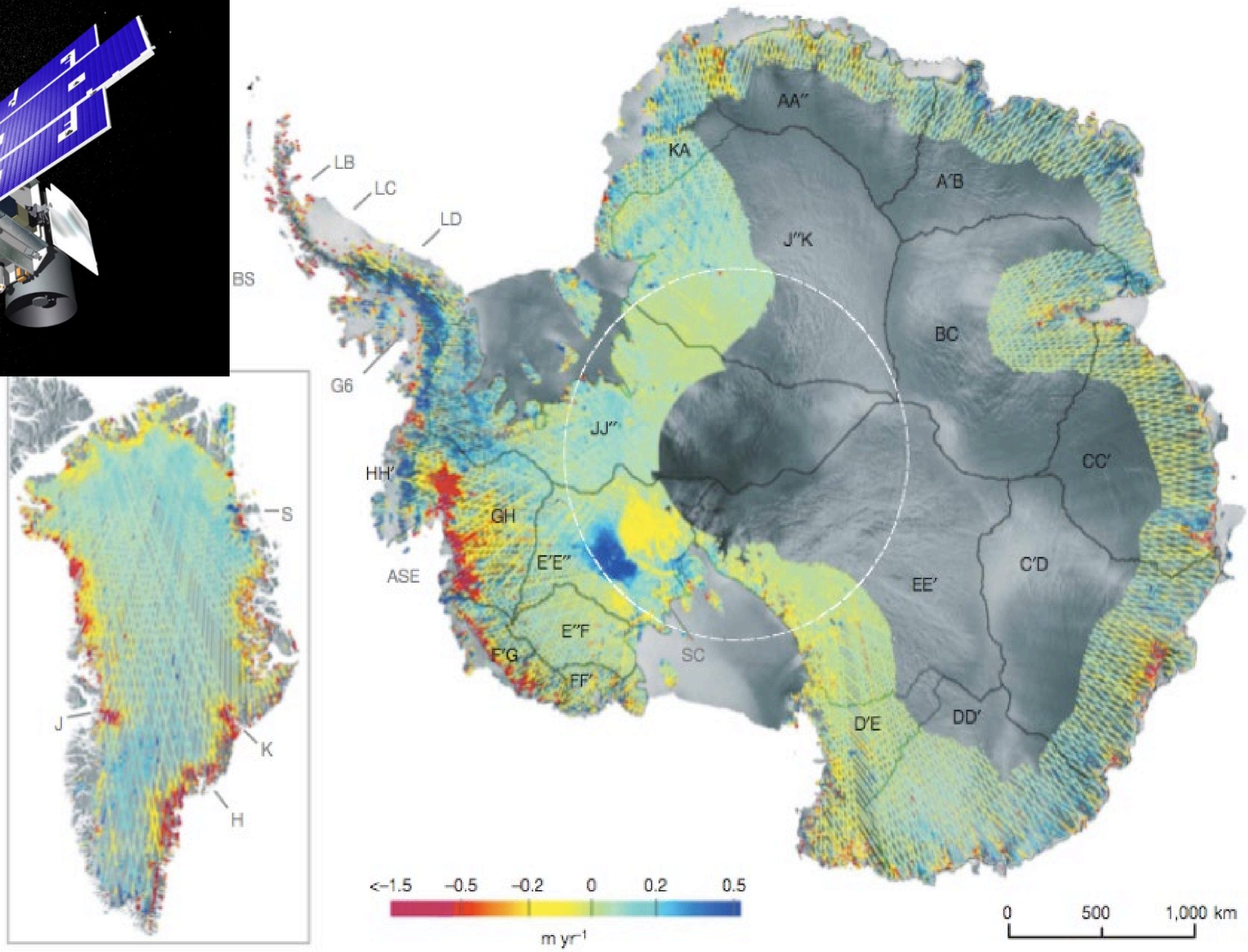
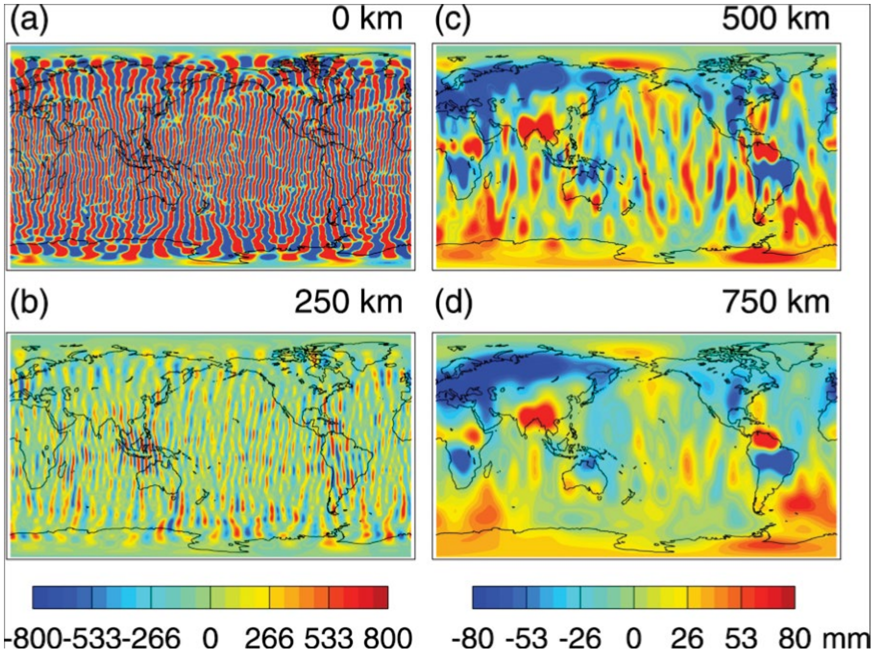


Figure 2 | Rate of change of surface elevation for Antarctica and Greenland. Change measurements are median filtered (10-km radius), spatially averaged (5-km radius) and gridded to 3 km, from intervals (Δt) of at least 365 d, over the period 2003–2007 (mean Δt is 728 d for Antarctica and 746 d for Greenland). East Antarctic data cropped to 2,500-m altitude. White dashed line (at 81.5° S) shows southern limit of radar altimetry measurements. Labels are for sites and drainage sectors (see text).

[Pritchard et al., 2009]

What limits GRACE?



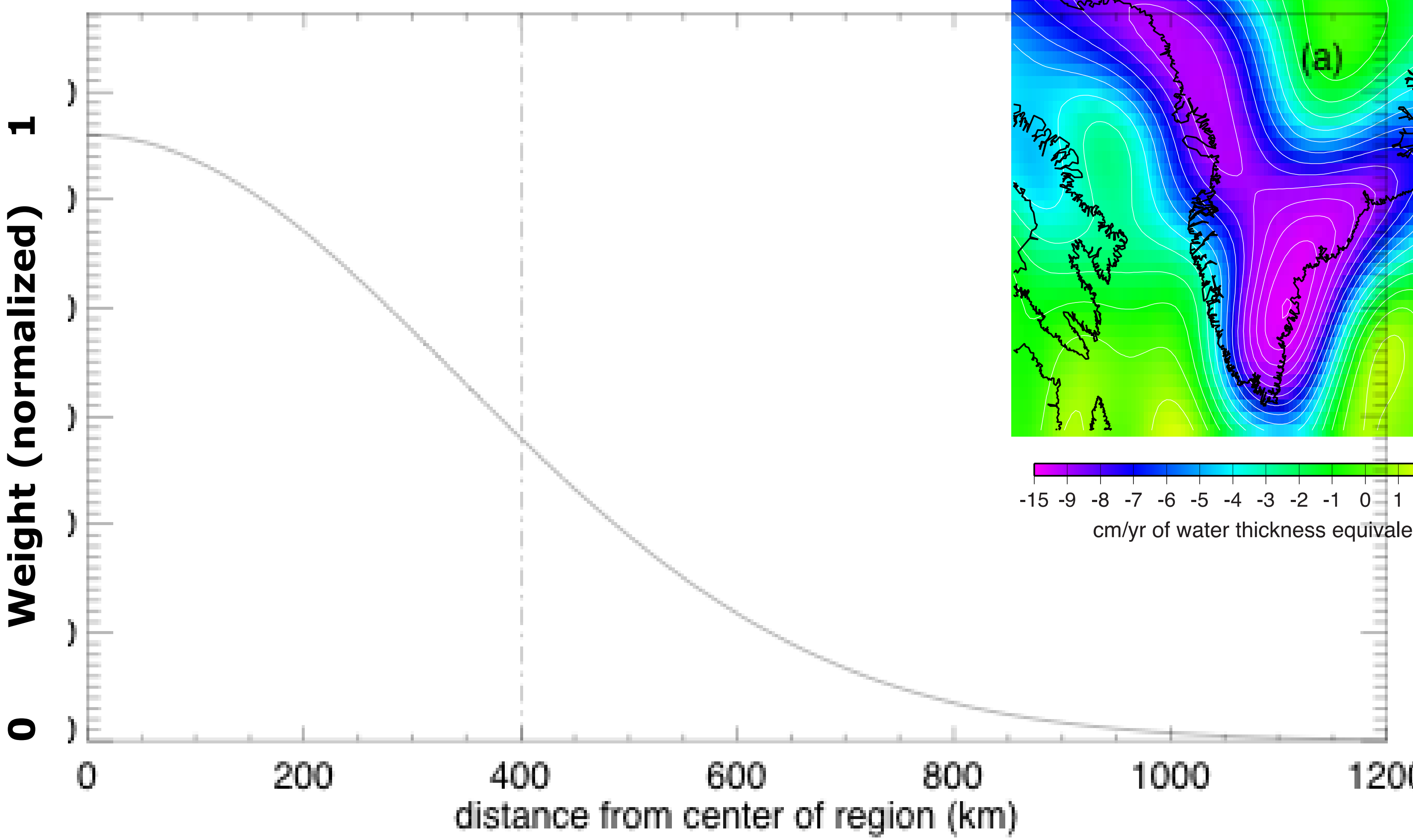
- **North South flying.**

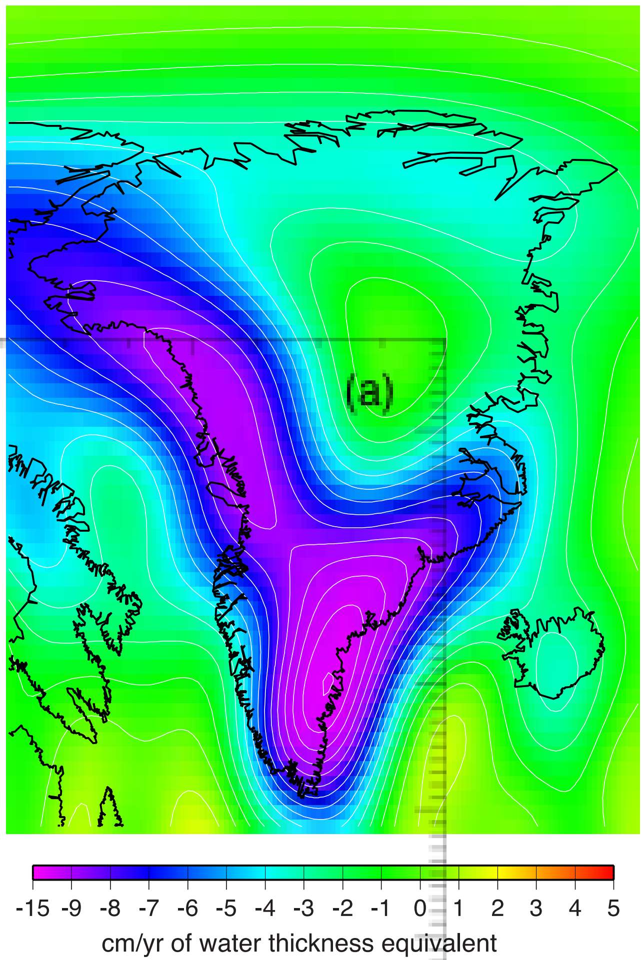
- Gaussian or more advanced filtering
- (called destribing).

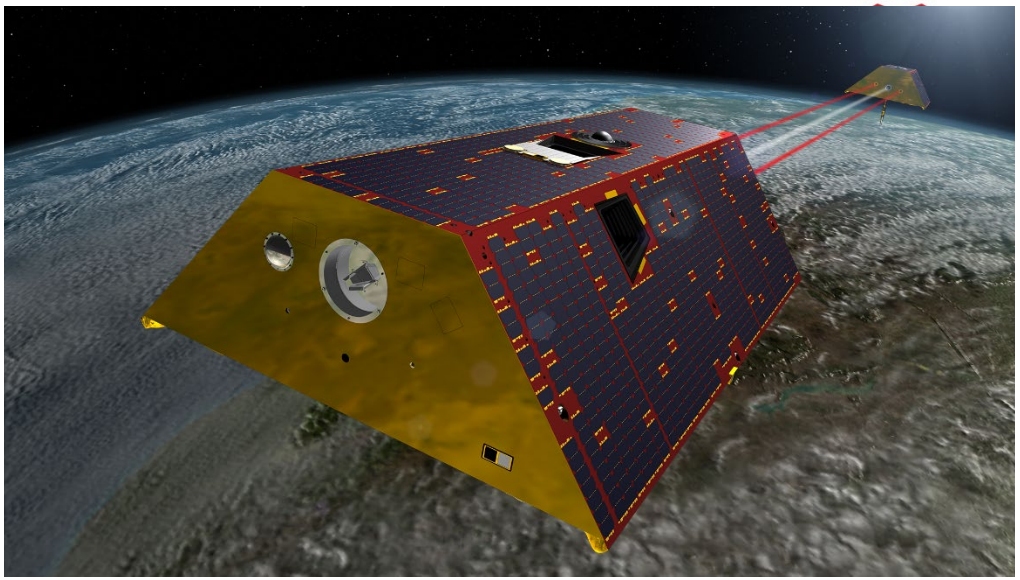
- **Instrumentation:**
- GRACE is limited at low frequencies by the accelerometer errors and at high frequency by the microwave phase noise. Also limited by orbit sampling in space and time.

- To get improved spatial resolution from space:
  - Must decrease phase noise, probably by moving from a microwave to an optical instrument
  - Should improve accelerometer as well for best performance
  - Flying at a lower altitude also is needed to improve performance
  - Fly multiple missions simultaneously?

Spatial filtering issues







Content

Repetition from last time:

GRACE satellite tracking and gravity.

Monthly solution (filtering limitations)

Mass movements in the Earth System

The water cycle

Equivalent water height

GRACE month fields.

GRACE discoveries.

Annual, Hydrology

Droughts and Earthquakes

Melting of the Ice caps + glaciers.

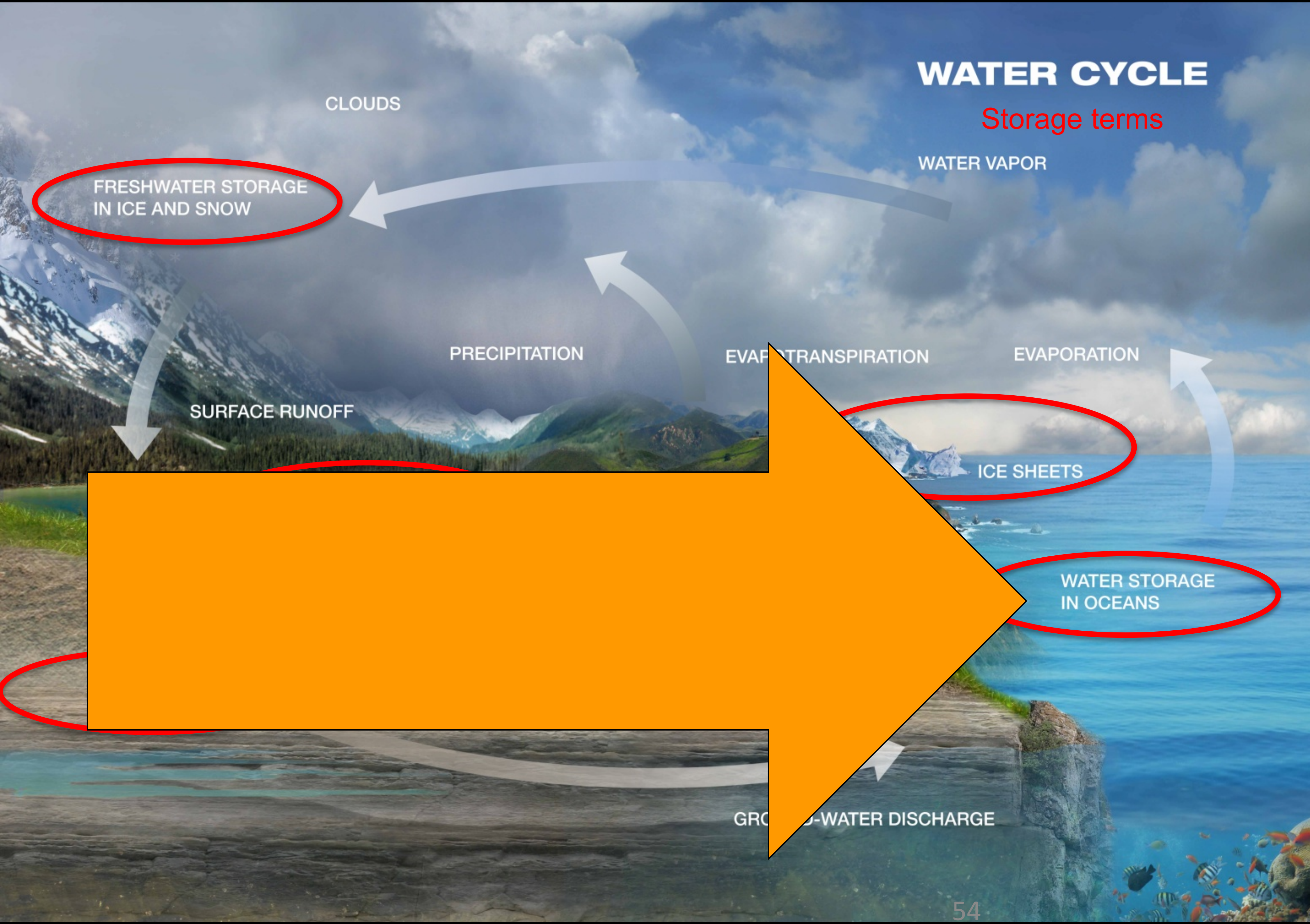
Grace limitations…

Sea level rise and closing the sea level budget.

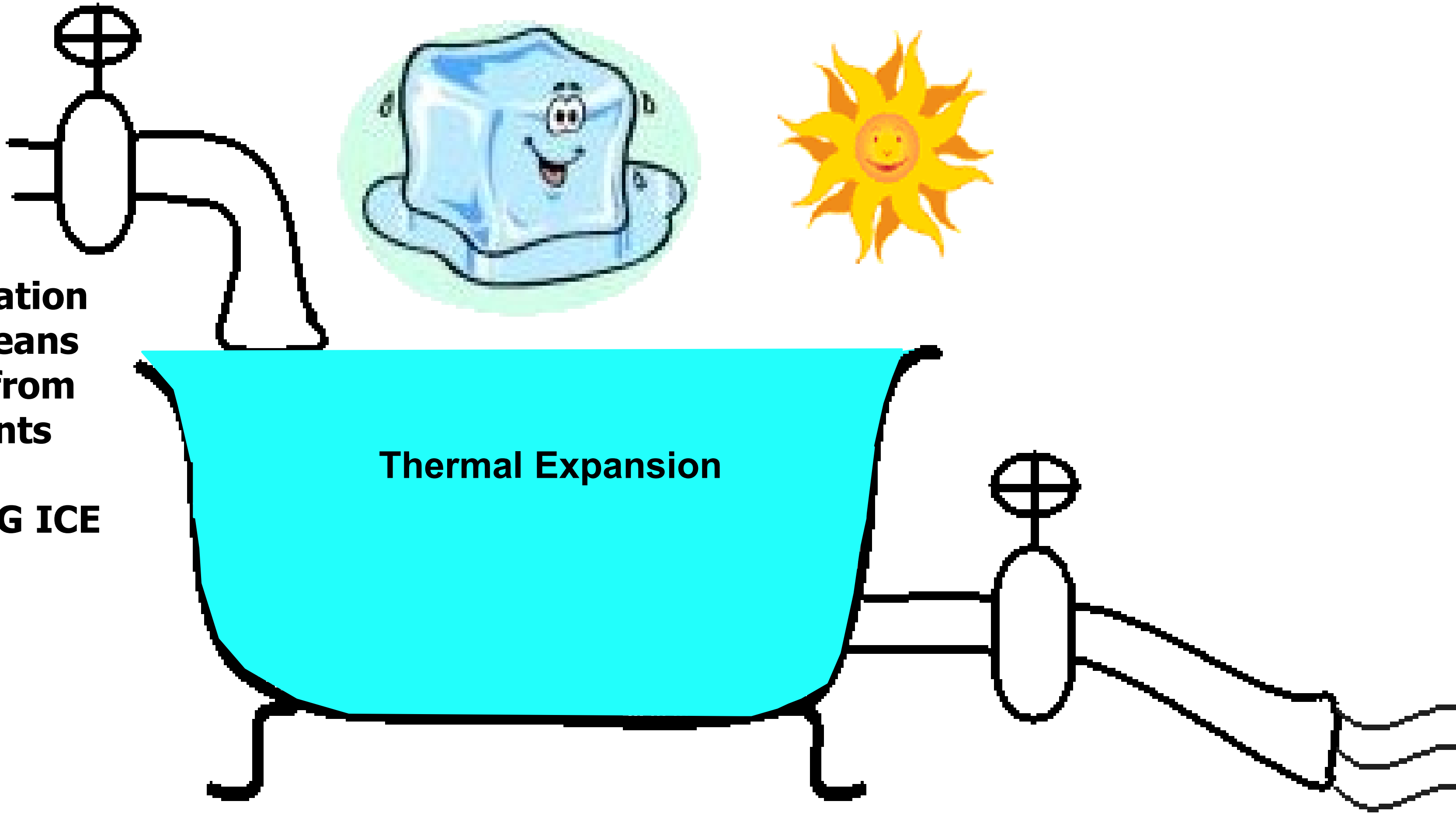
Mass changes

Steric changes

The end +

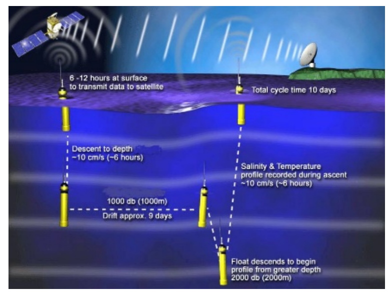

WATER CYCLE
Storage terms
CLOUDS
WATER VAPOR
FRESHWATER STORAGE IN ICE AND SNOW
PRECIPITATION
EVAPORATION
SURFACE RUNOFF
ICE SHEETS
WATER STORAGE IN OCEANS

Why does sea level change?
The Bathtub Model

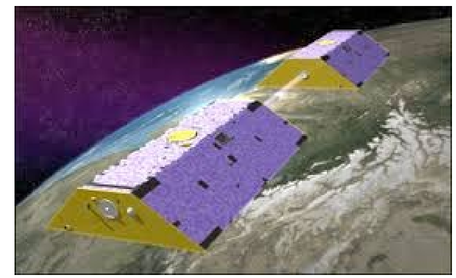


$$\Delta SLR_{total} = \Delta SLR_{steric} + \Delta SLR_{mass}$$

Jason-1&2, T/P,
Envisat (1993 - …)



Argo
(~2004 - …)



GRACE (2002-…)
GRACE-FO (2018 …)

↓ ↓ ↓

$$\Delta SLR_{total} = \Delta SLR_{steric(0\text{-}2000m)} + \Delta SLR_{mass}$$

Greenland Ice Mass Changes from GRACE

April, 2002 – June, 2010

Rate of Ice mass change:

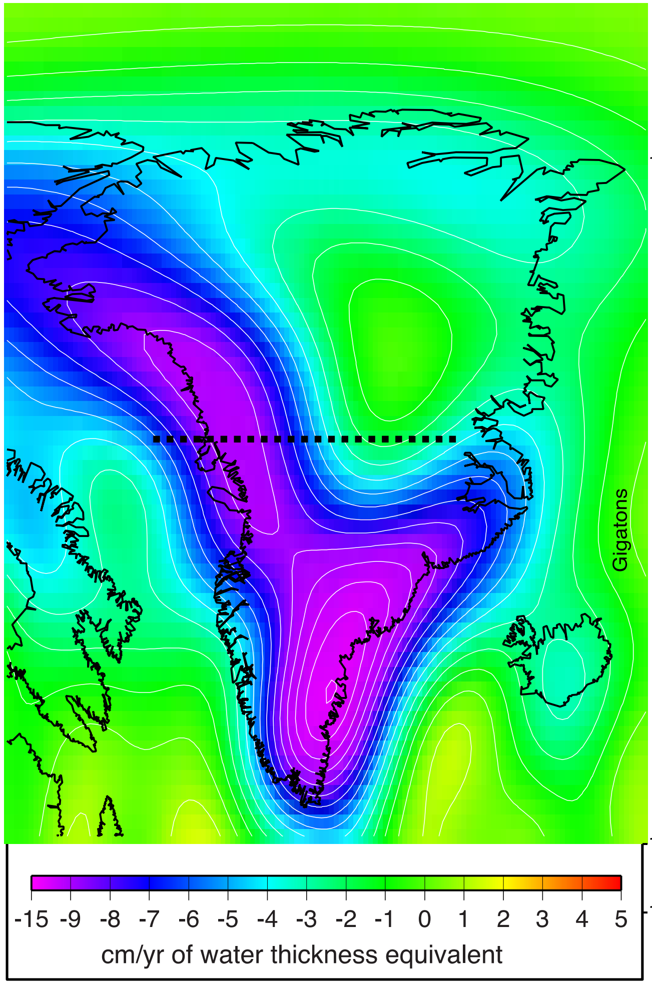
All Greenland: -239 Gt/yr

South Greenland: -162 Gt/yr

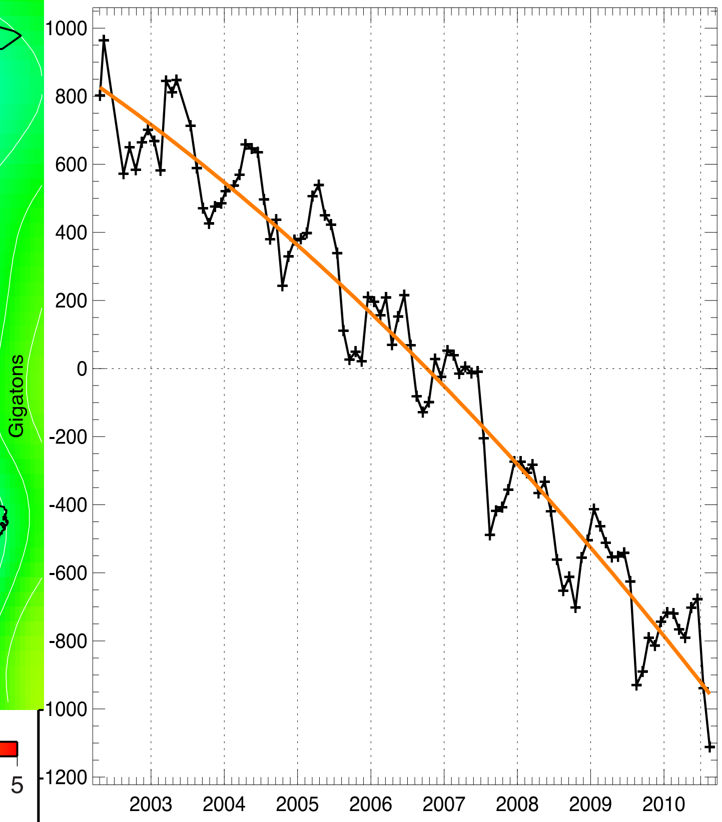
North Greenland: -77 Gt/yr

(1 Gton = 1 km^3 of water)

Greenland contributed 0.8 mm/y to sea level rise



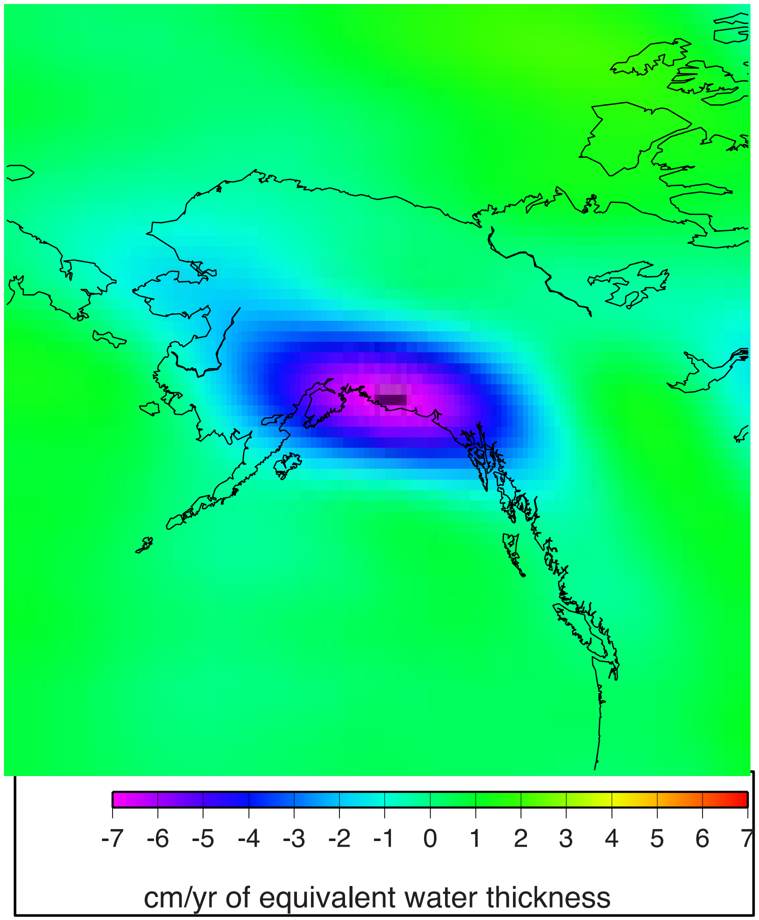
Total Greenland ice volume

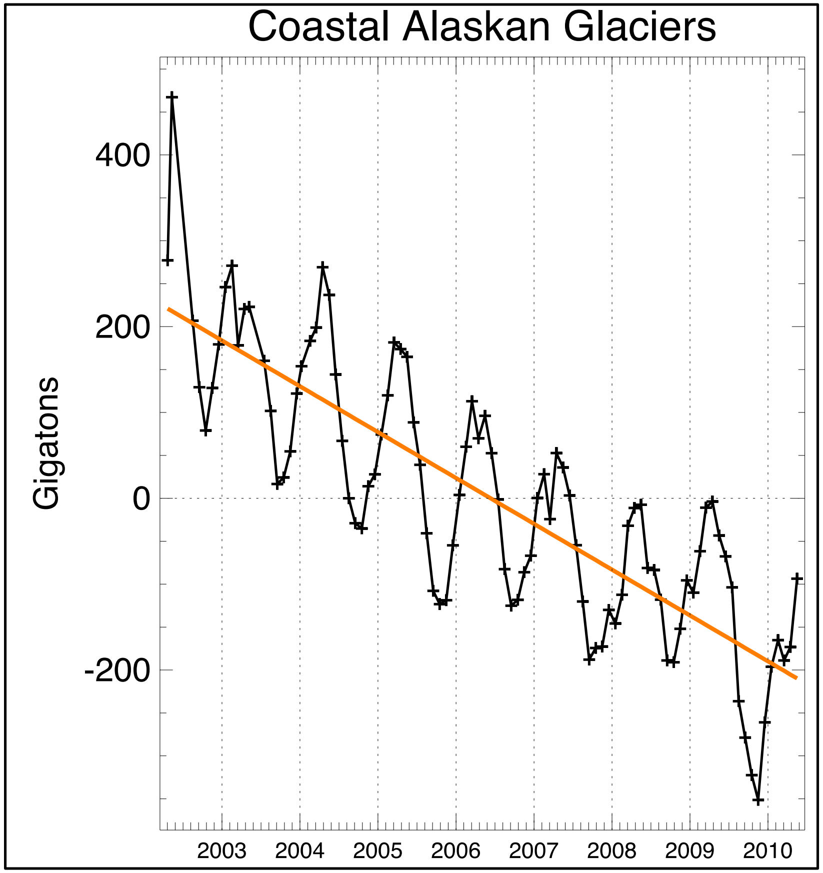


[Wahr, 2010]

Alaskan Glaciers from GRACE

Rate of mass change between April, 2002 and May, 2010

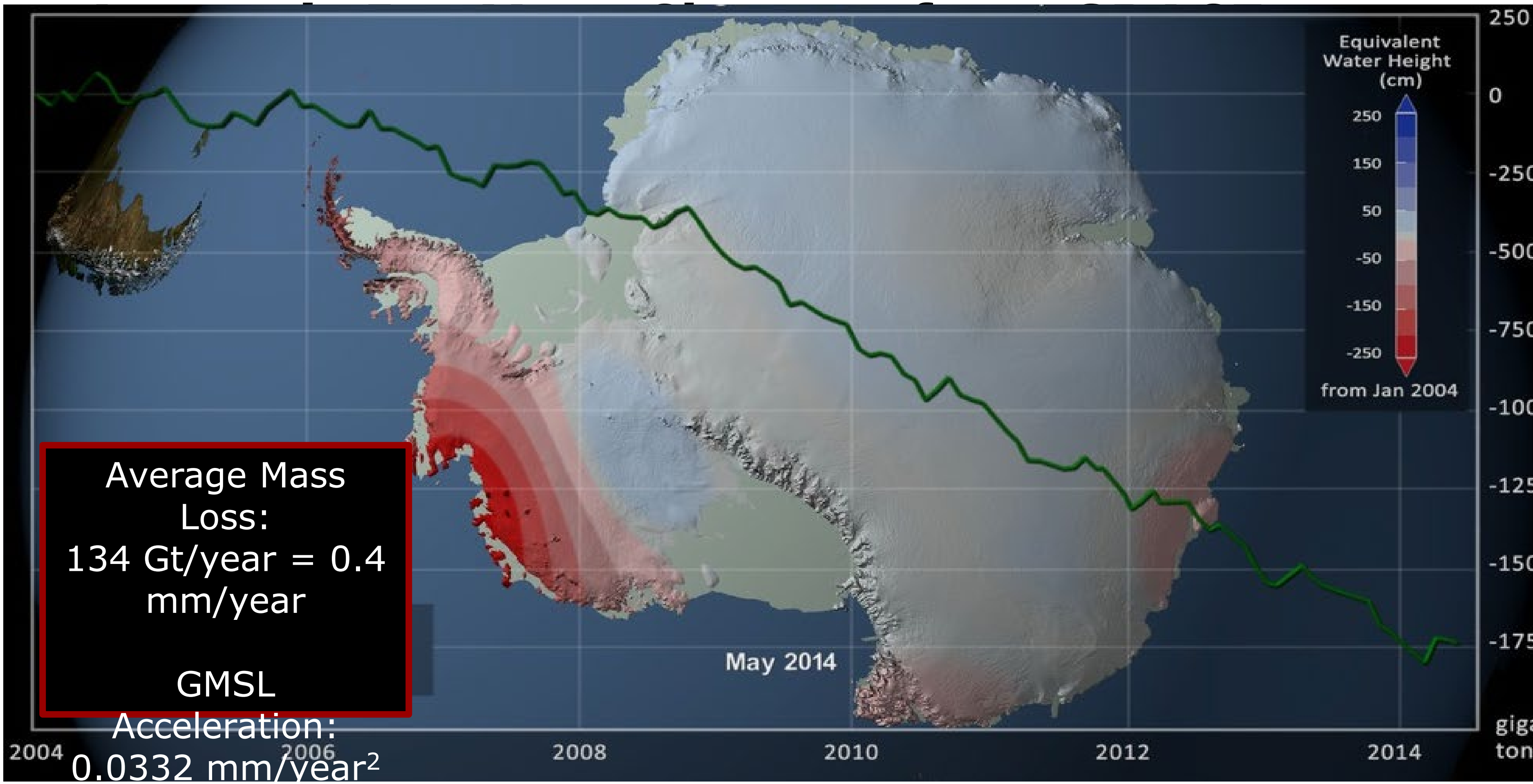




Rate of mass change: -55 Gton/yr = 0.15 mm/yr sea level rise

•

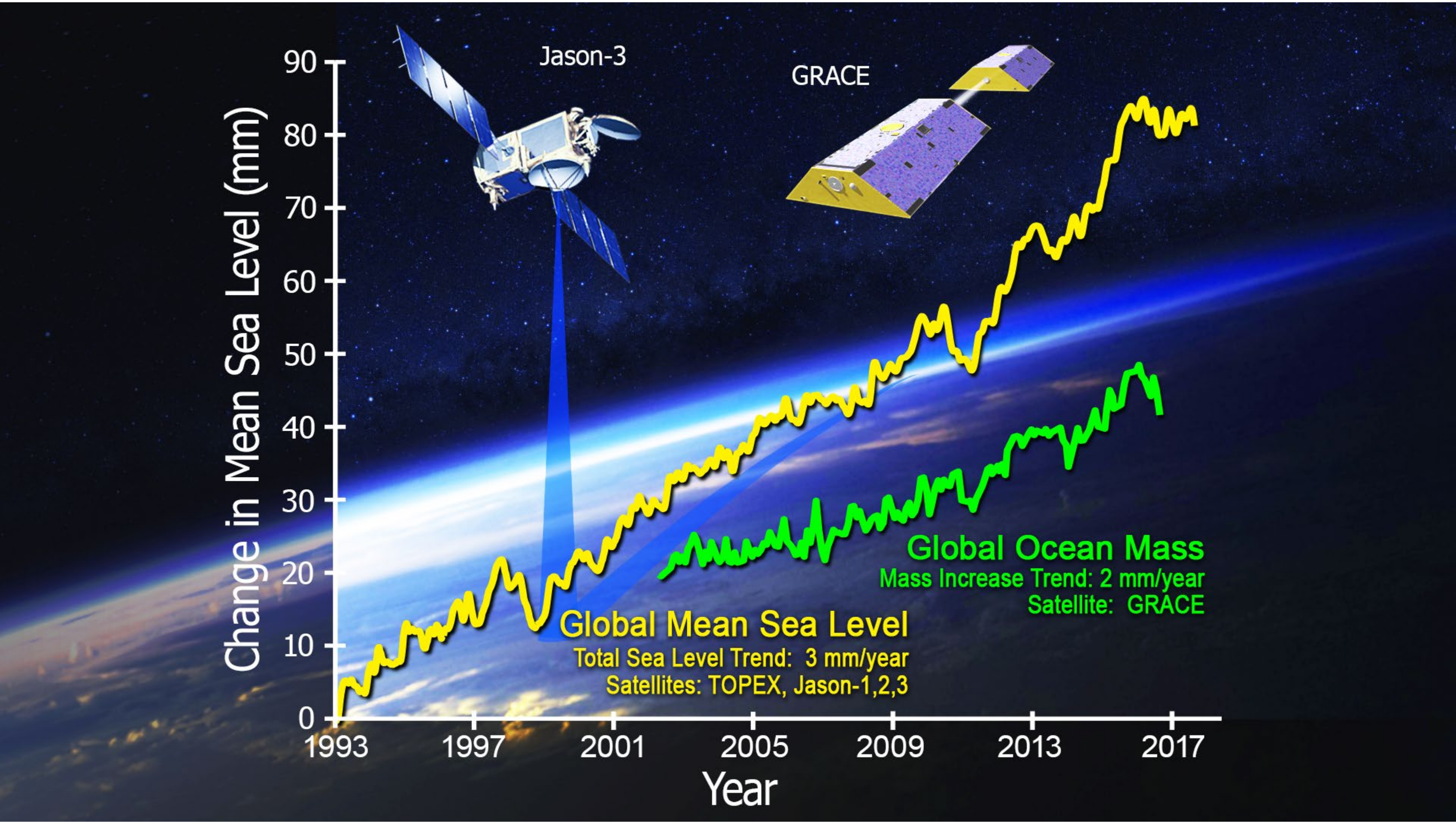
[Wahr, 2010]

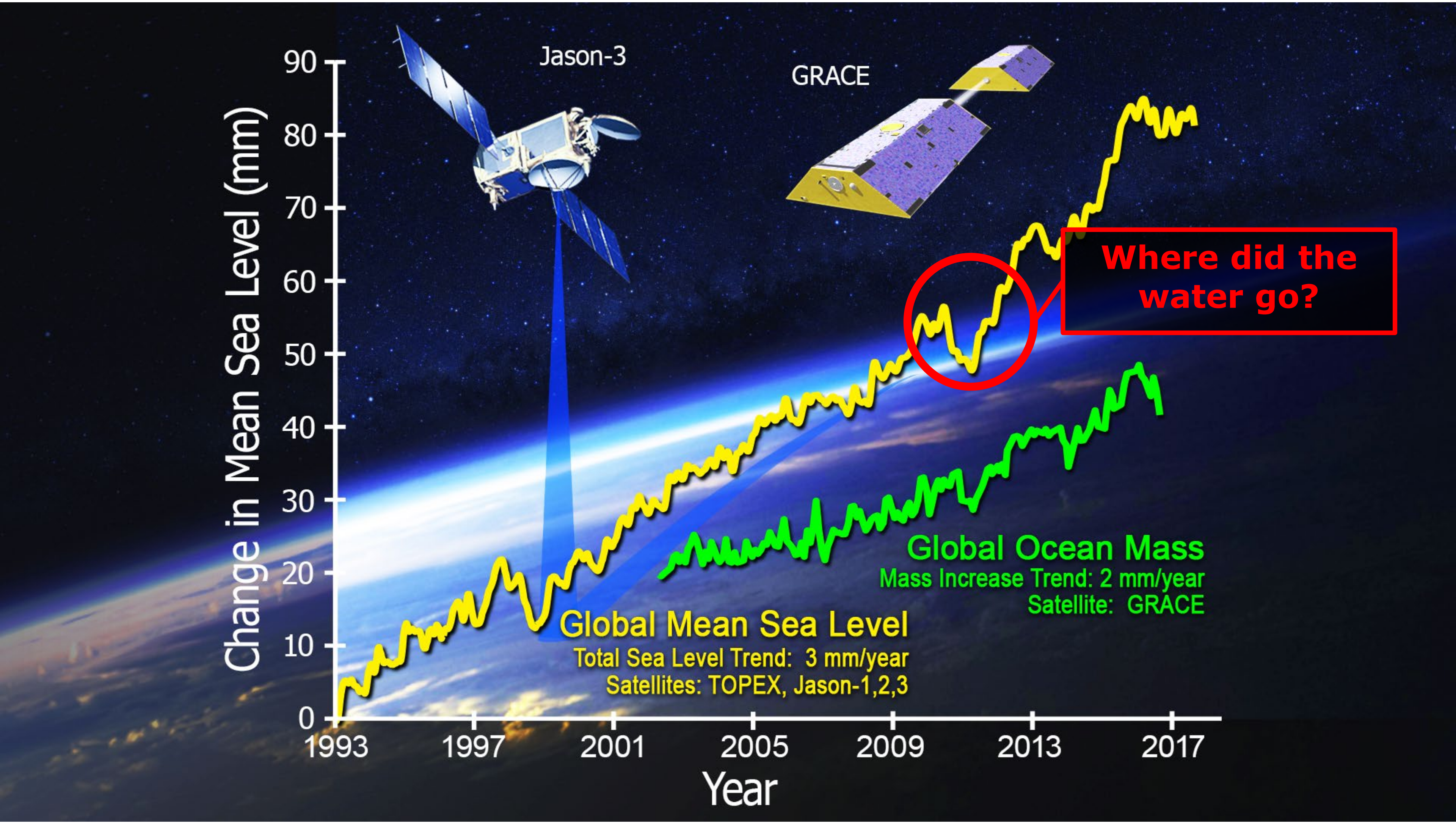


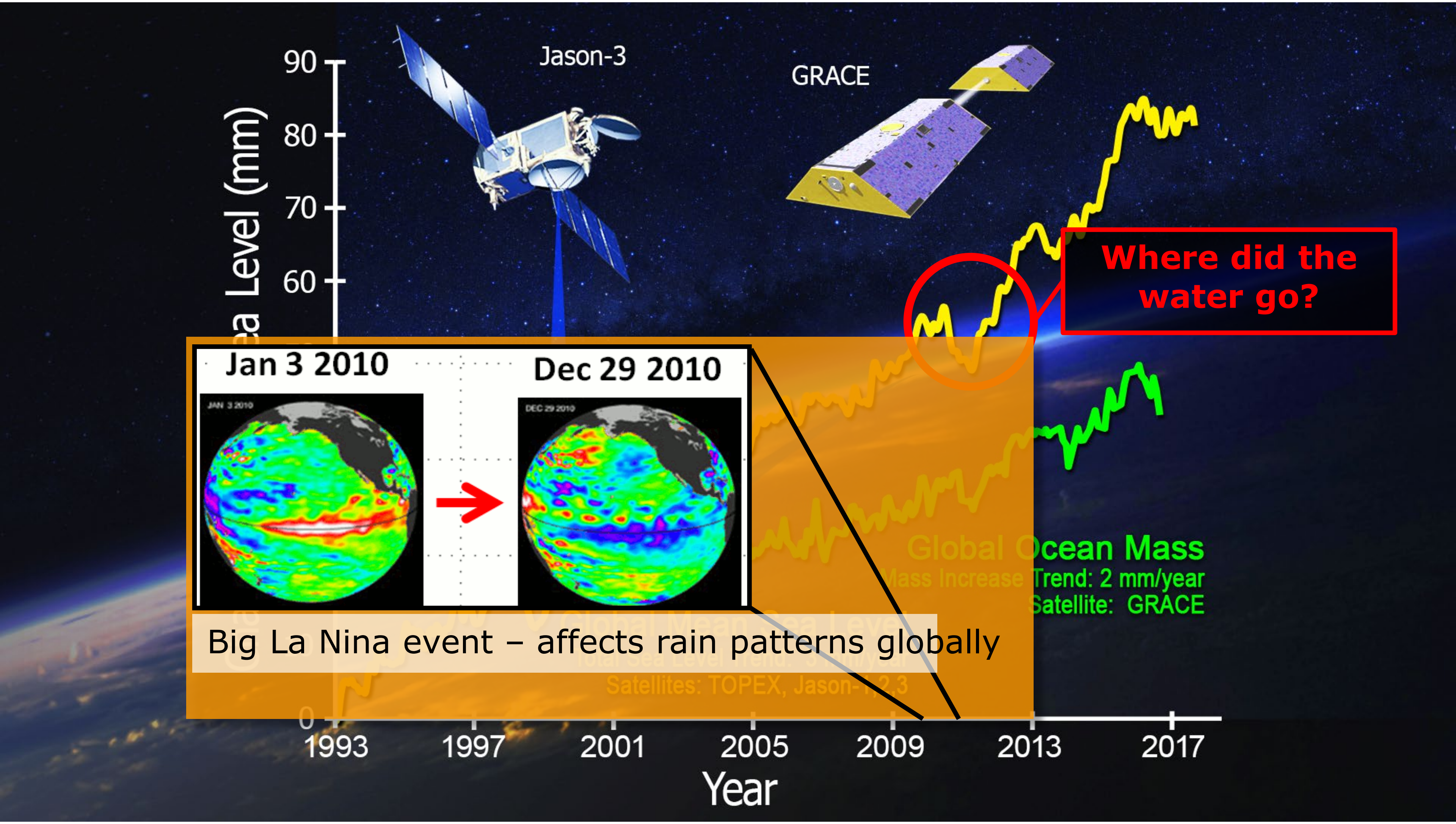
Average Mass Loss:
134 Gt/year = 0.4 mm/year

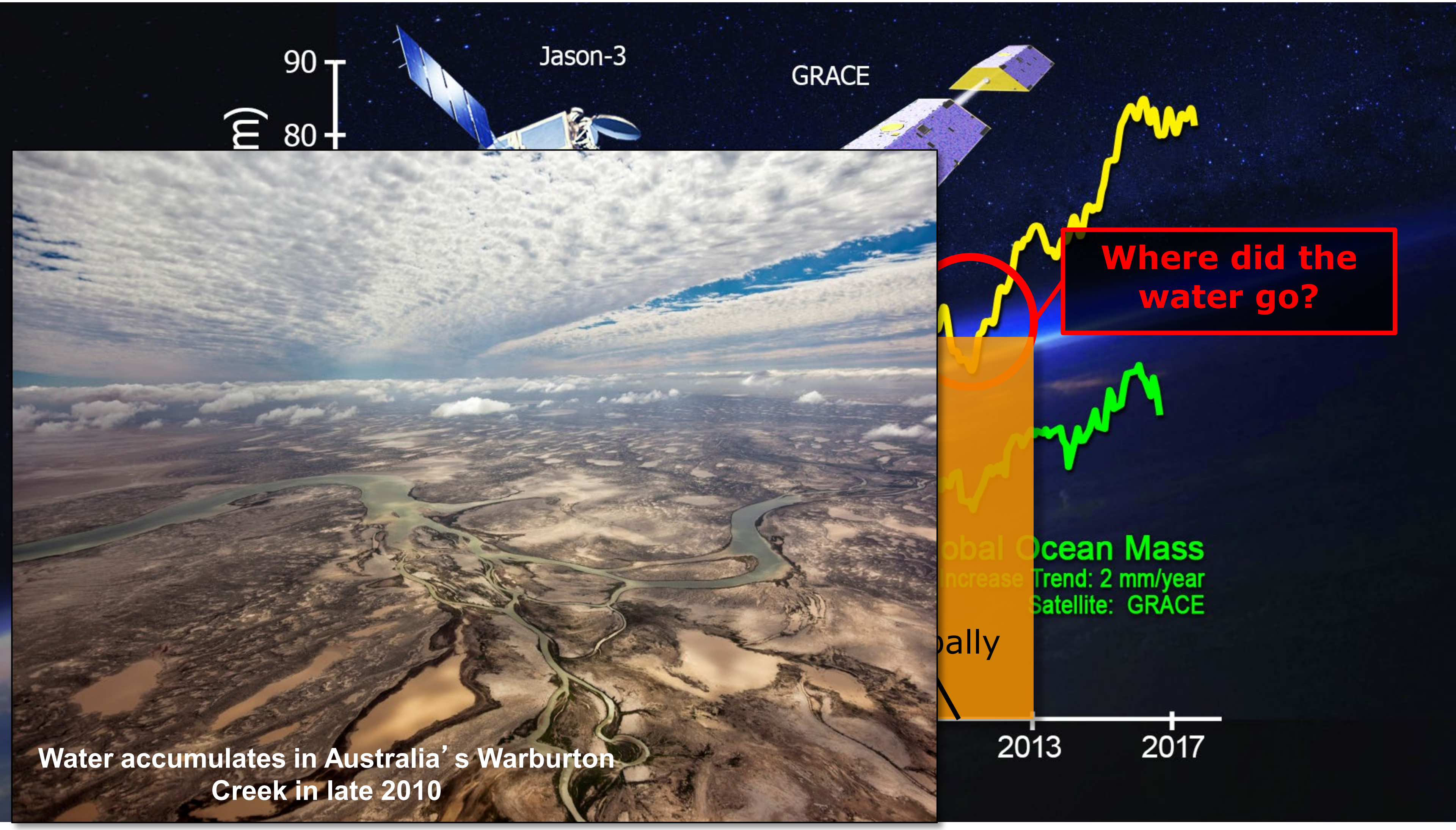
GMSL Acceleration:
0.0332 mm/year²

GRACE contribution to Sea Level.

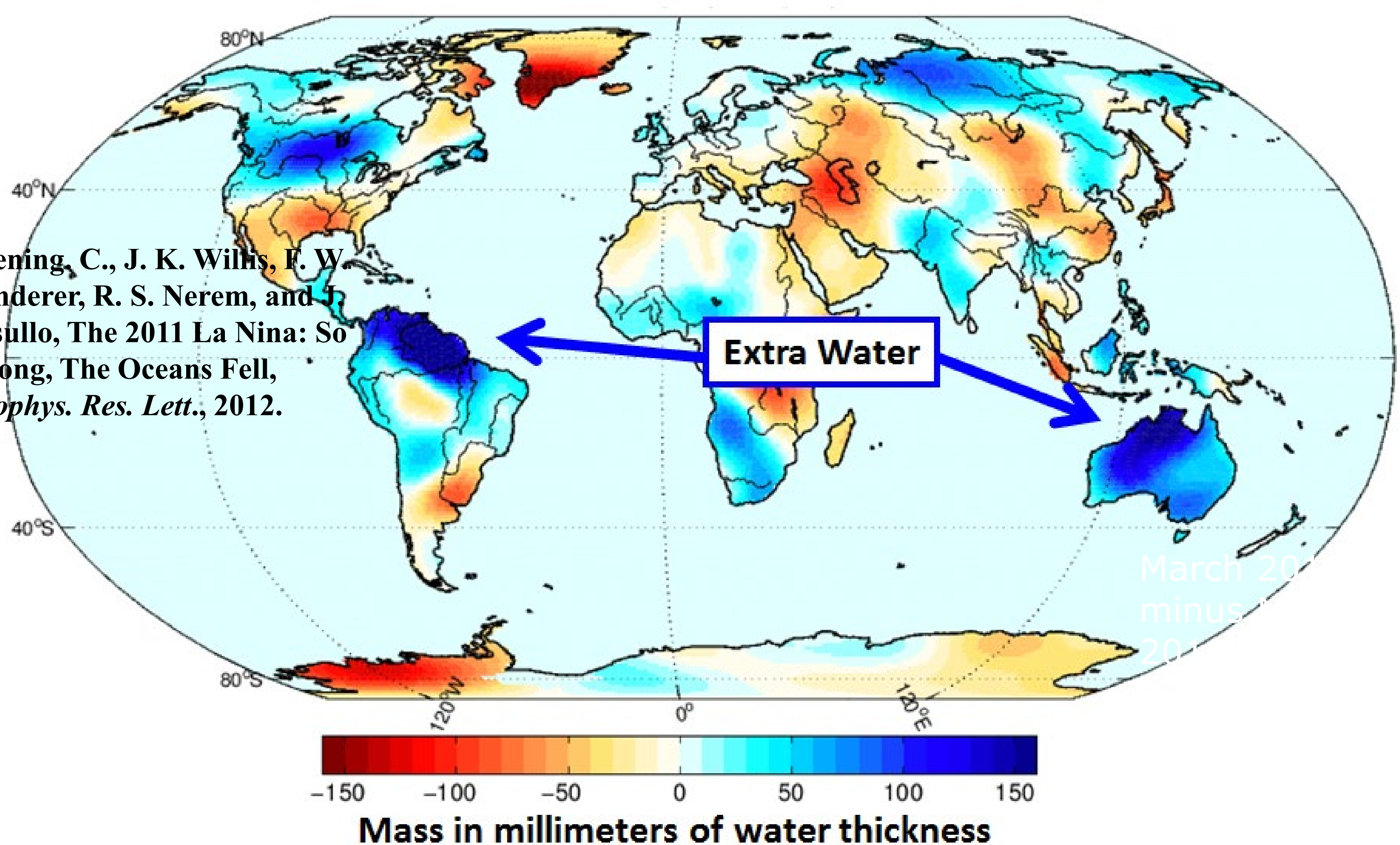



Jason-3
GRACE
Change in Mean Sea Level (mm)
90
80
70
60
50
40
30
20
10
0
1993
1997
2001
2005
2009
2013
2017
Year
Where did the water go?
Global Ocean Mass
Mass Increase Trend: 2 mm/year
Satellite: GRACE
Global Mean Sea Level
Total Sea Level Trend: 3 mm/year
Satellites: TOPEX, Jason-1,2,3


Jason-3
GRACE
90
80
70
60
0
1993
1997
2001
2005
2009
2013
2017
Year
Where did the water go?
Jan 3 2010
Dec 29 2010
Big La Nina event – affects rain patterns globally
Global Ocean Mass
Mass Increase Trend: 2 mm/year
Satellite: GRACE


90
80
Jason-3
GRACE
Where did the water go?
obal Ocean Mass
Increase Trend: 2 mm/year
Satellite: GRACE
ally
2013
2017
Water accumulates in Australia's Warburton Creek in late 2010

Extra water following El Nino.

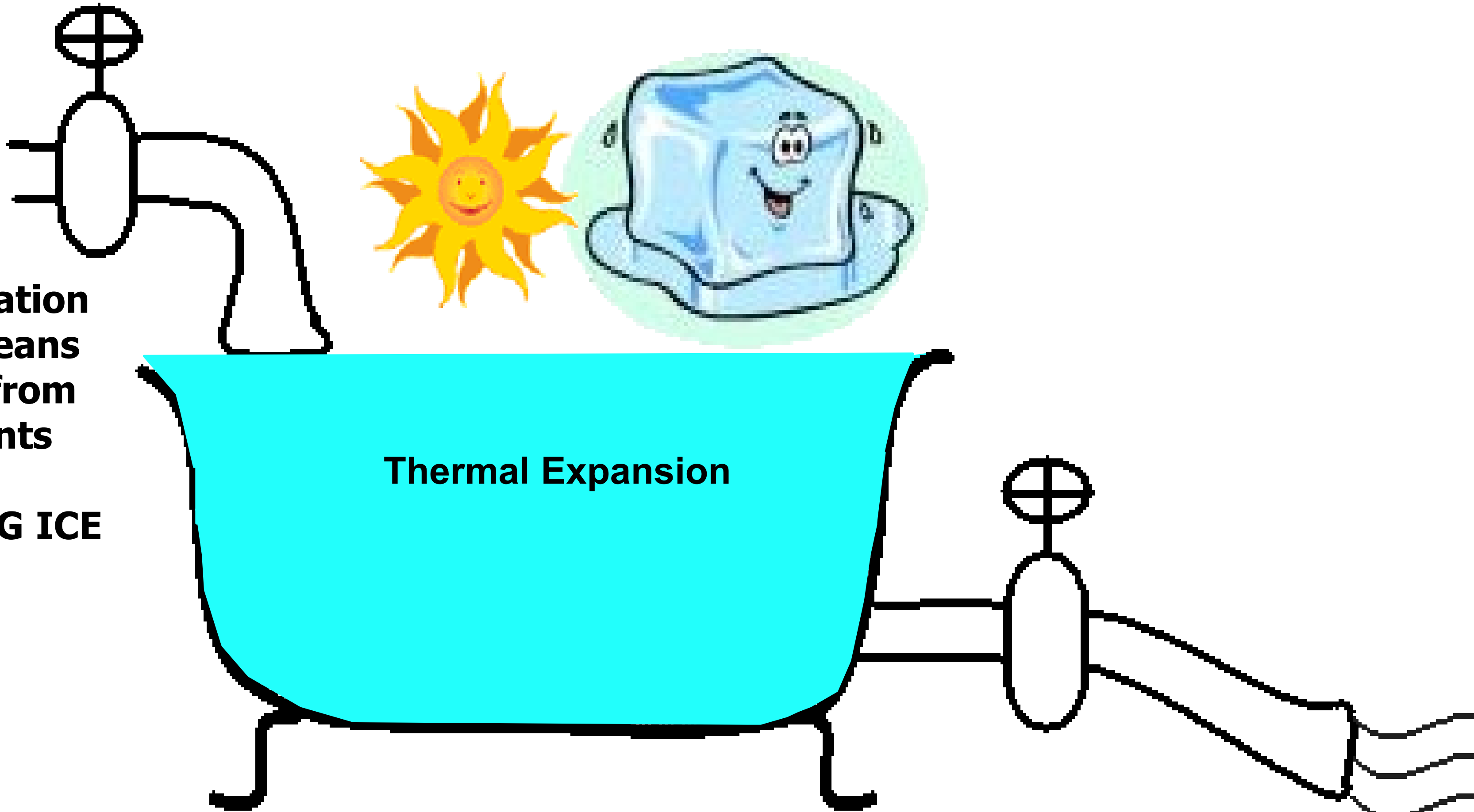


Boening, C., J. K. Willis, F. W. Landerer, R. S. Nerem, and J. Fasullo, The 2011 La Nina: So Strong, The Oceans Fell, *Geophys. Res. Lett.*, 2012.

Why does sea level change?
The Bathtub Model

Precipitation over Oceans
Runoff from Continents

MELTING ICE



$$\Delta SLR_{total} = \Delta SLR_{steric} + \Delta SLR_{mass}$$

Steric Changes

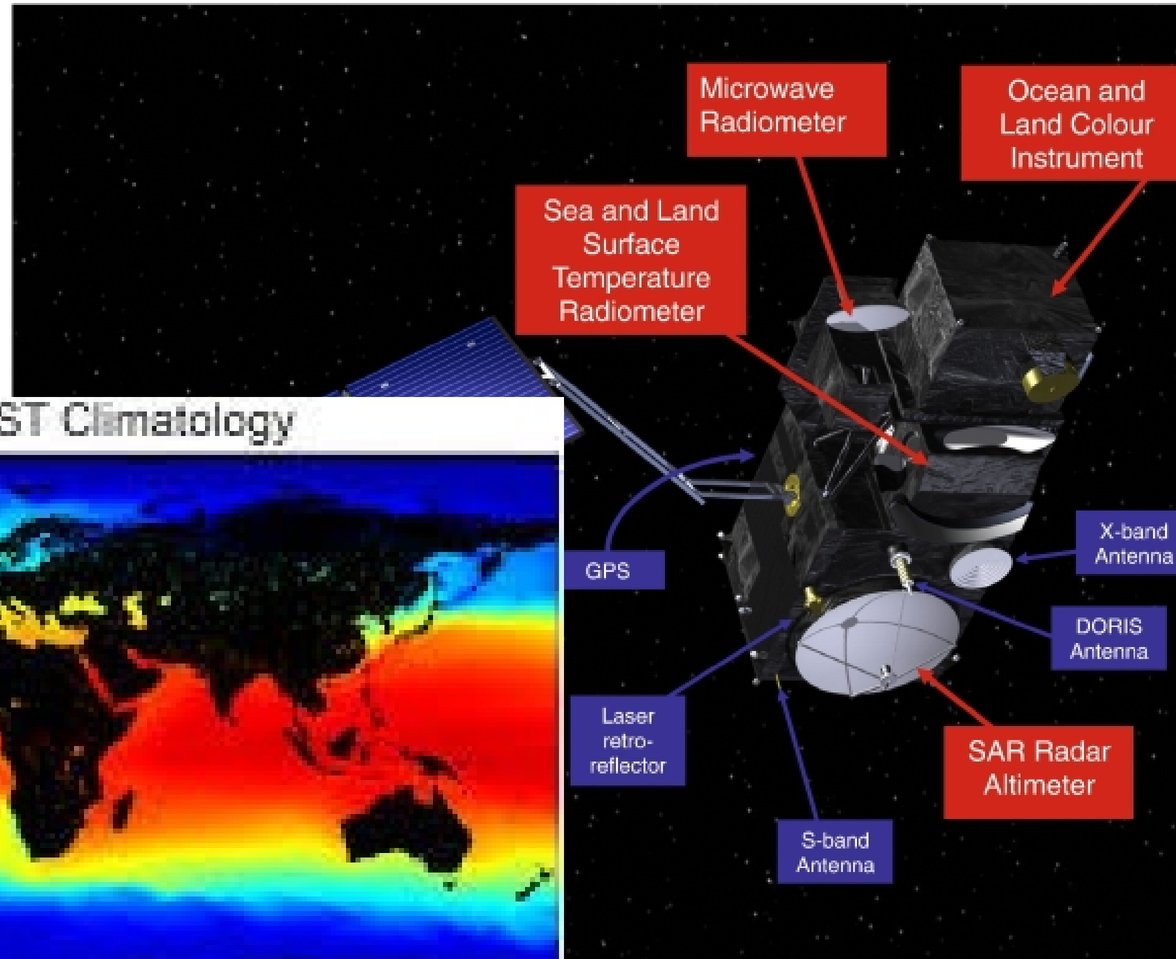
The formula for the steric height is derived from the hydrostatic equilibrium equation and can be expressed as

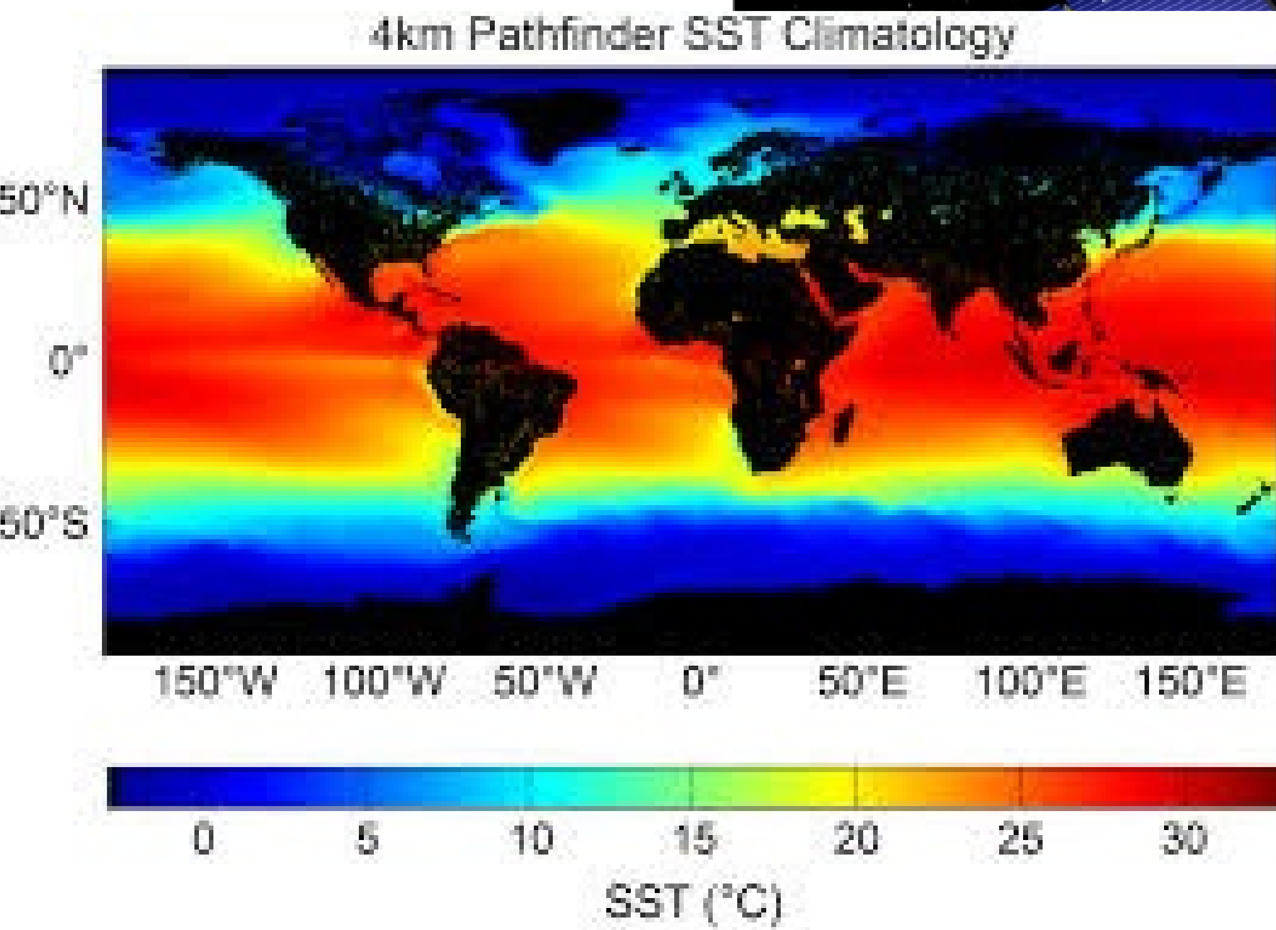
$$SH(z_1, z_2) = \frac{1}{g} \int_{z_1}^{z_2} \frac{\Delta\rho(T, S, p)}{\rho_0(T_0, S_0, p)} \, \mathrm{d}z \qquad (4)$$

Where ρ_0 is the reference density, ρ is the actual density and $\Delta\rho = \rho - \rho_0$. g is the gravitational acceleration. z_1 and z_2 is the depths in which between the water column is analysed.

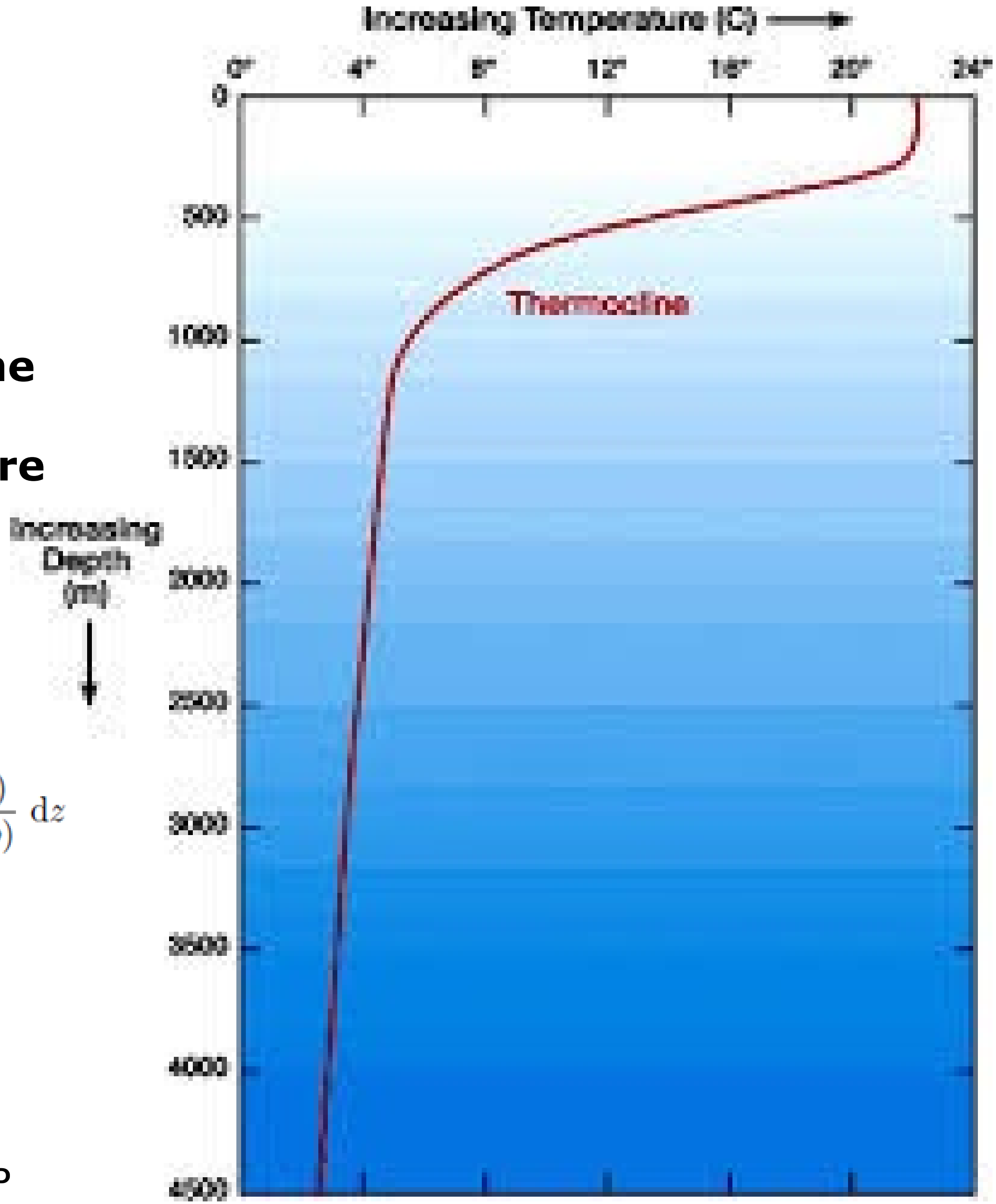
T0 = 0-30ºC and S0 = 35 psu. (practical salinity unit)

Sentinel-3A/B





**If you are to use spaceborne
Data you must assume a relation between depth and temperature to perform the integration**

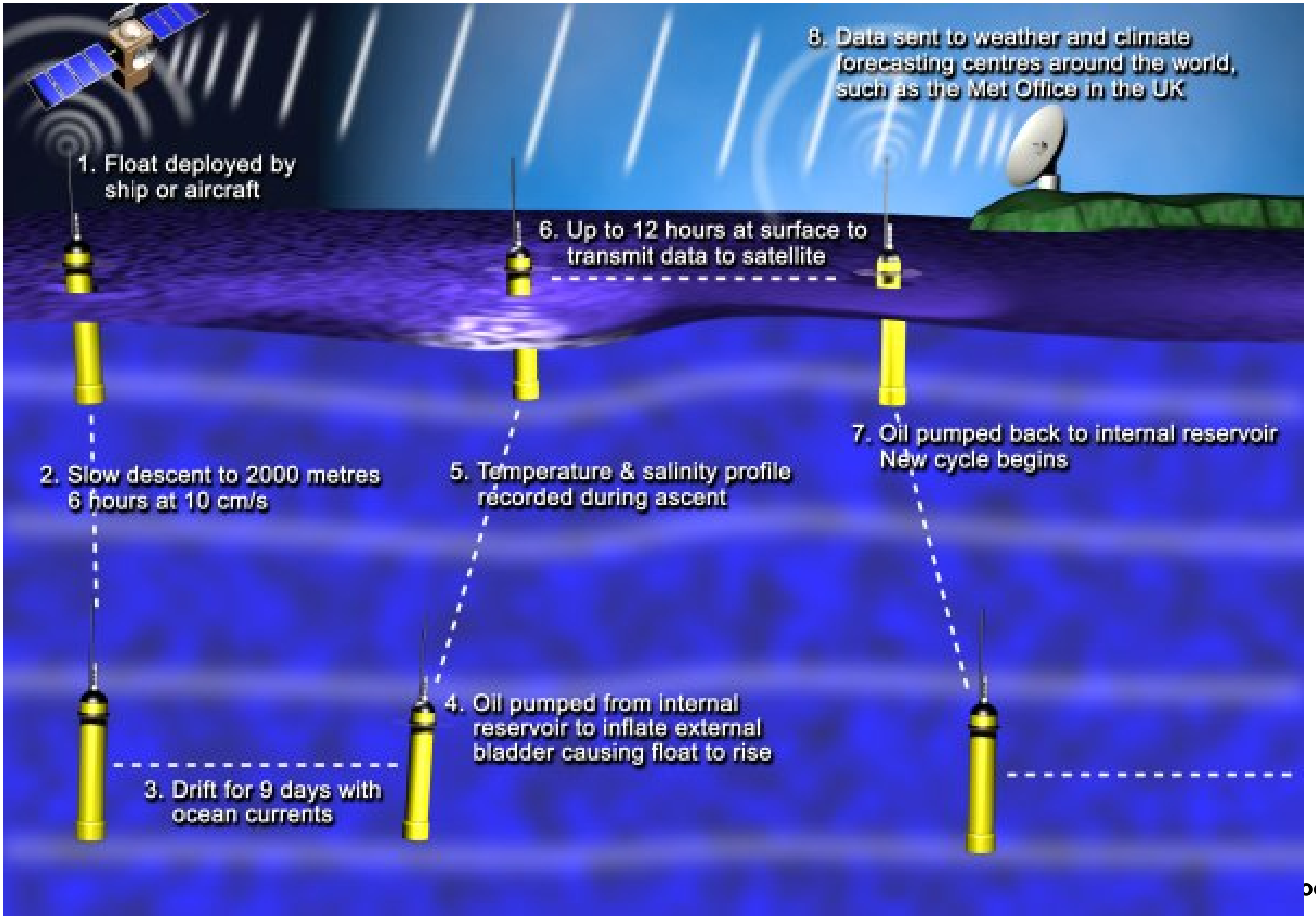


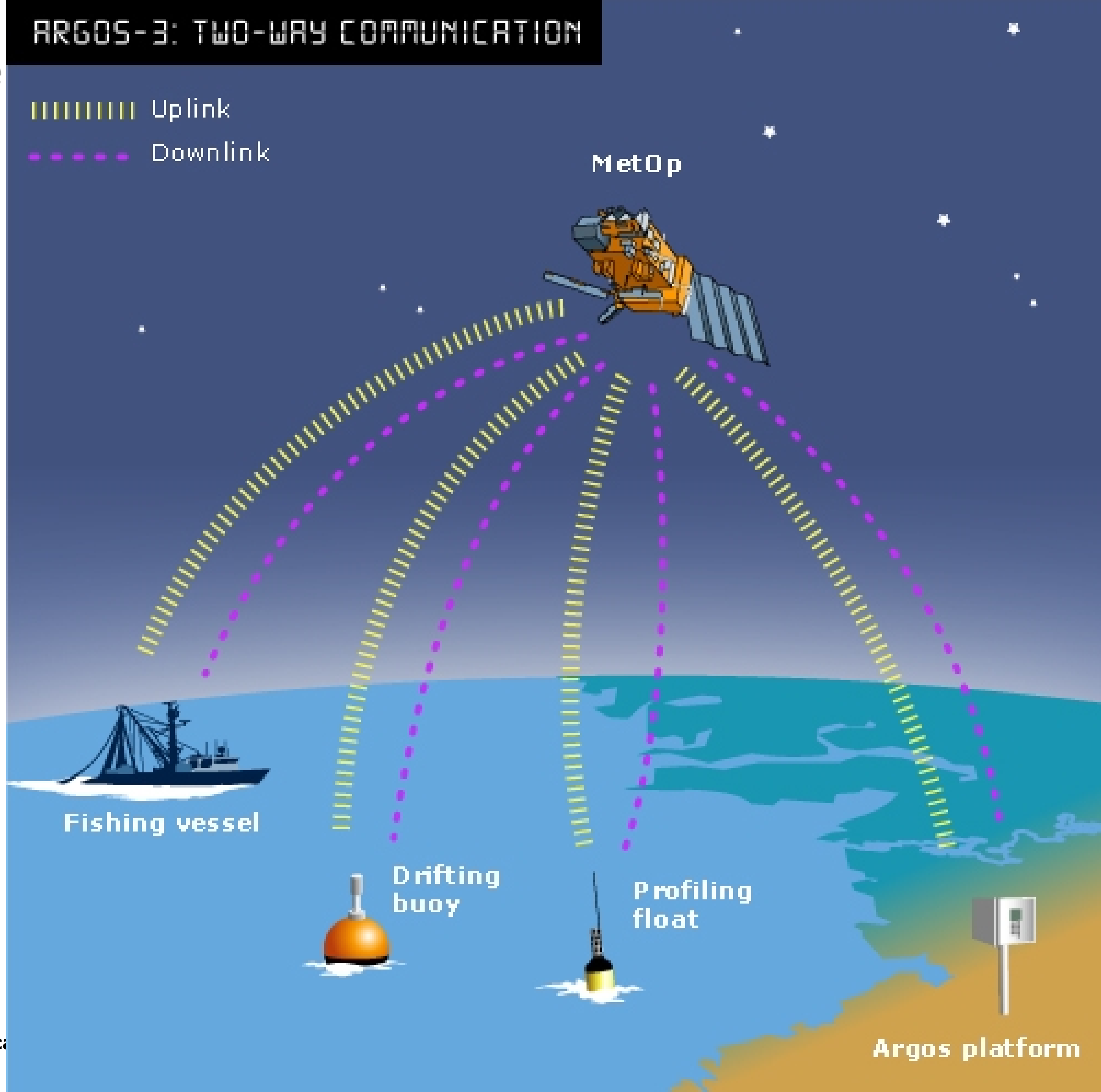
$$SH(z_1, z_2) = \frac{1}{g}\int_{z_1}^{z_2} \frac{\Delta\rho(T,S,p)}{\rho_0(T_0,S_0,p)}\,\mathrm{d}z$$

There's a better way.

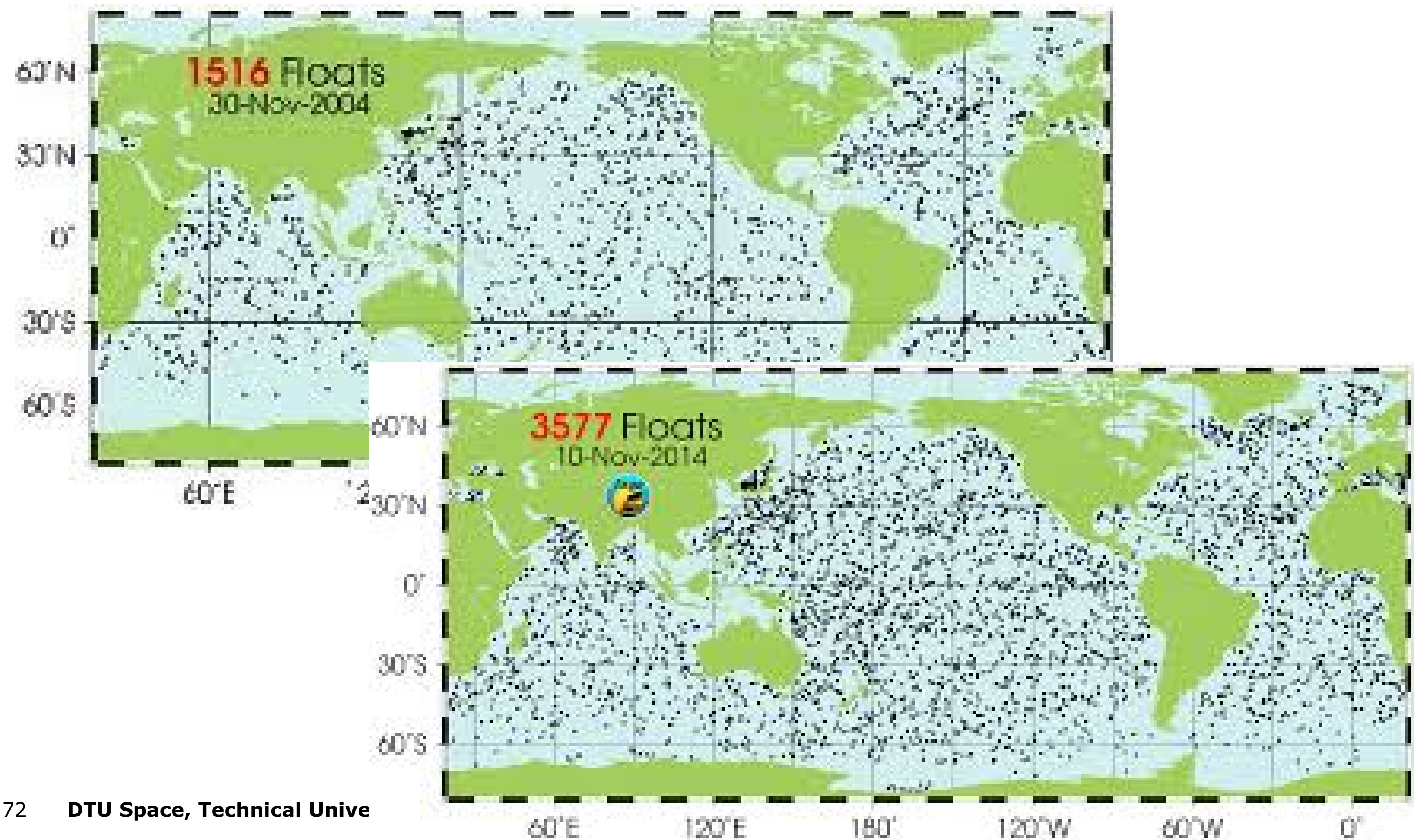
- **Since 2004 you can get temperature+Salinity as a function of depth.**

The revolution of ARGO




ARGOS-3: TWO-WAY COMMUNICATION
Uplink
Downlink
MetOp
Fishing vessel
Drifting buoy
Profiling float
Argos platform

ARGO floats……

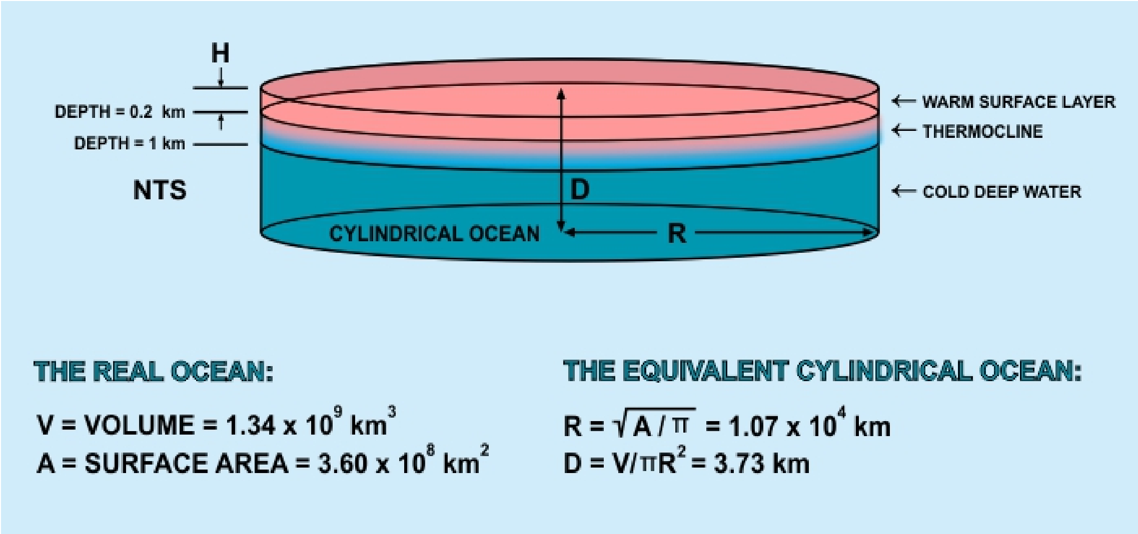

1516 Floats
30-Nov-2004
60°N
30°N
0°
30°S
60°S
60°E
3577 Floats
10-Nov-2014
60°N
30°N
0°
30°S
60°S
60°E
120°E
180°
120°W
60°W
0°

Now we can perform the integration but only for the period 2005-2017

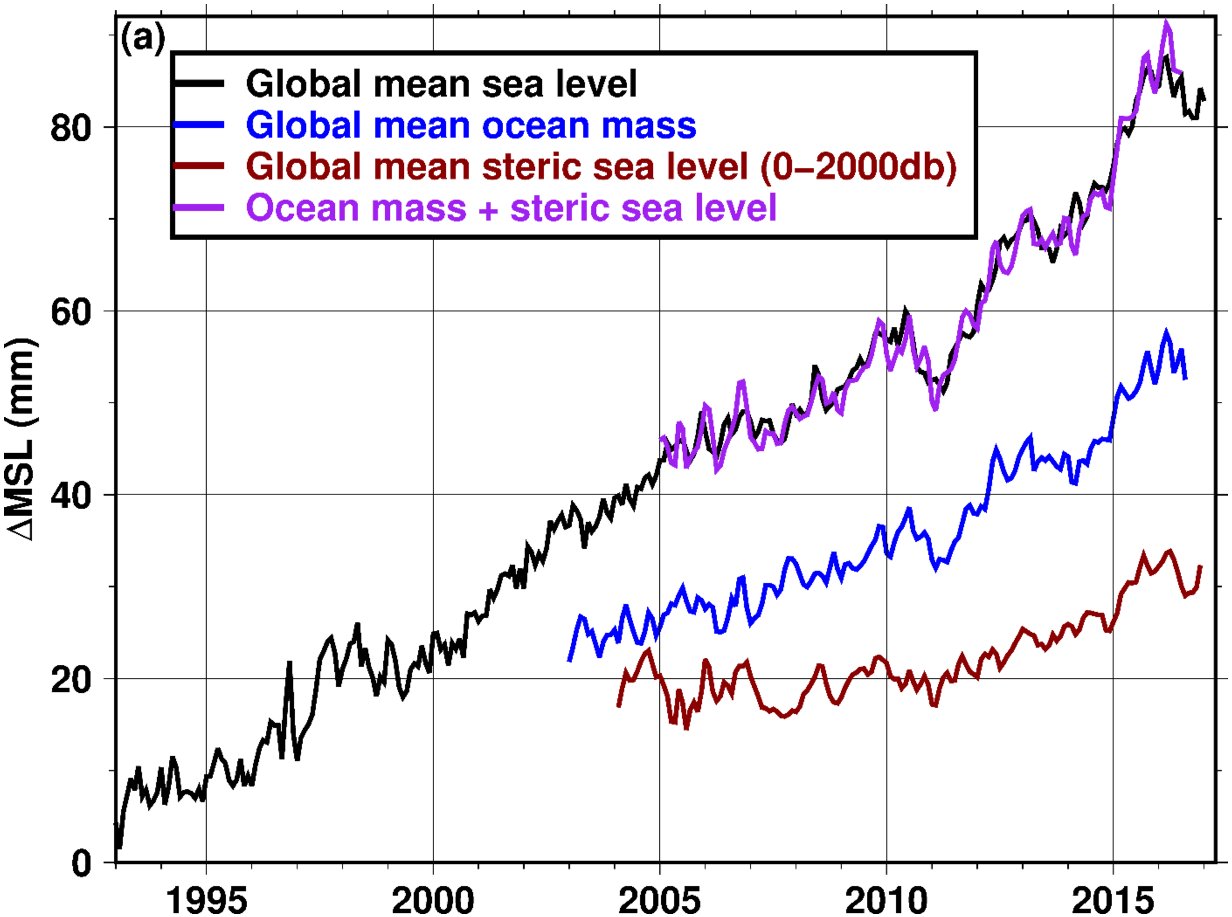
The formula for the steric height is derived from the hydrostatic equilibrium equation and can be expressed as

$$SH(z_1, z_2) = \frac{1}{g}\int_{z_1}^{z_2} \frac{\Delta\rho(T,S,p)}{\rho_0(T_0,S_0,p)}\,\mathrm{d}z \qquad (4)$$

Where ρ_0 is the reference density, ρ is the actual density and $\Delta\rho = \rho - \rho_0$. g is the gravitational acceleration. z_1 and z_2 is the depths in which between the water column is analysed.



Sea Level Budget: global mean



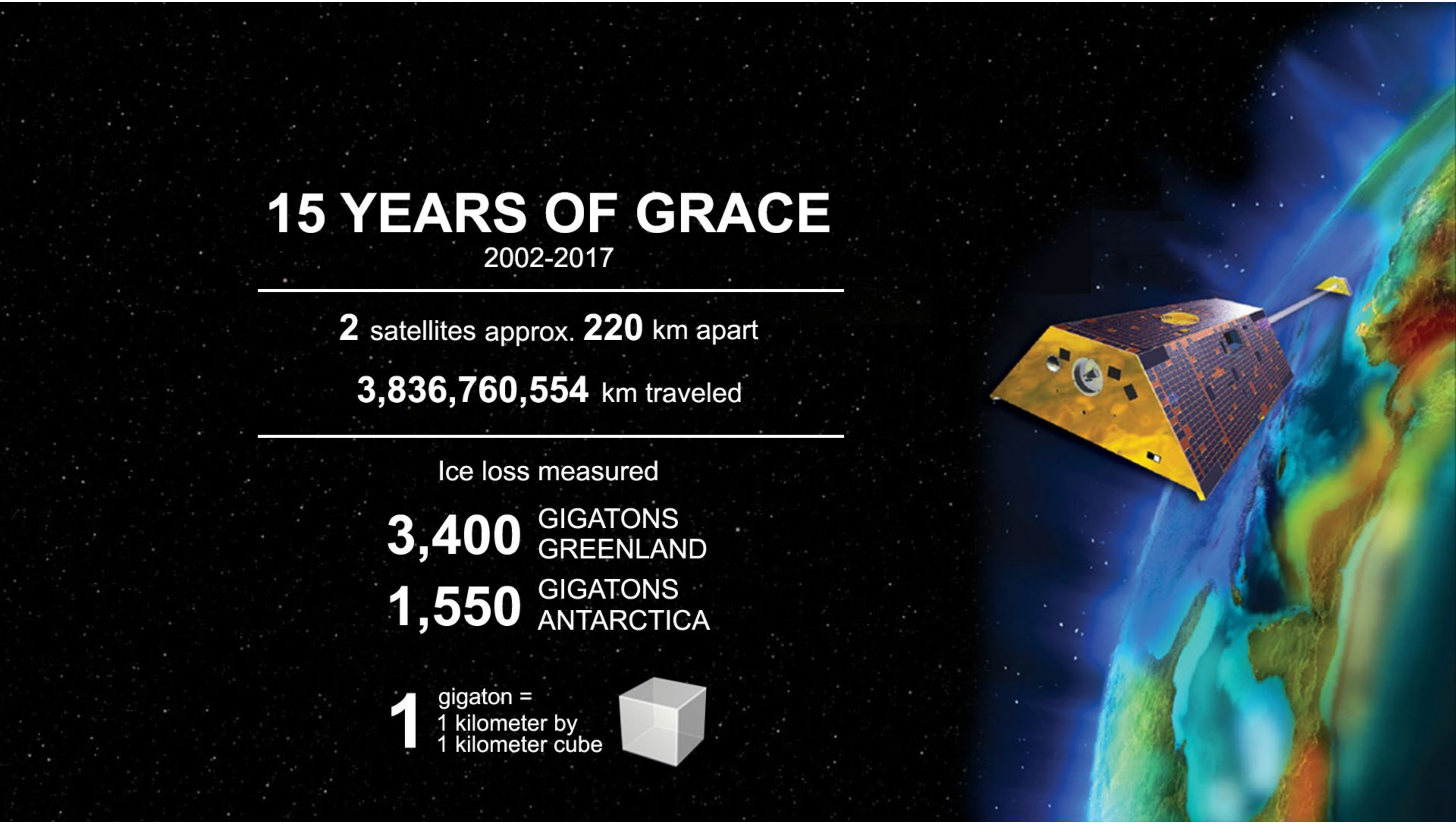
[From E. Leuliette]

15-year trend:

- 1/3 from heating (mostly above 2000 m)
- 2/3 from mass
- Locally, we've detected signs of deep (<2000m) ocean warming (e.g., in the S. Pacific)
- The Earth's ocean temperature is really it's fever thermometer, 93% of the current warming goes into the ocean!

[E. Leuliette & S. Nerem, 2017]

Summary: GRACE has been busy



In 2018 GRACE-FO took over.
In 2025 NGGM is planned (GRACE-2)


THANK YOU!

Questions

Lecture material:

Whats you feeling about the book – good/bad/ok.
Amount of reading: enough/too much
Inclusion of articles:

Lectures:

Lectures (8) Altimetry.
Lecture (9) mean fields – gravity
Lecture (10) time variations/sea level and GIA (+ Tadea)
Lecture (11) INSAR and Laser Altimetry
Lecture (12) Gravity field from laser ranging and gradiometry
Lecture (13) Gravity field variations and sea level change. today.

Ideas to improve lectures ?

Breaks?
Discussions?
Kahoot's?
Repetitions?
More less Externals
Summary? (of the day at the end?)

Assignments:

The assignments (particularly last 3) -
Too easy/ok/difficult/too much?.
I had a comment on assignment 6 – which is implemented now.

Focus on real data?

Assignment involving more mathematical computations?

Remember

Assignment can be handed in until 6 December (but no feedback).