Pre-GRACE Gravity Field Estimation Using SLR and GRACE Data

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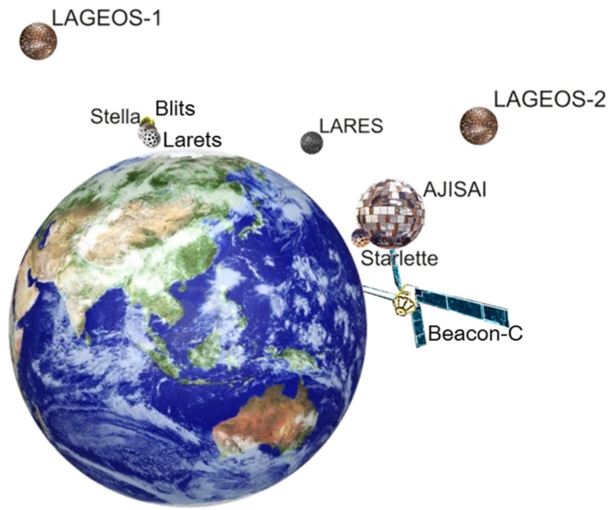
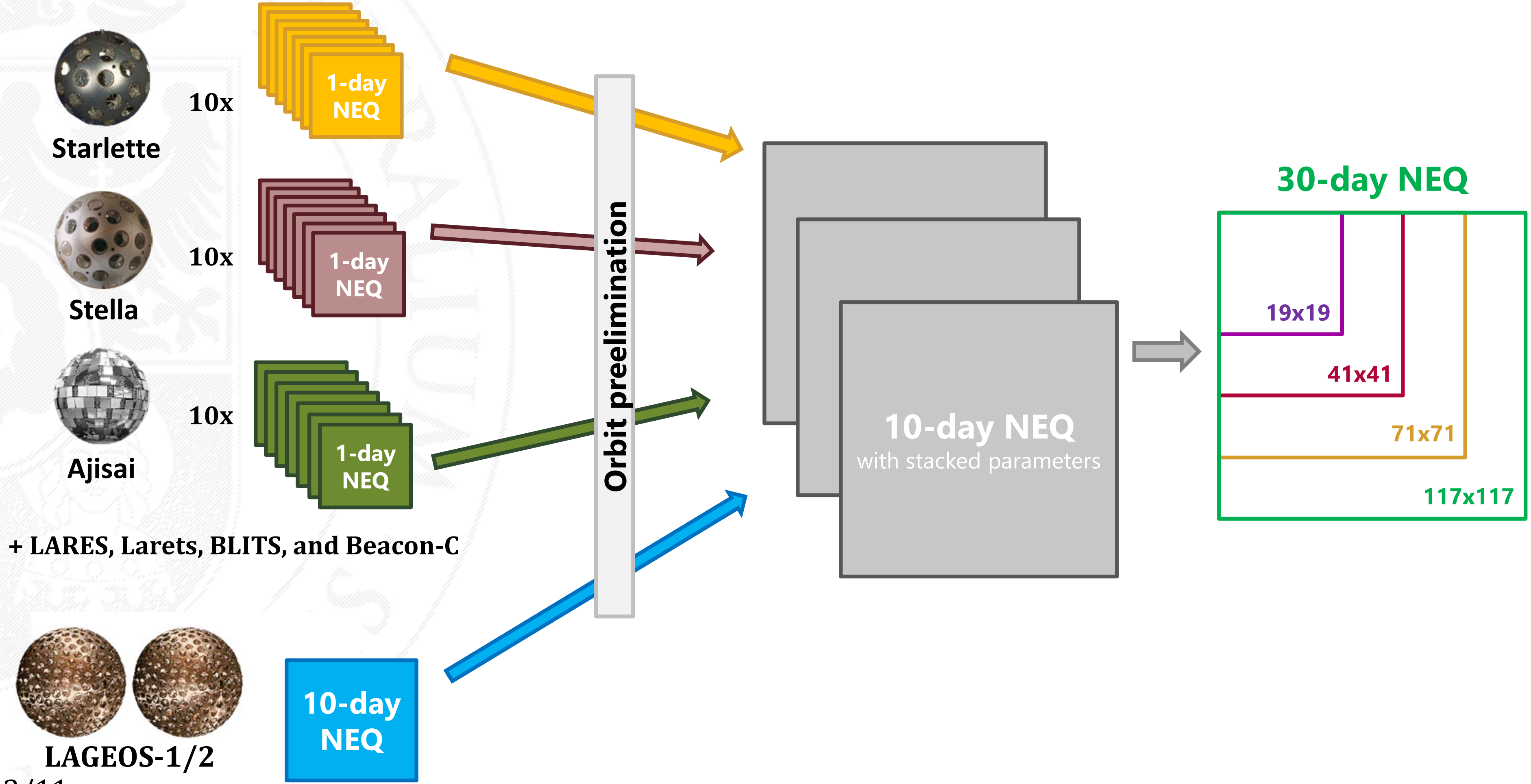
SLR solution

- Up to 9 geodetic satellites
- different altitudes
- different inclinations
- applied different weights for observations
- data from 1995 to December 2021



Satellite	Launch date	Orbit altitude	Inclination	Mass	A priori error
Beacon-C	1965	940-1300 km	41.21°	32 kg	50 mm
Starlette	1975	800-1100 km	49.84°	47 kg	20 mm
LAGEOS-1	1976	5860 km	109.90°	407 kg	8 mm
AJISAI	1986	1500 km	50.04°	685 kg	25 mm
LAGEOS-2	1992	5620 km	52.67°	405 kg	8 mm
Stella	1993	810 km	98.57°	48 kg	20 mm
Larets	2003	690 km	97.77°	23 kg	30 mm
LARES	2012	1440 km	69.56°	387 kg	15 mm

Processing strategy



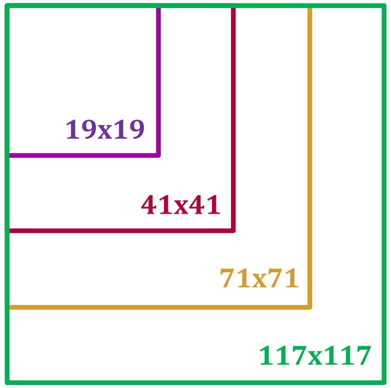
with stacked parameters:

- gravity field
- station coordinates
- ERPs
- geocenter
- range biases

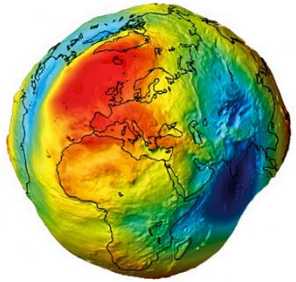
Processing strategy

N – left hand side of the normal equation system (NEQ)
b – right hand side of NEQ
x – estimated parameters

30-day NEQ



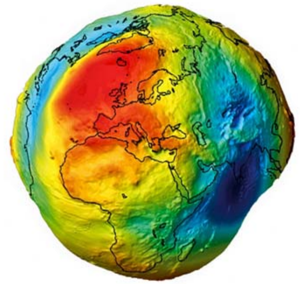
$$x_{10,10}^{\ SLR\ F} = (N_{10,10})^{-1}\ b_{10,10}$$



Monthly gravity field
d/o 10
SLR F

1) splitting NEQ up to defined expansion
2) stacking the previously splitted NEQs

d/o 10 + d/o 8 + d/o 6 + d/o 4 =



Monthly gravity field
d/o 10
SLR N

"+" sign denotes the process of stacking normal equations

3 x SLR N = SLR S

$$x_{10,10}^{\ SLR\ N} = \left(N_{10,10} + N_{8,8} + N_{6,6} + N_{4,4}\right)^{-1}\left(b_{10,10} + b_{8,8} + b_{6,6} + b_{4,4}\right)$$

SLR solution

- The noise is reduced by a **factor of four** in **SLR S** w.r.t. **SLR F**.
- The median noise of the **GRACE** solutions (**3.2 cm)** **->** a **factor of two smaller** than **SLR S** solution **(7.7 cm).**

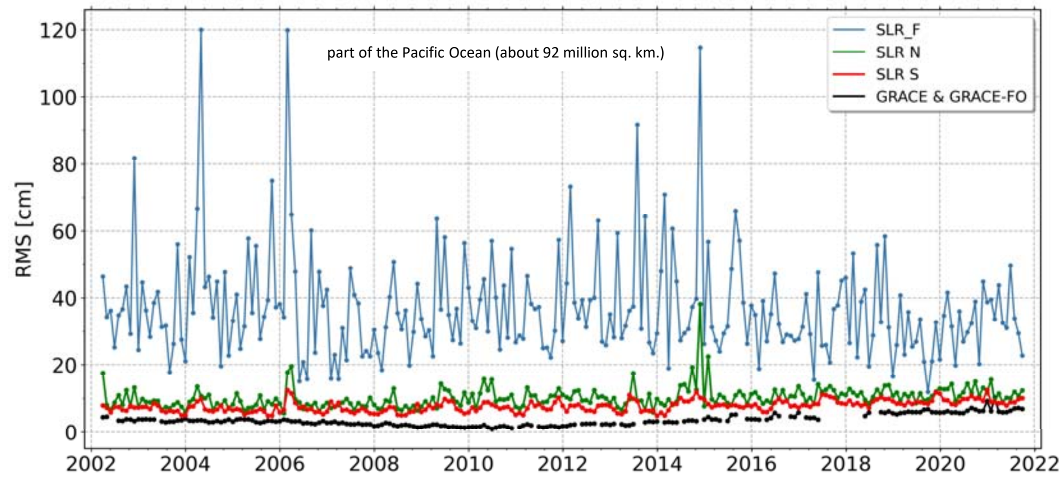
- SLR solution patterns **agree well** with GRACE and IMBIE data but some gravity signals could be lost due to ommission errors related to the solution expansion.
- SLR data **was rescaled** by a factor calculated between SLR and GRACE COST-G

The model has been published on ICGEM
International Centre for Global Earth Models (ICGEM)
https://icgem.gfz-potsdam.de/sp/04_SLR_/IGG_UPWr_SLR

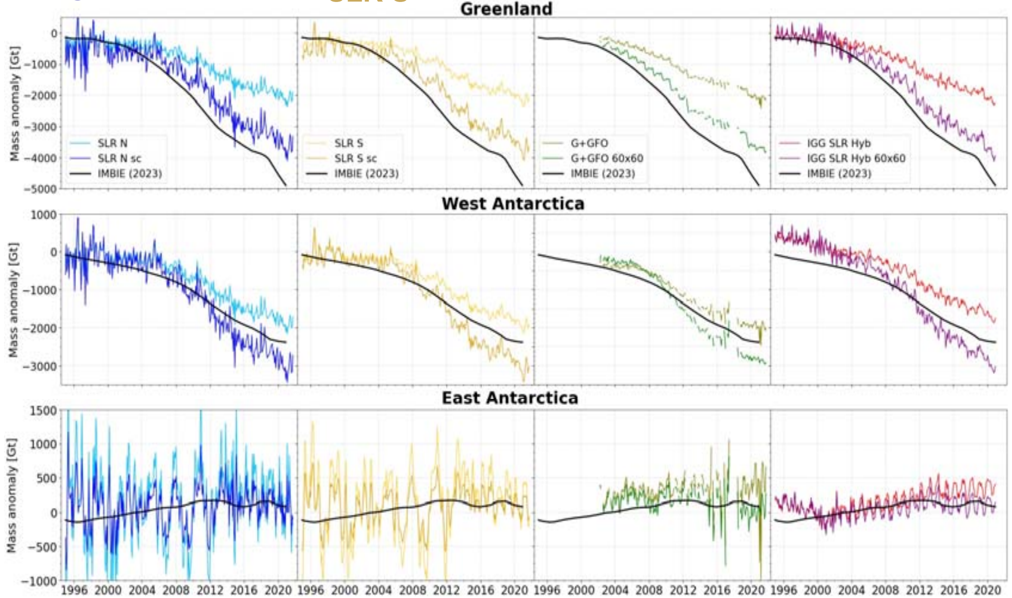
More information:

Gałdyn, F., Sośnica, K., Zajdel, R, Mayer, U., Jäggi., A. (2024). Long-term ice mass changes in Greenland and Antarctica derived from satellite laser ranging. *Remote Sensing of Environment*. https://doi.org/10.1016/j.rse.2024.113994

Noise over oceans



Solution	Median RMS [cm]
SLR F	33.9
SLR N	9.7
SLR S	7.7
IGG HYB	3.0
HLSST	6.4
GRACE+GFO	3.2



(Gt/year)

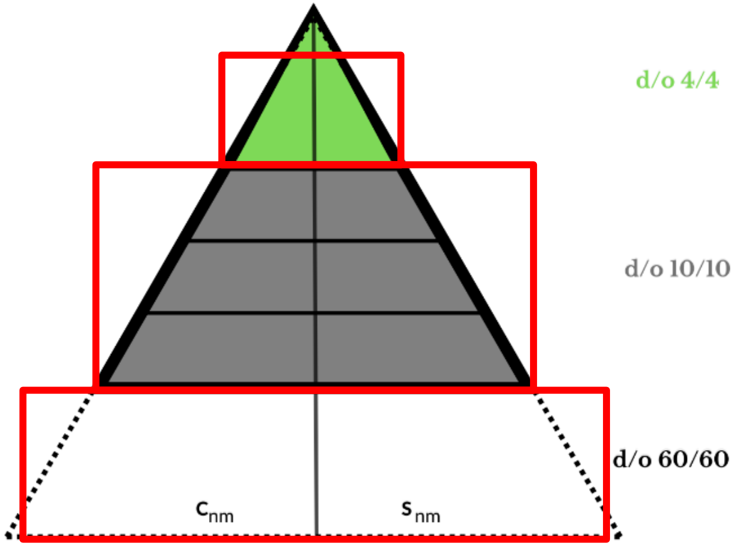
SLR N: -185.5
SLR S: -188.9
COST-G: -194.0
IMBIE: -237.8

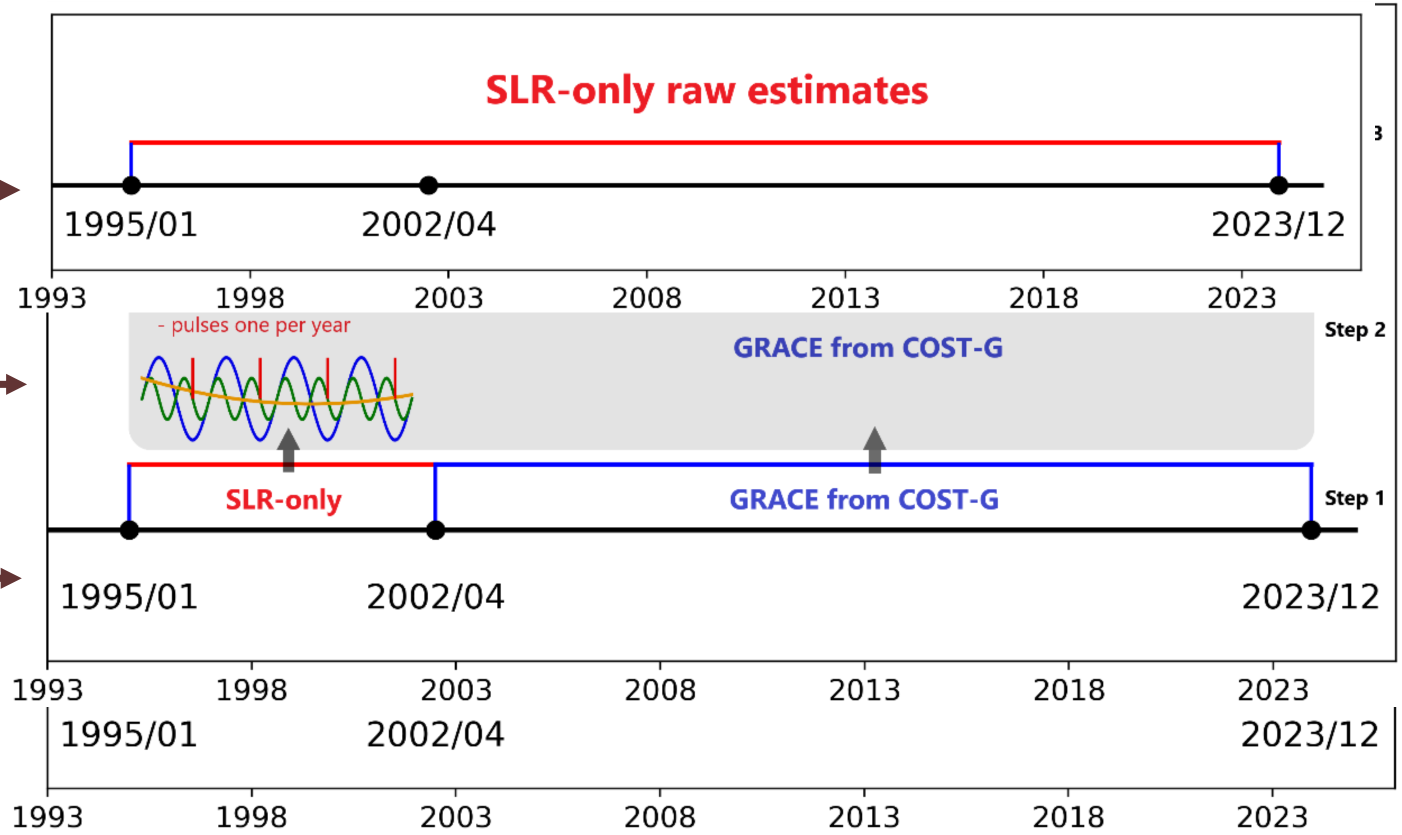
SLR N: -146.8
SLR S: -148.1
COST-G: -170.4
IMBIE: -120.1

SLR N: +5.5
SLR S: +7.8
COST-G: -9.5
IMBIE: +6.5

Model preparation

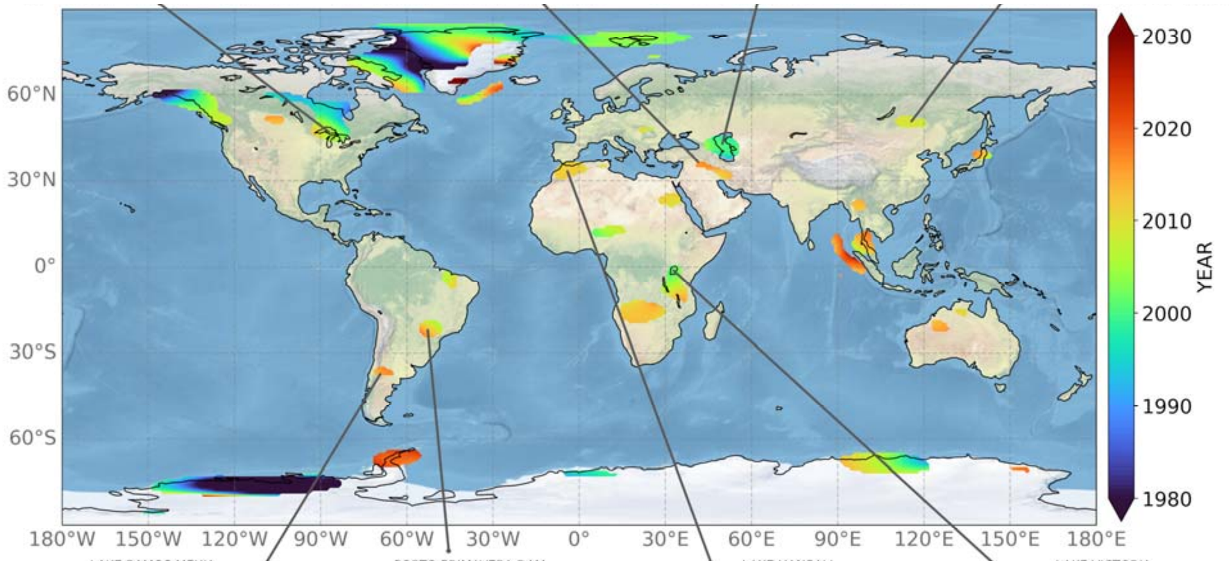
- SLR solution (Gałdyn et al., 2024) extended do December 2023
- GRACE&GFO solution – COST-G (Meyer et al., 2024)





Water Storage Accelerations - land

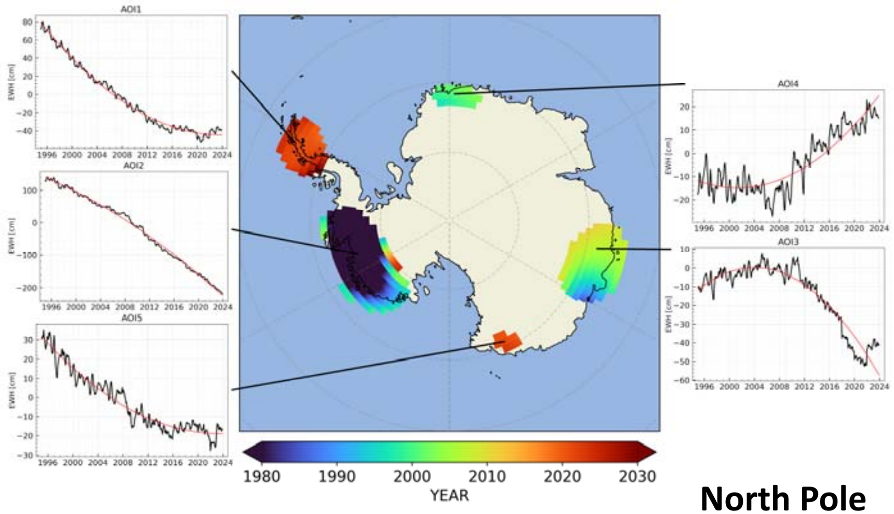
- trends and accelerations of EWH together with annual and semiannual signals from 1995 to 2024
- accelerations whose absolute values exceeded 2σ – statistically significant
- timestamps (in years) are determined for the maxima and minima of the function
- the largest trend and accelaration over the land with maximum in 2000 in Caspian Sea
- the significant accelerations occur on regions such as **Lake Michigan, Lake Therthar, Lake Hulun, Lake Ramos Mexia, Lake Hansali and Lake Victoria**



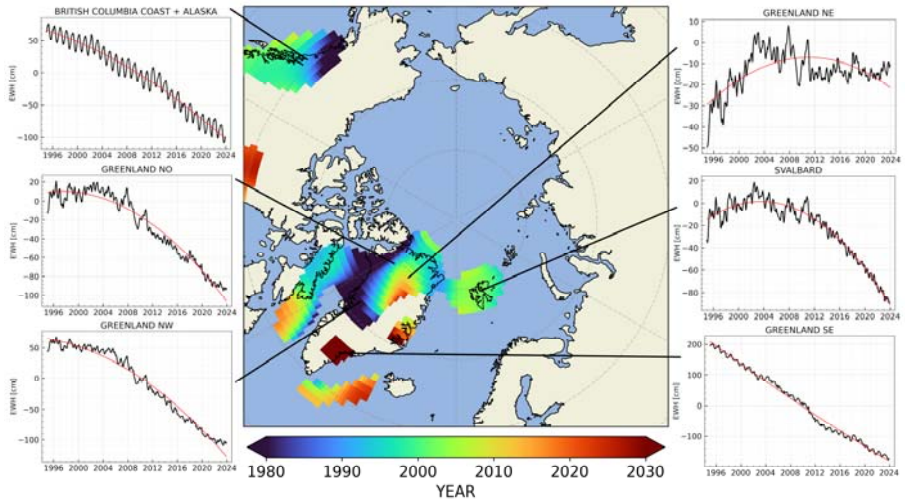
Water Storage Accelerations – polar regions

- selected areas exhibit high significant accelerations
- in the **eastern Antarctic** (AOI4), mass is being accumulated, whereas for AOI3 it is decreasing
- in AOI1 - **Antarctic Peninsula**, ice mass loss decelerated and the trend reversed around 2021
- AOI2 in **western Antarctica** continues to experience significant ice mass loss, confirming the long-term decline
- In Svalbard region, the function reached its maximum in the middle of the first decade of the 21st century due to climate warming
- A similar phenomenon is observed in the Gulf of Alaska Glaciers (seasonal changes)
- most areas identified in Greenland exhibit long-term mass loss

South Pole

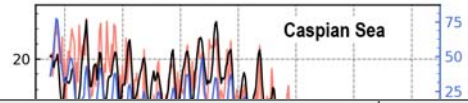


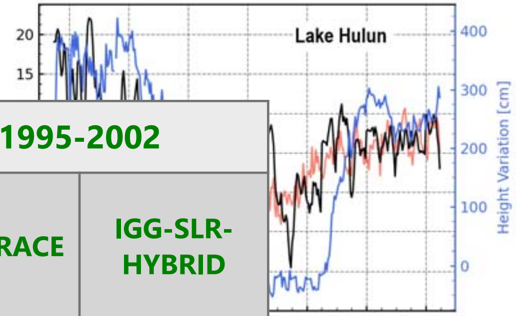
North Pole

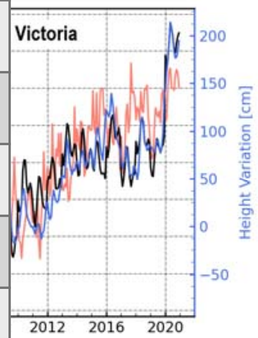


Correlation with altimetry data

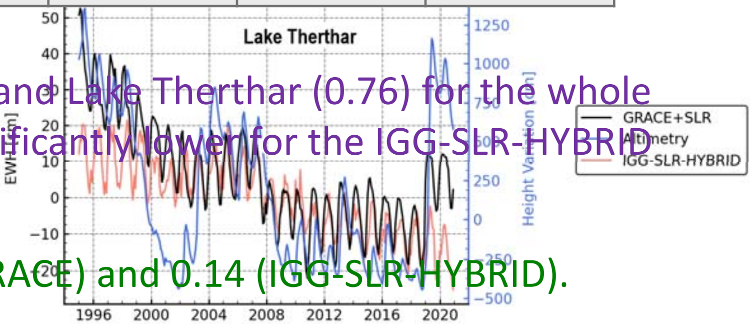
- As altimetry data, we use data from https://blueice.gsfc.nasa.gov/gwm for lake height variations
- We use IGG-SLR-HYBRID (ENS_MEAN) (Löcher & Kusche, 2021)
- We do not consider the steric parameter







	1995-2021		2002-2021			1995-2002	
	SLR+GRACE	IGG-SLR-HYBRID	SLR+GRACE	IGG-SLR-HYBRID	COST-G	SLR+GRACE	IGG-SLR-HYBRID
Caspian Sea	**0.93**	**0.91**	0.97	0.93	0.99	**0.51**	**0.64**
Lake Michigan	**0.82**	**0.50**	0.83	0.68	0.89	**0.64**	**0.38**
Lake Hulun	**0.71**	**– 0.18**	0.53	0.53	0.53	**0.32**	**0.14**
Lake Victoria	**0.63**	**0.49**	0.90	0.79	0.92	**0.44**	**– 0.05**
Lake Therthar	**0.64**	**0.50**	0.58	0.34	0.72	**0.76**	**0.52**



- SLR+GRACE model shows higher correlations for Lake Hulun (0.71) and Lake Therthar (0.76) for the whole period with altimetry data. Correlations for the same areas are significantly lower for the IGG-SLR-HYBRID model, equalling -0.18 and 0.52, respectively.
- For pre-GRACE period, correlations for Lake Hulun are 0.32 (SLR+GRACE) and 0.14 (IGG-SLR-HYBRID). For Lake Victoria: 0.44 (SLR+GRACE) vs -0.05 (IGG-SLR-HYBRID).

Summary and Outlook

- **Significant Accelerations Detected:** Using nearly 30 years of SLR and GRACE data, we identify continental regions showing substantial accelerations in mass change, notably in polar regions (Svalbard, Greenland) and areas affected by water exploitation (Caspian Sea, Nile, Lake Victoria).

- **Correlations and validation:** High correlations between satellite altimetry and the proposed gravity models (SLR+GRACE) validate the model's ability to replicate mass changes in water bodies, including smaller lakes, before the GRACE mission.

- **ENSO and SSTA:** The combined SLR+GRACE model shows strong correlations with ENSO events, particularly during the pre-GRACE era, highlighting its robustness in capturing climate signals like El Niño/La Niña.

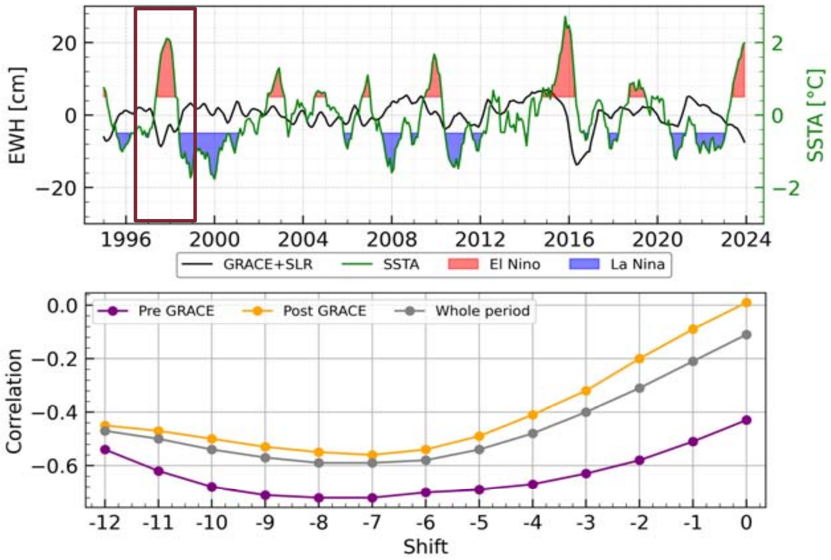


Fig. Nino3.4's SSTA index (5° North – 5° South) (170° – 120° West) and mass anomaly time series from the proposed model for the Amazon River basin (top). The value of correlation between Nino3.4 SSTA and mass anomalies with time shift (bottom).

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Thank you for your attention

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Gałdyn, F., Sośnica, K., Zajdel, R, Mayer, U., Jäggi., A. *(under review)*. Non-linear global ice and water storage changes from a combination of SLR and GRACE data

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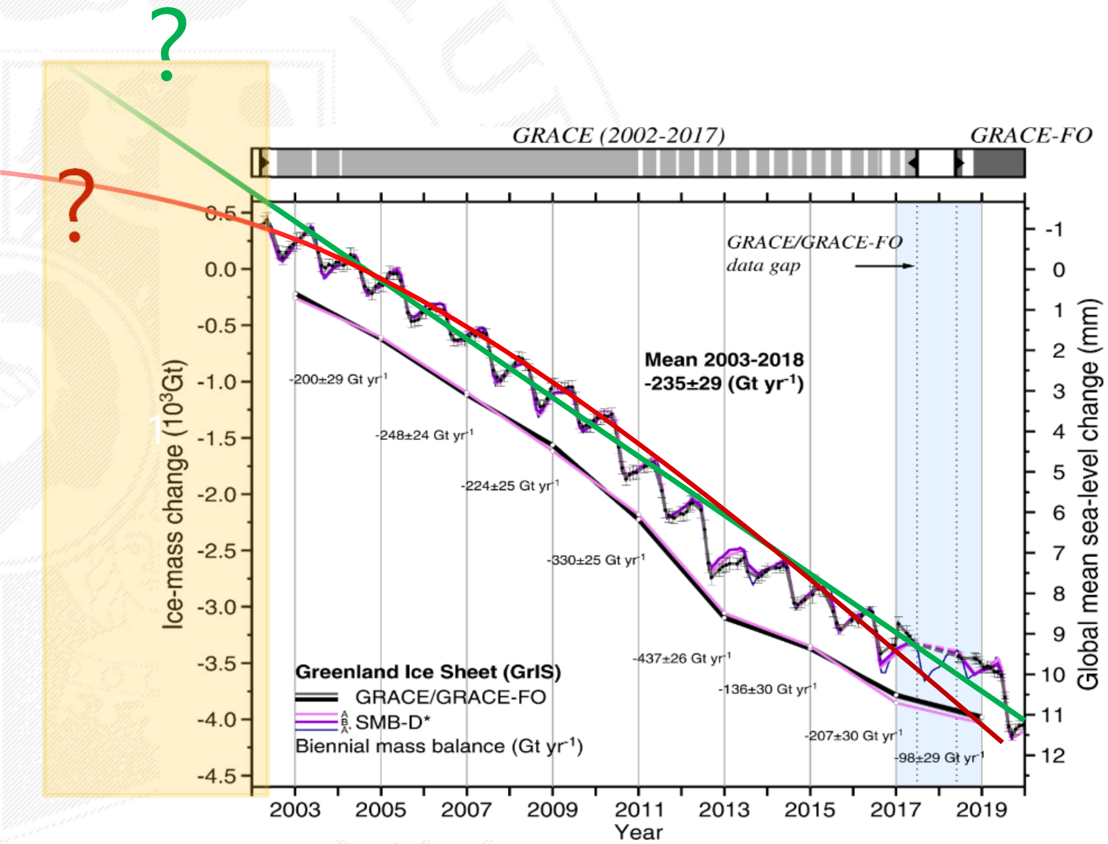
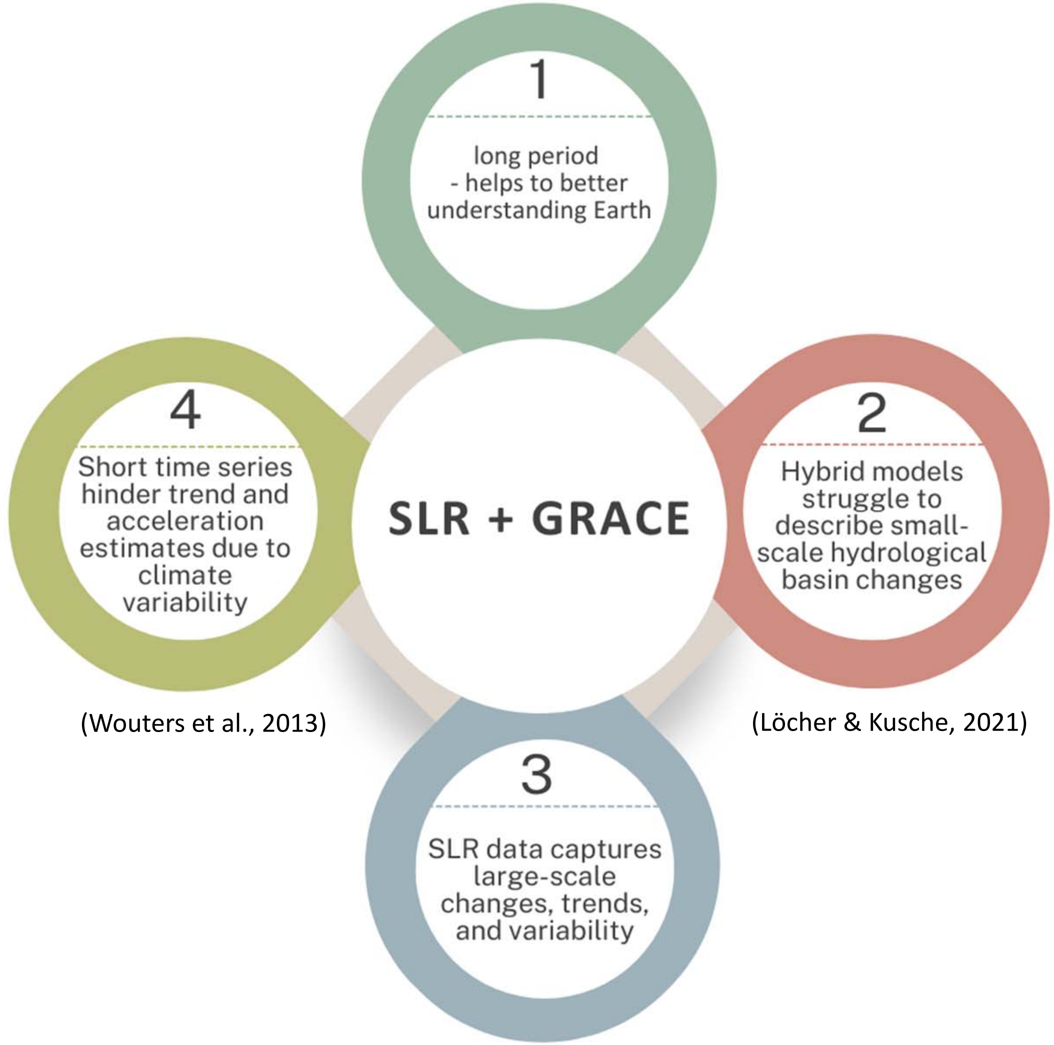
BACKUP SLIDES

Motivation



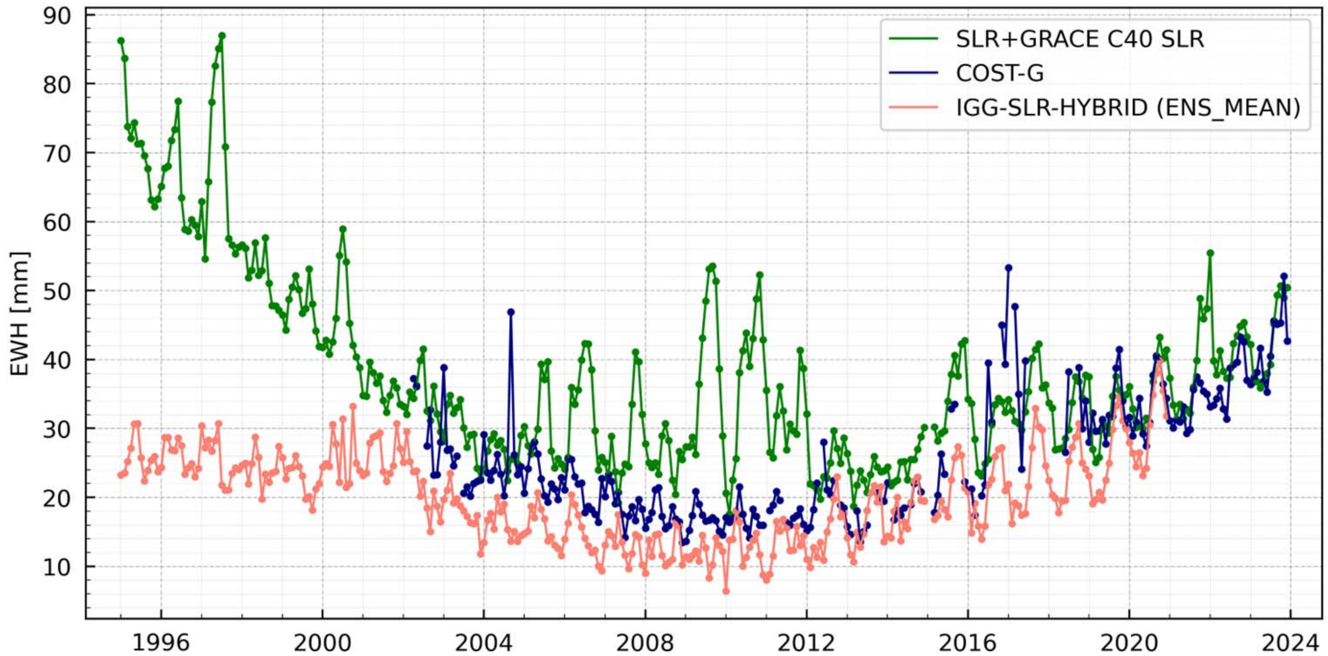
(Sasgen et al., 2020)

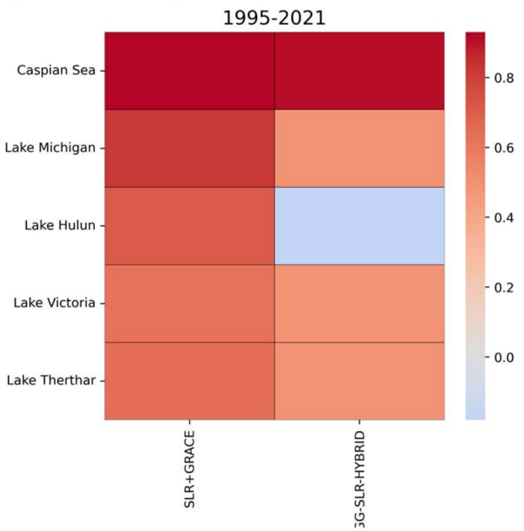


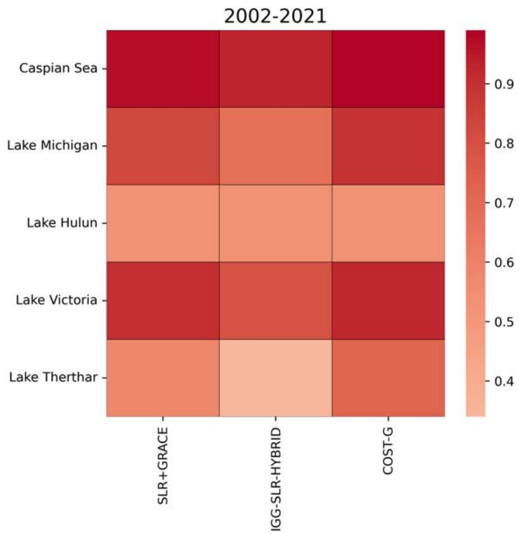
(Wouters et al., 2013)

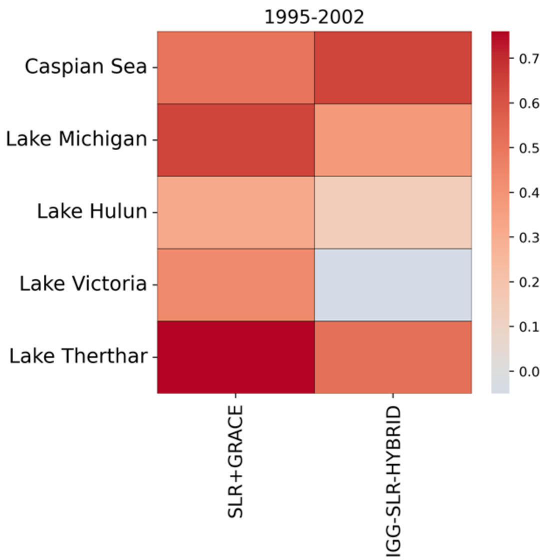
(Löcher & Kusche, 2021)

(Gałdyn et al., 2024)


90
80
70
60
50
40
30
20
10
EWH [mm]
1996
2000
2004
2008
2012
2016
2020
2024
SLR+GRACE C40 SLR
COST-G
IGG-SLR-HYBRID (ENS_MEAN)

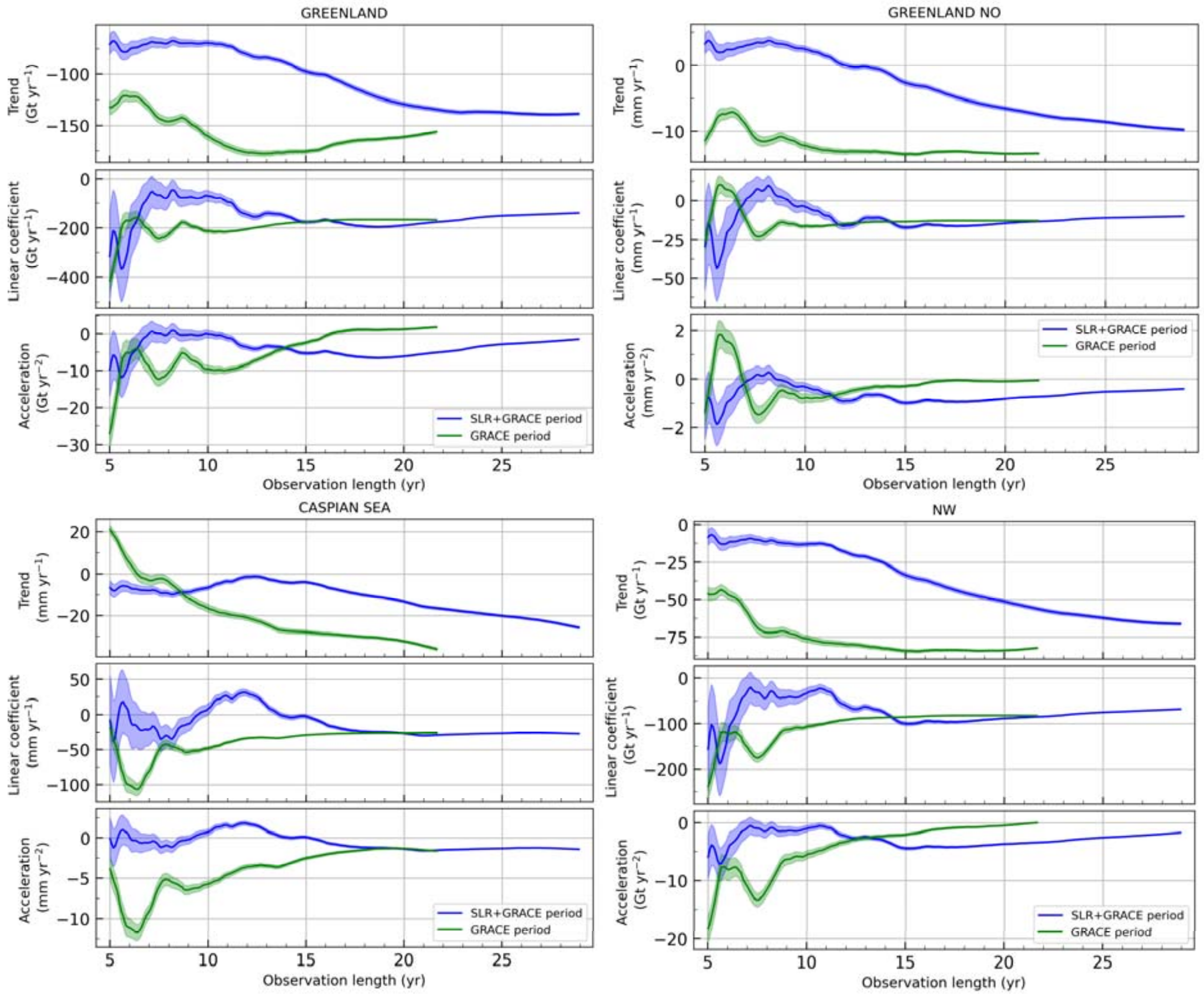

1995-2021
Caspian Sea
Lake Michigan
Lake Hulun
Lake Victoria
Lake Therthar
SLR+GRACE
G-SLR-HYBRID
0.8
0.6
0.4
0.2
0.0


2002-2021
Caspian Sea
Lake Michigan
Lake Hulun
Lake Victoria
Lake Therthar
SLR+GRACE
IGG-SLR-HYBRID
COST-G
0.9
0.8
0.7
0.6
0.5
0.4


1995-2002
Caspian Sea
Lake Michigan
Lake Hulun
Lake Victoria
Lake Therthar
SLR+GRACE
IGG-SLR-HYBRID
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

Water Storage Accelerations – polar regions

- The trend is not always a reliable indicator, as even with over 25 years of data, its stabilization **can be difficult to achieve when estimating a trend alone without an acceleration component.**
- In case of the indified regions, a model with the acceleration component is much more reliable, showing **good stabilization after 15-20 years** of observations when estimated together with the linear coefficients
- A model with both linear and acceleration coefficients better captures long-term global gravity field changes, stabilizing after 15-20 years depending on the region.



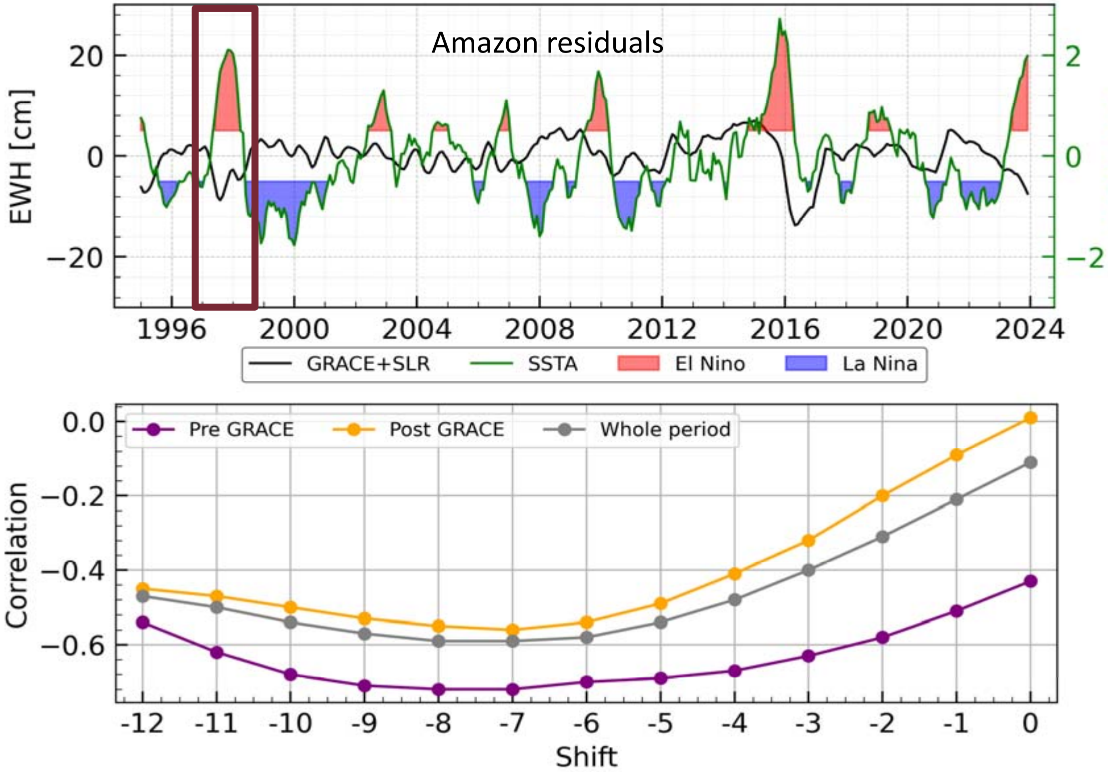
SSTA

- By extending time series by over 7 years using SLR data we can check the 1997/1998 El Niño event.
- For this purpose we use Amazon region after removing the trend, annual, and semi-annual signals

- For the pre-GRACE period, the highest correlation with the Nino3.4's SSTA index is obtained after 7 months and equals to -0.72

- For the GRACE period, the highest correlation with SSTA is also obtained after 7 months and equals to -0.56

- **The El Niño 1997/1998 event is clearly visible in the proposed SLR+GRACE solution**



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