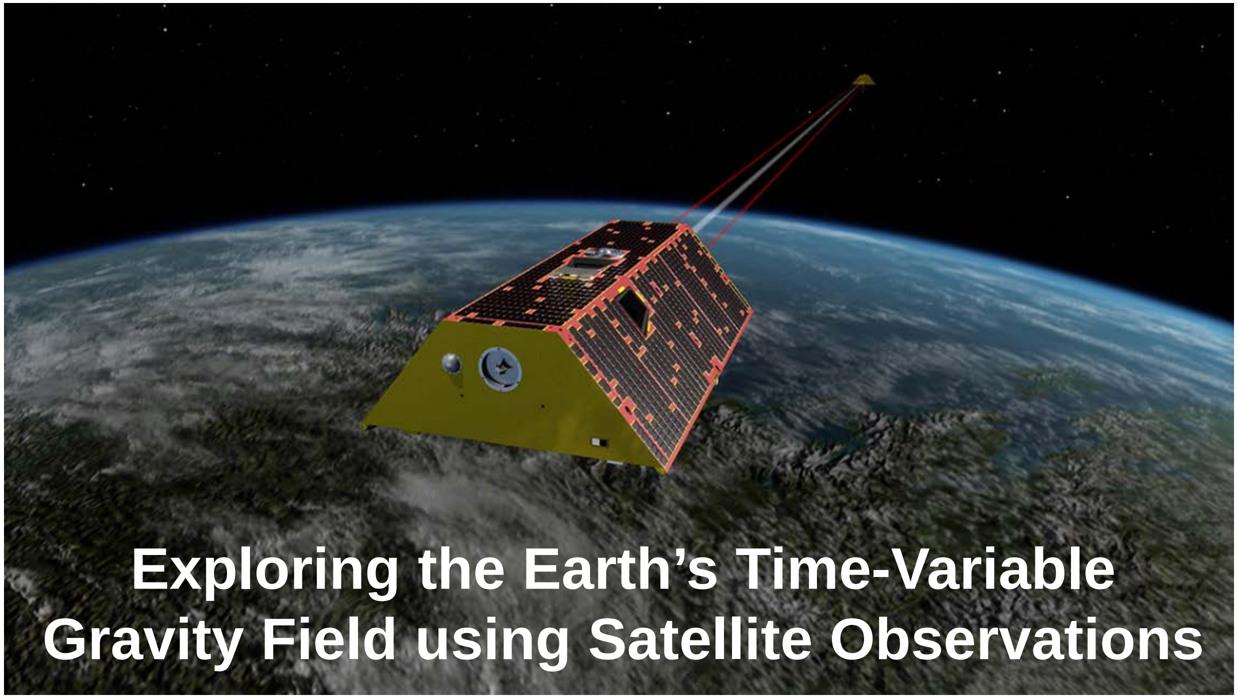


Exploring the Earth’s Time-Variable Gravity Field using Satellite Observations

Adrian Jäggi

Astronomical Institute

University of Bern

EGSIEM
European Gravity Service for Improved Emergency Management

COST-G
Combination Service for Time-variable Gravity Models

G3P

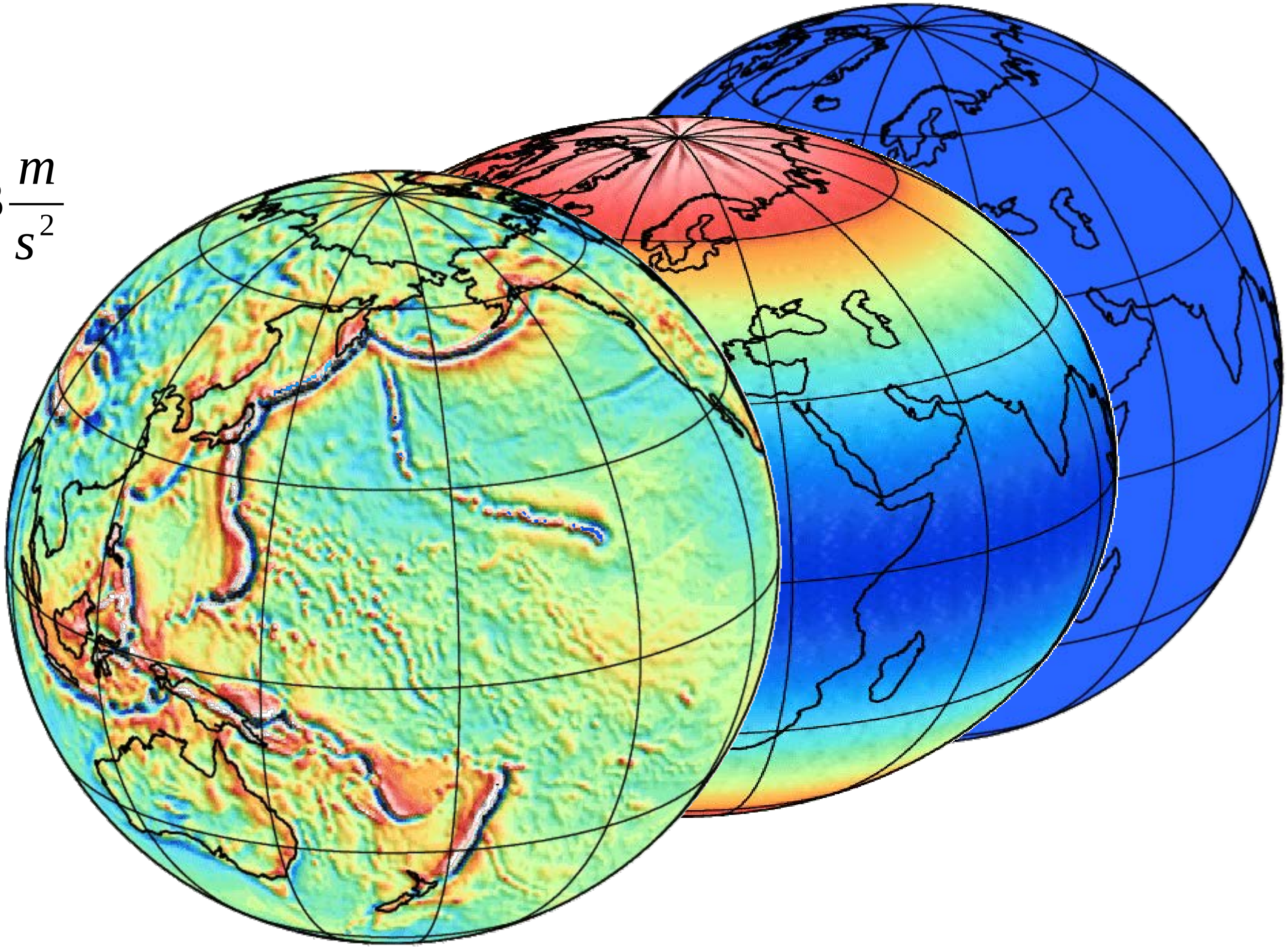
INTERNATIONAL SPACE SCIENCE INSTITUTE

Earth’s Gravity Field

Gravitational pull at
the Earth‘s surface

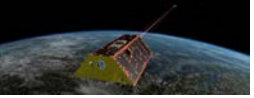
$$g = 9{,}78\frac{m}{s^2}\ldots 9{,}83\frac{m}{s^2}$$

$$\pm\, 0{,}0004\frac{m}{s^2}$$

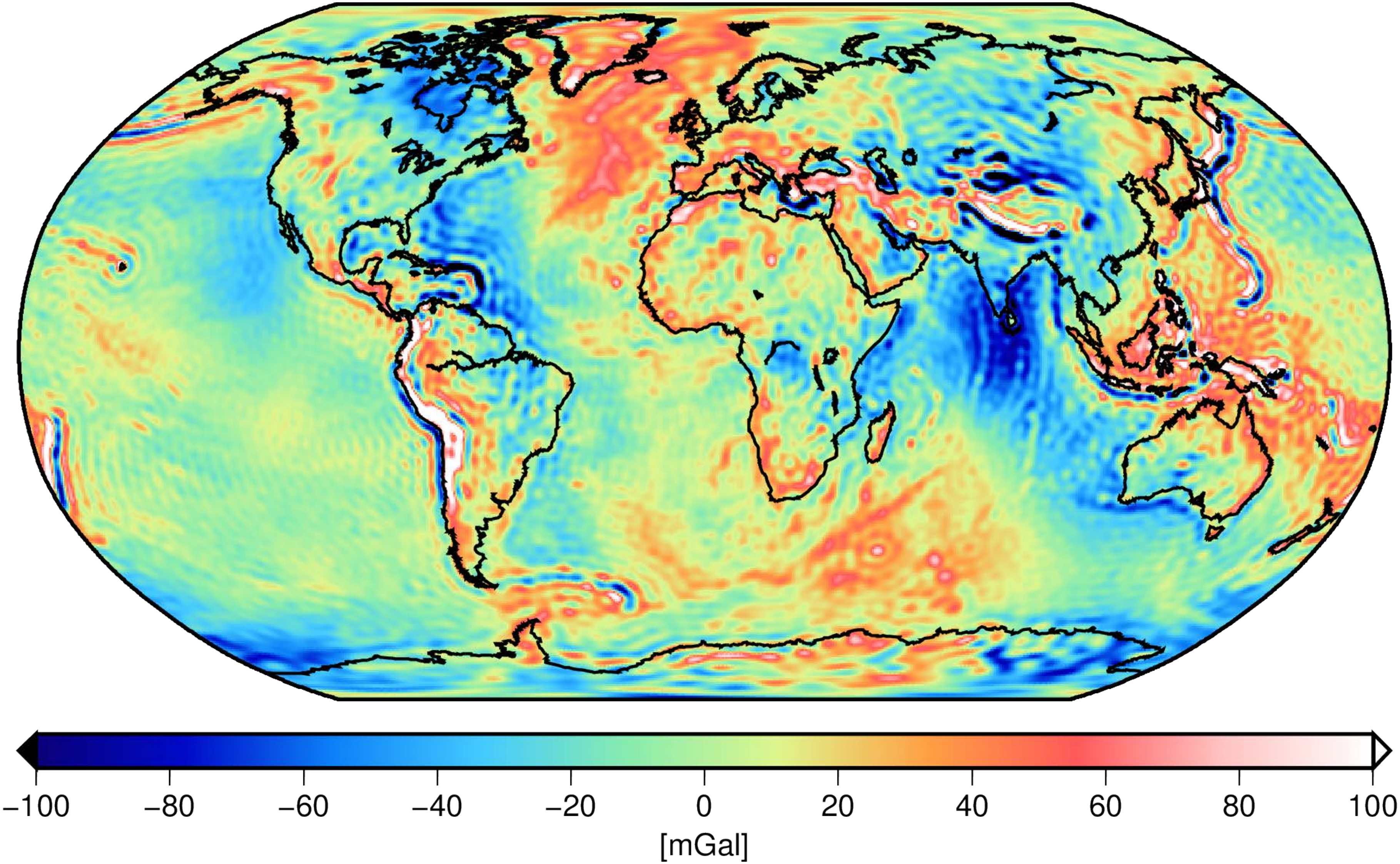


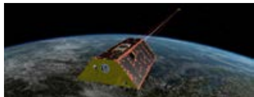
$$\left[1\,\mathrm{mGal} = 0{,}00001\frac{m}{s^2}\right]$$

1 millionth of the pull
at the Earth‘s surface

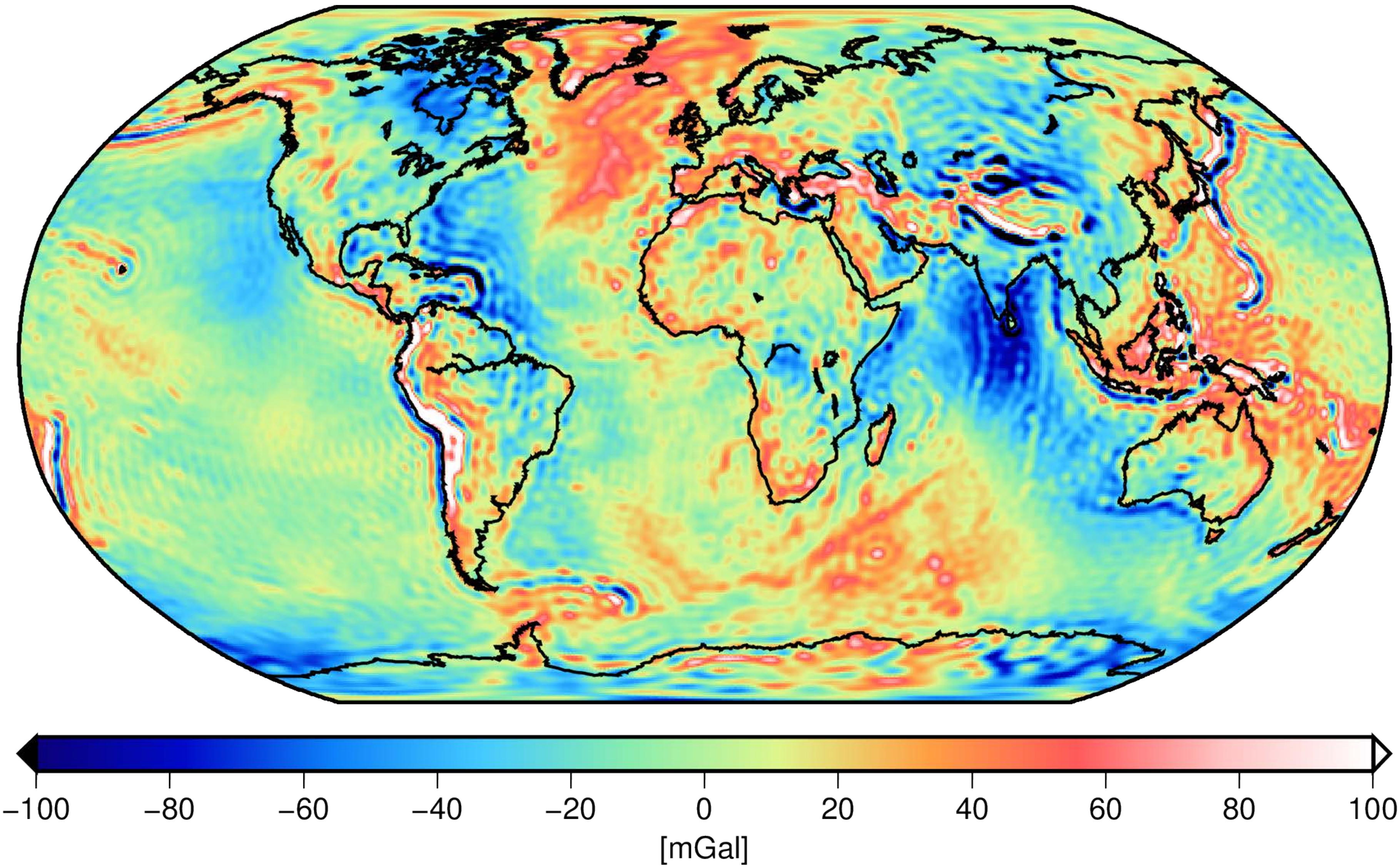


Earth’s Gravity Field in March

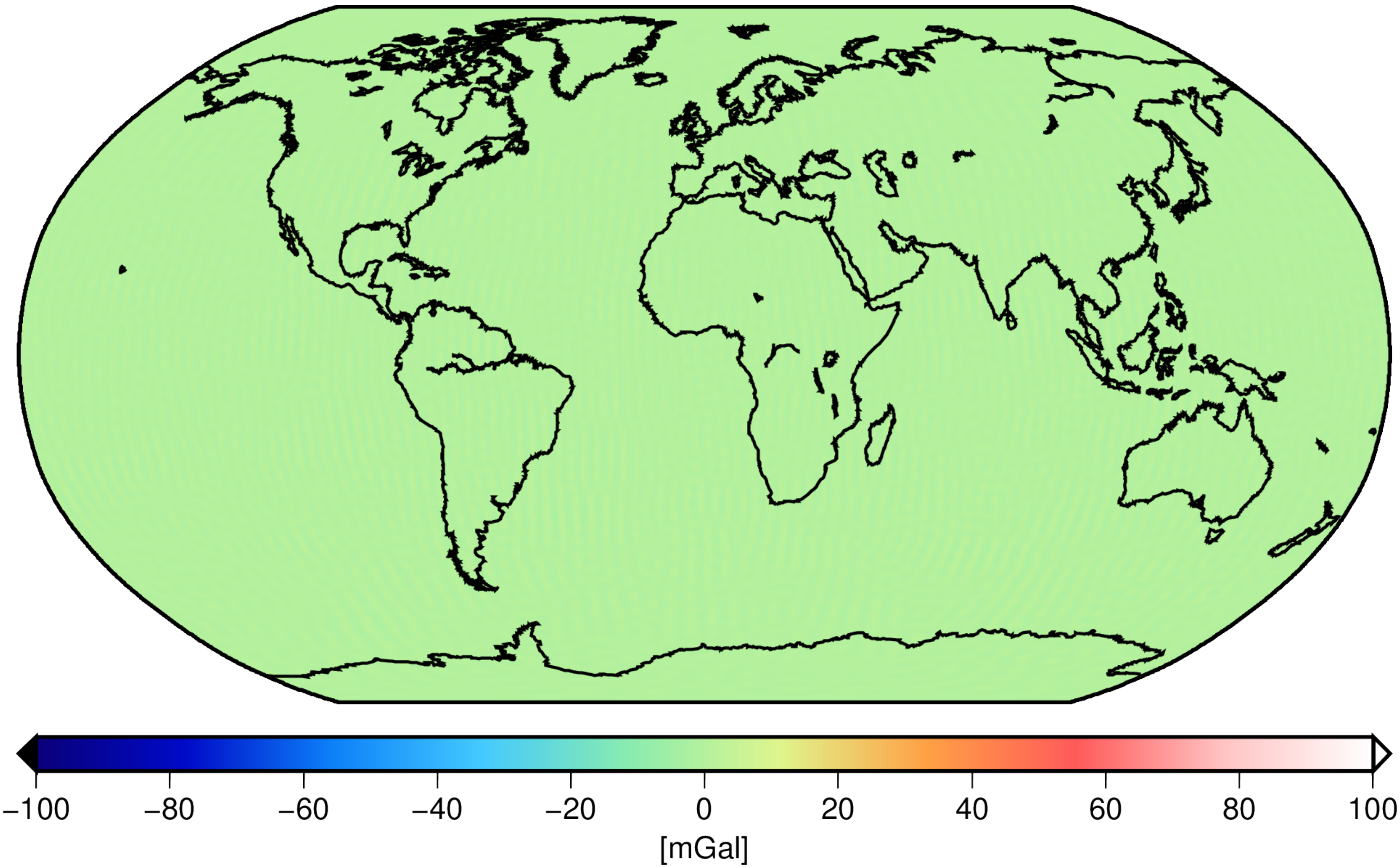




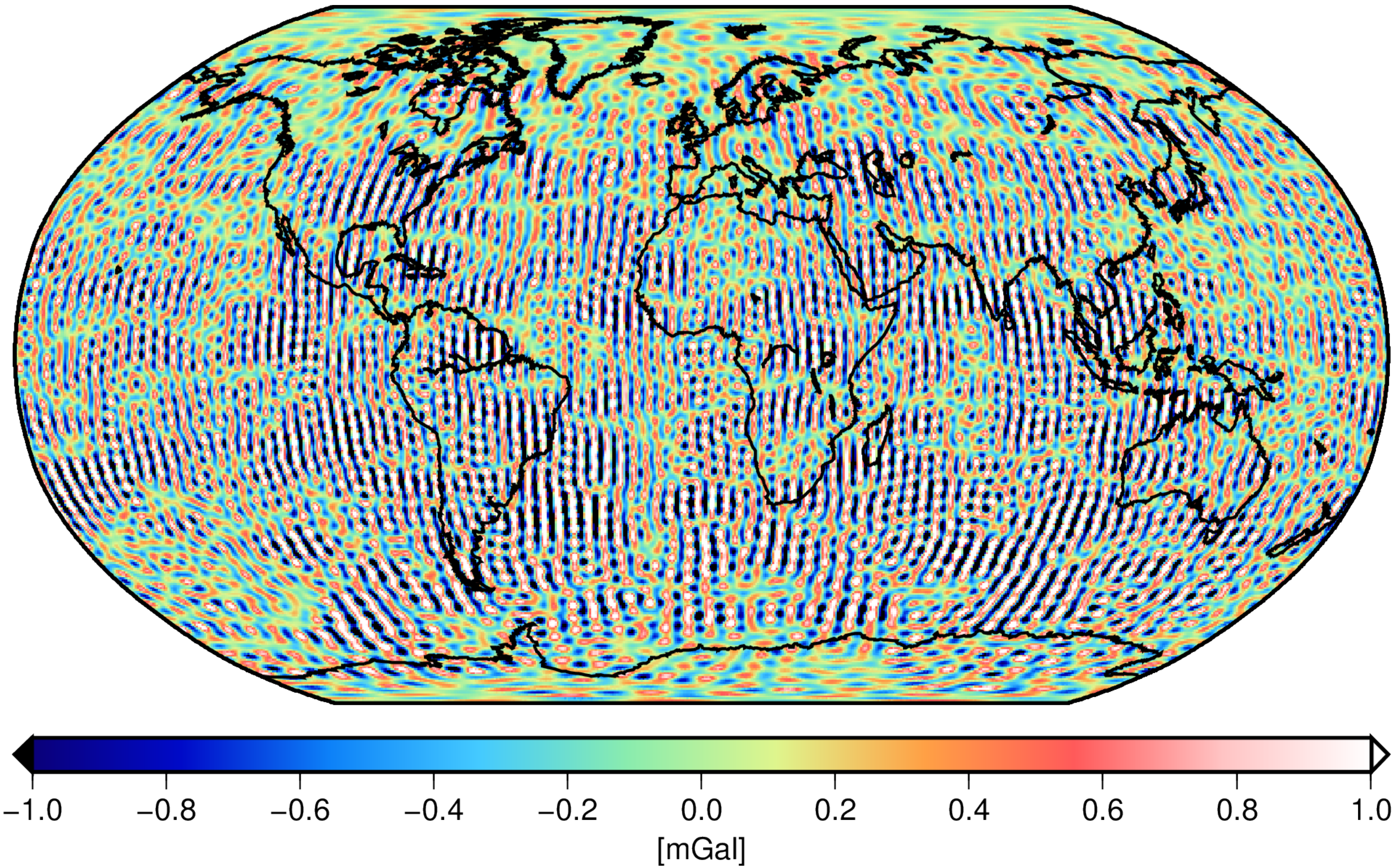
Earth’s Gravity Field in September

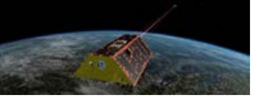


September – March

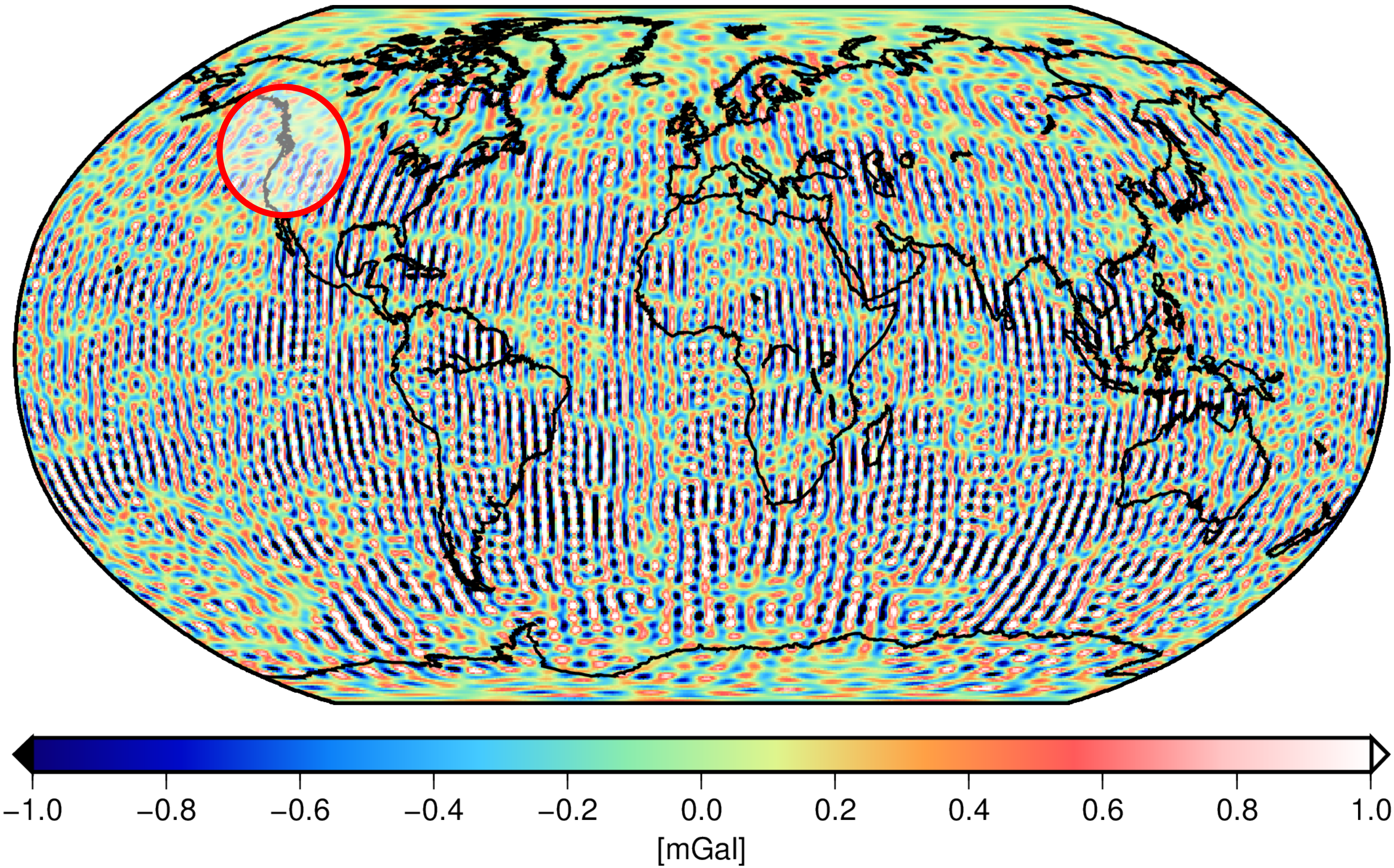


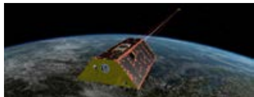
September – March



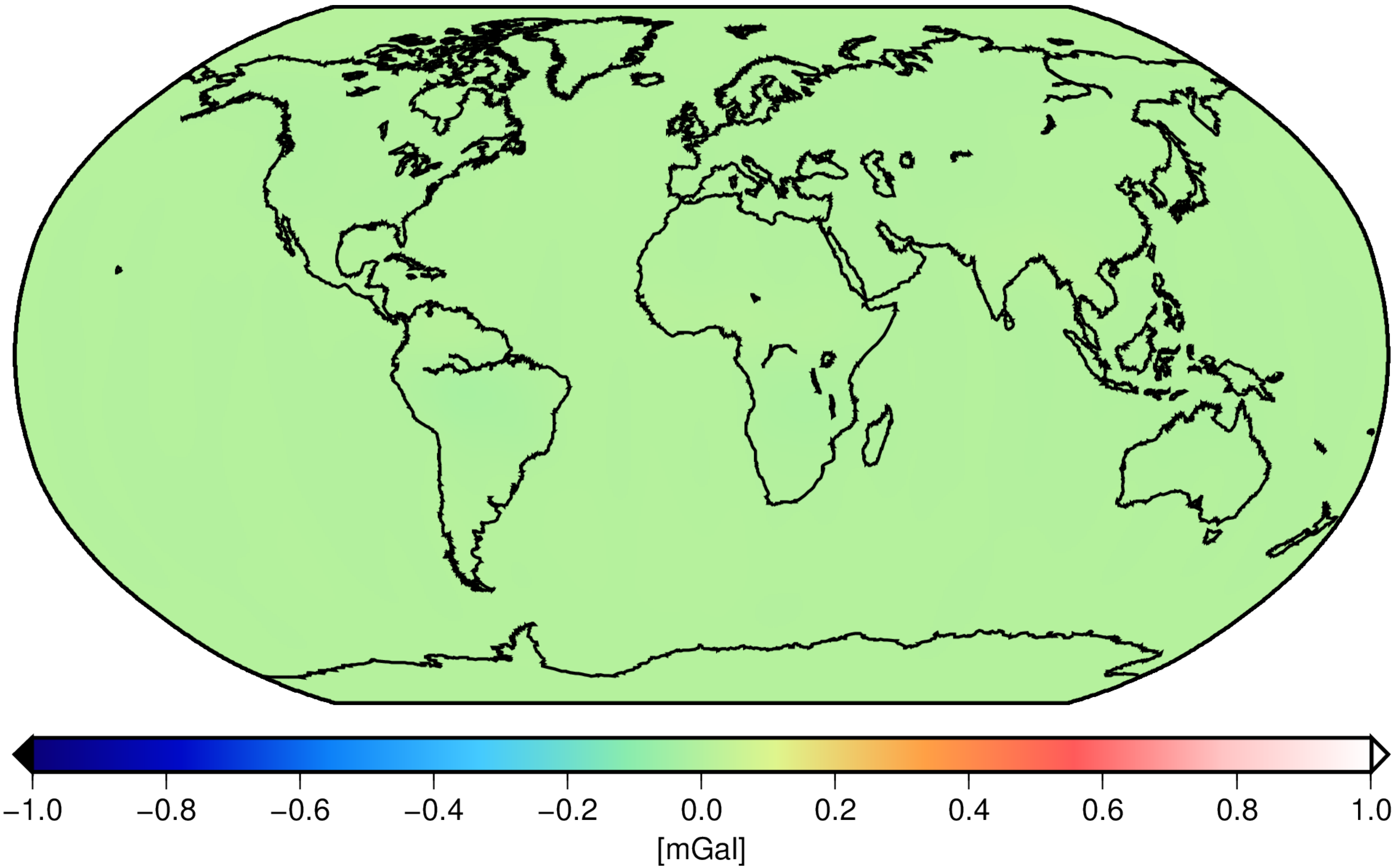


September – March

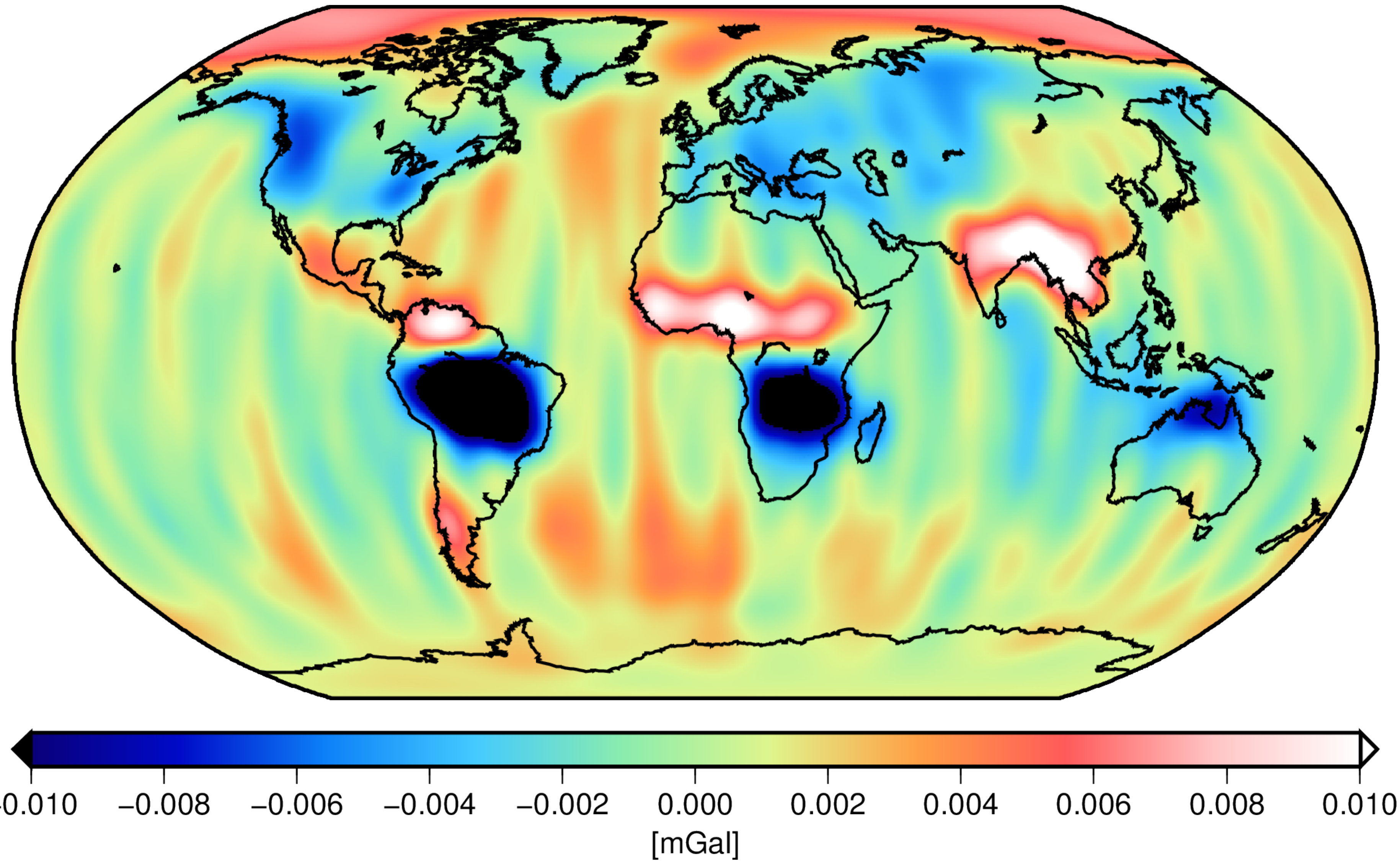


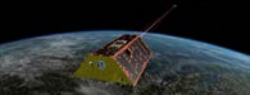


September – March

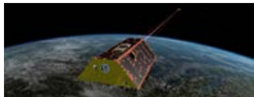


September – March

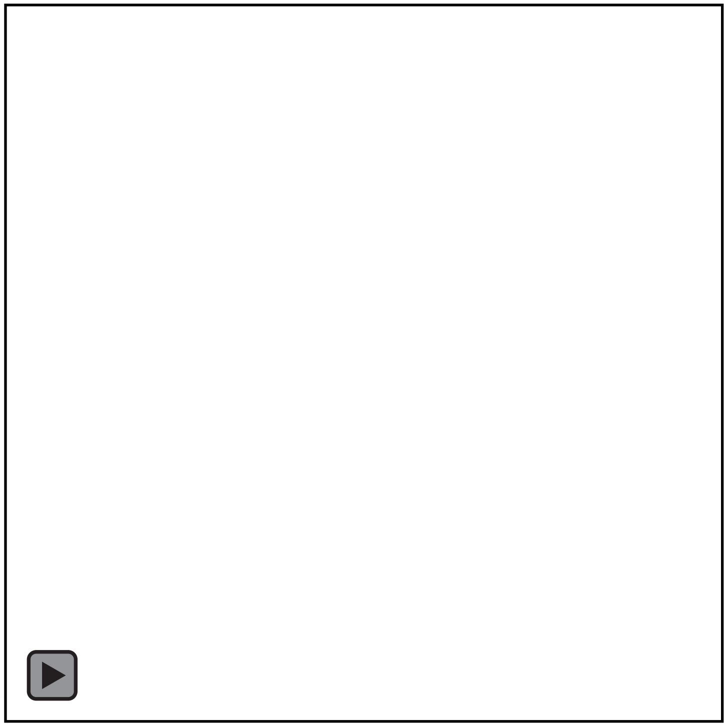


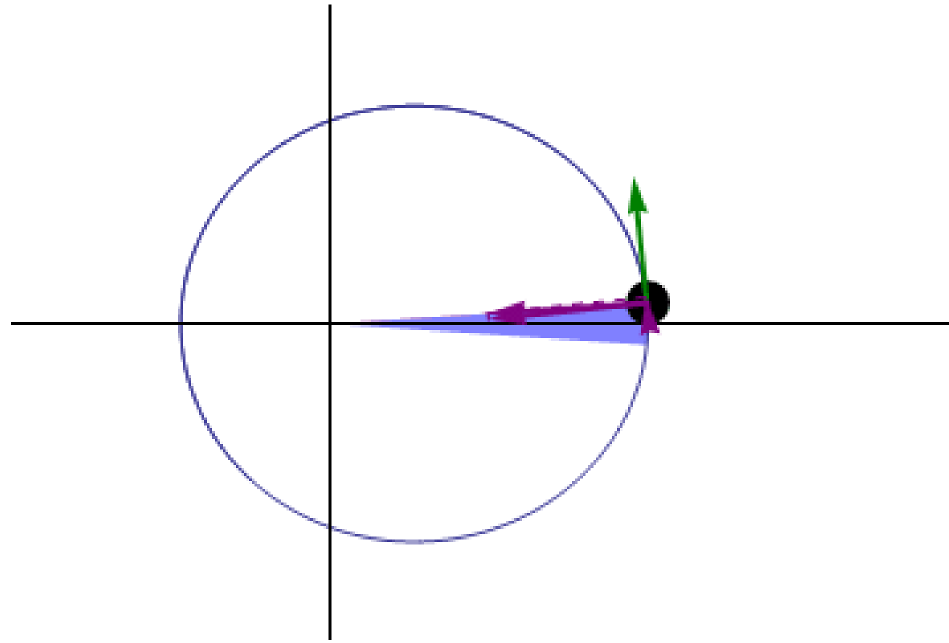


How do we measure these changes?



From Newton to satellites …





Satellites at a height of

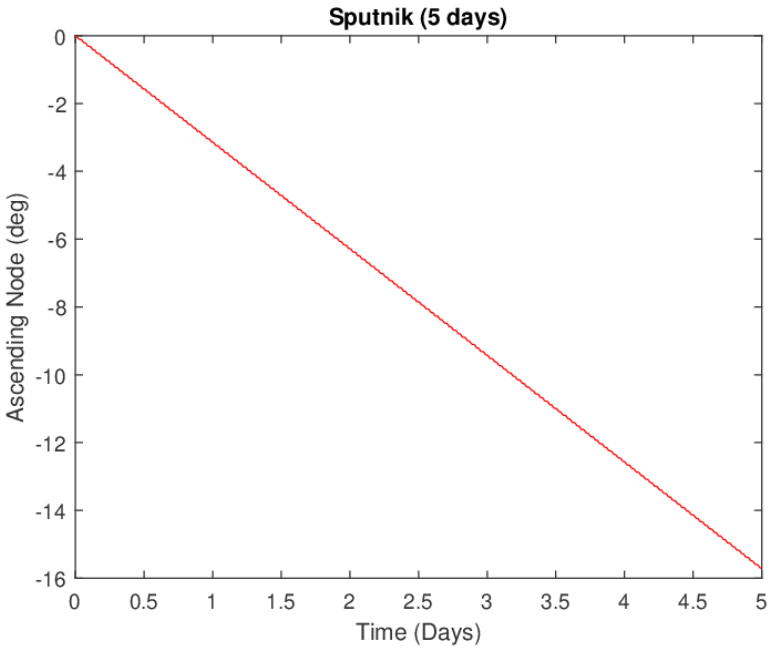
200 – 500 km

Measuring the trajectory, or

- the velocity
- the acceleration


Bahnspur des sowj. Erdtrabanten
Sternbild: Ursa Major
Aufnahme: Schulsternwarte Rodewisch/Vgtl.
13. Okt. 1957 4^{51} h MEZ
δ
ε
ζ
γ
η
Bahnspur

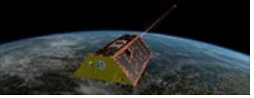
Orbit Perturbations



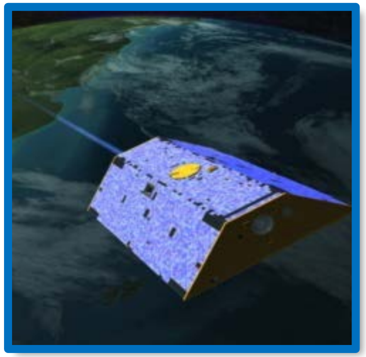
a: semi-major axis
e: numerical eccentricity
i: inclination
Ω: right ascension of ascending node
ω: argument of perigee
u_0: argument of latitude at t_0

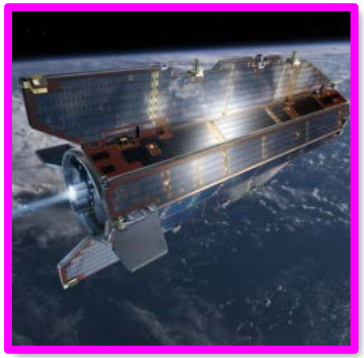
Orbit perturbations caused by the Earth's oblateness result in, e.g., a secular precession of the satellite's orbital plane.

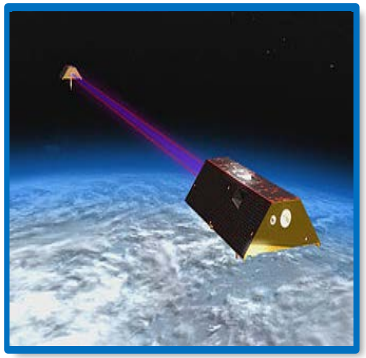
Observing satellites thus allowed it to determine the Earth's oblateness based on very short time spans of observed orbital arcs – revolutionizing the work of decades of terrestrial surveying.



Dedicated Gravity Missions







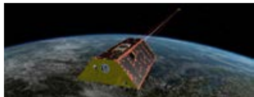
CHAMP (GFZ, 2000-2010)

GRACE (NASA/DLR, 2002-2017)

GRACE-FO (NASA/GFZ, 2018-2022)

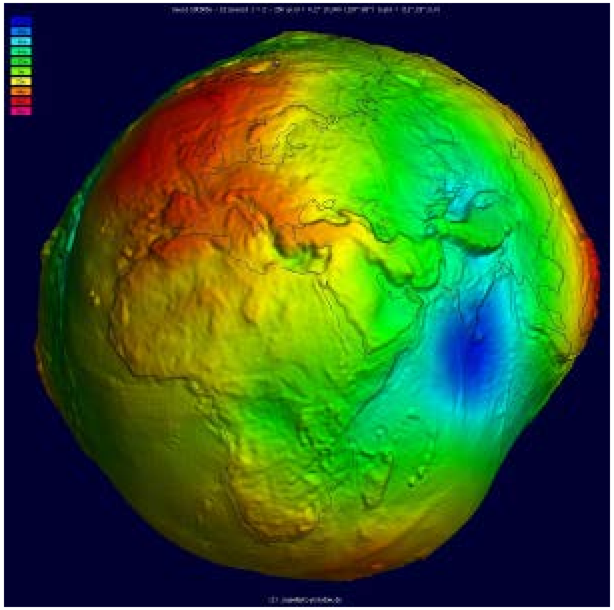
GOCE (ESA, 2009-2013)

- High-low satellite-to-satellite tracking (hl-SST)
- Low-low satellite-to-satellite tracking (ll-SST)
- Satellite gravity gradiometry (SGG)



Modeling the Earth's Gravity Potential

$$V(r,\theta,\lambda)=\frac{GM}{R}\sum_{l=0}^{l_{\max}}\left(\frac{R}{r}\right)^{l+1}\sum_{m=0}^{l}\overline{P}_{lm}(\cos\theta)\cdot\left[\overline{C}_{lm}\cos(m\lambda)+\overline{S}_{lm}\sin(m\lambda)\right]$$



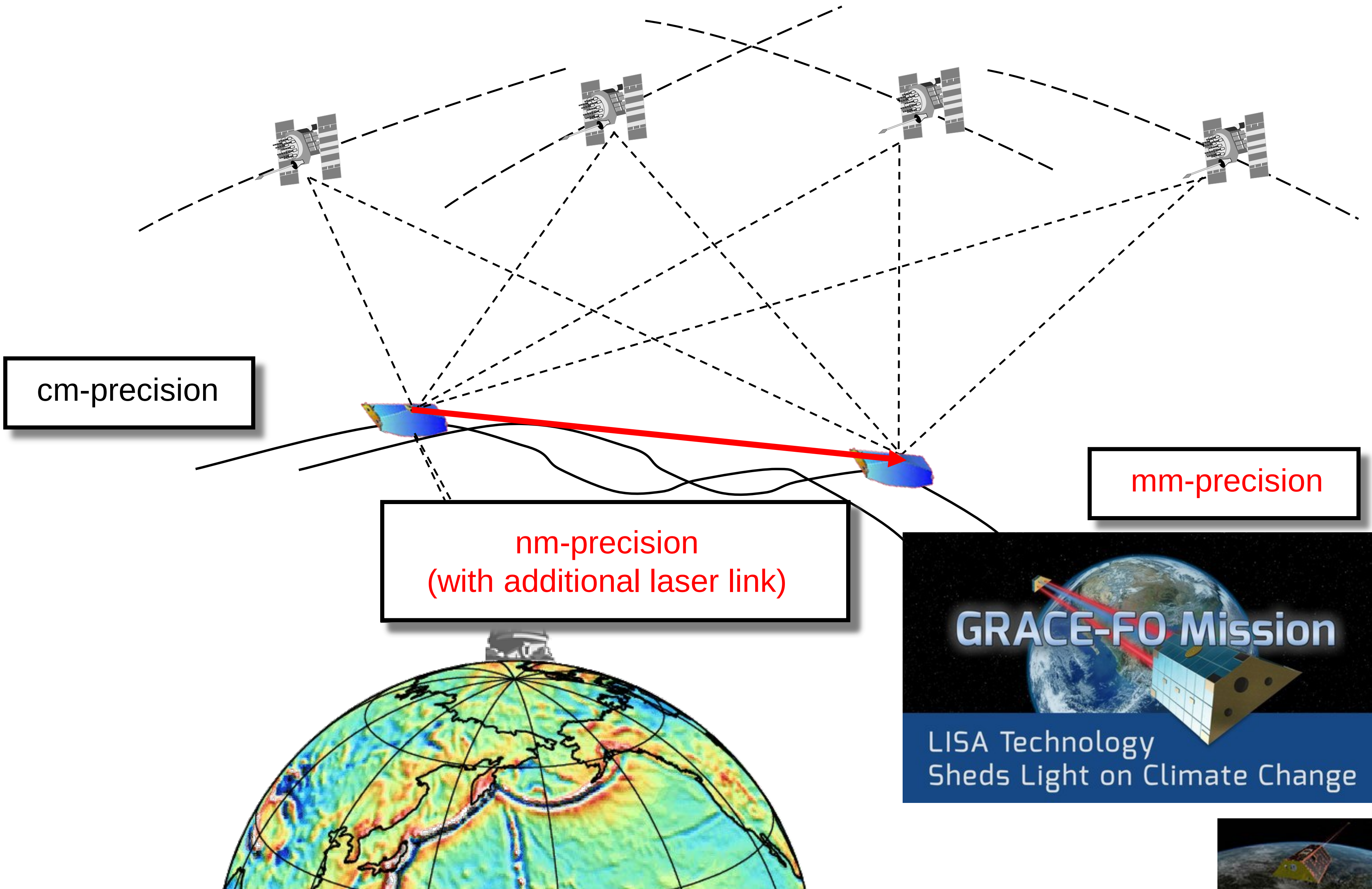
(geoid heights)

l_{max}	# Coeff.	λ [km]
20	441	1000
100	10 201	200
200	40 401	100
250	63 001	80

λ … spatial (half) wavelength

A spherical harmonic expansion up to a certain maximum degree l_{max} is most commonly used to represent the Earth's gravity potential.

Measuring Satellite Motion

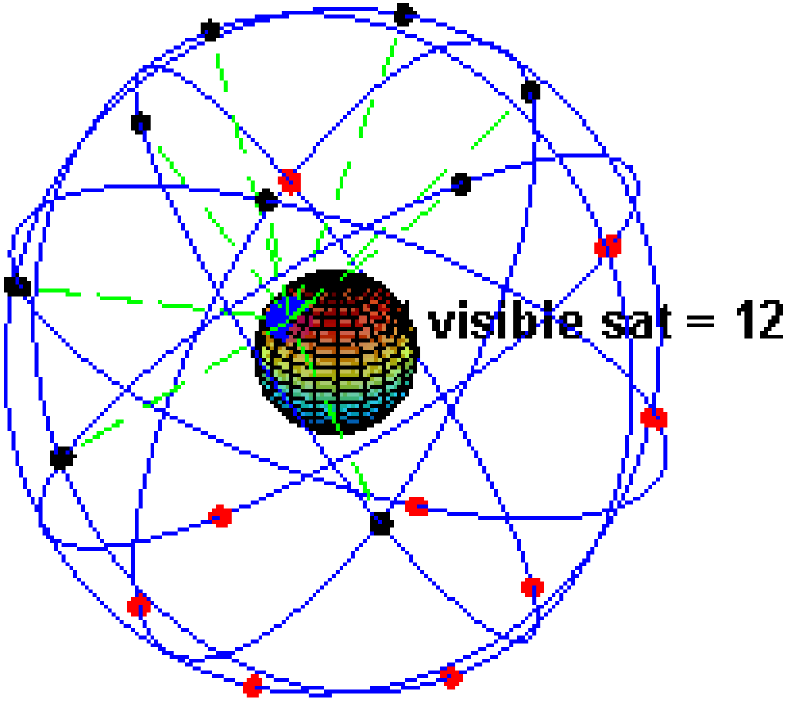


Swiss Optical Ground Station and Geodynamics Observatory in Zimmerwald

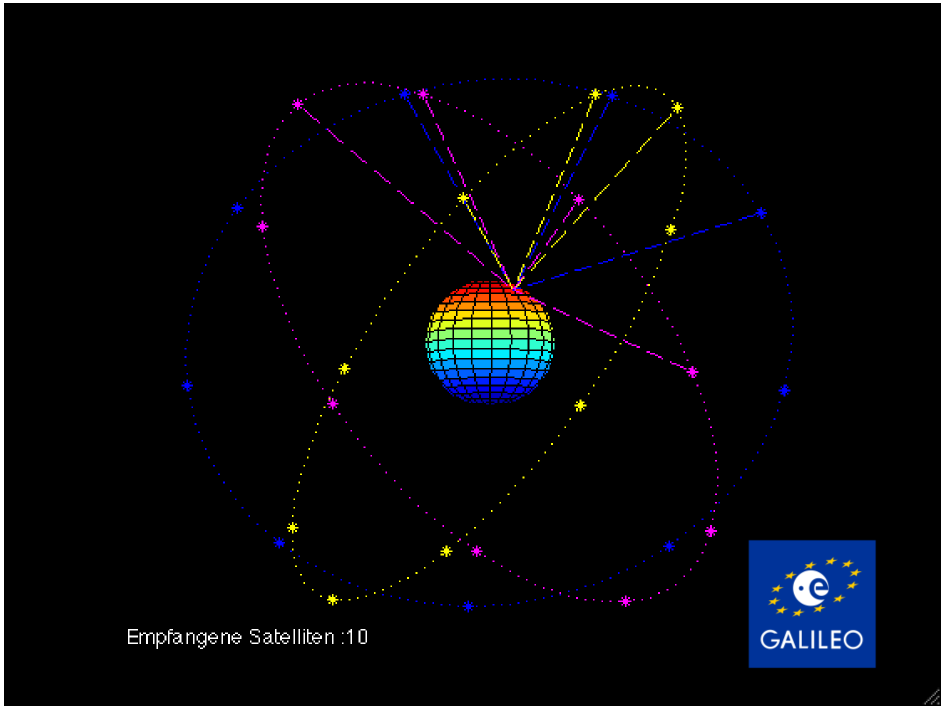
- Measuring distances to satellites equipped with retro-reflectors with Satellite Laser Ranging (SLR)
- Fully automated, 24/7 operations
- Telescope used for both SLR and optical astronomy
- One of the most productive SLR stations worldwide (and usually the most productive one on the Northern hemisphere).

Center for Orbit Determination in Europe

Global Positioning System (GPS)

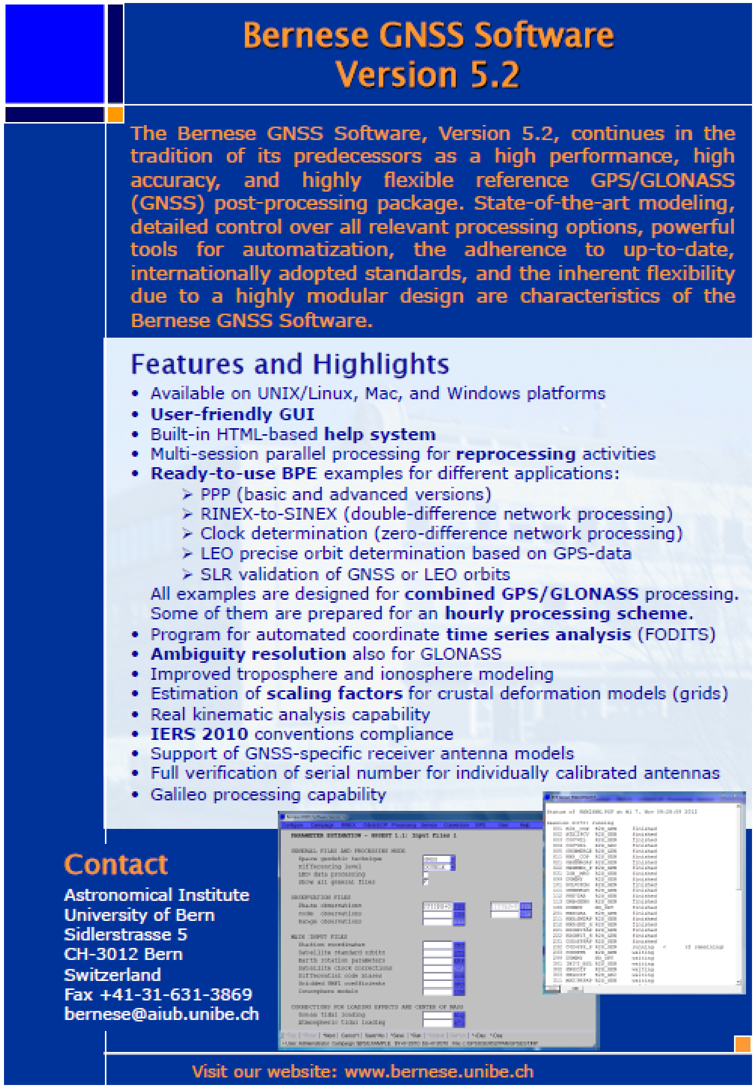


Galileo



Precise orbits for GPS, Galileo und other Global Navigation Satellite Systems are operationally computed at the Center for Orbit Determination in Europe located at the Astronomical Institute of the University of Bern.

Bernese GNSS Software



Bernese GNSS Software Version 5.2

The Bernese GNSS Software, Version 5.2, continues in the tradition of its predecessors as a high performance, high accuracy, and highly flexible reference GPS/GLONASS (GNSS) post-processing package. State-of-the-art modeling, detailed control over all relevant processing options, powerful tools for automatization, the adherence to up-to-date, internationally adopted standards, and the inherent flexibility due to a highly modular design are characteristics of the Bernese GNSS Software.

Features and Highlights

- Available on UNIX/Linux, Mac, and Windows platforms
- **User-friendly GUI**
- Built-in HTML-based **help system**
- Multi-session parallel processing for **reprocessing** activities
- **Ready-to-use BPE** examples for different applications:
  - PPP (basic and advanced versions)
  - RINEX-to-SINEX (double-difference network processing)
  - Clock determination (zero-difference network processing)
  - LEO precise orbit determination based on GPS-data
  - SLR validation of GNSS or LEO orbits

  All examples are designed for **combined GPS/GLONASS** processing. Some of them are prepared for an **hourly processing scheme**.
- Program for automated coordinate **time series analysis** (FODITS)
- **Ambiguity resolution** also for GLONASS
- Improved troposphere and ionosphere modeling
- Estimation of **scaling factors** for crustal deformation models (grids)
- Real kinematic analysis capability
- **IERS 2010** conventions compliance
- Support of GNSS-specific receiver antenna models
- Full verification of serial number for individually calibrated antennas
- Galileo processing capability

Contact

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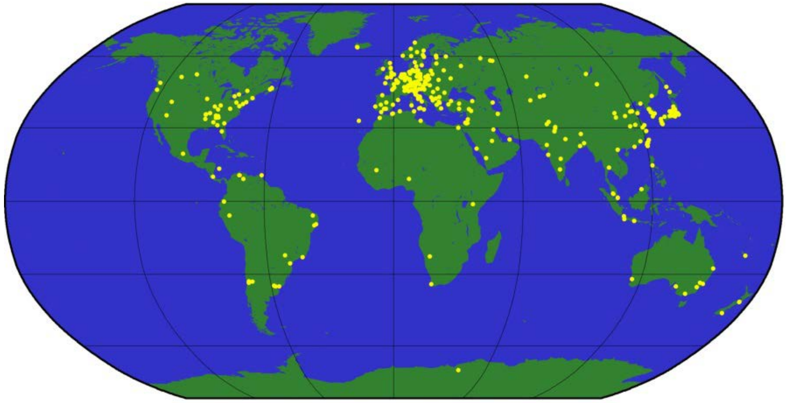
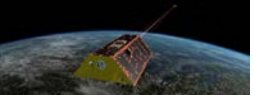


The Bernese GNSS Software is a scientific software package for high precision analysis of various space geodetic data. It is developed since many years at the Astronomical Institute of the University of Bern and is meanwhile used by more than 700 institutions worldwide.



Modeling Satellite Motion

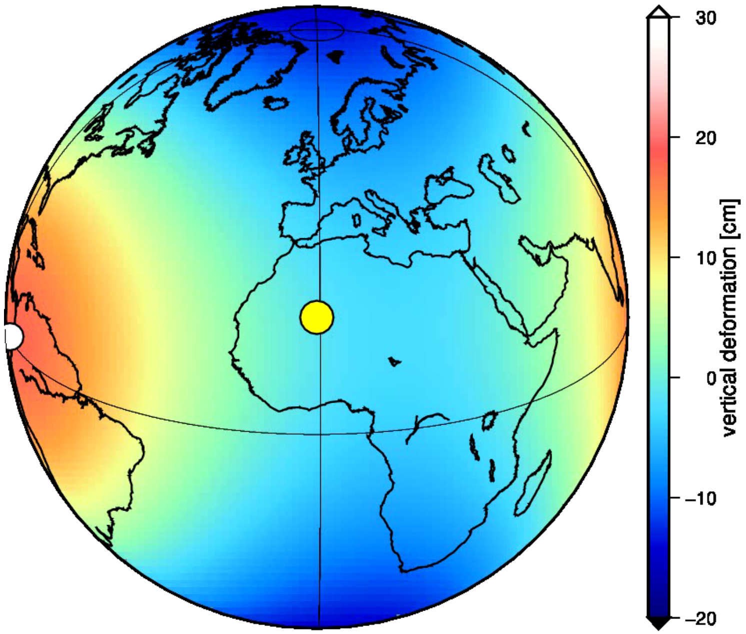
Equation of motion

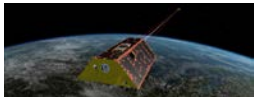
$$m \cdot \ddot{\vec{x}} = \vec{F}(t, \vec{x}, \ldots)$$

=> Numerical integration of the orbit

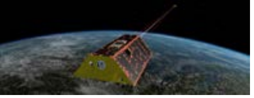
Force modeling:

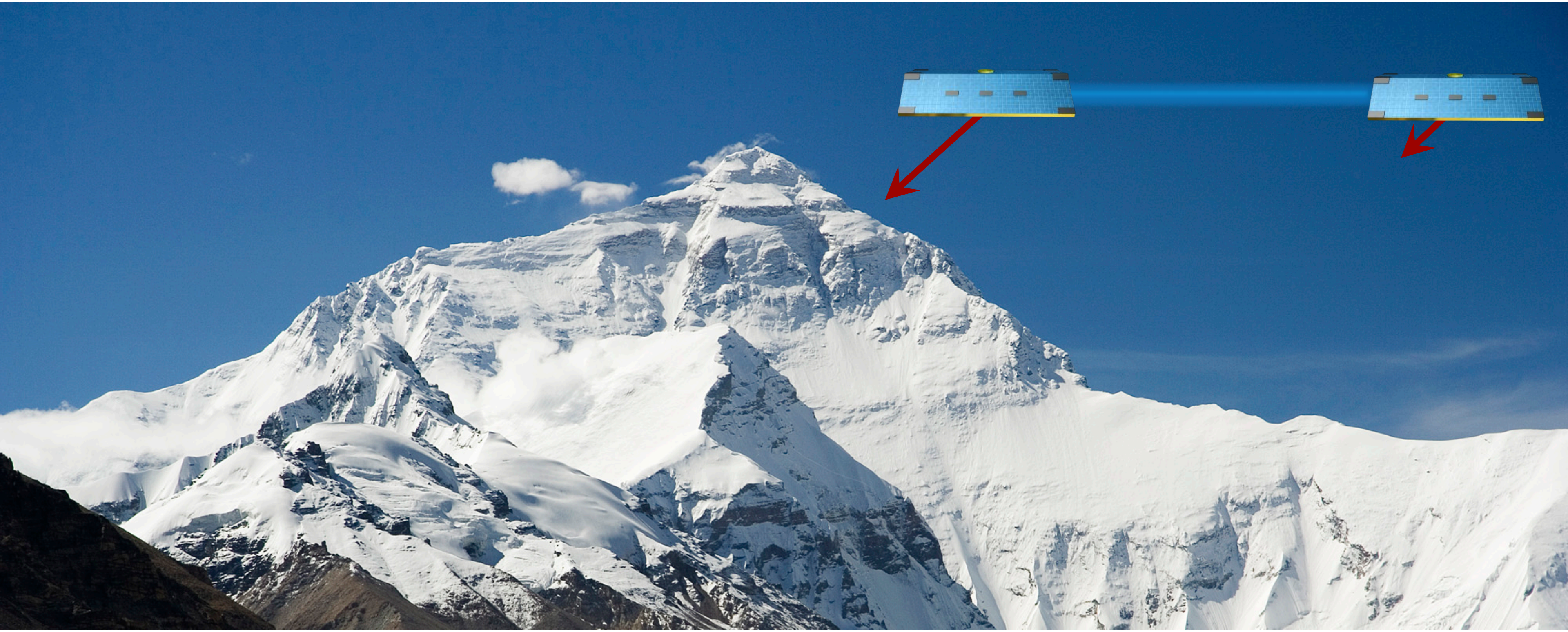
- Static gravity field
- Additional bodies (sun, moon, planets)
- Solid Earth tides
- Ocean tides
- Pol tides
- Ocean pole tides
- Atmospheric tides
- Dealiasing (atmosphere, ocean)
- Non-gravitational forces
- Relativistic effects

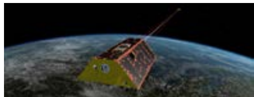




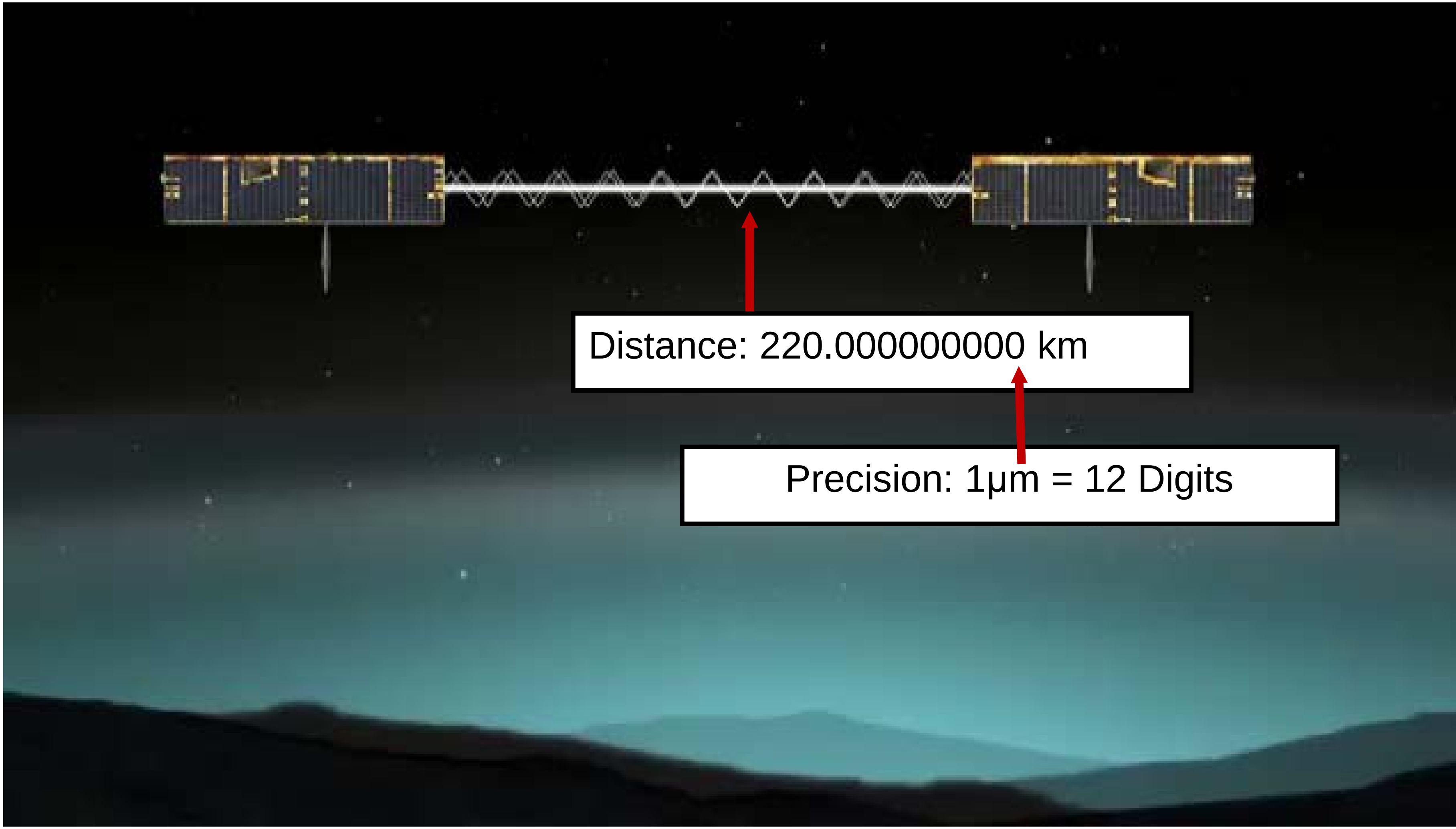
Measurement Principle







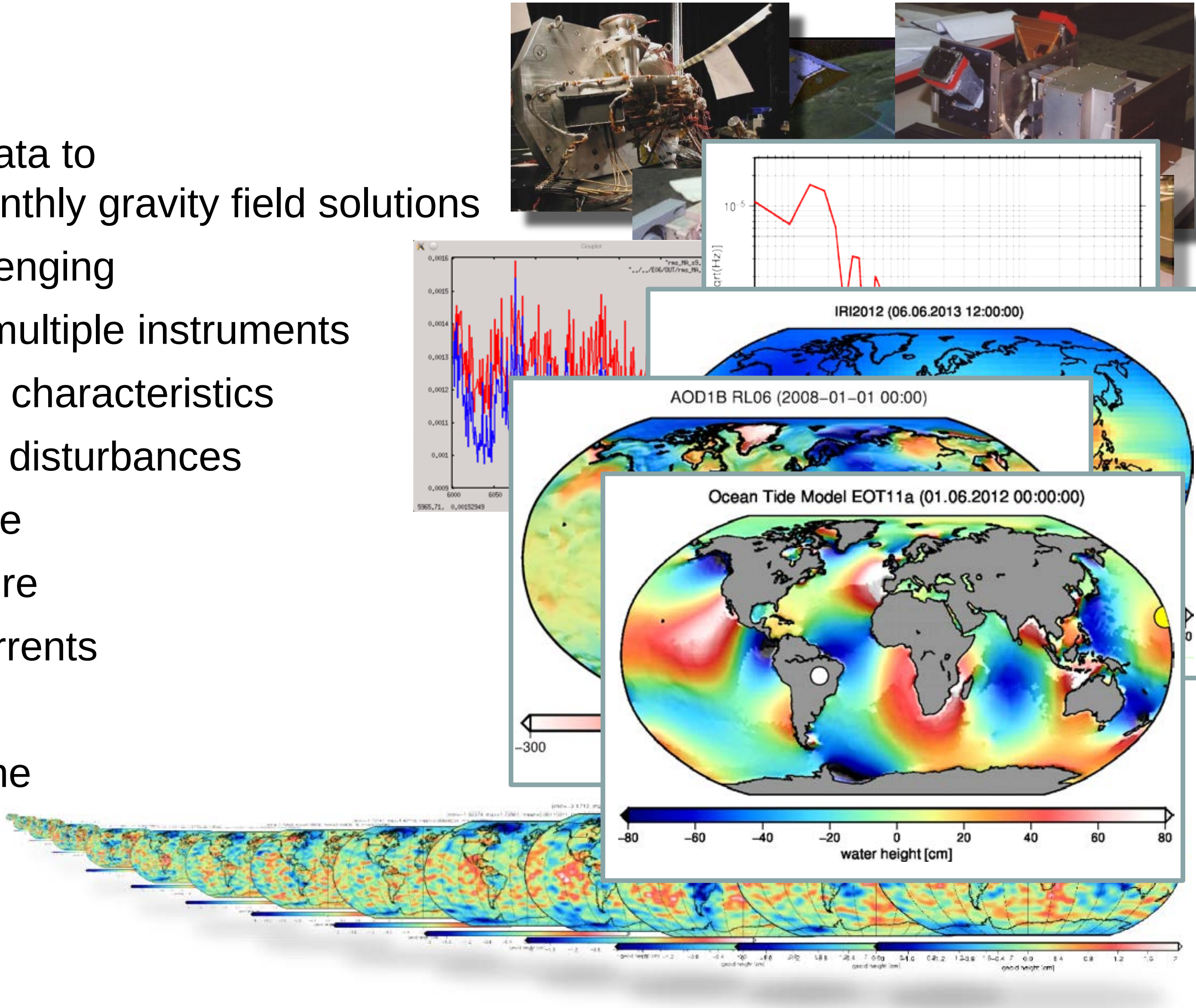
Measurement Principle



That’s much more precise than measuring the absolute or relative position with GPS or SLR (cm or mm).

Challenging Data Processing

- Process GRACE data to
  a time series of monthly gravity field solutions
- Processing is challenging
  - Interaction of multiple instruments
  - Different noise characteristics
  - Environmental disturbances
    - Ionosphere
    - Atmosphere
    - Ocean currents
    - Tides
  - There is not one
    „true“ solution

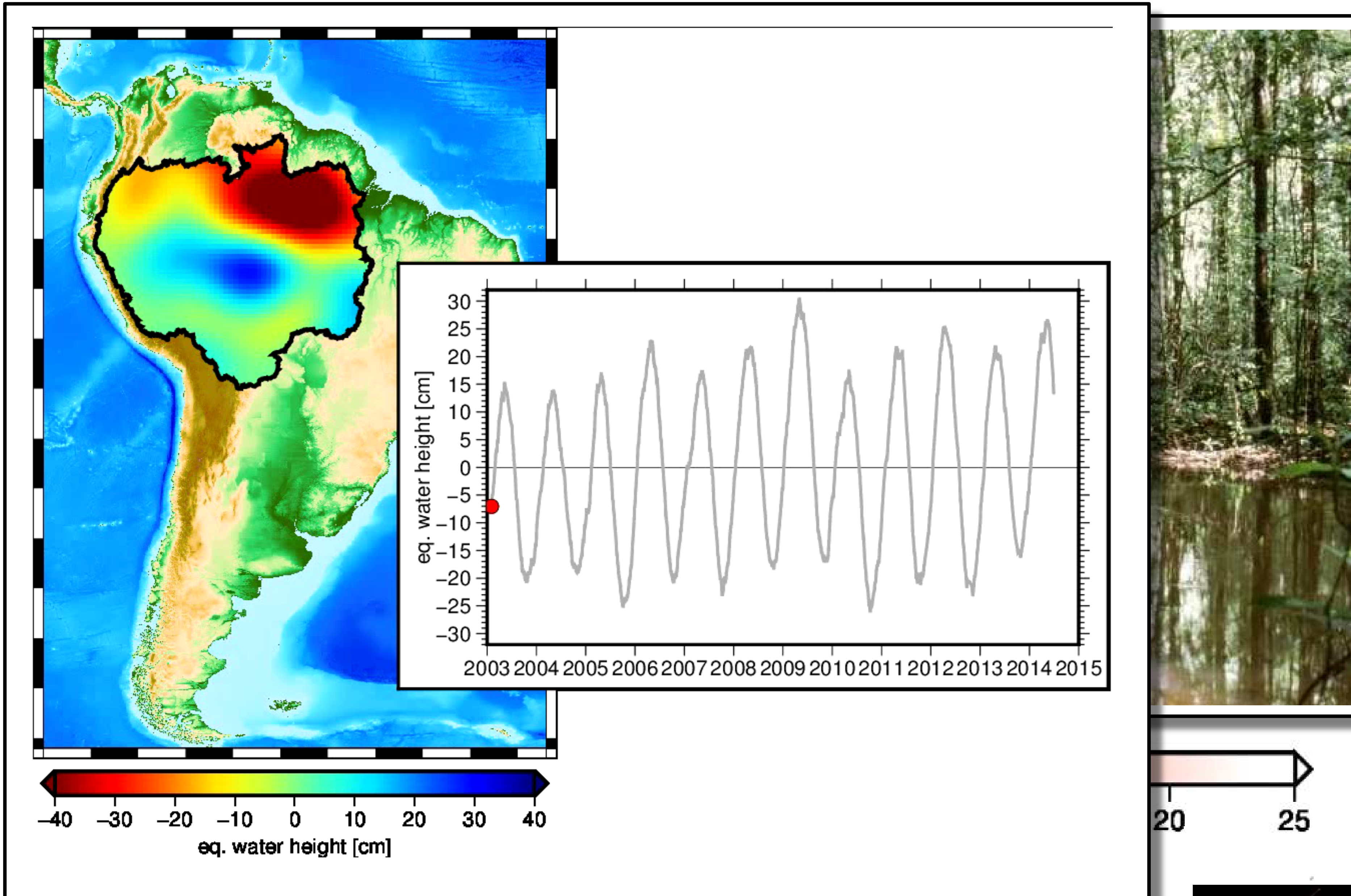


... and even more challenging with laser

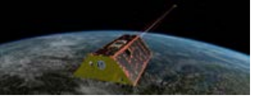
LISA: Laser Interferometer Space Antenna, launched in May 2018

Which changes can be measured

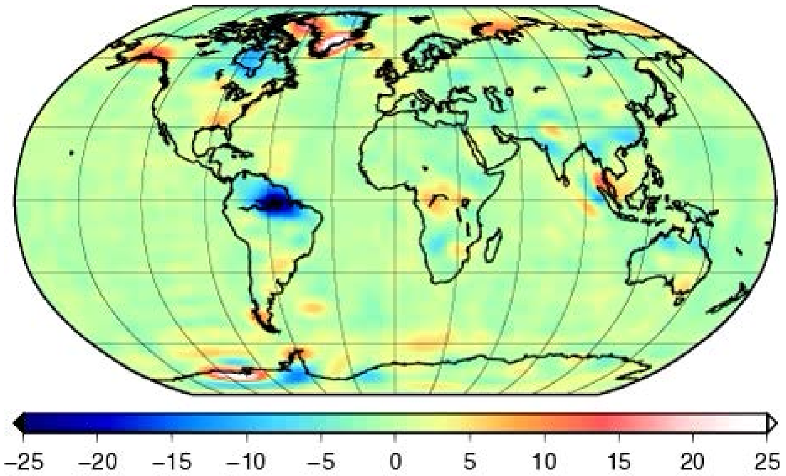
Time Variations

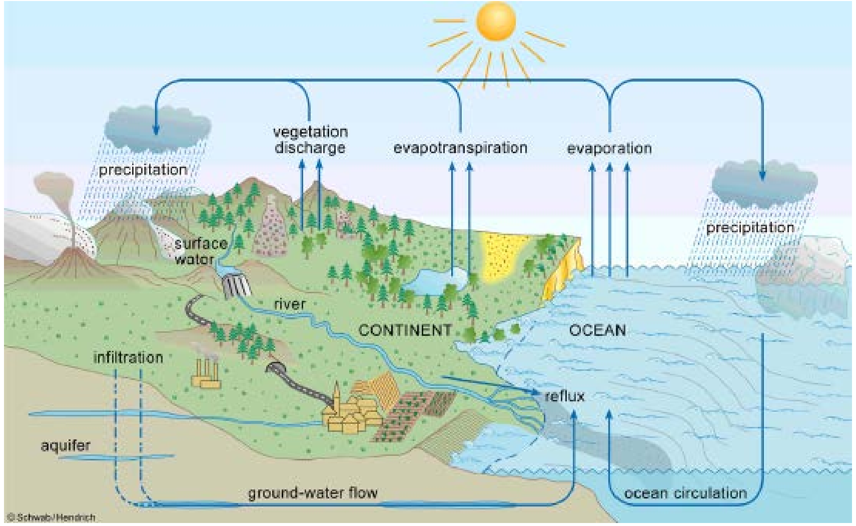


[$1km^3$ = 1Gt water]



Global Water Cycle





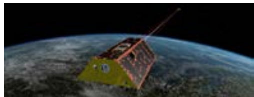
ΔTWS(t) = ΔGW(t) + ΔSW(t) + ΔSWE(t) + ΔSM(t) - ΔRO(t)

ΔTWS(t) = Total Water Storage **Can only be measured by GRACE!**

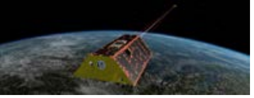
ΔGW(t) = Ground Water
ΔSW(t) = Surface Water } ΔAW(t) = Accessible Water
ΔSWE(t) = Snow Water Equivalent

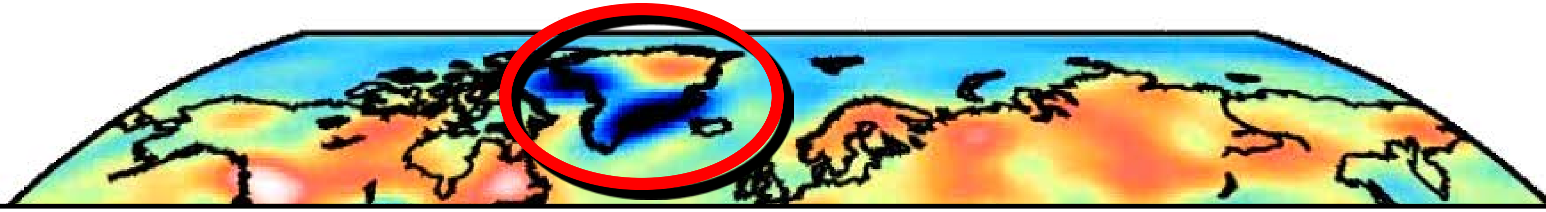
ΔSM(t) = Soil Moisture
ΔRO(t) = Run Off

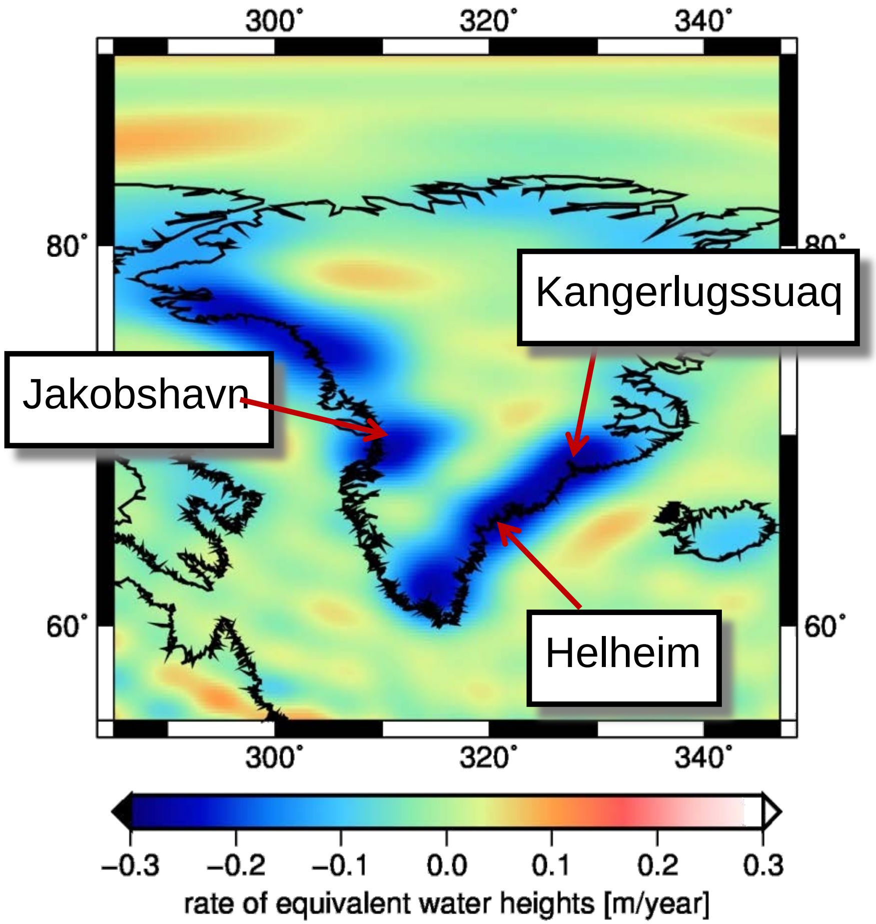
} **Separation needs further measurements**

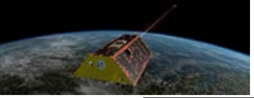


Time Variations

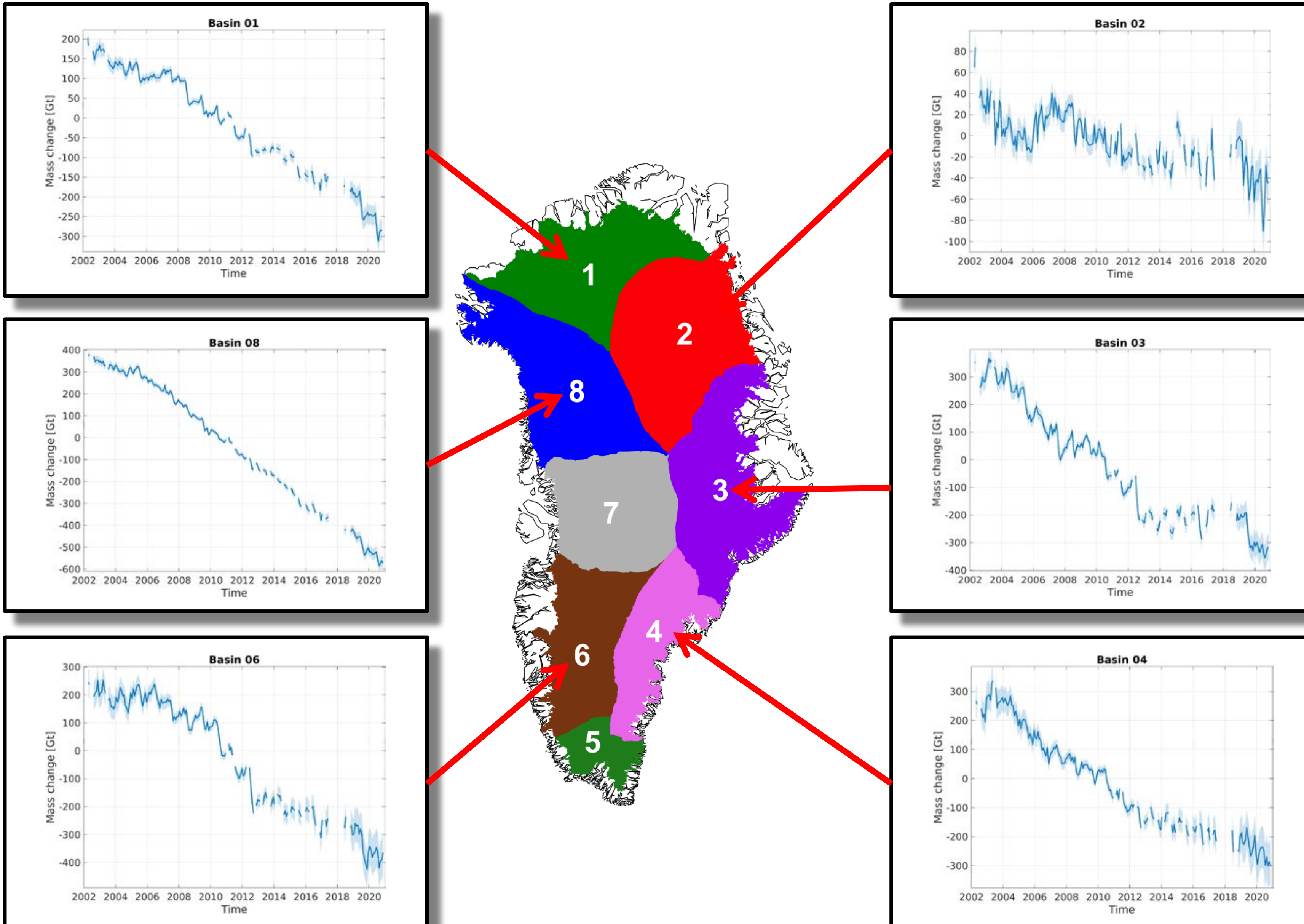








Melting Ice in Greenland



Mass Loss: ≈ 250 Gt/year

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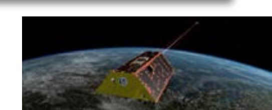


Melting Ice in Greenland

30 June, 2019: "Bern im All", Quiz on Bundesplatz:

How many

of these blocks are melting
in Greenland

every second ?

Melting Ice in Greenland

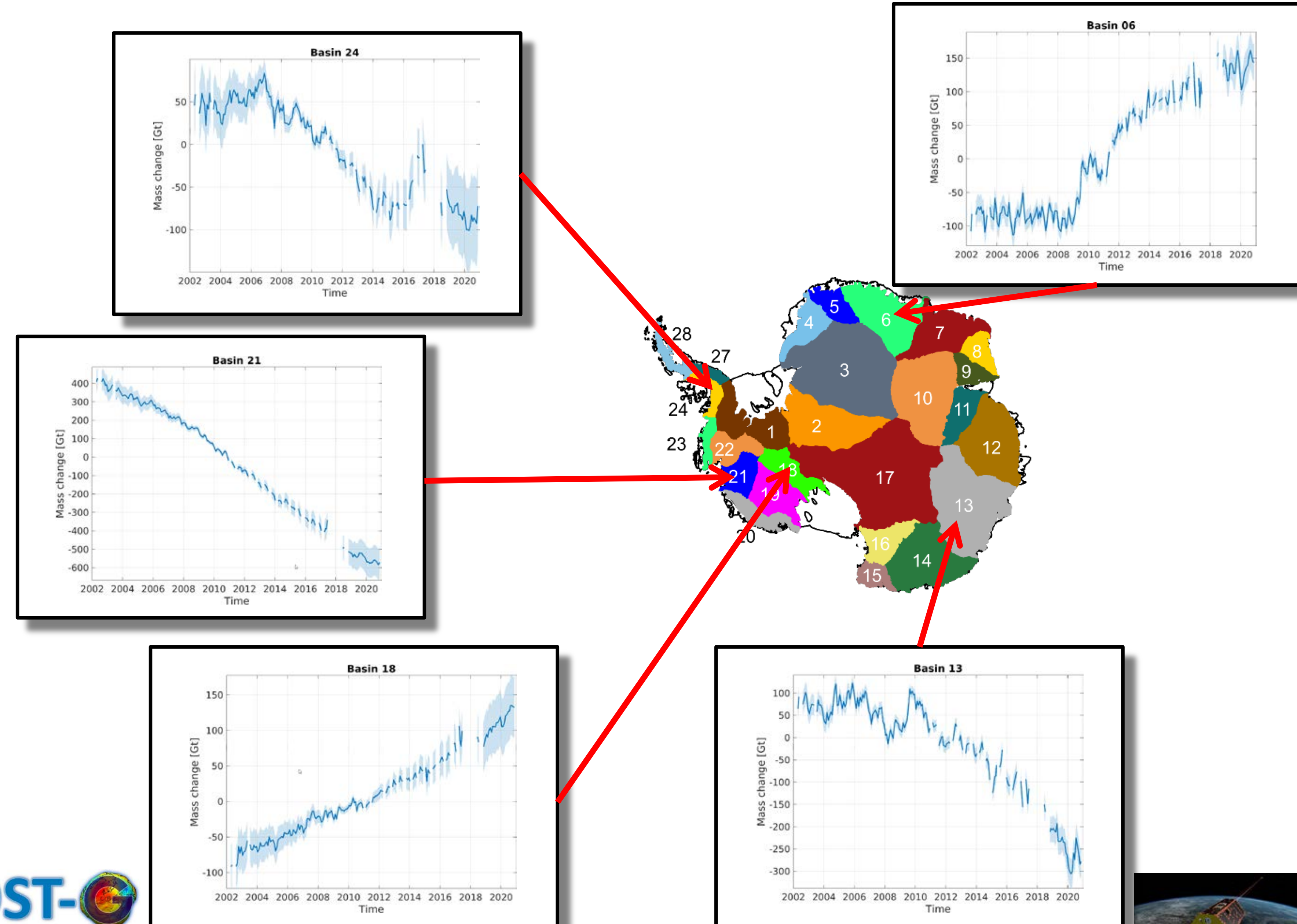
30 June, 2019: "Bern im All", Quiz on Bundesplatz:

≈10´000

of these blocks are melting
in Greenland

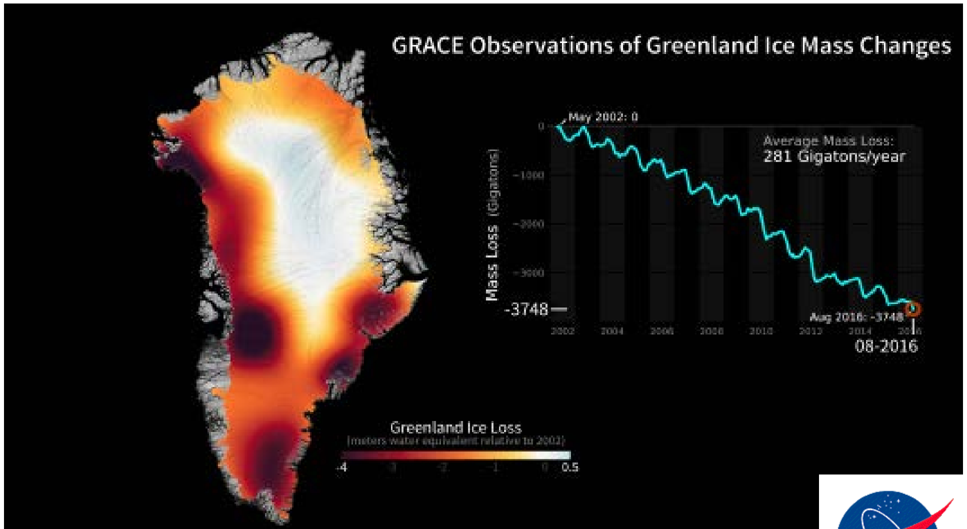
every second

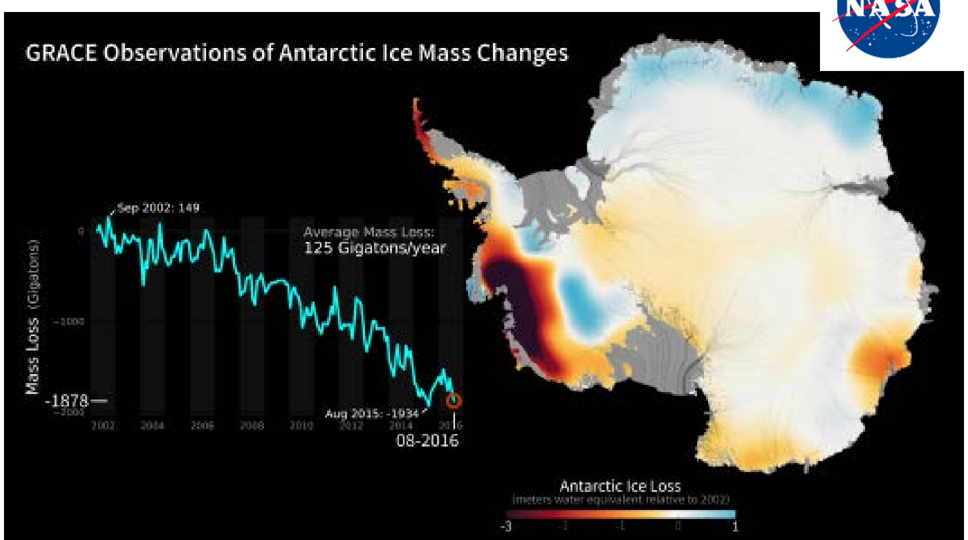
Melting Ice in Antarctica



COST-G
Combination Service for Time-variable Gravity Models

Melting Ice in Greenland

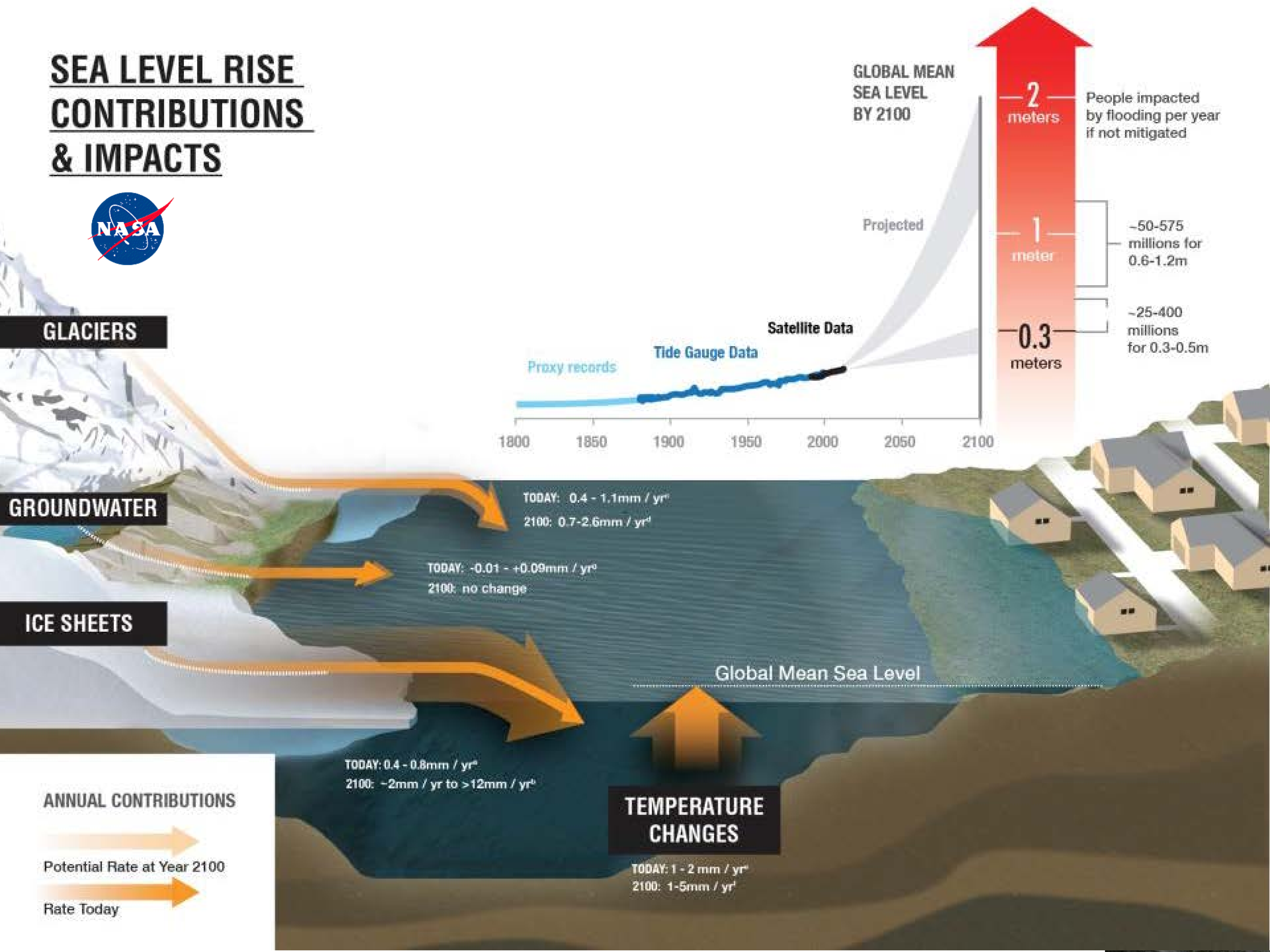




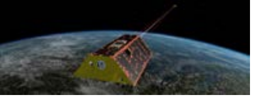
Greenland: ~7 m sea level eqv.
Antarctica: ~60 m sea level equivalent.

GRACE weighs the ice sheets and identifies loss and gain on regional level

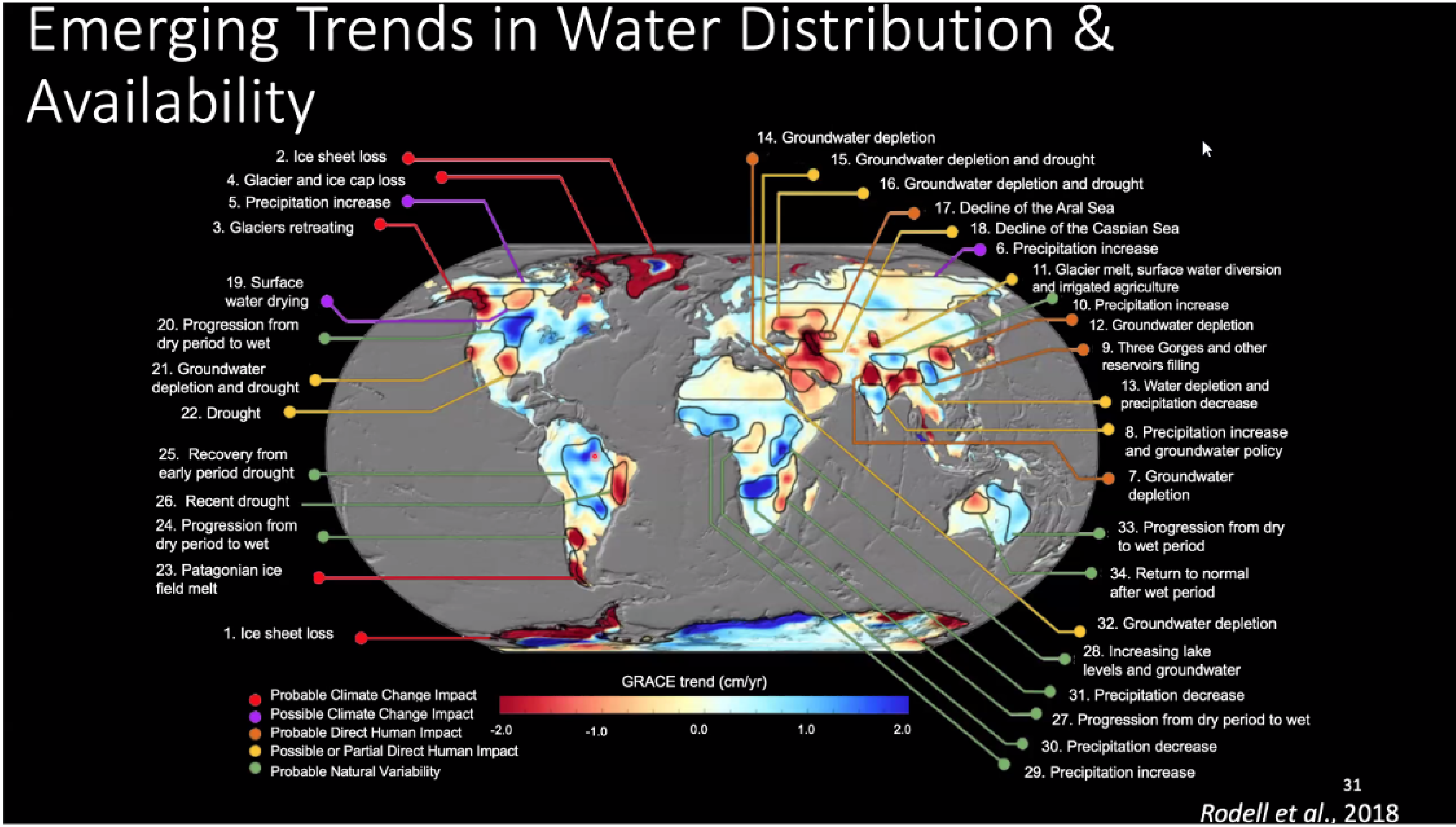
Continuous measurements ensure we identify regional change and long term vs short term variations which ensures an “early warning system”

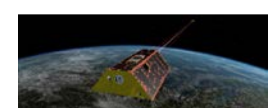


SEA LEVEL RISE CONTRIBUTIONS & IMPACTS
NASA
GLOBAL MEAN SEA LEVEL BY 2100
Projected
Satellite Data
Tide Gauge Data
Proxy records
1800
1850
1900
1950
2000
2050
2100
2 meters
1 meter
0.3 meters
People impacted by flooding per year if not mitigated
~50-575 millions for 0.6-1.2m
~25-400 millions for 0.3-0.5m
GLACIERS
TODAY: 0.4 - 1.1mm / yr
2100: 0.7-2.6mm / yr
GROUNDWATER
TODAY: -0.01 - +0.09mm / yr
2100: no change
ICE SHEETS
TODAY: 0.4 - 0.8mm / yr
2100: ~2mm / yr to >12mm / yr
Global Mean Sea Level
TEMPERATURE CHANGES
TODAY: 1 - 2 mm / yr
2100: 1-5mm / yr
ANNUAL CONTRIBUTIONS
Potential Rate at Year 2100
Rate Today

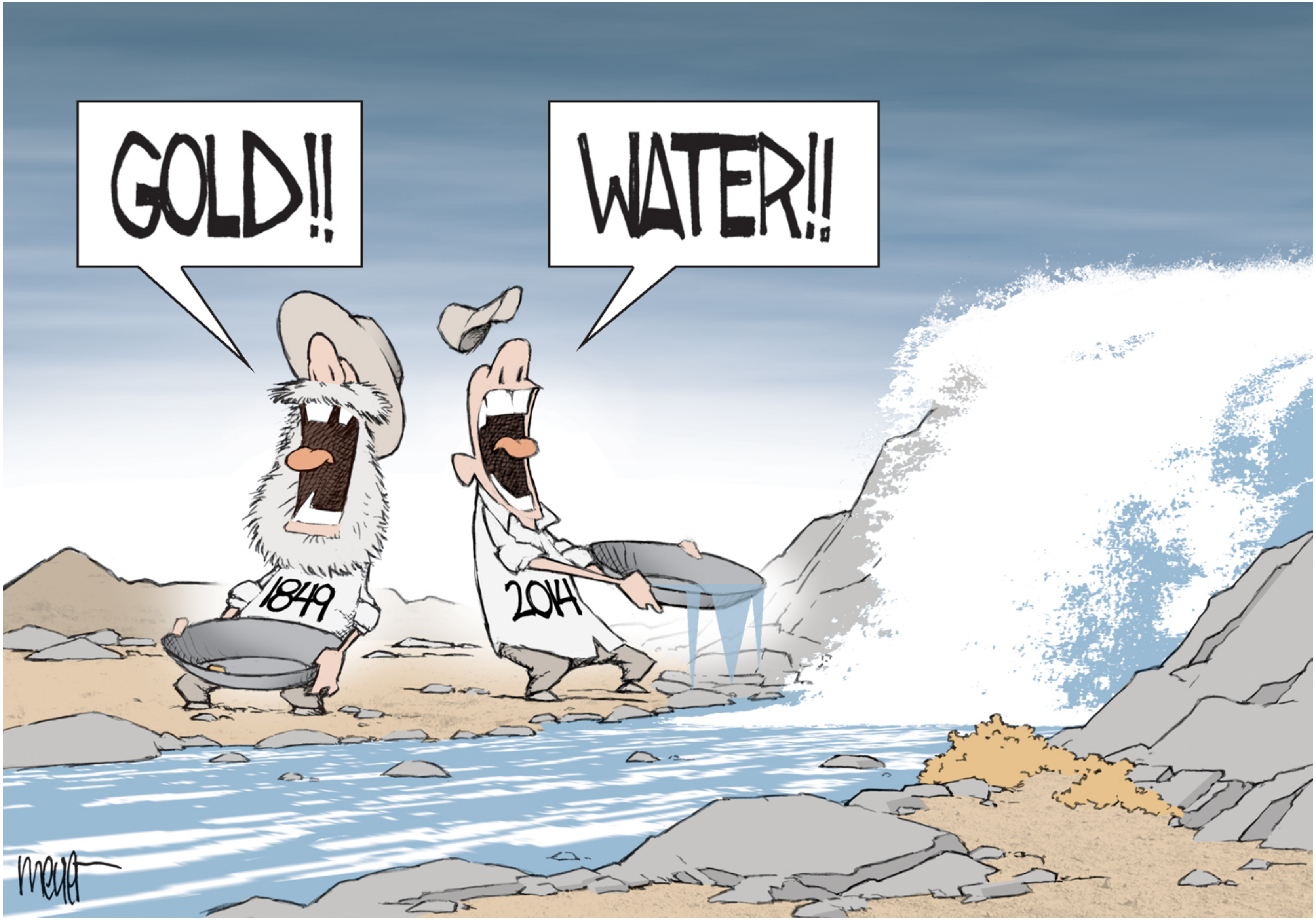


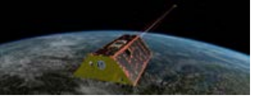
Availability of Water





Example: Drought in California



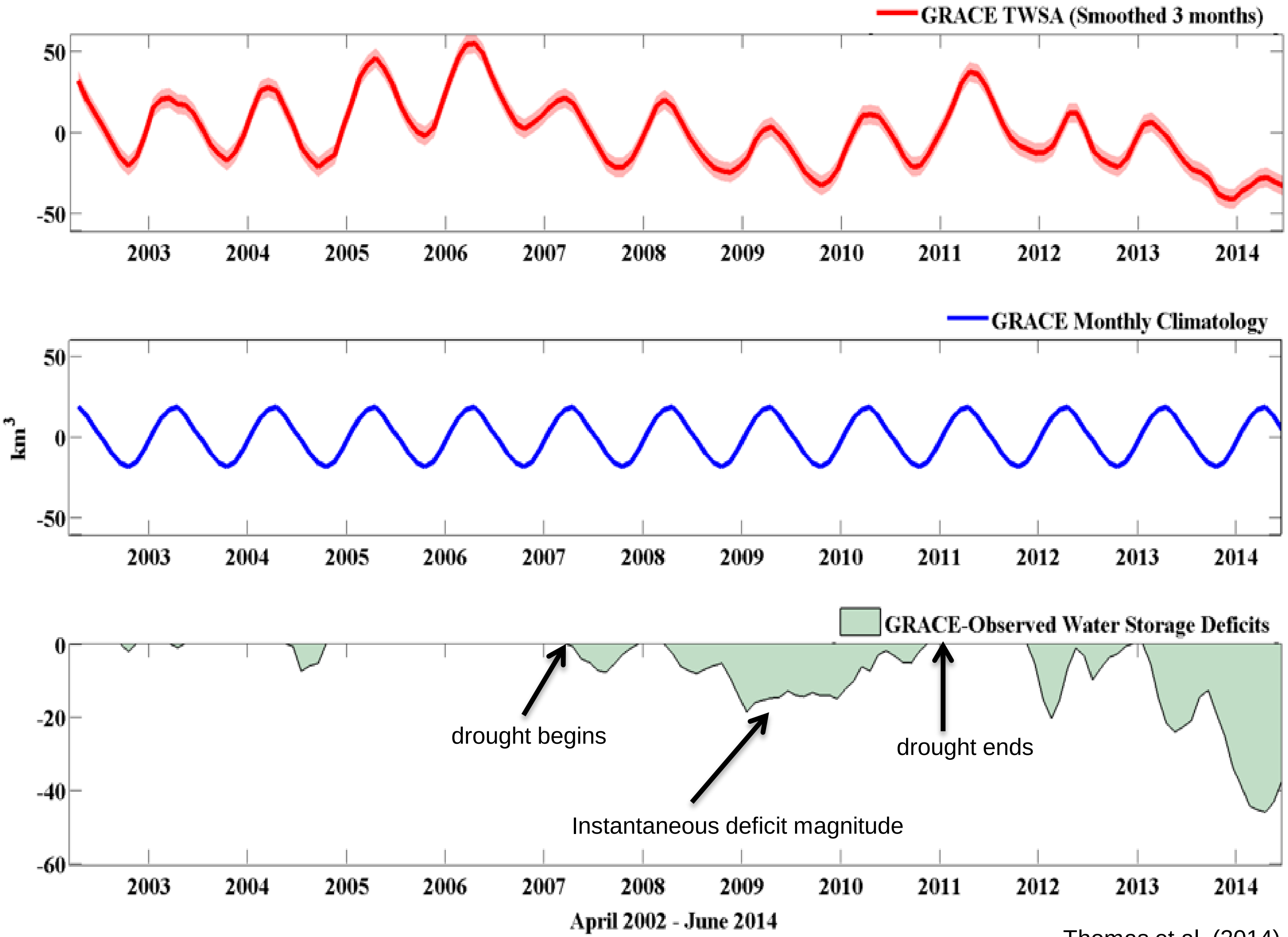


Example: Drought in California

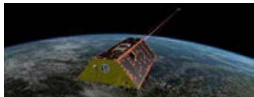
Actual Water Storage Variations

'Normal' range of Water Storage Variations

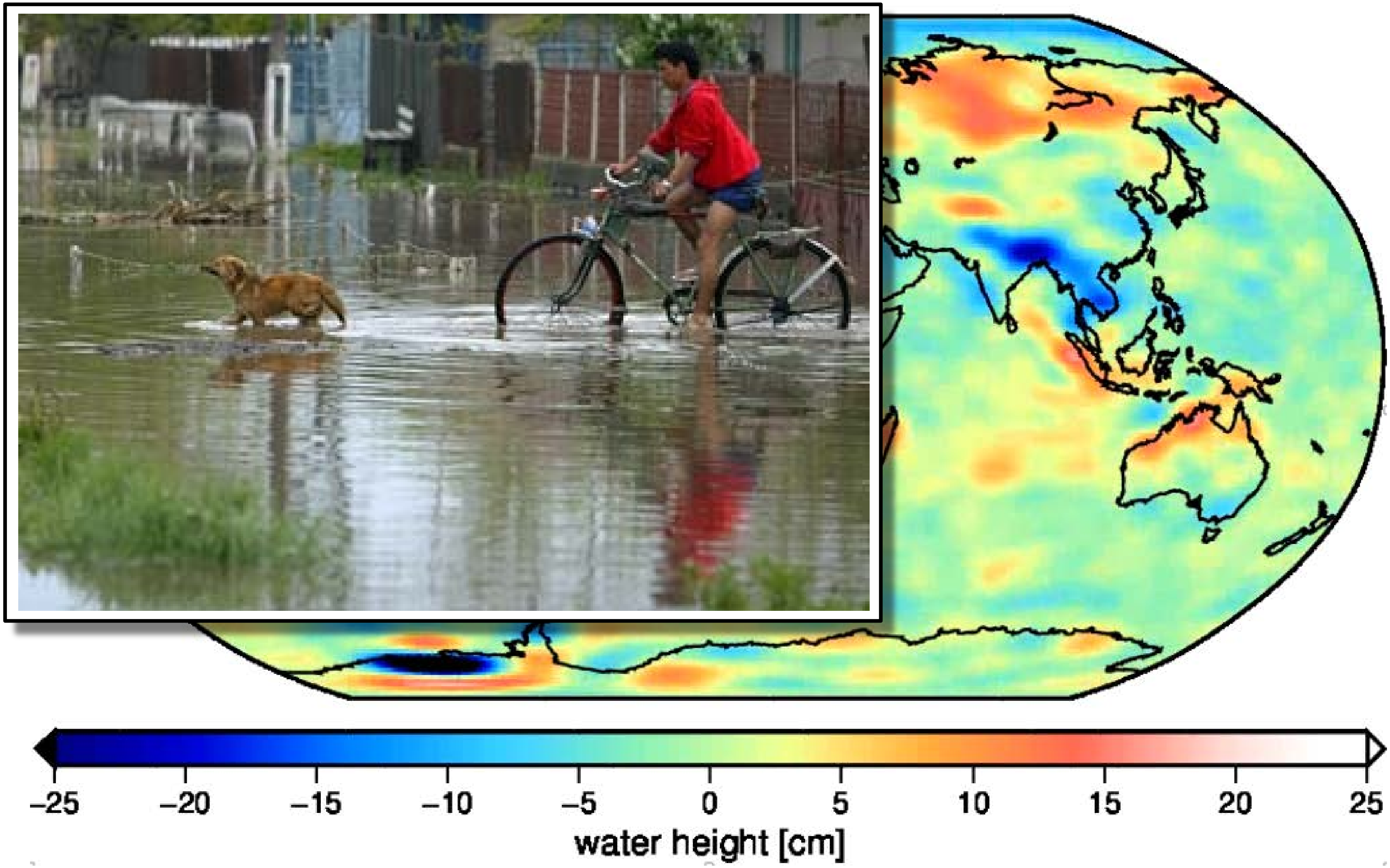
Difference to 'normal' dry conditions

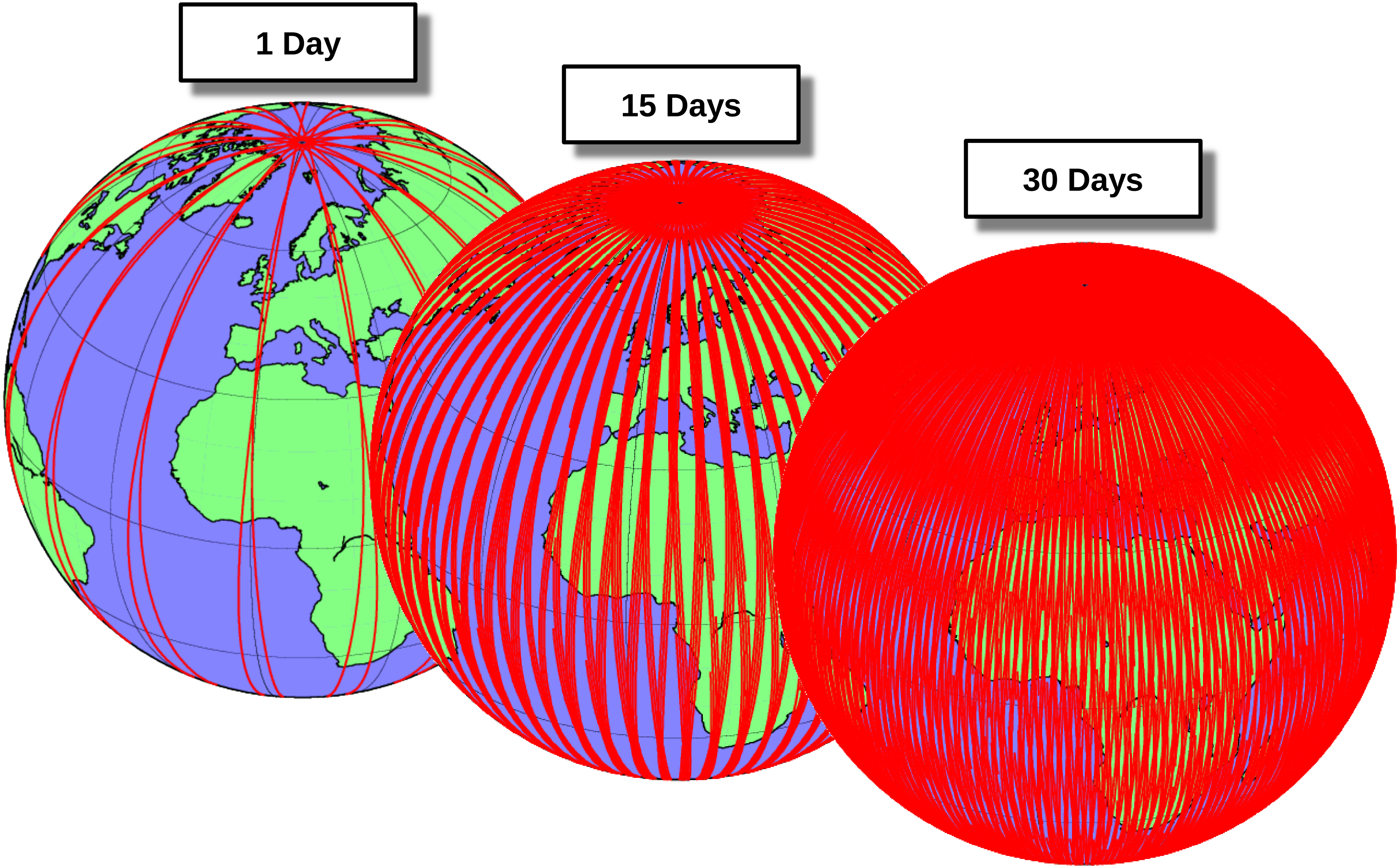


Thomas et al. (2014)

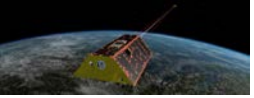


Example: Floods

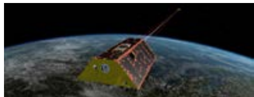



1 Day
15 Days
30 Days


EGSIEM
Hydrological Extreme Events
as Seen by GRACE
November 01, 2005
−25 −15 −5 5 15 25
Total Water Storage Anomaly [cm]
(seasonal and secular variations removed)



Could these data be helpful for early warning?

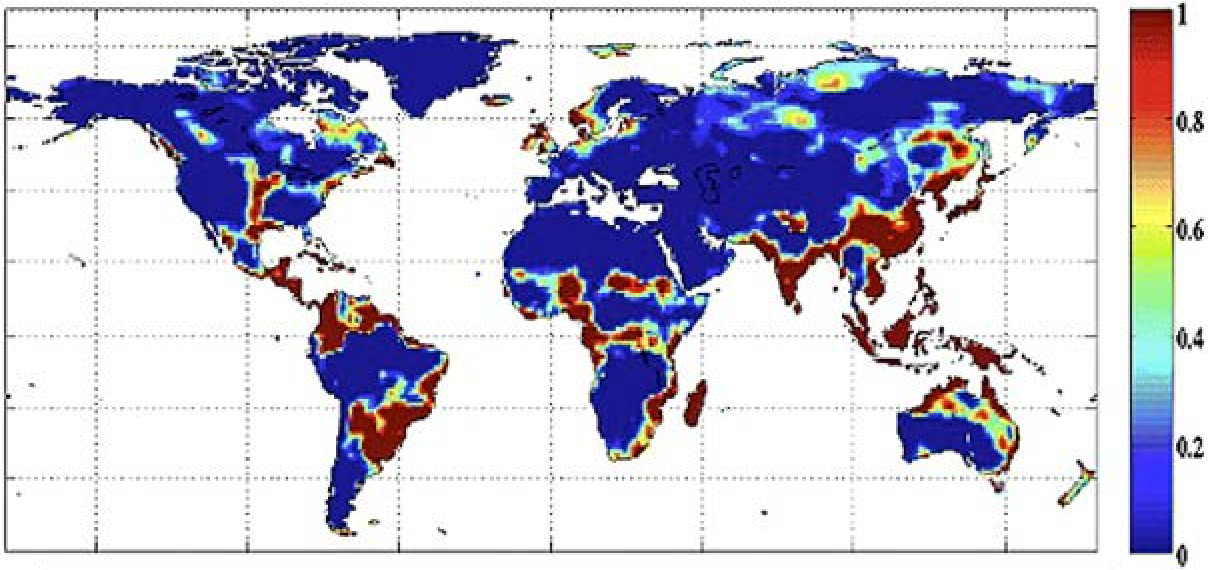


Potentially yes, …

Saturated soils → One factor, which may favor the development of floods

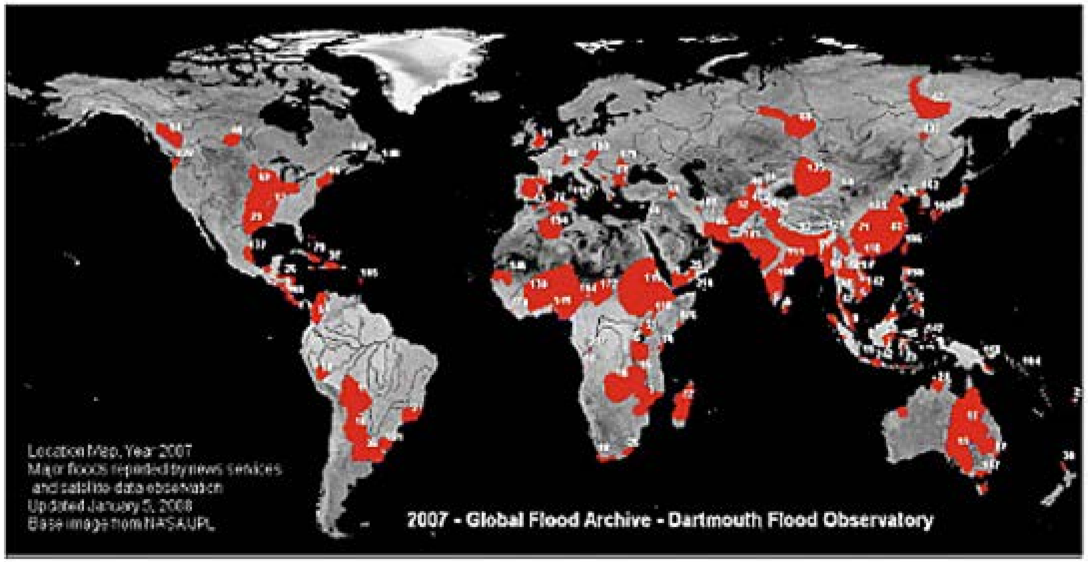
Unusual developments in Total Water Storage may serve in the future as an additional indicator for the potential development of floods.

Potentially yes, …



GRACE-derived flood index for May 2007.

Usually this information is only available two months later, and only with a time resolution of one month.

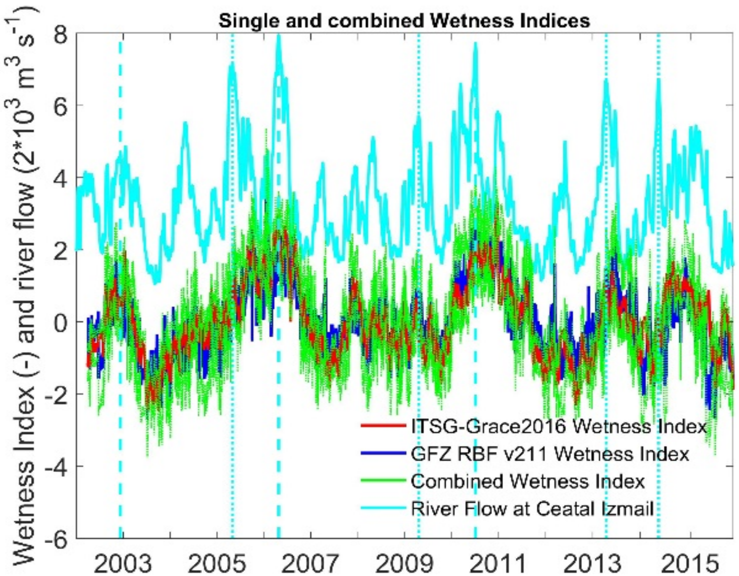


In May 2007 actually occurring floods.

In order to be useful, it will be necessary to have this information in near real-time and significantly improved (daily) time resolution.

Reager and Famiglietti (2009)

Wetness index for early flood warning

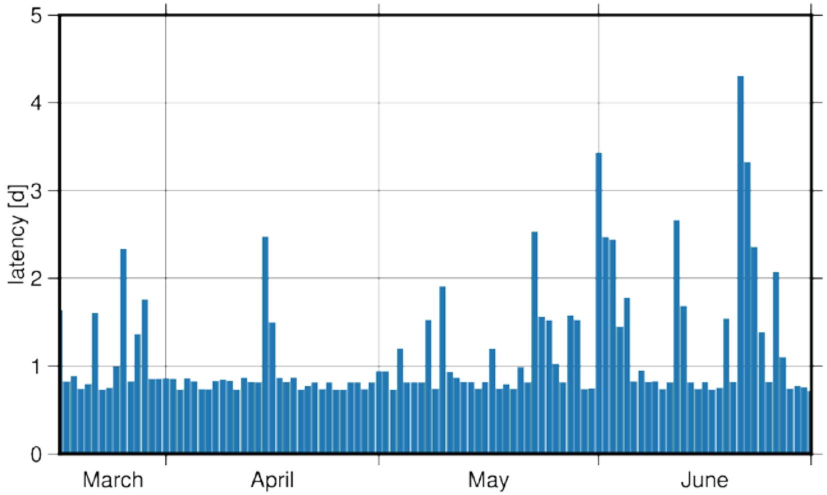


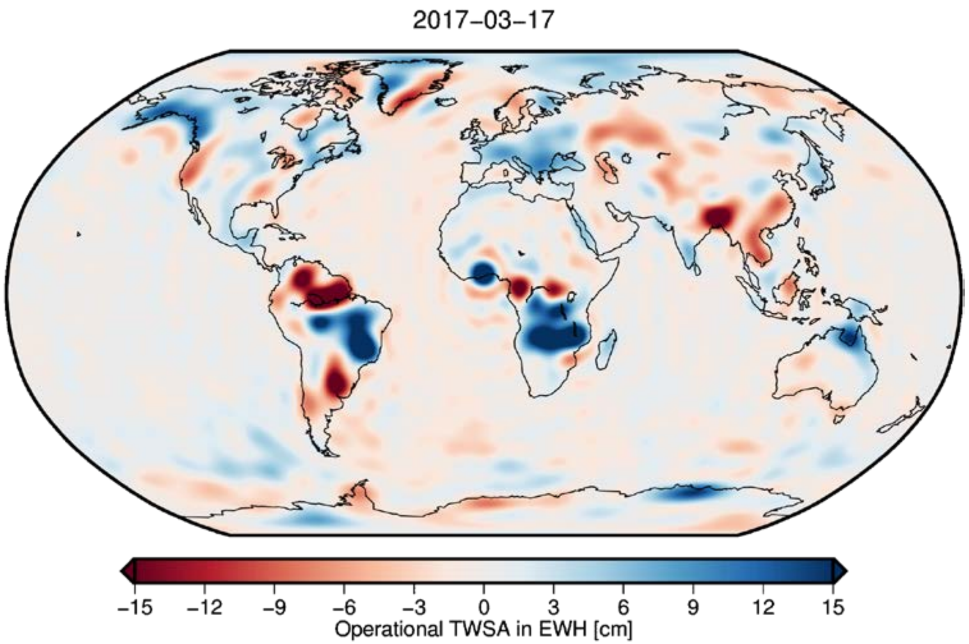
Year	Major flood event in the basin	Peak Flow at Ceatal Izmal		Flood Warning if WI > 2		Lead time (days)	Comment
		Date	Qmax (10^3 m^3/s)	Date	WI		
2002	x	02.09.	17.4	-			False negative
2003	x	20.01.	19.5	12.01.	2.0	8	Correct positive
2004		29.04.	22.2	-			Correct negative
2005	x	02.05.	28.8	-			False negative
2006	x	26.04.	31.8	14.03.	2.4	43	Correct positive
2007		14.12.	17.2	-			Correct negative
2008		28.04.	20.6	-			Correct negative
2009	x	21.04.	22.8	02.03.	(0.9)	42	False negative
2010	x	06.07.	30.9	30.05.	2.3	37	Correct positive
2011		04.01.	23.1	26.01.	2.2	-12	False positive
2012		03.06.	20.1	-			Correct negative
2013	x	18.04.	26.8	02.04.	(1.2)	16	False negative
2014	x	09.06.	27.0	-			False negative
2015		18.03.	21.7	-			Correct negative

Retrospective analysis of daily solutions for the Danube basin.

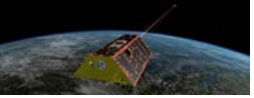
Particularly relevant with respect to early flood warning is the build-up of basin-wide water storage of several weeks duration prior to the larger flood events.

Near Real-Time Solutions





An operational test run of near real-time gravity field solutions has been demonstrated in the final months of the GRACE mission.



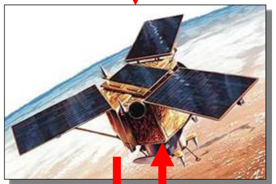
Rapid Mapping

ZKI: Center for satellite-based crisis information

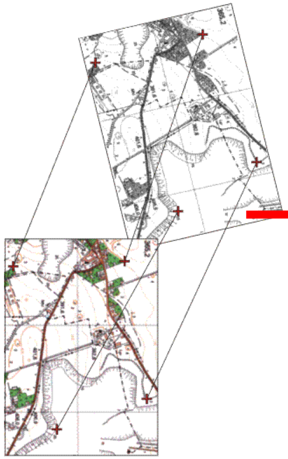
ZKI

alarm

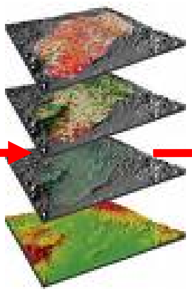
Possible idea for the future:
Earlier alarms thanks to
gravity based indicators



Data provision



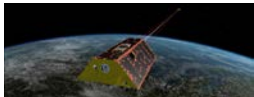
Pre-processing

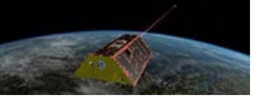


Analysis

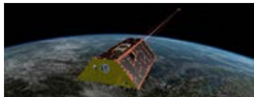
Map generation

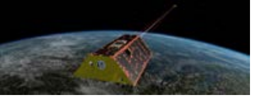
Transfer





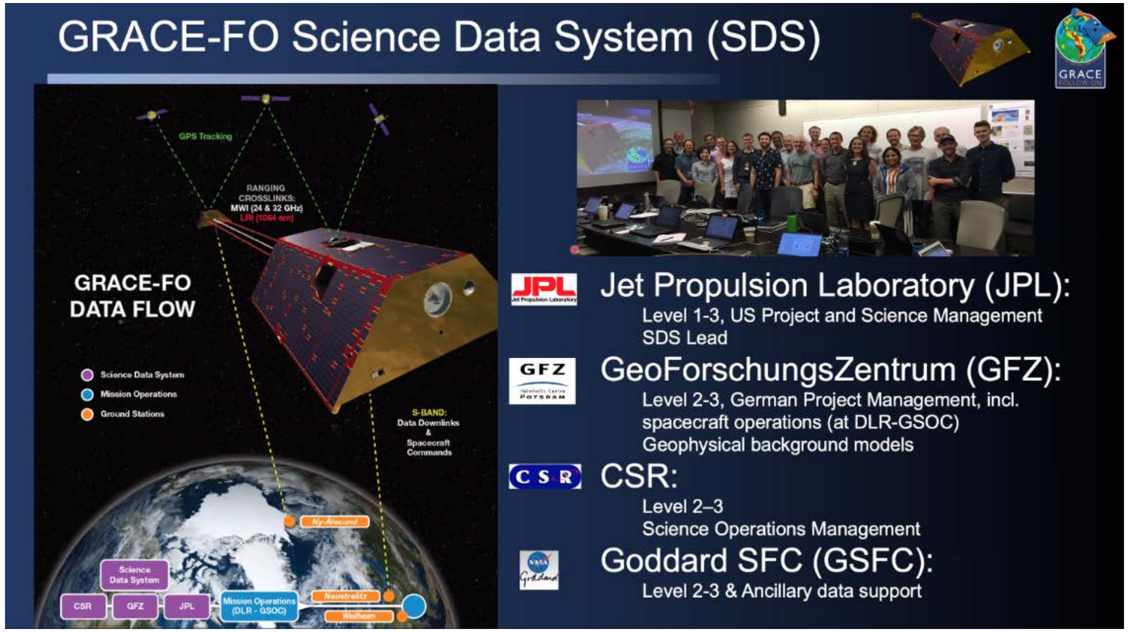
European initiatives and future perspectives





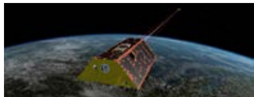
GRACE-FO Analysis Centers

SDS Analysis Centers



European Analysis Centers

Chinese Analysis Centers



European Gravity Initiatives

The University of Bern coordinated the H2020 project EGSIEM (2015-2017). It was explicitly mentioned in NASA's Decadal Survey and paved the way for the current activities.

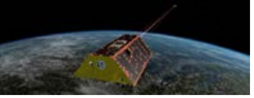
EGSIEM
European Gravity Service for Improved Emergency Management
http://egsiem.eu/

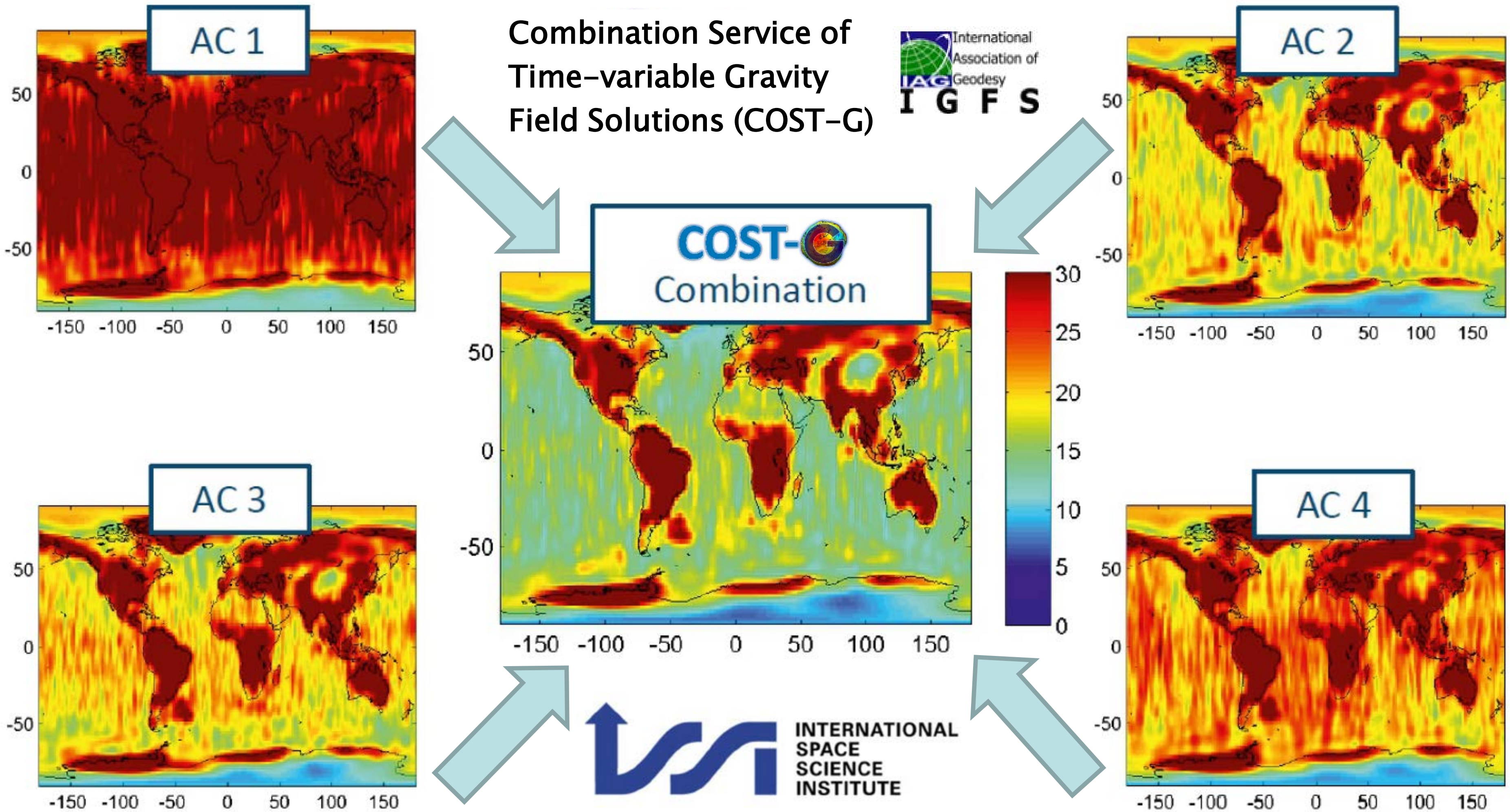
Parts of EGSIEM are now continued as a new IAG activity called COST-G, coordinated again by the University of Bern.

COST-G
Combination Service for Time-variable Gravity Models
http://cost-g.org/

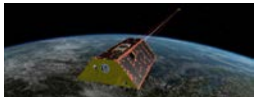
The University of Bern initiated to strive for a H2020 follow-up of EGSIEM with the same gravity core-group as in EGSIEM: Global Gravity-based Groundwater Product (G3P), a H2020 project coordinated by GFZ (2020-2022).

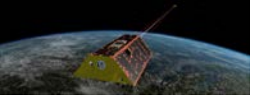
G3P
https://www.g3p.eu/





Improved and consolidated product integrating the strengths of all ACs





COST-G

Combination Service for Time-variable Gravity Fields

Home | Introduction | Consortium | Service | Products | The COST-G Plotter | Documents | Contact

Welcome to COST-G

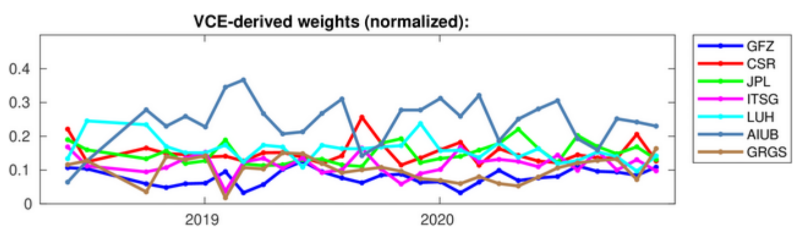
The International Combination Service for Time-variable Gravity Fields (**COST-G**) is a product center of the International Gravity Field Service (IGFS) and is dedicated to the combination of monthly global gravity field models. COST-G stems from the activities of the former H2020 project European Gravity Service for Improved Emergency Management (EGSIEM) and is further developed within the follow-up project Global Gravity-Based Groundwater Product (G3P), which is funded from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement no. 870353 (funding period 2020-2022).

Please use the top menu to visit the various parts of our website!

Best regards,
Your COST-G Team.

Latest GRACE-FO combination results

Weights



Latest News

January 11th 2021

COST-G is having its annual start of the year meeting from 11th to 15th of January!

November 23rd 2020

COST-G GRACE-FO monthly models are now available!

November 4th 2020

Benchmark data for verifying background model implementations in orbit and gravity field determination software available here (Martin Lasser et al. 2020)

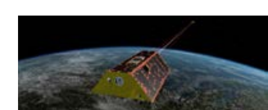
June 16th 2020

COST-G RL01 Level 2B and Level-3 products are available and the GravIS portal has been updated!

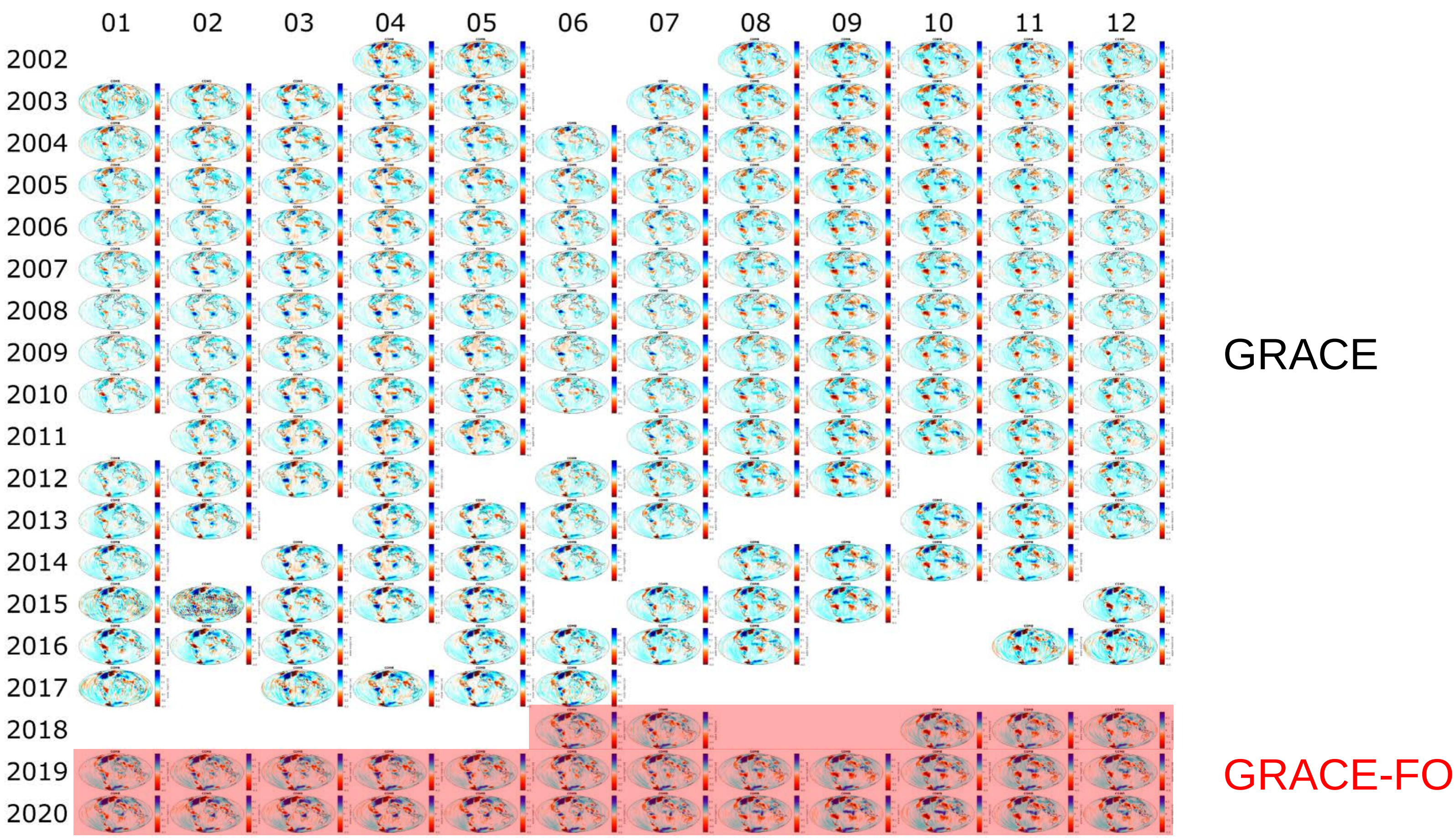
May 19th 2020

https://cost-g.org/

COST-G
Combination Service for Time-variable Gravity Models



COST-G

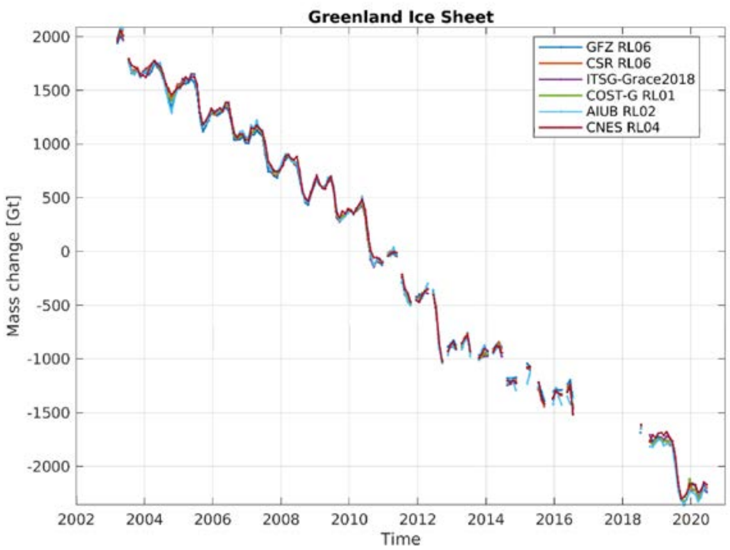


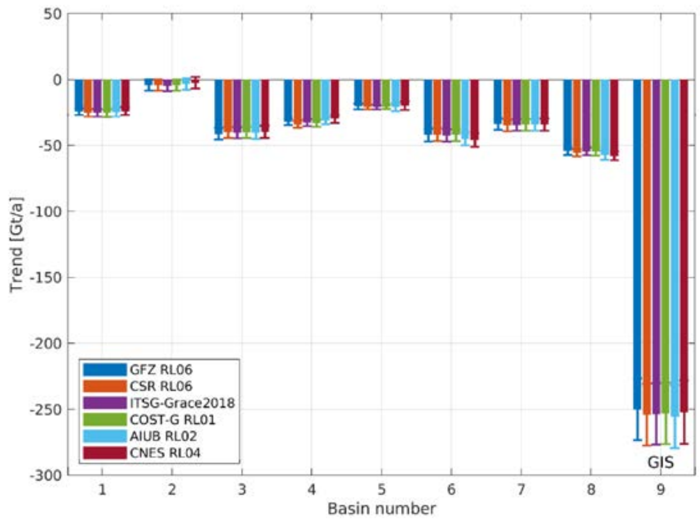
Missing solutions are caused by the gap between GRACE and GRACE-FO, battery saving measures in the final years of the GRACE mission, or instrument issues.

Consistency of Input Products

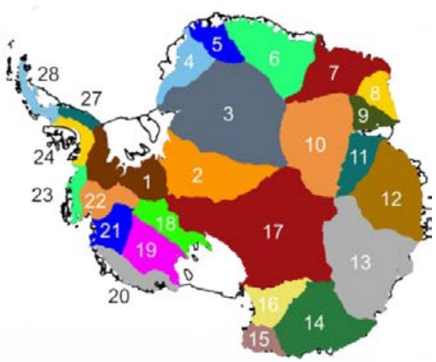
Basin-integrated Greenland/Antarctic Ice Sheet (GIS/AIS) mass changes based on the sensitivity kernel approach by TU Dresden.

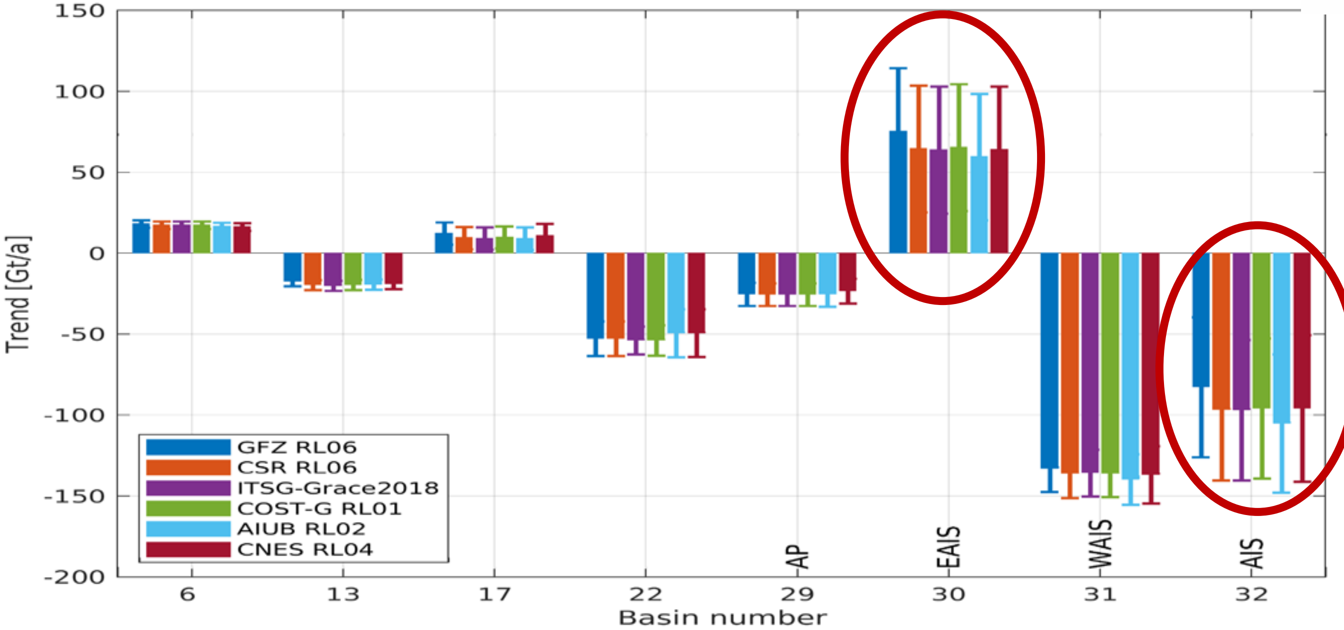
Trends are calculated from GRACE and GRACE-FO results (from a fitted linear, quadratic and seasonal model).



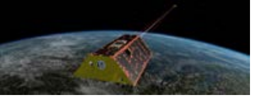


Consistency of Input Products





Basin numbers:
29: Ant. Peninsula (AP)
30: East Ant. (EAIS)
31: West Ant. (WAIS)
32: AIS



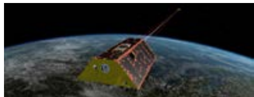
Institutional Support

- **International Space Science Institute (ISSI):**
  - International Team funded from 2019 to 2021: Set-up of initial COST-G structures, computation of initial GRACE release and operational GRACE-FO release

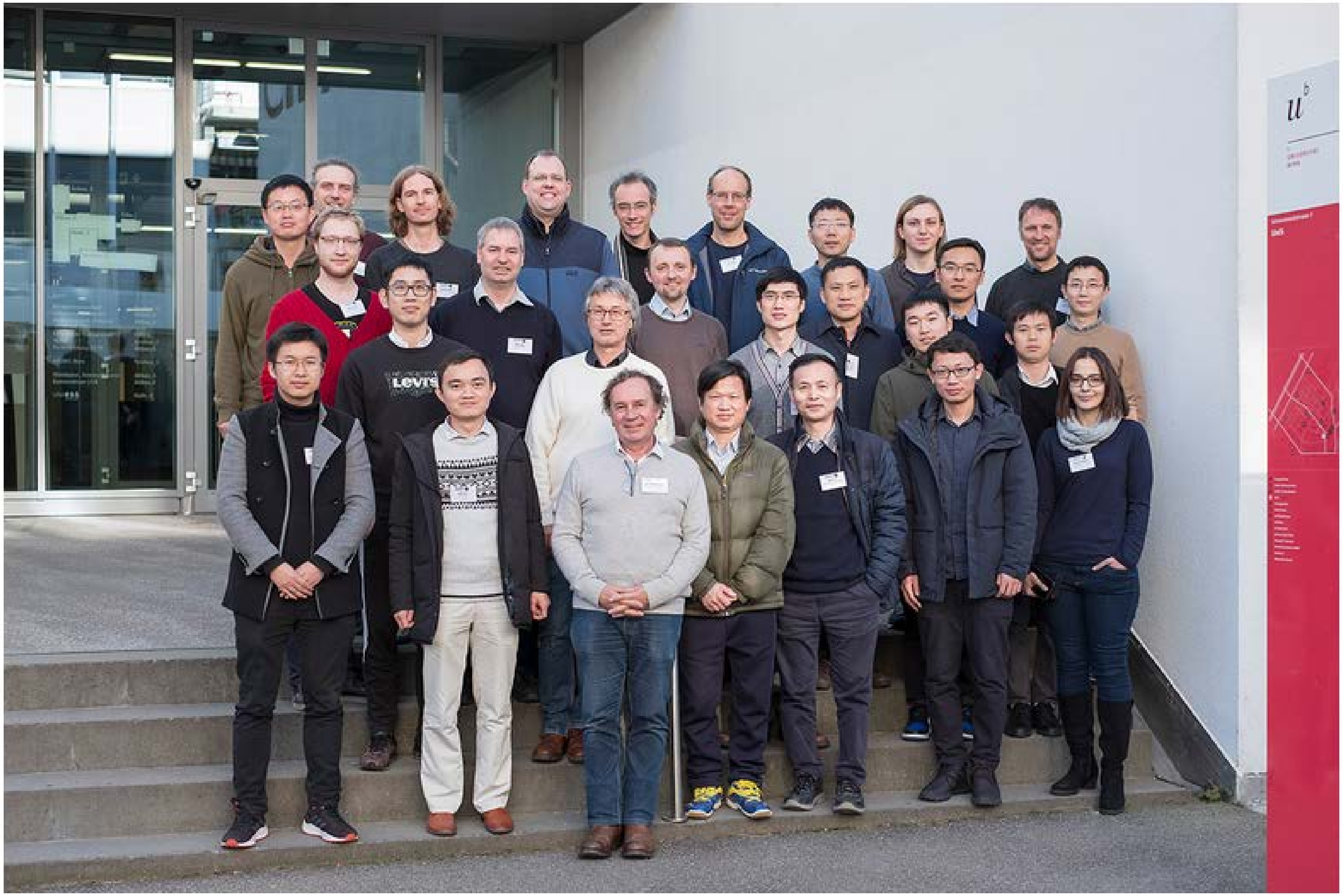
- **ESA / Swarm DISC:**
  - Funded from 2020 to 2021: Operational provision of Swarm release

- **International Space Science Institute Beijing (ISSI-Beijing):**
  - Funded from 2021 to 2022: Extension with Chinese Analysis Centers

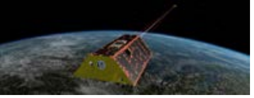
COST-G
Combination Service for Time-variable Gravity Models



Collaboration with Chinese Analysis Centers



Meeting with the Chinese delegation in Bern just before the pandemic started (16-17 Jan., 2020) to discuss future collaborations. There, the idea was born for a further team supported by ISSI-Beijing.



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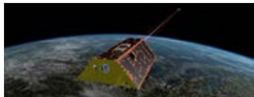
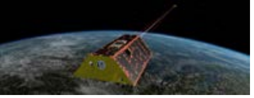
- **International Space Science Institute Beijing (ISSI-Beijing):**
    - Funded from 2021 to 2022: Extension with Chinese Analysis Centers

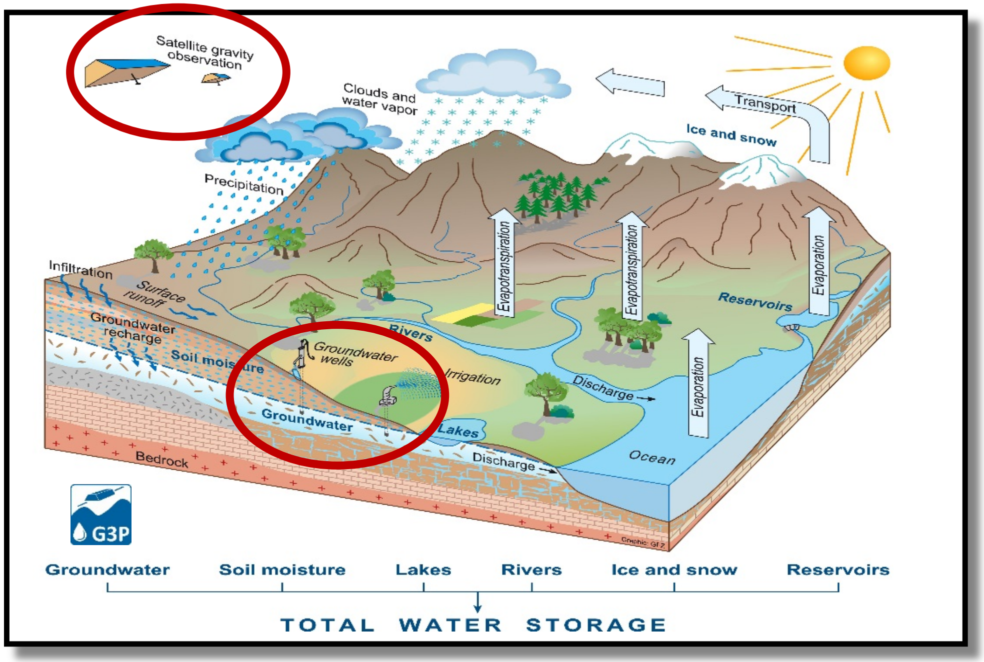
- **H2020:**
    - Funded from 2020 to 2022: Optimization and Operationalization of COST-G workflow within G3P



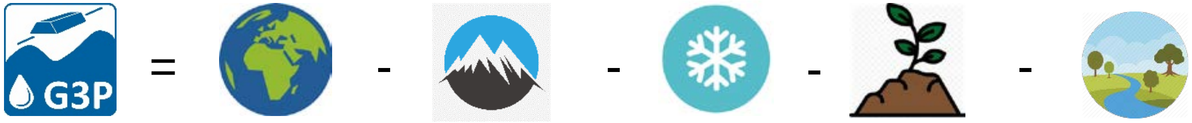


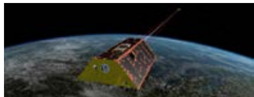
Groundwater and the Earth’s Gravity Field

- Satellite gravimetry with GRACE (2002 - 2017) and GRACE-FO (2018 -) is the only technique to observe **Total Water Storage** (TWS) variations
- A prototype for a global groundwater product shall be established for the Copernicus Climate Change Service.

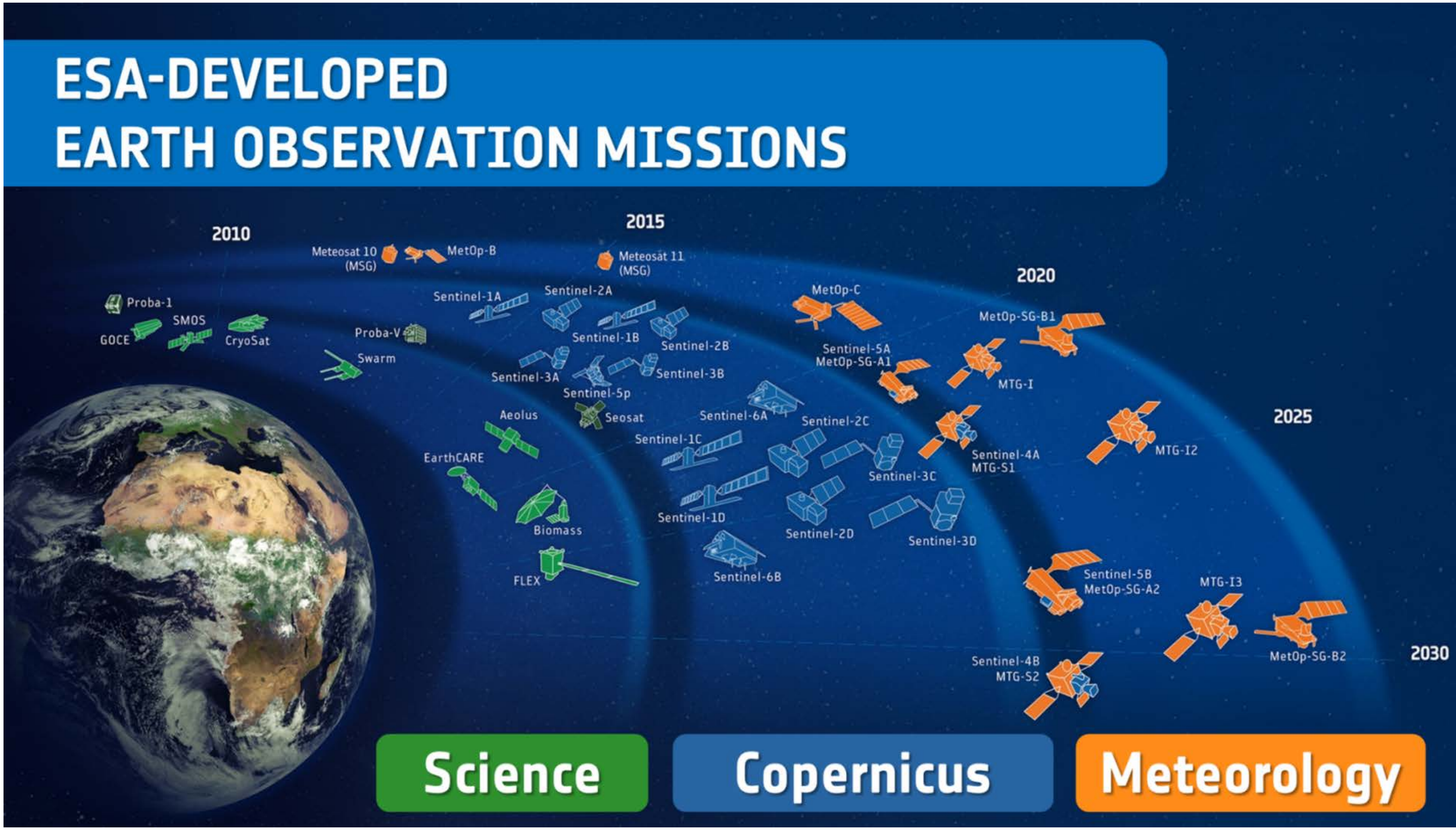


Groundwater = TWS - glaciers - snow - soil moisture - storage in surface water bodies

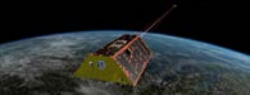




Perspectives in Terms of Missions



Courtesy: ESA



Europe’s Earth Observation Programme

Atmosphere monitoring

Marine environment monitoring

Emergency management

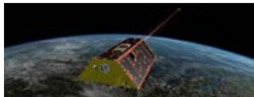
Land monitoring

Climate change

Security

Copernicus
Europe’s eyes on Earth

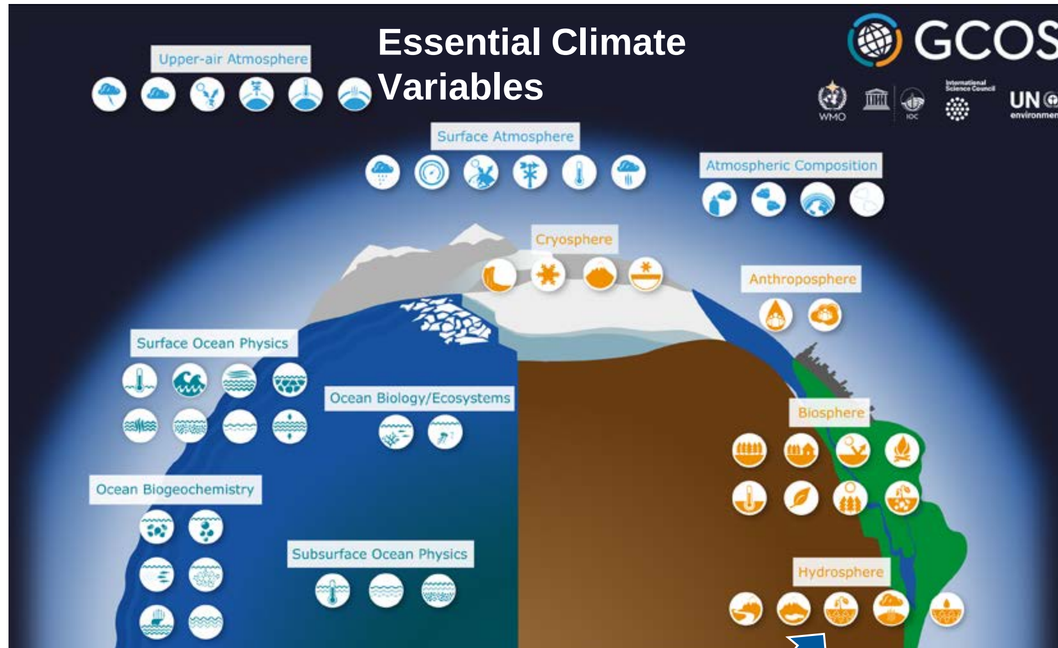
https://www.copernicus.eu/



Essential Climate Variables

The Global Climate Observing System (GCOS) defines several **Essential Climate Variables** (ECVs):

- an ECV is a variable that is critical for characterizing the climate system and its changes
- ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to assess risks, to guide adaptation measures, to underpin climate services, …

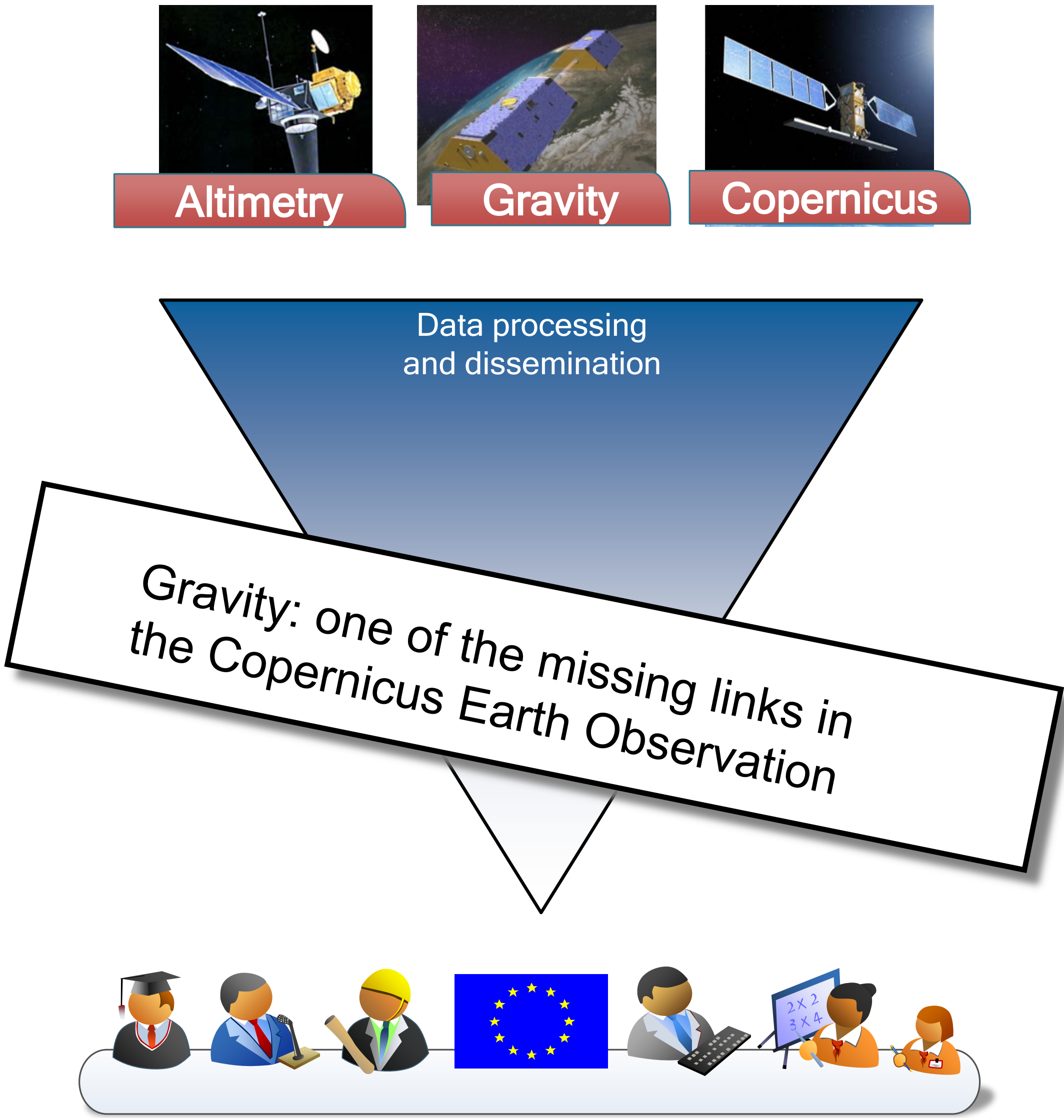


ECV Groundwater 

https://gcos.wmo.int

Latest News: New ECV Terrestrial Water Storage is now approved by GCOS

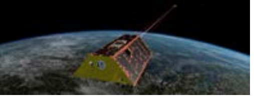
Sustainable Satellites are serving Society



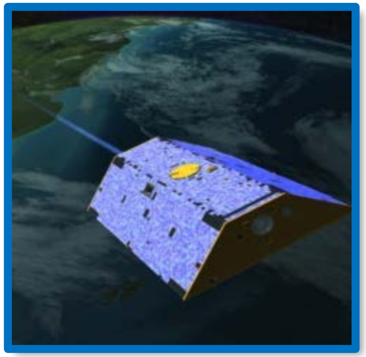
Service evolution:

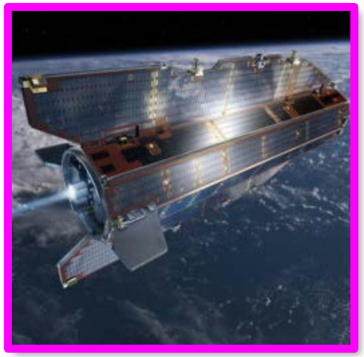
- Atmosphere monitoring
- Marine environment monitoring
- Emergency management
- Land monitoring
- Climate change

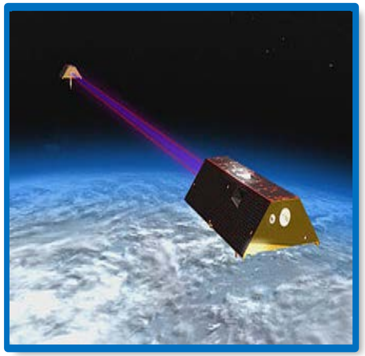
Copernicus
Europe's eyes on Earth



Continuity of Gravity Missions ?







CHAMP (GFZ, 2000-2010)

GRACE (NASA/DLR, 2002-2017)

GRACE-FO (NASA/GFZ, 2018-2022)

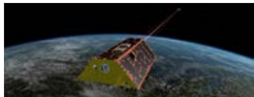
GOCE (ESA, 2009-2013)

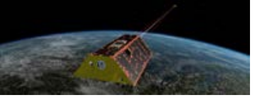
GRACE-?? / Sentinel-??

Gravity missions enabled spectacular results:

- insights into the global water cycle
- polar and mountain ice mass loss
- changes in ocean surface currents
- unification of height systems
- sea level rise

→ There is a strong need for sustained observation.





Thanks a lot for your attention !