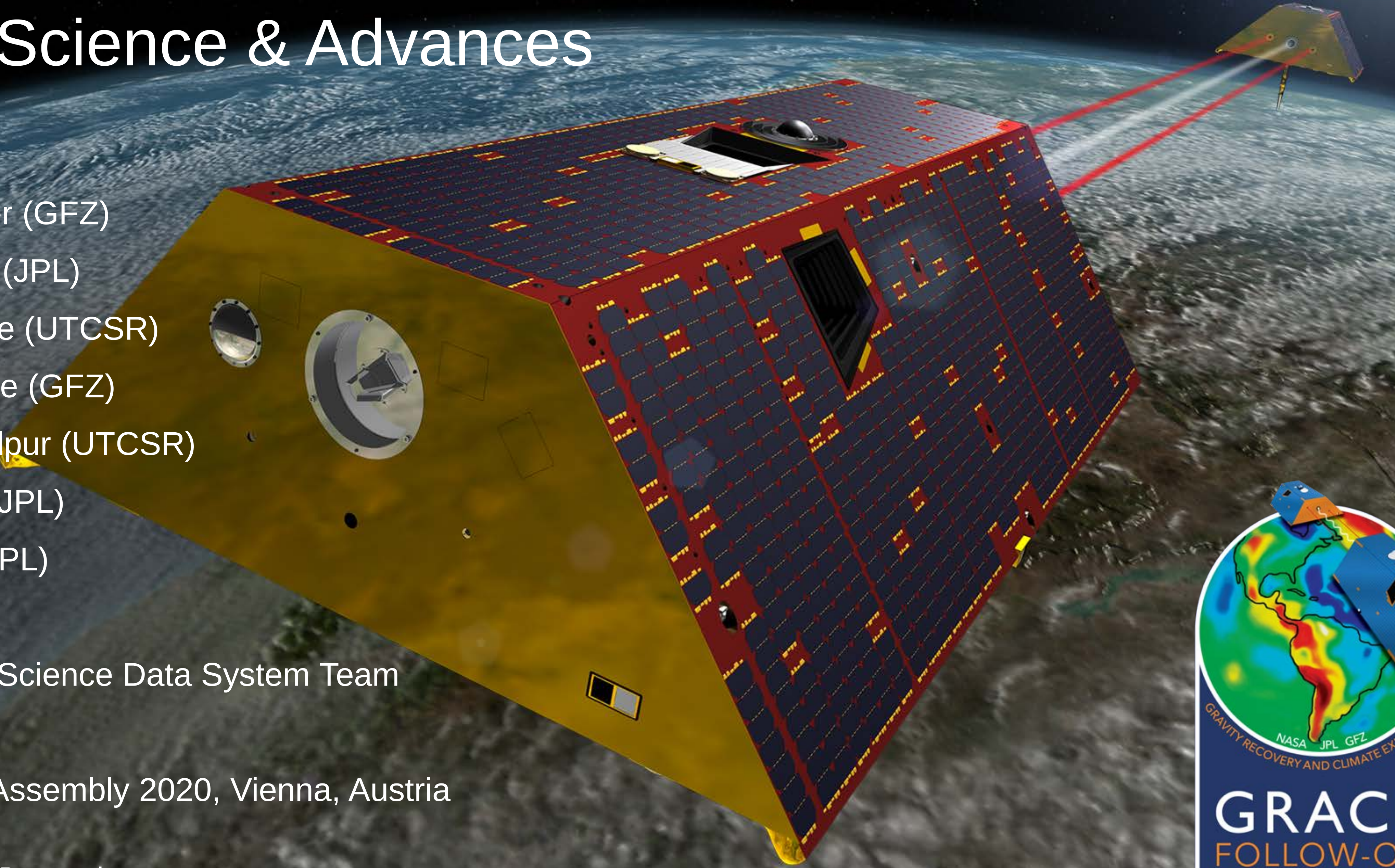
NASA and GFZ GRACE-FO Mission: Status, Science & Advances



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& GRACE-FO Science Data System Team

EGU General Assembly 2020, Vienna, Austria

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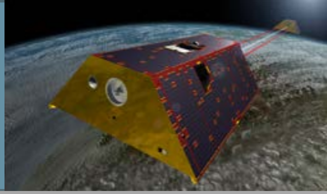
GRACE-FO: Mission Overview & Status



- **Science Goals & Objectives**
  - Extend the monthly gravity field and mass change record at a precision and temporal sampling equivalent to that of GRACE.
  - Demonstrate satellite-to-satellite laser ranging interferometry in low Earth orbit.
  - Collect 200 radio occultation measurements per day to derive atmospheric temperature and humidity profiles.

- **Mission Partners**
  - NASA / JPL
  - German Research Centre for Geosciences (GFZ, Potsdam)

Nominal GRACE-FO Launch:
- May 22, 2018
- Commercial rideshare contributed by GFZ

First Science Data:
- May 30, 2018

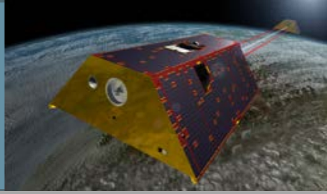
Launch-Early Orbit Phase (LEOP) & In-Orbit-Checkout (IOC):
- May-22 – Jan-27, 2019

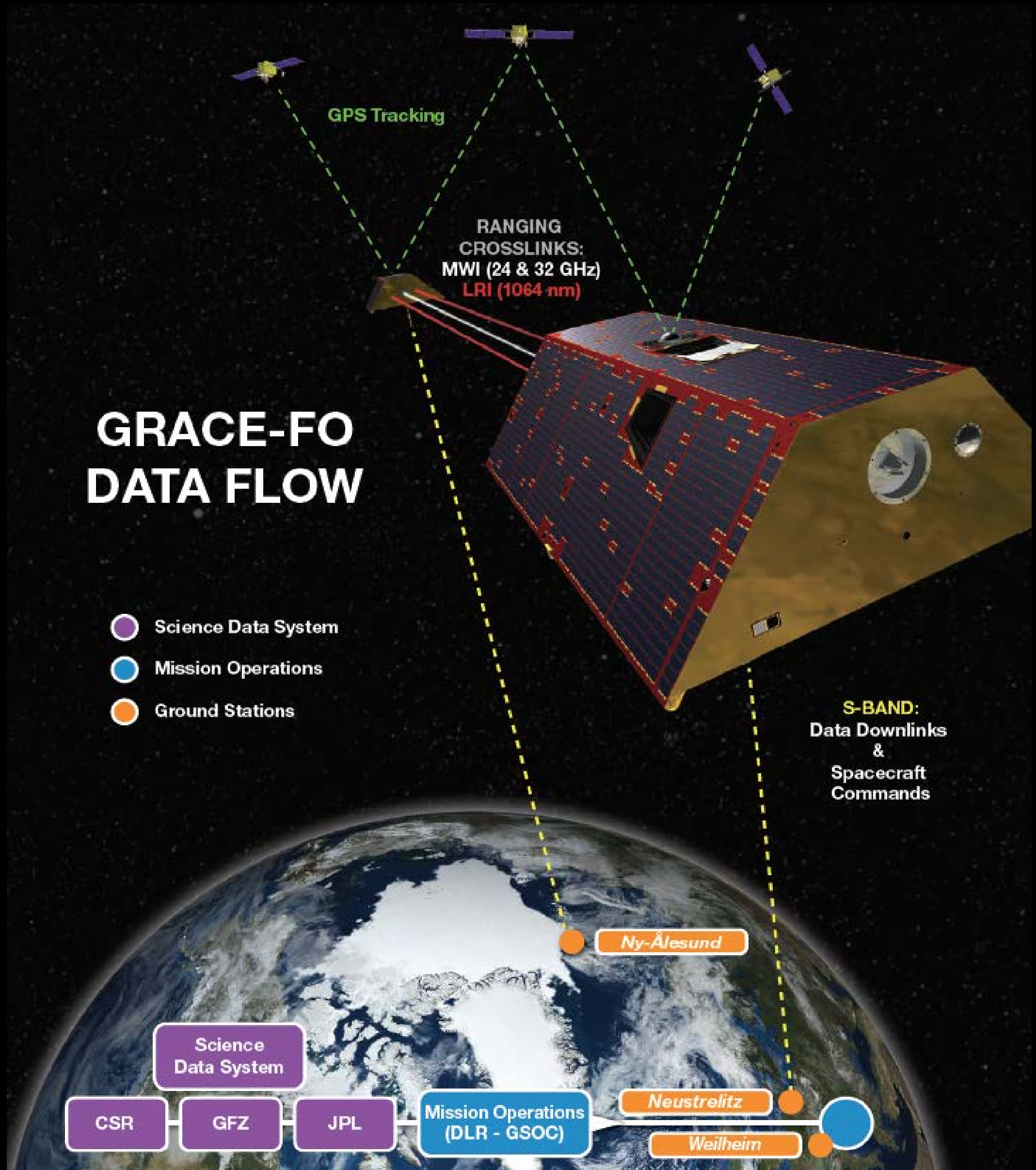
Start of Science Phase (E):
- Jan 28, 2019

First Data Delivery:
- May 28, 2019

Baseline Mission Lifetime:
- 5-years

GRACE-FO Science Data System





Jet Propulsion Laboratory (JPL):

Level 1-3, US Project and Science Management
SDS Lead

GeoForschungsZentrum (GFZ):

Level 2-3, German Project Management, incl. spacecraft operations (at DLR-GSOC)
Geophysical background models

UTCSR:

Level 2–3
Science Operations Management

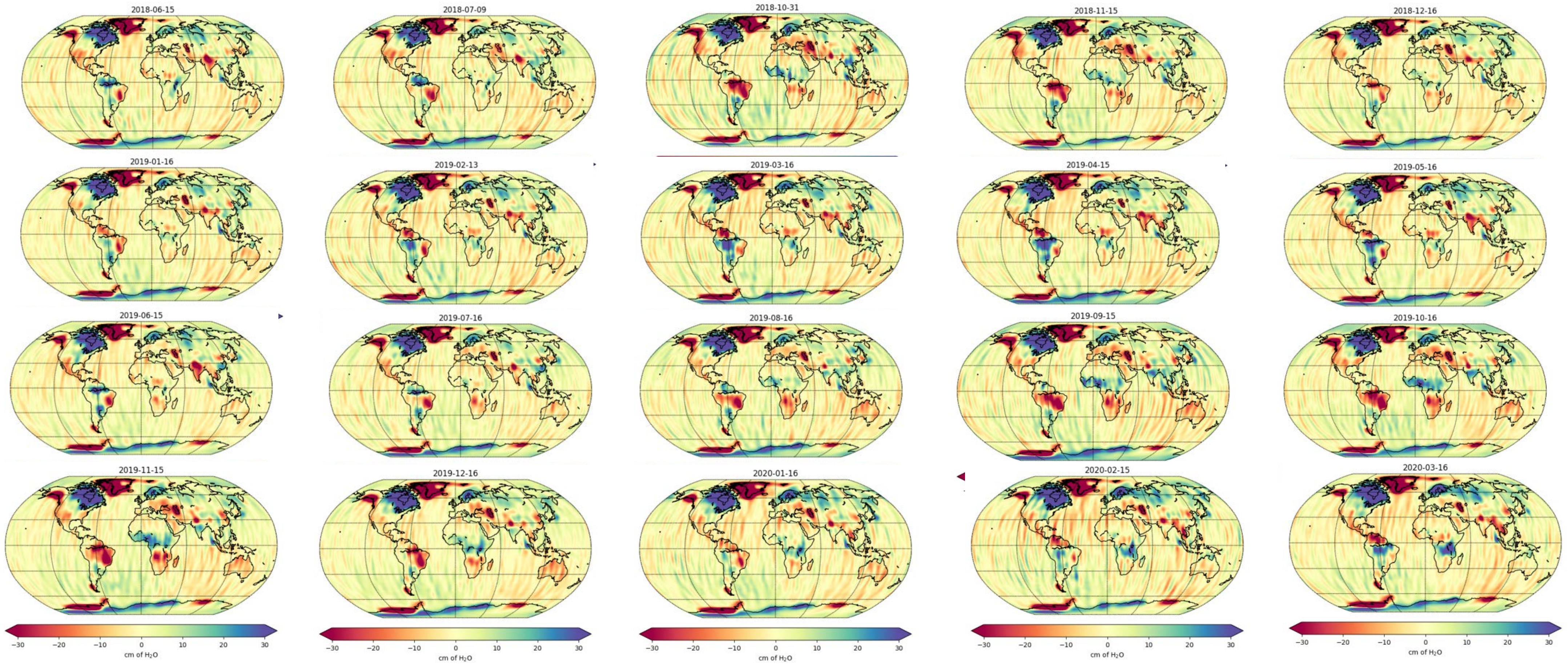
Goddard SFC (GSFC):

Level 2-3 & Ancillary data support

GRACE-FO: System / Instrument Status (Summary)

- GPS, KBR radio-metric instruments
  - Nominal (lower noise than GRACE)
- Star Camera (SCA/STR) / IMU
  - Nominal (lower noise than GRACE)
- Accelerometers (ACC)
  - GF2 Currently in Large Range Mode (LRM)
    - High noise levels
    - Science data processing uses a ‘transplant’ approach, applying the GF1 observations to GF2
- LRI (technology demonstration)
  - Nominal (LRI obs obtained parallel to KBR for intercomparison)
  - Very low noise in the intersatellite range measurements
- Attitude System (AOCS)
  - GRACE-FO performing better than GRACE (e.g., improved pointing & attitude measurements, fewer thruster firings)
  - Orbit decay during the first two years since launch: <1 km

20 Gravity Fields & Mass Anomaly Fields Released

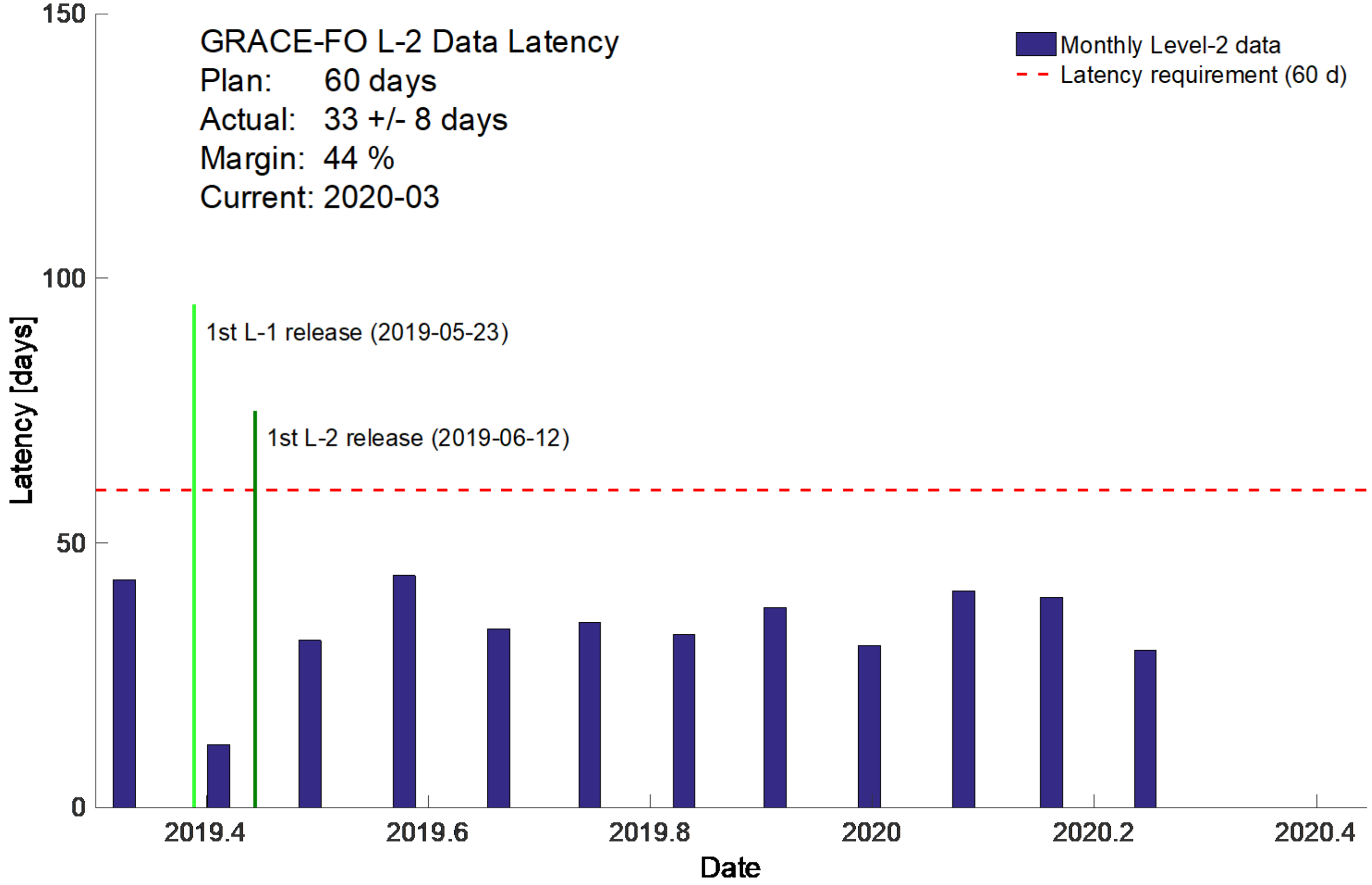


- Most recent available data: 03/2020 (as of 2020-05-02)
- Shown are anomalies (cm equivalent water height), relative to ggm05c
- All fields have been smoothed at 300 km

20 Gravity Fields & Mass Anomaly Fields Released

Science Data delivery latency:

- Since 1st Level-2 delivery on 2019-06-12, 60-day latency requirement has been beat by 44% (actual average latency: 33 days)

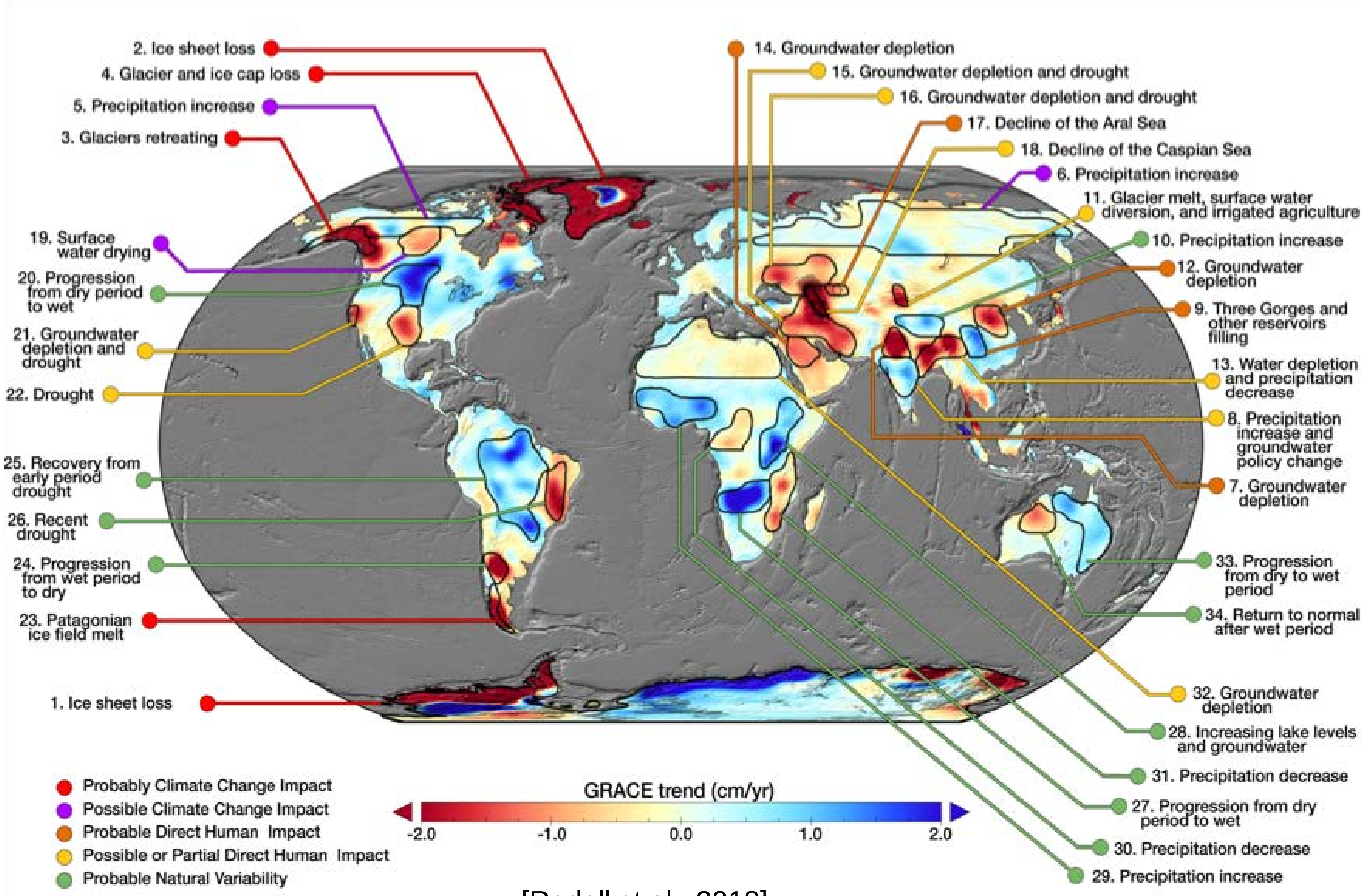


Verification and Validation of the GRACE-FO Data

Emerging trends in global freshwater availability from 15 years of mass change measurements

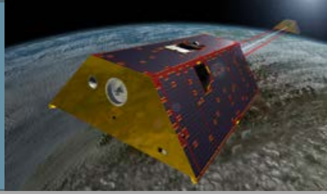
Changes in:

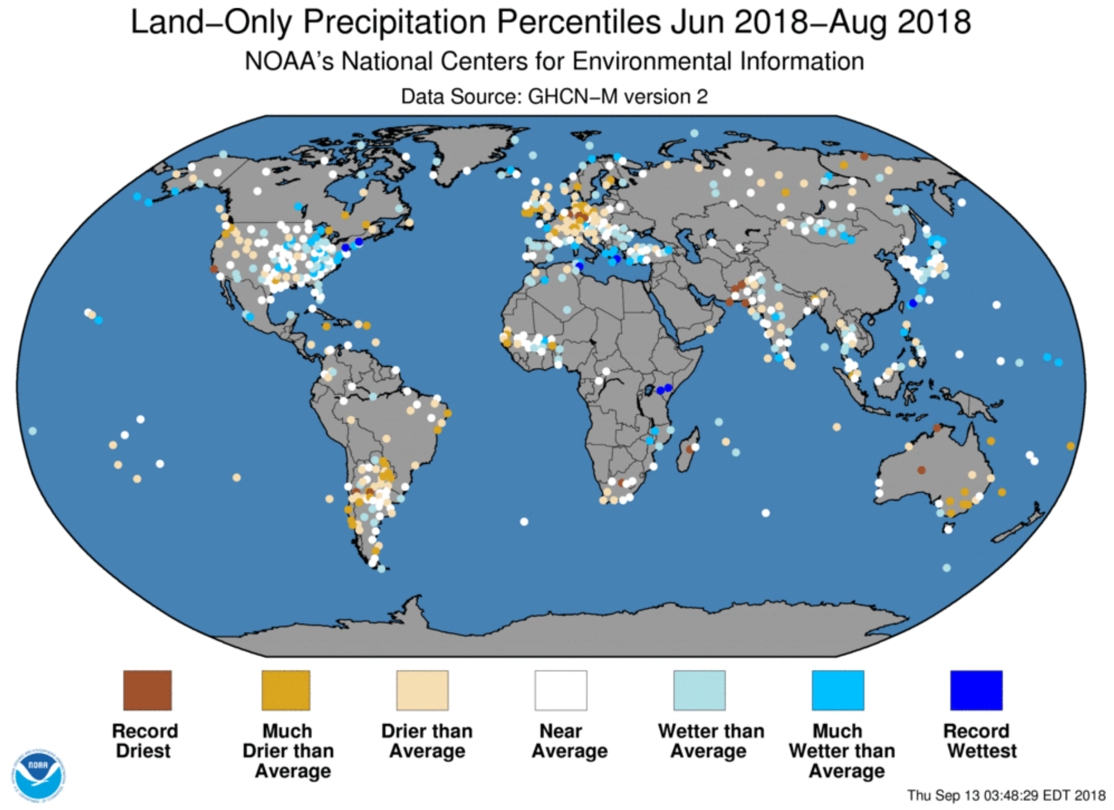
- Glaciers & ice sheets
- Groundwater
- Snow
- Soil Moisture
- *Ocean mass*

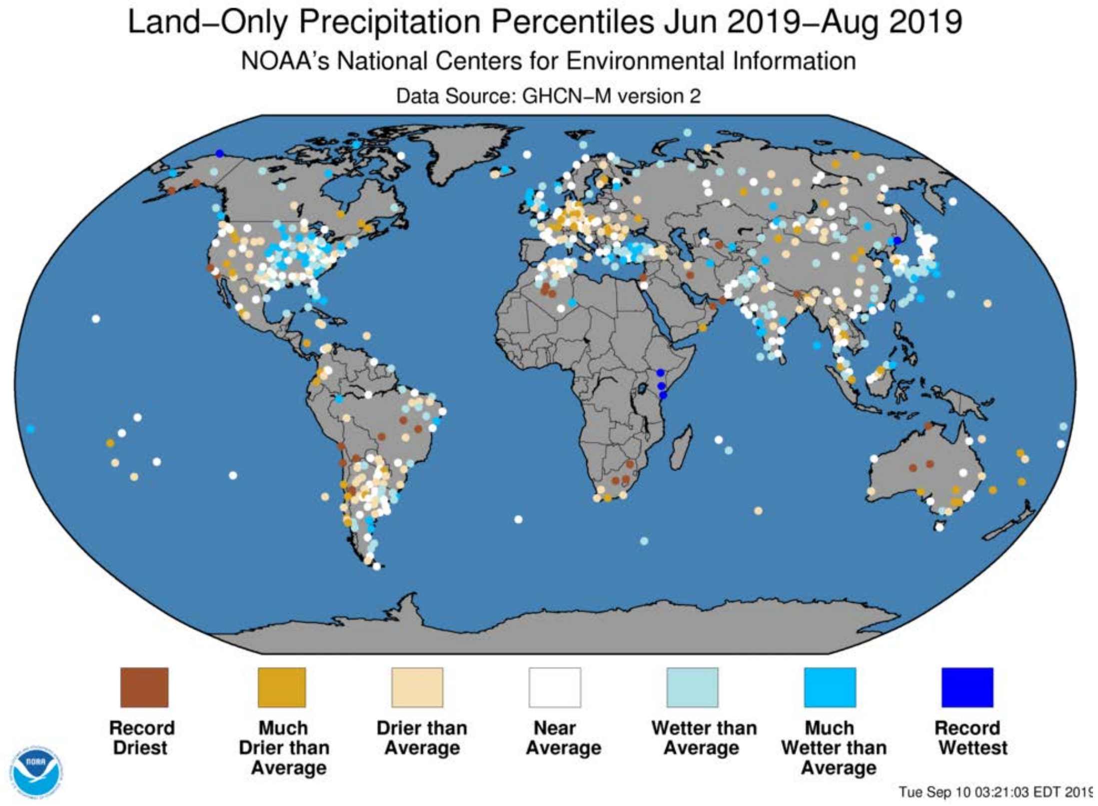


[Rodell et al., 2018]

Earth's climate has been doing lots of interesting things since 2018 …



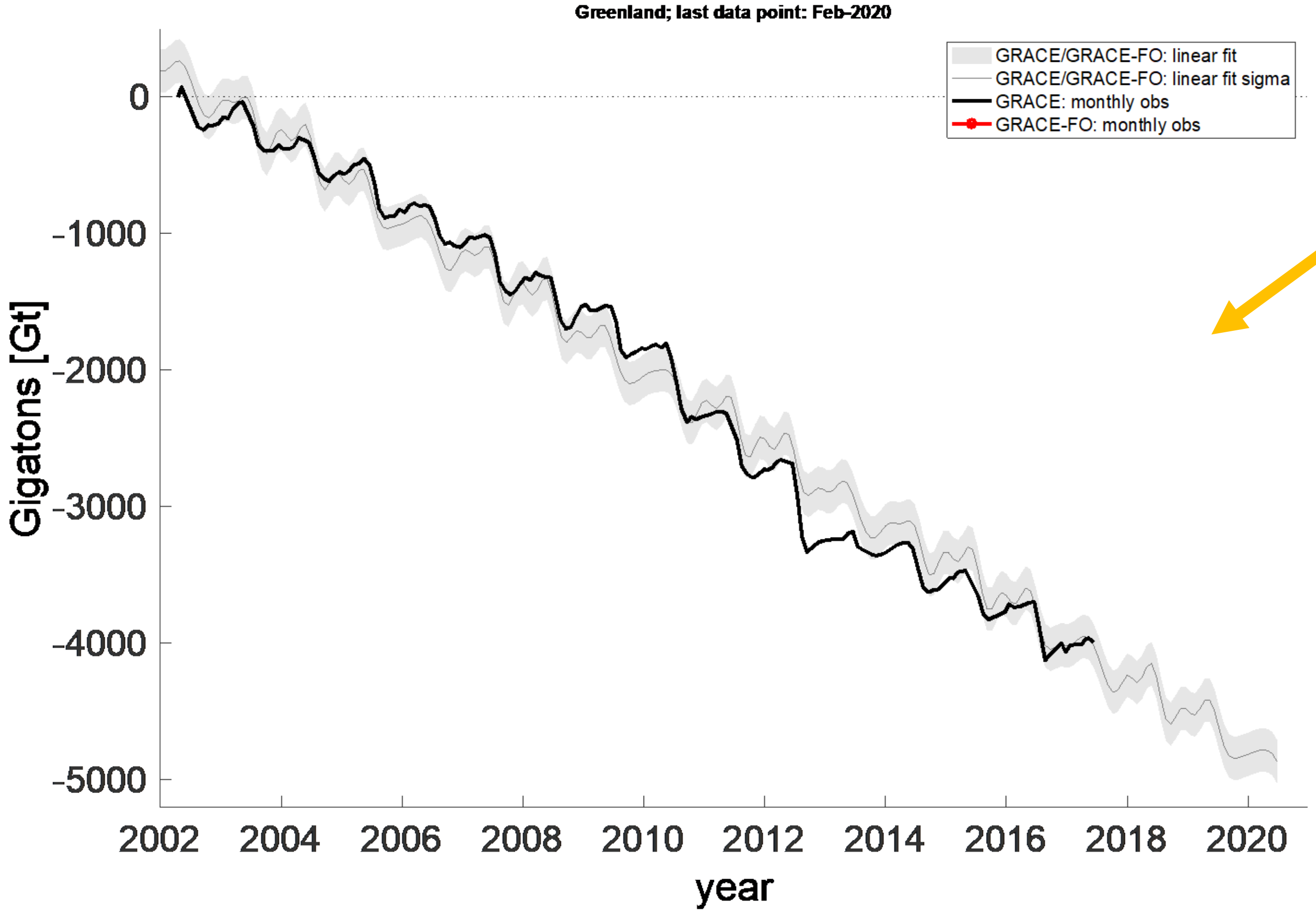


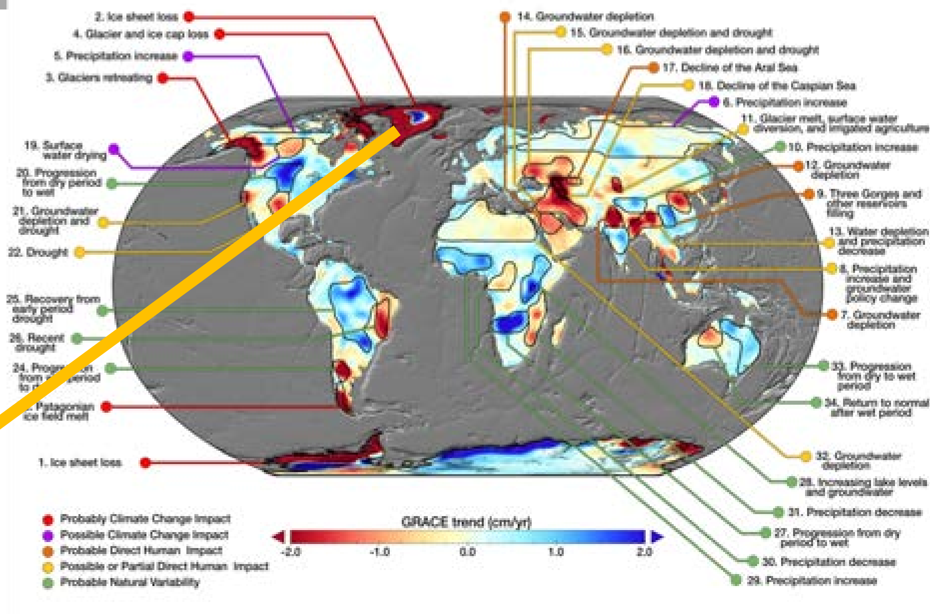


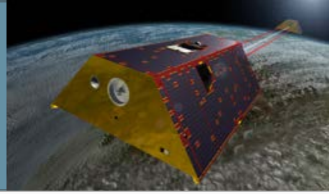
- Period from June 2018 through June 2019 was the wettest ever recorded in continental US, with much of the excess rainfall concentrated in the upper Midwest region;
- Europe experienced an exceptionally dry and hot summer in 2018 & 2019, leading to regional water shortages and hindering commercial river shipping as water levels dropped;
- The Middle East region (Iran / Iraq) experienced anomalously high rainfall starting in early 2019, which led to large TWS anomalies;

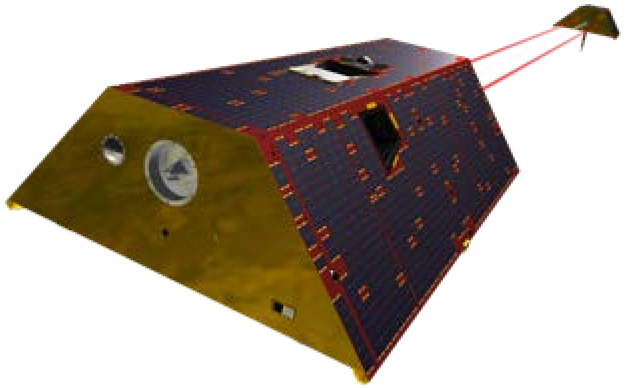
Greenland Ice Mass Loss

GRACE-FO provides continuity of the global record
Steady decrease in Greenland ice mass from 15 yr of GRACE



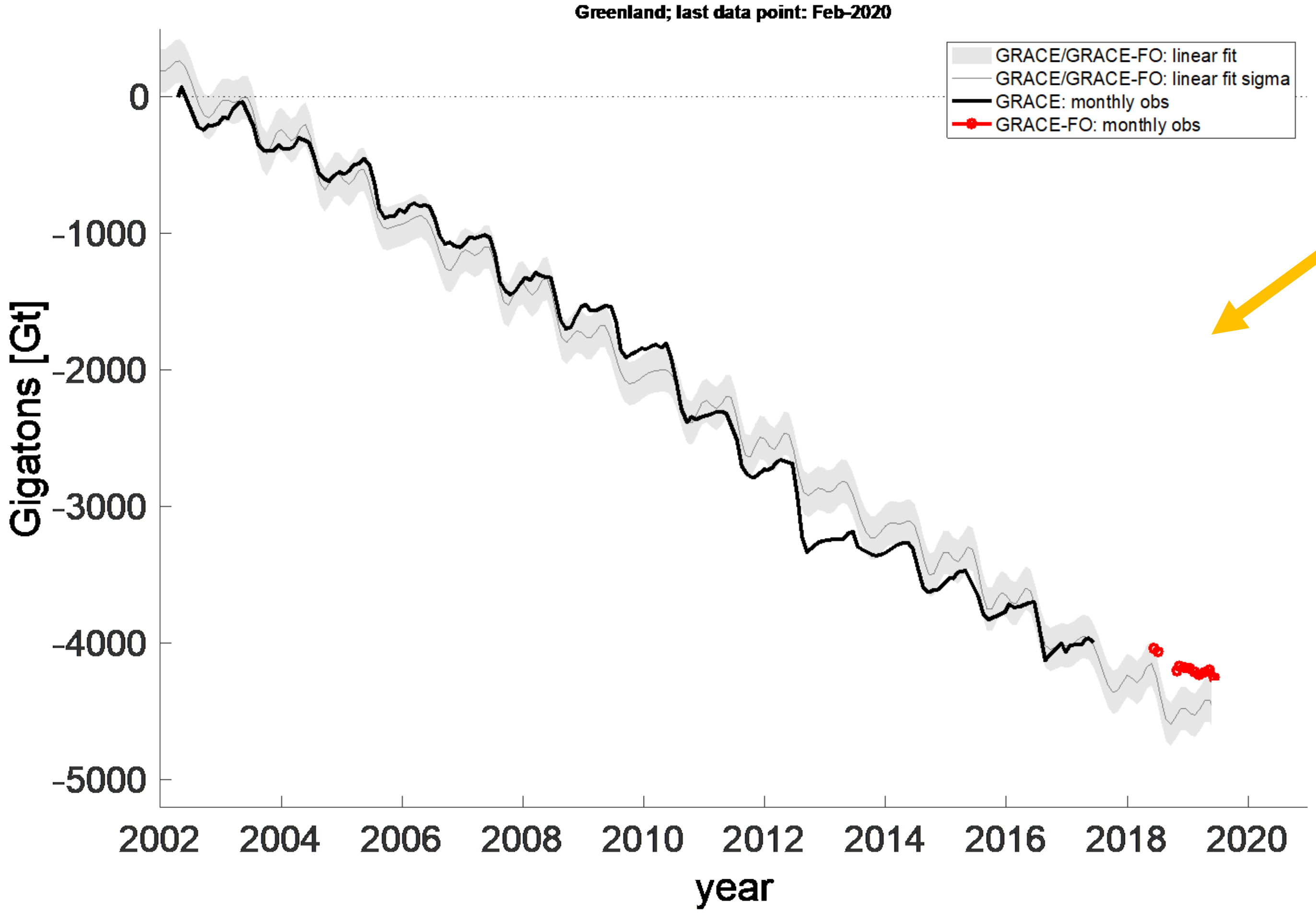


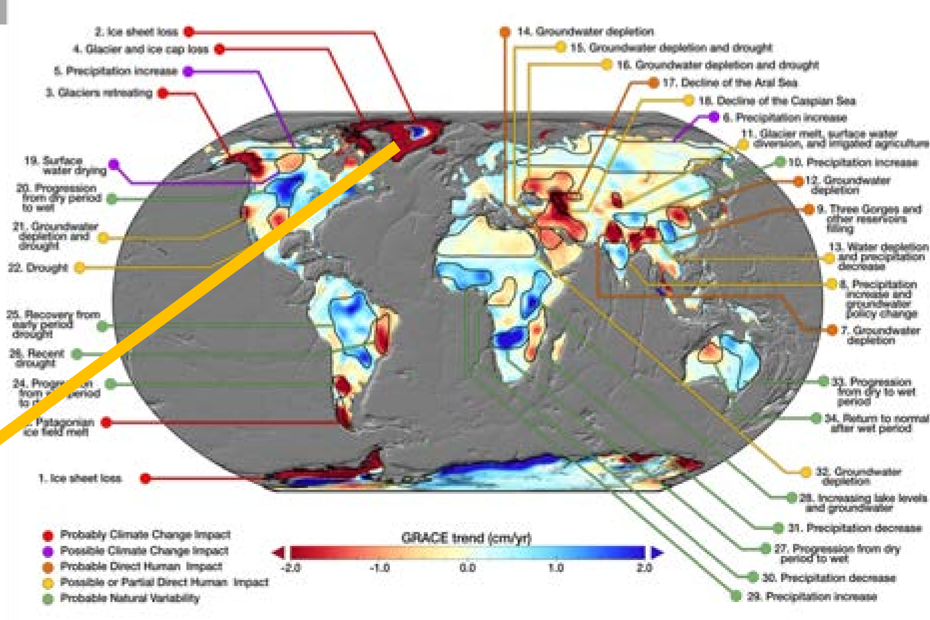




Greenland Ice Mass Loss

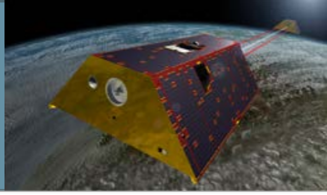
Initial GRACE-FO results show continued, though slower, loss of ice mass



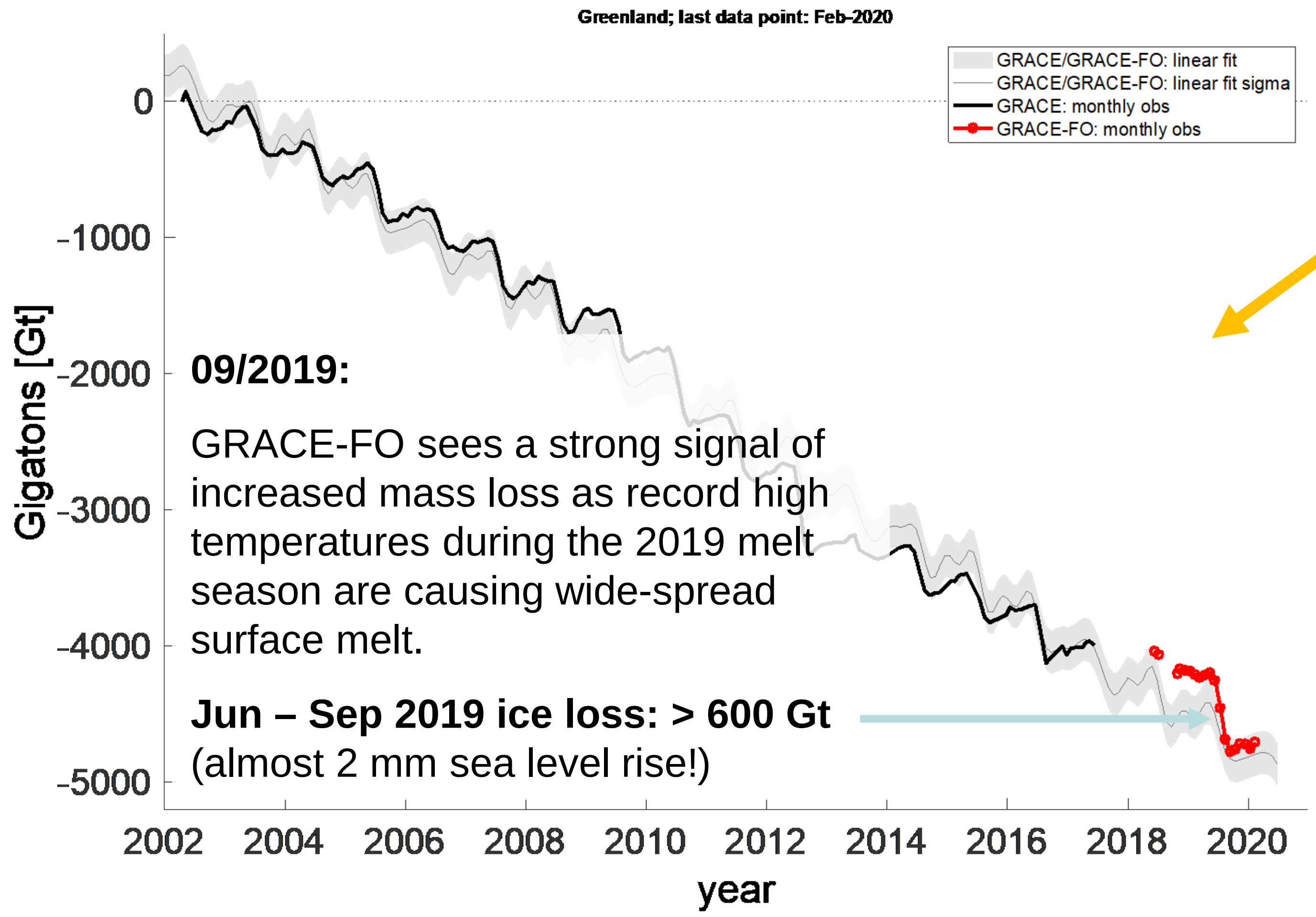


Northeast Greenland, summer 2018, Credit: Lars Holst Hansen
https://phys.org/news/2019-10-year-extreme-snowfall-arctic-animals.html

Greenland Ice Mass Loss



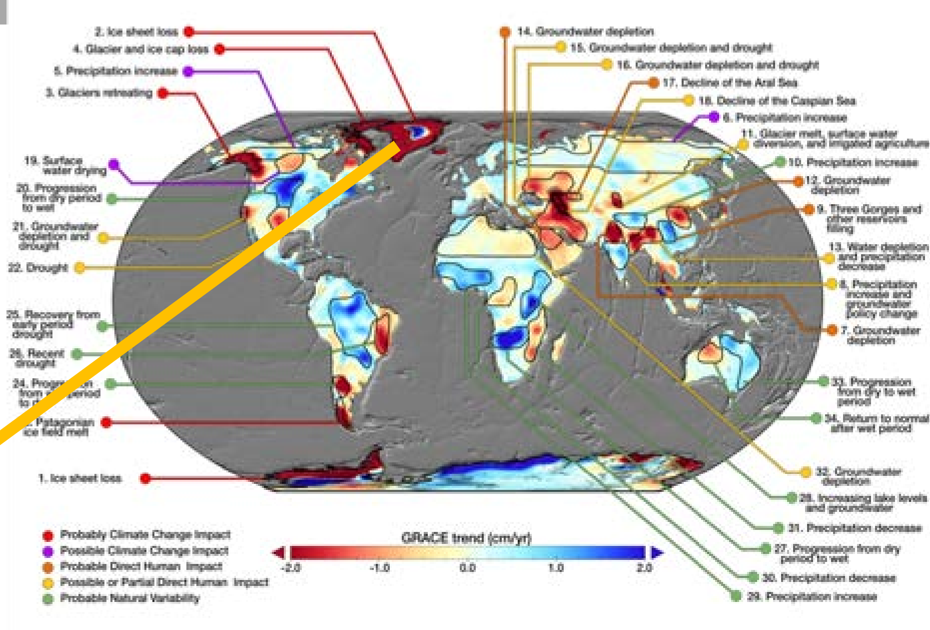
Summer 2019: GRACE-FO Observes Abrupt Transition To Rapid Greenland Mass Loss Rates In 2019



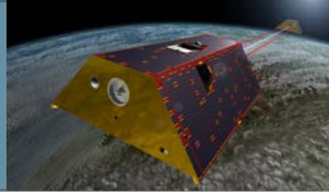
09/2019:

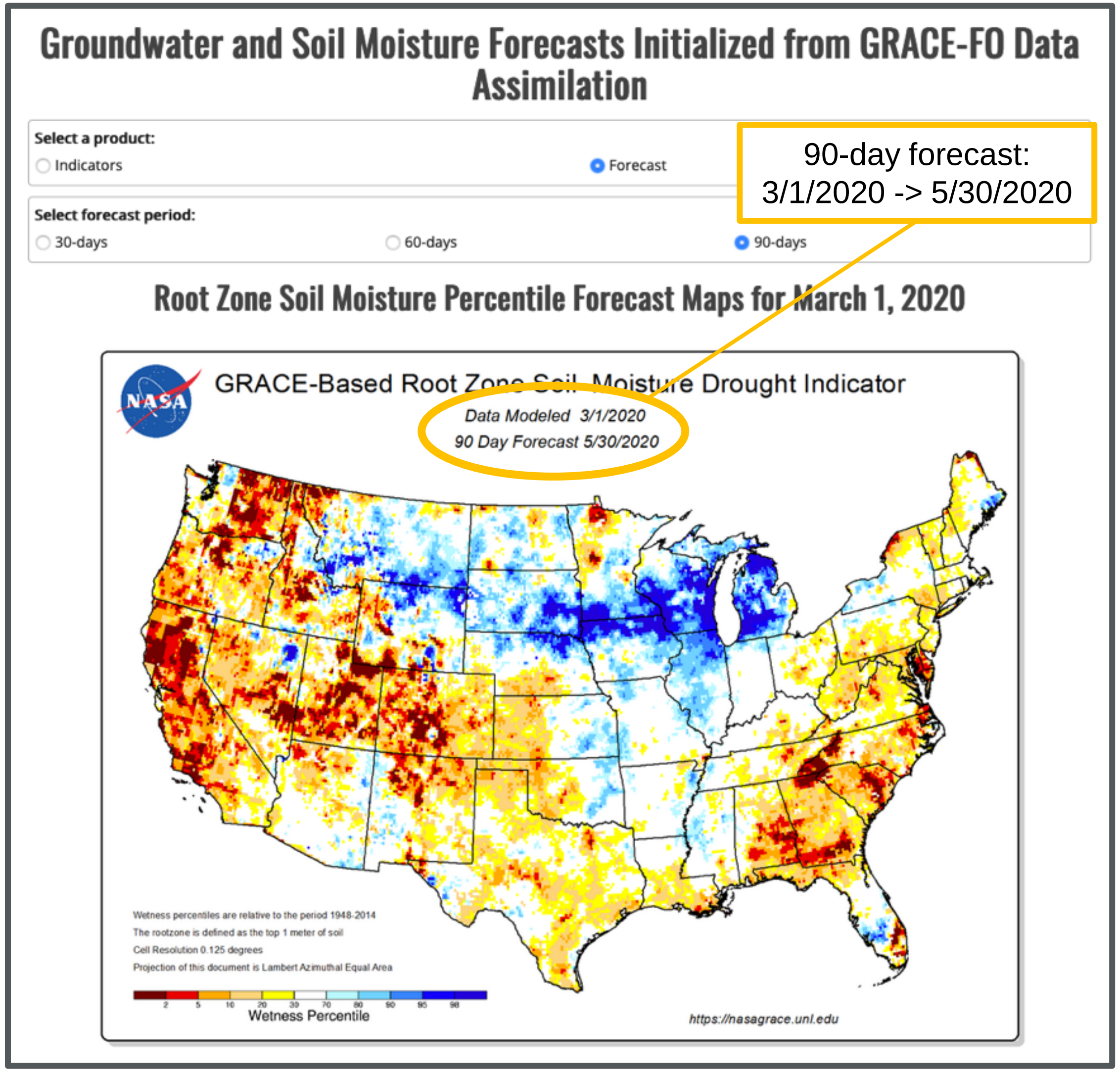
GRACE-FO sees a strong signal of increased mass loss as record high temperatures during the 2019 melt season are causing wide-spread surface melt.

Jun – Sep 2019 ice loss: > 600 Gt
(almost 2 mm sea level rise!)



New U.S. Drought 30-90 Day Forecasts using GRACE-FO observations



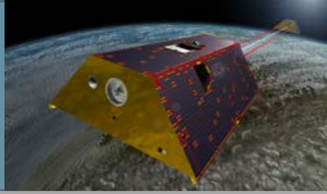


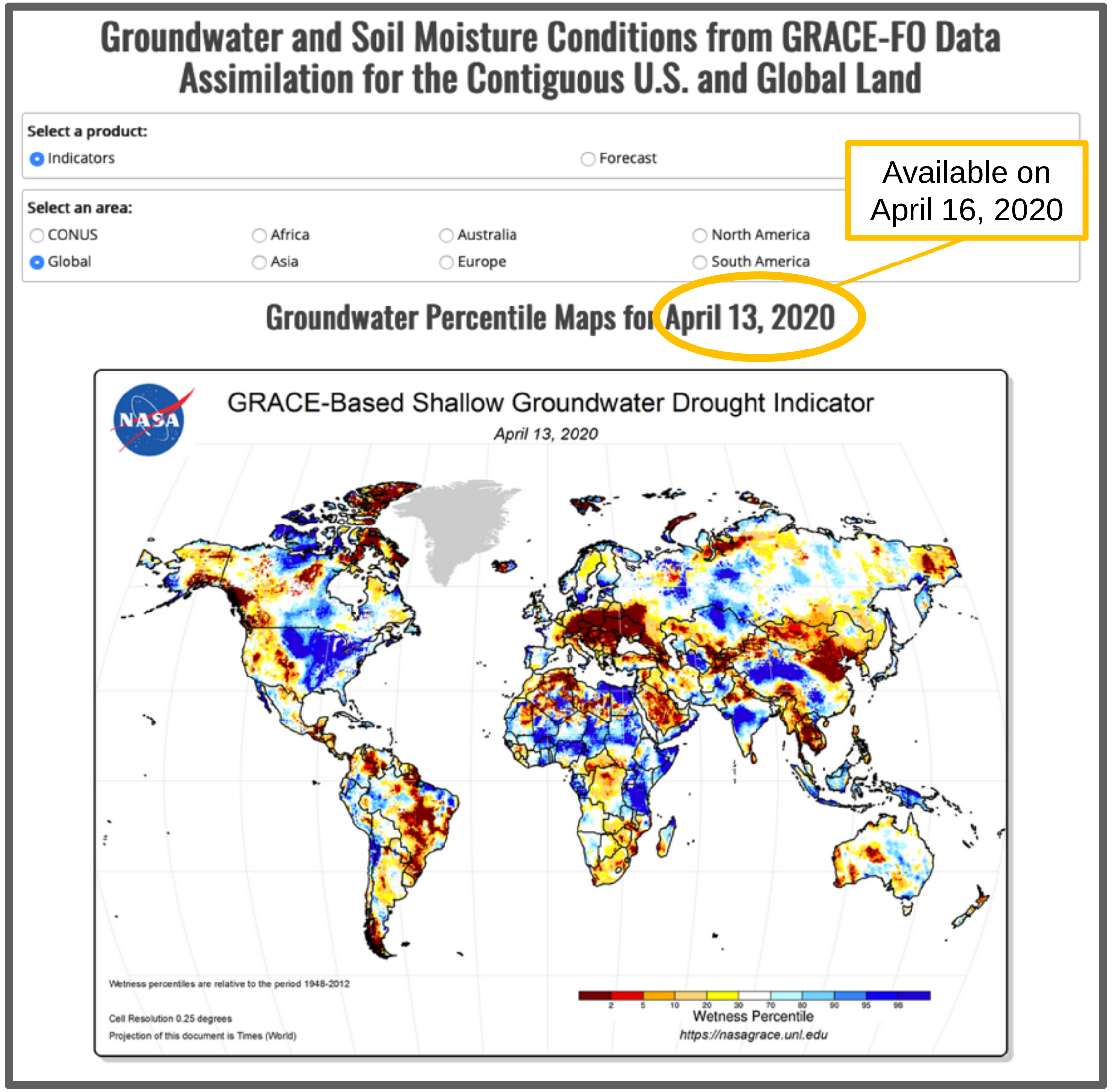
https://nasagrace.unl.edu/

- NASA-GSFC has generated first seasonal forecasts of **Groundwater and Soil Moisture** for the contiguous U.S. that incorporate ***Mass Change Observations*** from the *GRACE-FO* satellites as a starting point.
- The forecasts of groundwater changes feed into the U.S. Drought Monitor, and support management and decision-making by the USDA and FEMA.
- These forecasts with lead times of 30, 60 & 90 days are updated on a monthly basis.
  - The model is driven into the future using downscaled seasonal meteorological forecasts from NASA's GEOS-5 Earth system model.
  - The drought indicators describe current **wetter** or **dryer** conditions than normal, expressed as a percentile showing the probability of occurrence for that particular location and time of year.

[Getirana et al. 2020]

First Global Groundwater Maps using GRACE-FO observations (Updated weekly for near real-time decision-making support)





https://nasagrace.unl.edu/

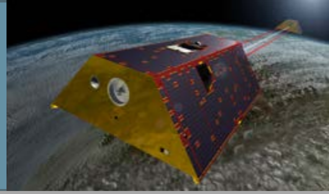
- NASA-GSFC is now generating weekly updates of **Groundwater and Soil Moisture Conditions** around the world that incorporate ***Mass Change Observations*** from the *GRACE-FO* satellites as a starting point.

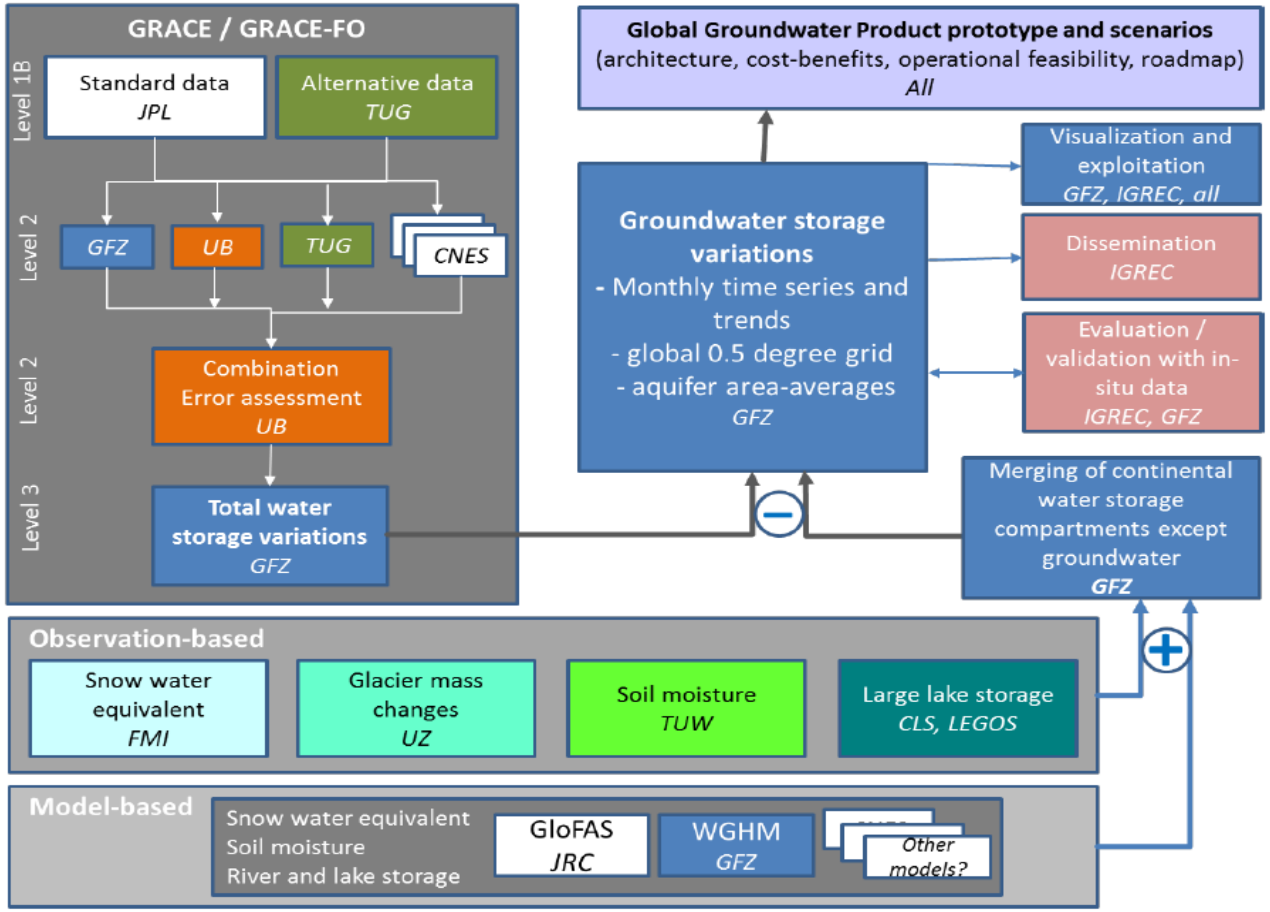
- The maps support management and decision-making by the USDA and FEMA, and soon by the U.S. Agency for International Development and the World Bank.

- New GRACE/GRACE-FO and hydrology assessments enable monitoring of both groundwater and extreme wetness and drought conditions globally in near-real time (<4 day lag) – these capabilities were severely lacking before.

[Li et al. 2020]

Global Gravity-based Groundwater Product (G3P)





GFZ leads EU funded project „Global Gravity-based Groundwater Product (G3P, 2020-22).

G3P will integrate the Essential Climate Variable groundwater as new product into Copernicus Services.

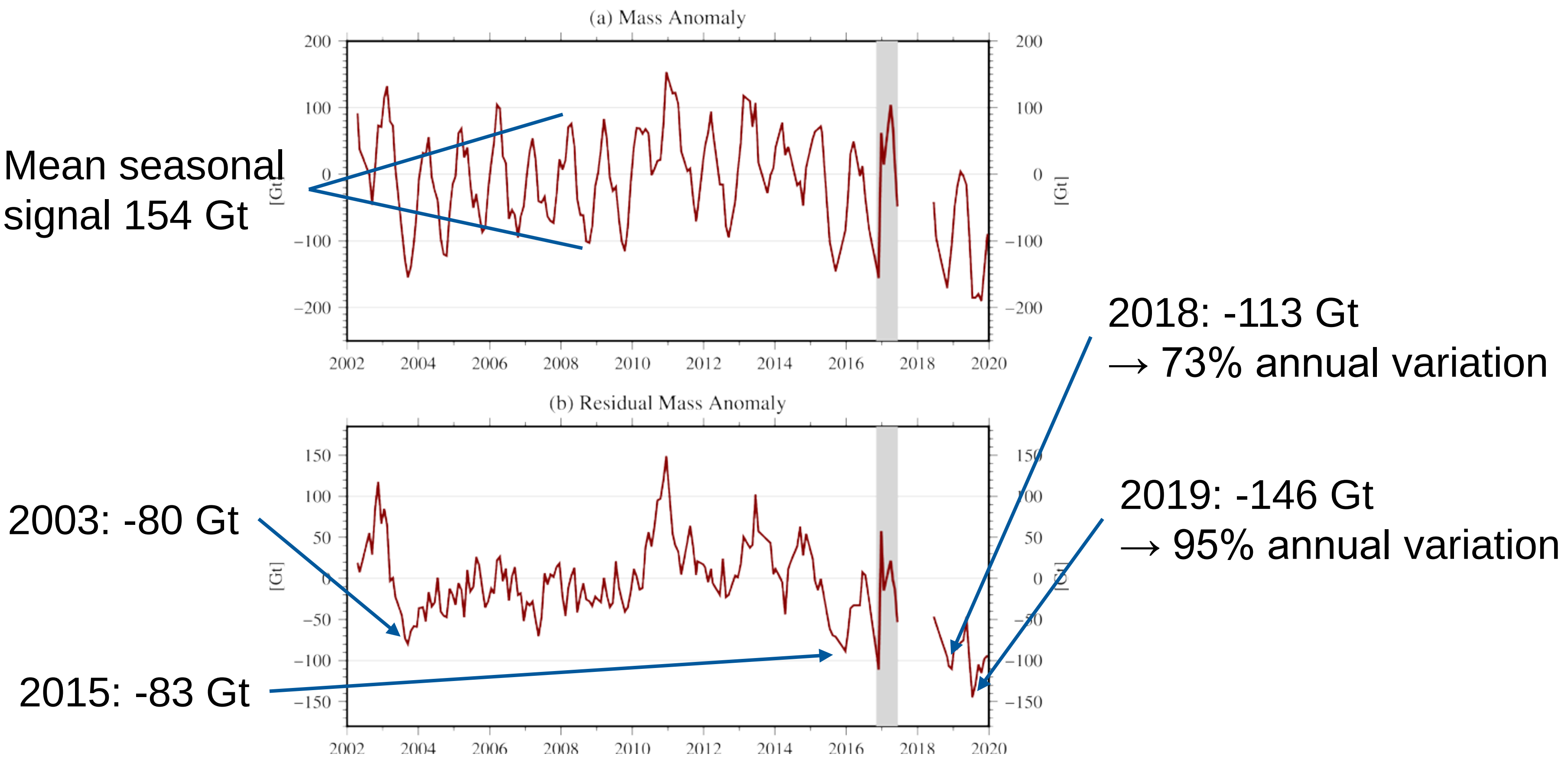
For this, GRACE and GRACE-FO gravity data will be combined with other operational Copernicus products such as soil moisture or surface water.

US and European groundwater services complement each other as different in-situ and model data will be used (Cal/Val activity).

Horizon2020

Central Europe

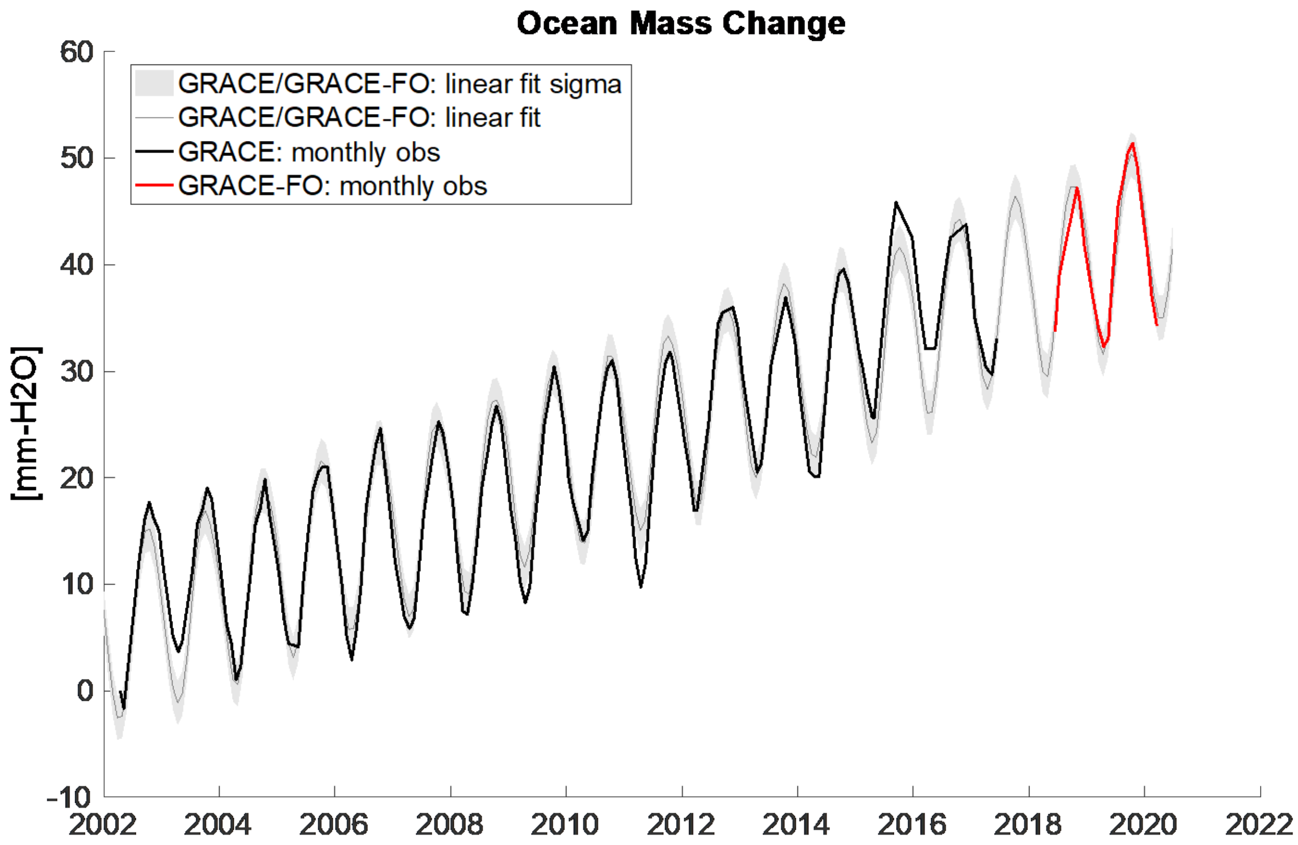
Changes in terrestrial water due to severe droughts in 2018 and 2019



Boergens et al., GRL, under revision

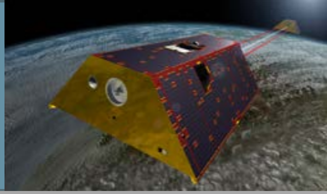
Sea Level Changes – Measuring the Global Mean Ocean Mass Contribution

- Ocean mass trend 2002-2020: **2.1 +/- 0.3 mm/yr**
- Ocean mass trends make up approx. 2/3 of the global mean sea level rise
- GRACE-FO observations fall within the GRACE extrapolation

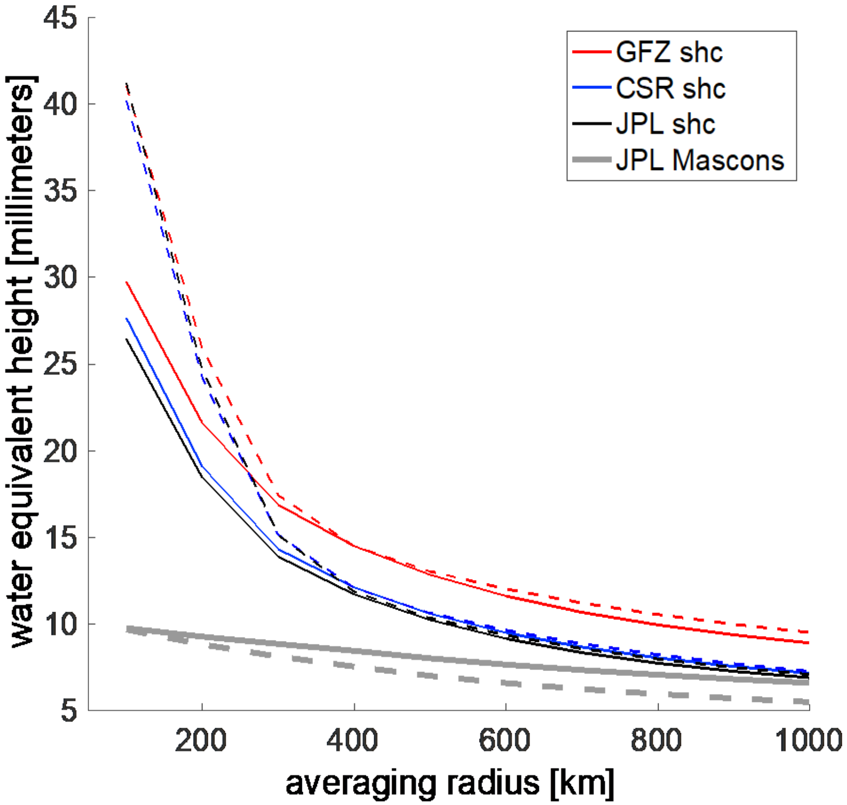


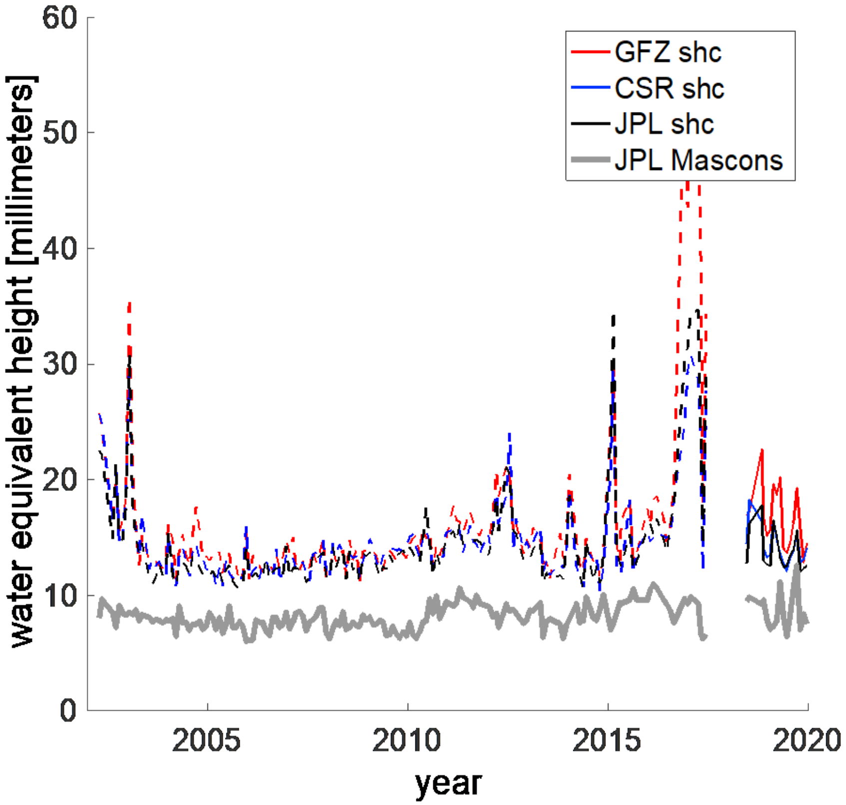
Data Source: https://sealevel.nasa.gov/ [accessed 2020-05-05]

GRACE-FO meets L1 Science Requirements



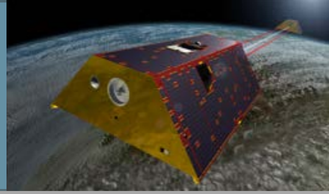
- RMS error over the ocean of monthly gravity fields through 12/2019 consistent across SDS center solutions
- Somewhat higher month-to-month scatter in GFO – with 20 monthly fields it's still too early to assess this rigorously

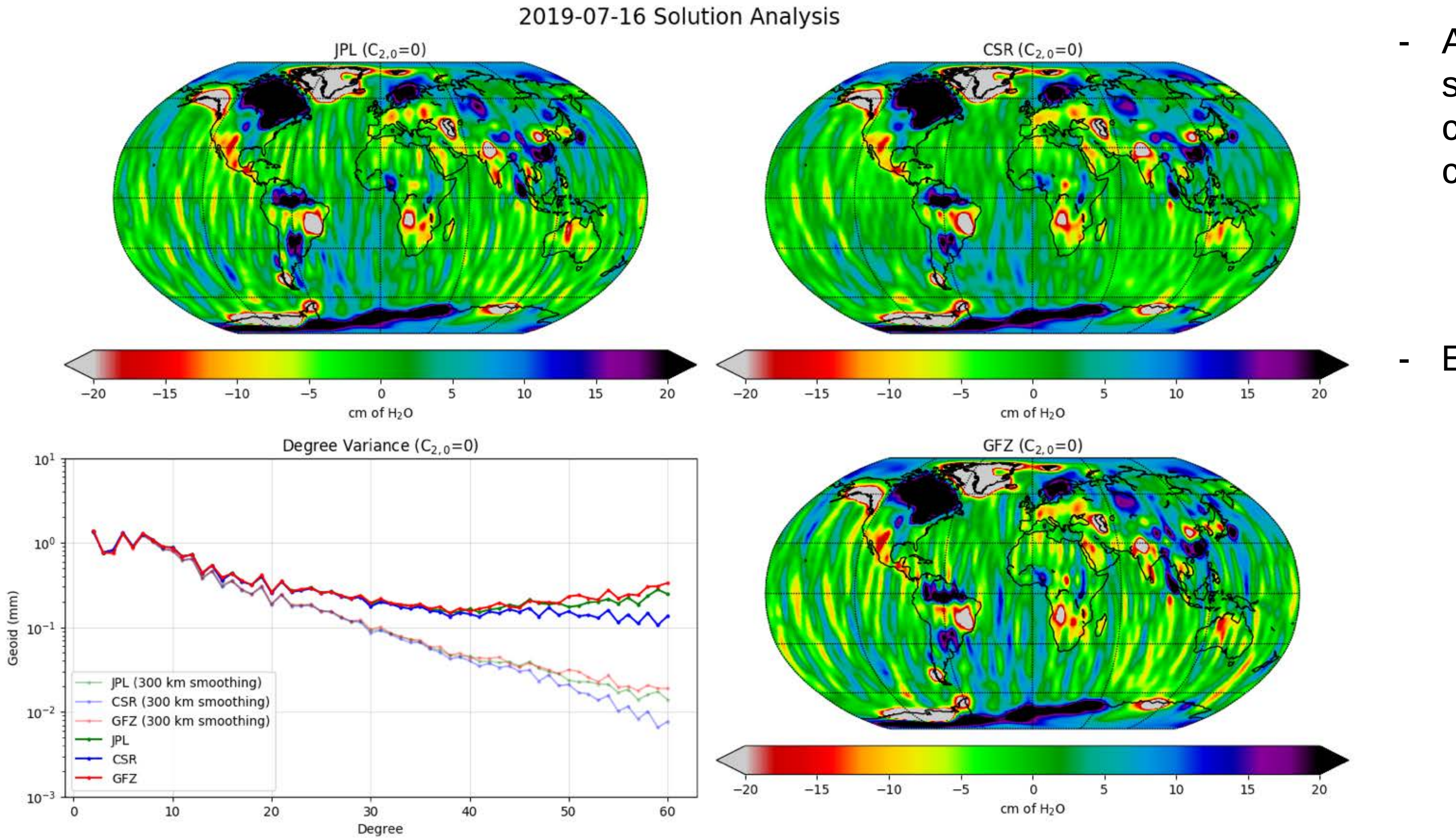




Landerer et al., GRL, submitted (minor revisions)

GRACE-FO Performance (I)

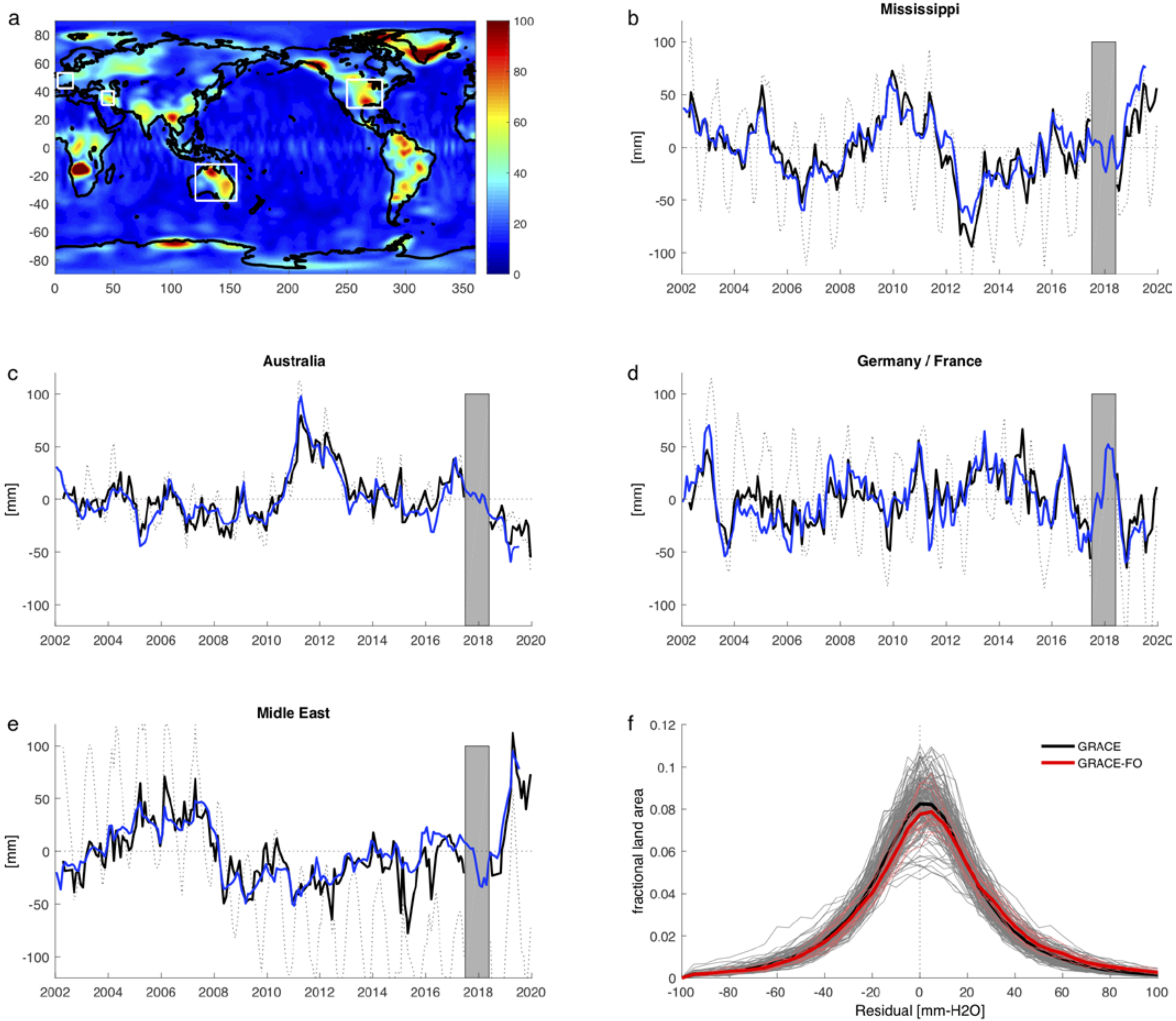




- All GRACE-FO SDS solutions have consistent signal content
  - Slightly different noise characteristics at higher degrees

- Example: July 2019

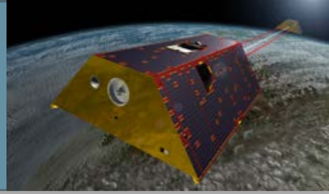
GRACE-FO Performance (II)



(a) Spatial distribution of the RMS of GRACE-FO June 2018 to December 2019 (mean of JPL, CSR, GFZ RL06 solutions). Mean annual signal and trends have been removed. (b-e): Basin-mean TWS anomalies from GRACE and GRACE-FO (black), and from a TWS reconstruction (blue). (f) Histogram of the differences between GRACE/GRACE-FO observations and the TWS reconstruction over the entire observational period (2002 – 2019). The regional anomalies in GRACE-FO agree well with the reconstruction, indicating that they are physical and that no GRACE / GRACE-FO bias exists. Inter-mission gap between GRACE and GRACE-FO indicated by grey bar; dotted line shows full GRACE and GRACE-FO monthly anomaly.

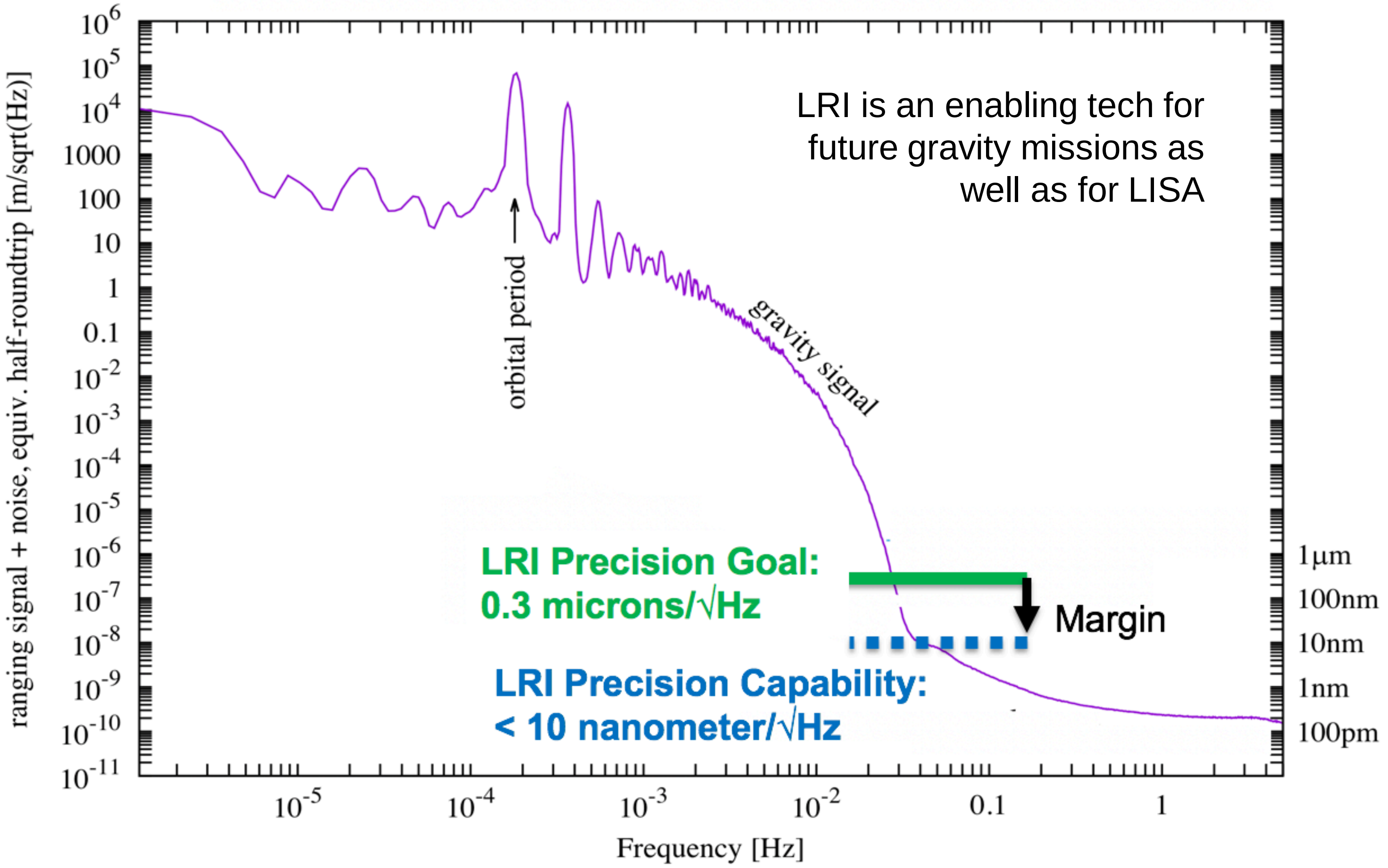
Landerer et al., GRL, submitted (minor revisions)

LRI meets L1 tech demo requirement & goal

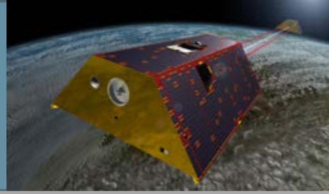


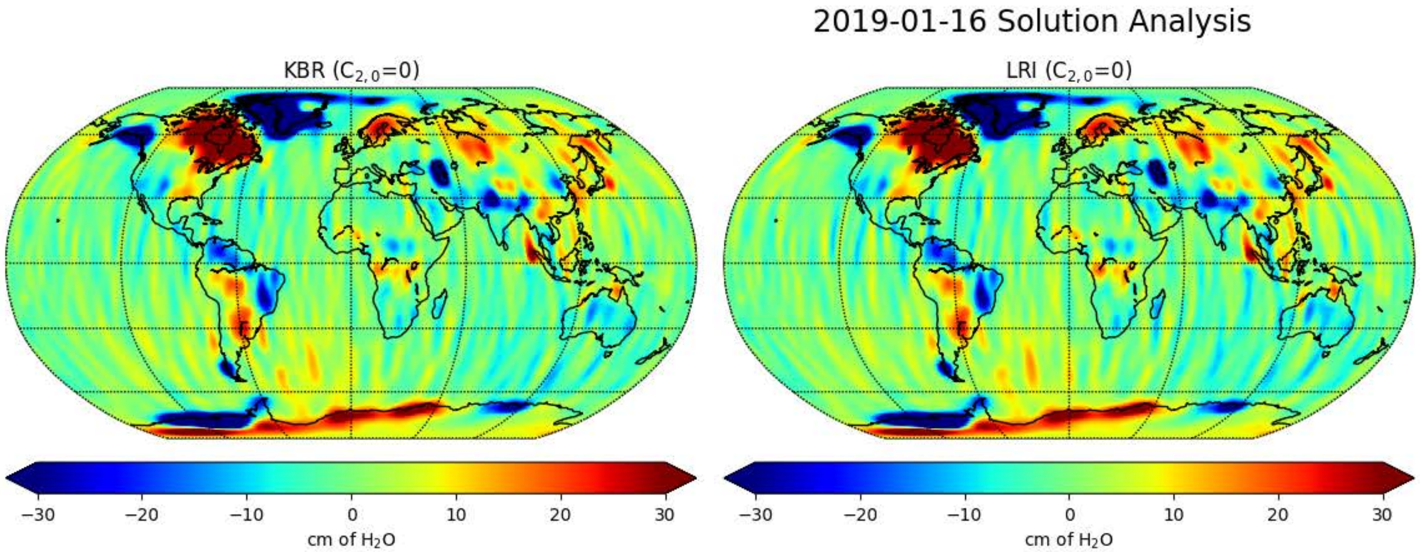
- Satellite-to-satellite Laser Ranging Interferometry (LRI) demonstrated in low Earth orbit during in-orbit-checkout (IOC) with a precision >30x better than goal (> 100x better than MWI capability).

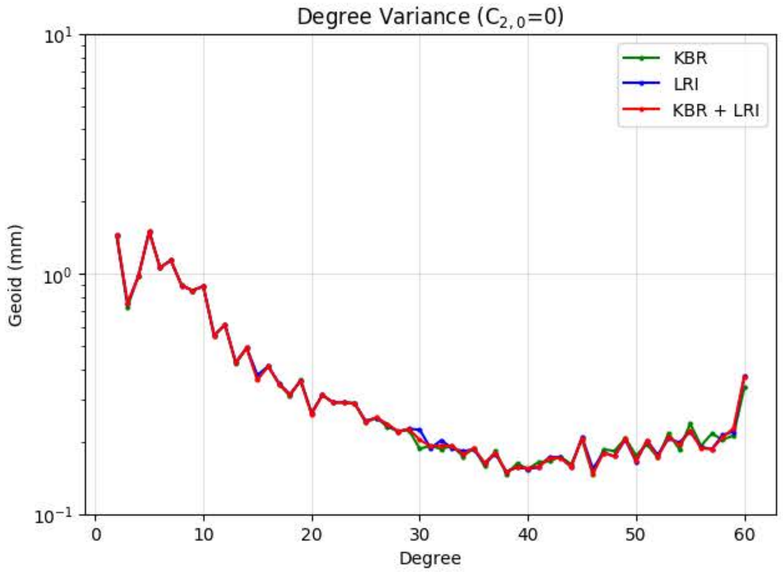
LRI Measurement of Gravity Signal and Noise



LRI Gravity Fields – work in progress







- LRI monthly gravity fields are consistent with KBR fields (expected, but not trivial result)
- SDS is exploring data combination and weighting schemes to optimally process the LRI data
- Much lower noise levels in LRI ranging data provide new opportunities to study higher-frequency mass change signals (e.g., earthquakes, sub-monthly ocean / atmosphere variations, fast hydrology events etc.)

Improved SST Measurement Accuracy

- **'Range-Rate-Residuals'** provide a metric of the ranging measurement system noise

Residuals:

GRACE MWI

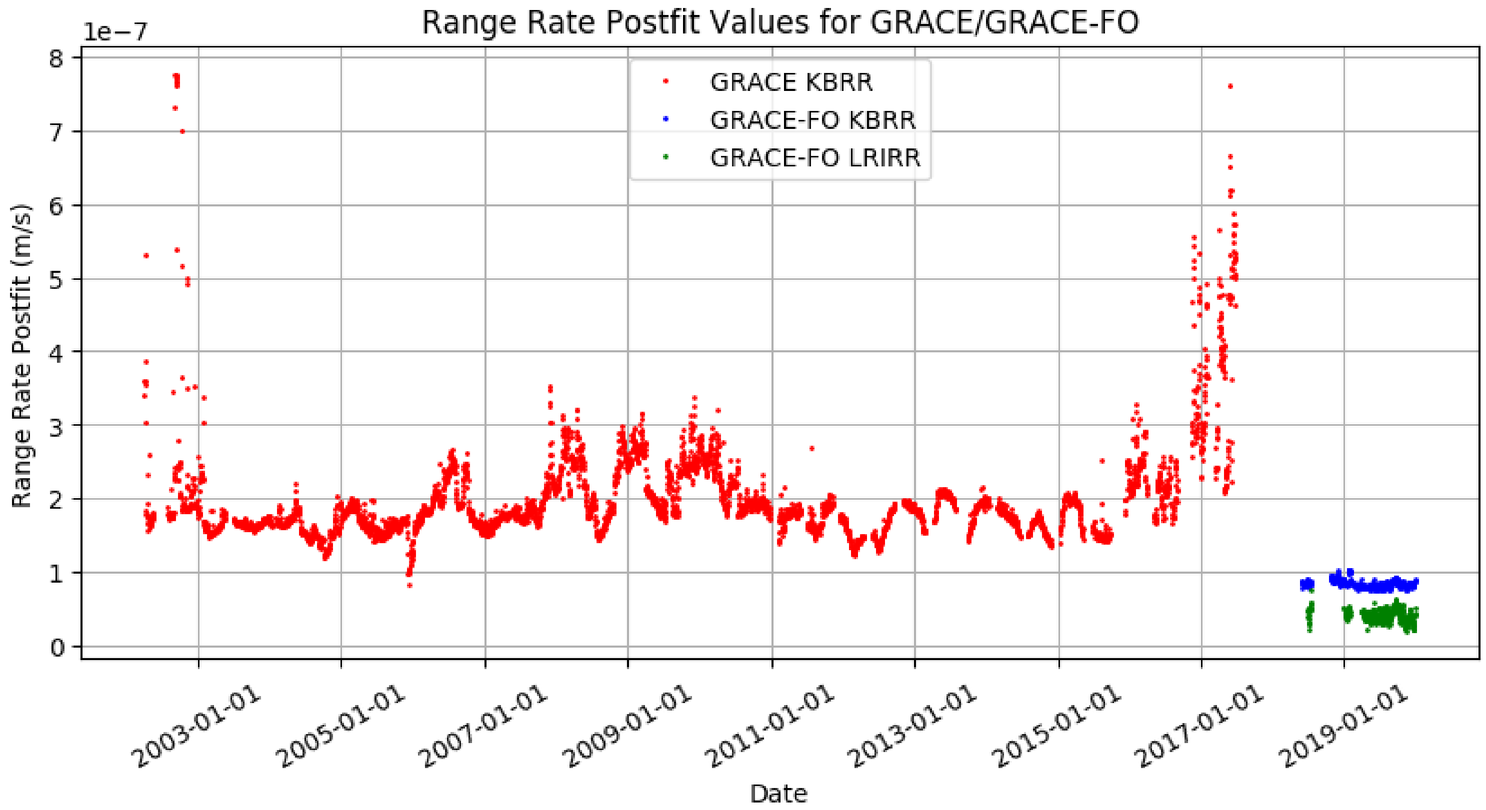
RMS = 140 nm/s

- GRACE-FO MWI

RMS = 77 nm/s

- GRACE-FO LRI

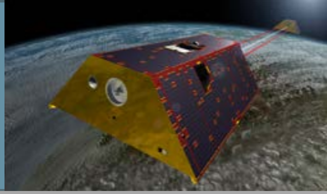
RMS = 37 nm/s



Reduced range rate residuals are consistent with an overall lower noise level on the GRACE-FO KBR system, in conjunction with an improved AOCS performance. Similarly, the very low measurement noise of the LRI results in even lower post-fit residuals from LRI-based gravity fields, at approximately 50% relative to the GRACE-FO KBR

Landerer et al., GRL, submitted (minor revisions)

GF2 Accelerometer: Status and Plans

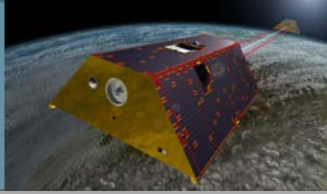


- Following the transition to Large Range Mode (LRM) on June 21, 2018 the GF2 ACC continues to measure real accelerations but common-mode error signals appeared on each of the six components of the GF2 Accelerometer (ACC) science data.

- GF2 ACC is currently operating in Large Range Mode (LRM)
  - Because both satellites are on the same trajectory separated by roughly 30 seconds, it is possible to transplant the non-gravitational forces detected by the GF1 ACC to GF2 which enables production of high quality gravity solutions using a single ACC. The mission is meeting level 1 requirements using the transplant method.

- An activation test of a relay (multiple open/close activations, performed in Nov-2019) did not change the performance of the GF2 ACC

- Next step is to switch to Nominal Range Mode (NRM) and assess the GF2 ACC performance
  - The GF2 ACC performance is not likely to improve in any significant way but transition to NRM may enable development of improved calibrations and transplant methods (i.e., hybrid transplant)
  - Science requirements will continue to be met using the transplant method while the difference in the non-gravitational forces on the two satellites is small.
  - Fuel is available to optimize science data quality and mission lifetime by maintaining orbit altitude.



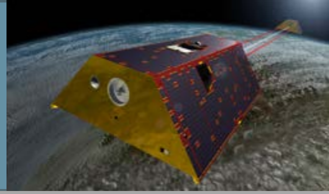
Plans - What’s next?

- Continuous data delivery Level-1, 2 & 3
  - Archives at JPL PO.DAAC (https://podaac.jpl.nasa.gov/) and GFZ ISDC (https://isdc.gfz-potsdam.de/grace-fo-isdc/)
  - Monthly L3 products at JPL Tellus (https://grace.jpl.nasa.gov/) and GFZ GravIS (http://gravis.gfz-potsdam.de): global grids over land, ice sheets, and oceans)
  - GRACE-FO Mascon delivery by JPL, CSR and GSFC
  - Technical Notes (**TN-13** for geocenter; **TN-14** for C20, C30 from SLR) – regular updates

- Information on mission status provided in monthly SDS Newsletters

- GRACE/GRACE-FO Science Team Meeting Oct. 27-29,2020 at GFZ in Potsdam, Germany
  - Webpage available at https://www.gstm-2020.eu/
  - Important Note: It is still under discussion if the GSTM can be held “face to face” (Check webpage and SDS newsletter for updates)

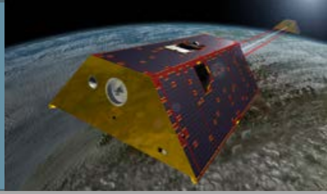
GRACE-FO Project Science - Summary



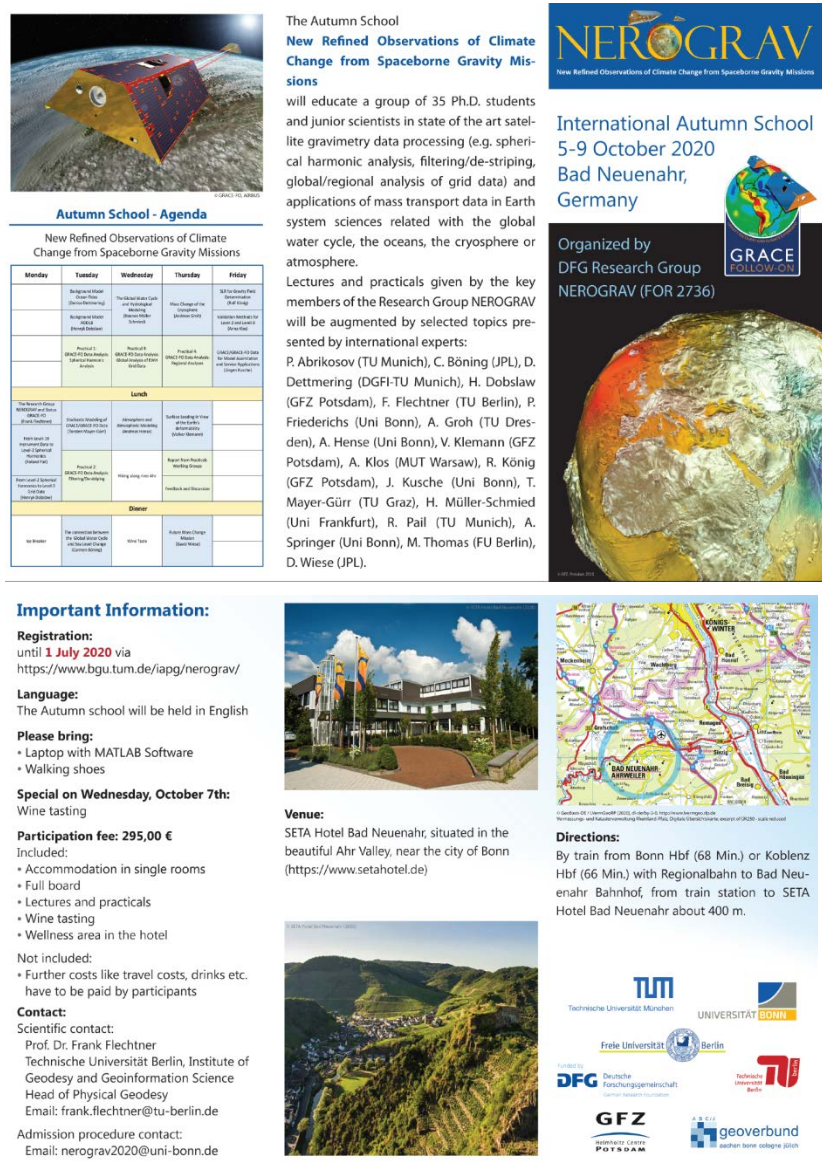
The project is meeting its Level-1 and product delivery requirements.

- All Level-1 requirements are being met at the required performance
  - Monthly gravity solutions (RL06) are extending the record at a precision and temporal sampling equivalent to that achieved with GRACE.
  - LRI has successfully demonstrated satellite-to-satellite interferometry in low Earth orbit and has exceeded the precision capability goal of better than below 0.3 microns/sqrt(Hz).
  - Approximately 200 radio occultation measurements are being made per day.
- All science data products are being delivered as planned (L2 much faster than required)
  - Gravity science data products were released ahead of schedule and are delivered routinely to NASA-PODAAC and GFZ-ISDC.
- Mission operations or data processing not impacted by COVID-19 crisis.
- First science results provide valuable new insights into Earth system processes and changes.
- Data processing approach is likely to meet mission objectives throughout prime 5-year mission.
  - Improved analysis and operational strategies are being investigated to assess data processing applicability beyond prime mission.

NEROGRAV Autumn School



- will take place **5-9 October 2020** in **Bad Neuenahr (near Bonn), Germany**
- is **organized by the Research Group NEROGRAV** (New Refined Observations of Climate Change from Spaceborne Gravity Missions) funded by German Research Foundation (DFG)
- will **educate a group of 35 Ph.D. students and junior scientists in state of the art satellite gravimetry data processing and applications of mass transport data in Earth system sciences** related with the global water cycle, the oceans, the cryosphere or the atmosphere.
- **Participation Fee: 295 EUR**
- **Registration** until **1. July 2020**
- All details incl. Flyer available at **https://www.bgu.tum.de/iapg/nerograv/**



Autumn School - Agenda

New Refined Observations of Climate Change from Spaceborne Gravity Missions

The Autumn School **New Refined Observations of Climate Change from Spaceborne Gravity Missions** will educate a group of 35 Ph.D. students and junior scientists in state of the art satellite gravimetry data processing (e.g. spherical harmonic analysis, filtering/de-striping, global/regional analysis of grid data) and applications of mass transport data in Earth system sciences related with the global water cycle, the oceans, the cryosphere or atmosphere.

Lectures and practicals given by the key members of the Research Group NEROGRAV will be augmented by selected topics presented by international experts:

P. Abrikosov (TU Munich), C. Böning (JPL), D. Dettmering (DGFI-TU Munich), H. Dobslaw (GFZ Potsdam), F. Flechtner (TU Berlin), P. Friederichs (Uni Bonn), A. Groh (TU Dresden), A. Hense (Uni Bonn), V. Klemann (GFZ Potsdam), A. Klos (MUT Warsaw), R. König (GFZ Potsdam), J. Kusche (Uni Bonn), T. Mayer-Gürr (TU Graz), H. Müller-Schmied (Uni Frankfurt), R. Pail (TU Munich), A. Springer (Uni Bonn), M. Thomas (FU Berlin), D. Wiese (JPL).

NEROGRAV

New Refined Observations of Climate Change from Spaceborne Gravity Missions

International Autumn School
5-9 October 2020
Bad Neuenahr, Germany

Organized by
DFG Research Group
NEROGRAV (FOR 2736)

GRACE FOLLOW-ON

Important Information:

Registration:
until **1 July 2020** via
https://www.bgu.tum.de/iapg/nerograv/

Language:
The Autumn school will be held in English

Please bring:
- Laptop with MATLAB Software
- Walking shoes

Special on Wednesday, October 7th:
Wine tasting

Participation fee: 295,00 €
Included:
- Accommodation in single rooms
- Full board
- Lectures and practicals
- Wine tasting
- Wellness area in the hotel

Not included:
- Further costs like travel costs, drinks etc. have to be paid by participants

Contact:
Scientific contact:
Prof. Dr. Frank Flechtner
Technische Universität Berlin, Institute of Geodesy and Geoinformation Science
Head of Physical Geodesy
Email: frank.flechtner@tu-berlin.de

Admission procedure contact:
Email: nerograv2020@uni-bonn.de

Venue:
SETA Hotel Bad Neuenahr, situated in the beautiful Ahr Valley, near the city of Bonn (https://www.setahotel.de)

Directions:
By train from Bonn Hbf (68 Min.) or Koblenz Hbf (66 Min.) with Regionalbahn to Bad Neuenahr Bahnhof, from train station to SETA Hotel Bad Neuenahr about 400 m.

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UNIVERSITÄT BONN
Freie Universität Berlin
DFG Deutsche Forschungsgemeinschaft
Technische Universität Berlin
GFZ
geoverbund