Inferring Missing Solutions within and between GRACE and GRACE-FO Missions

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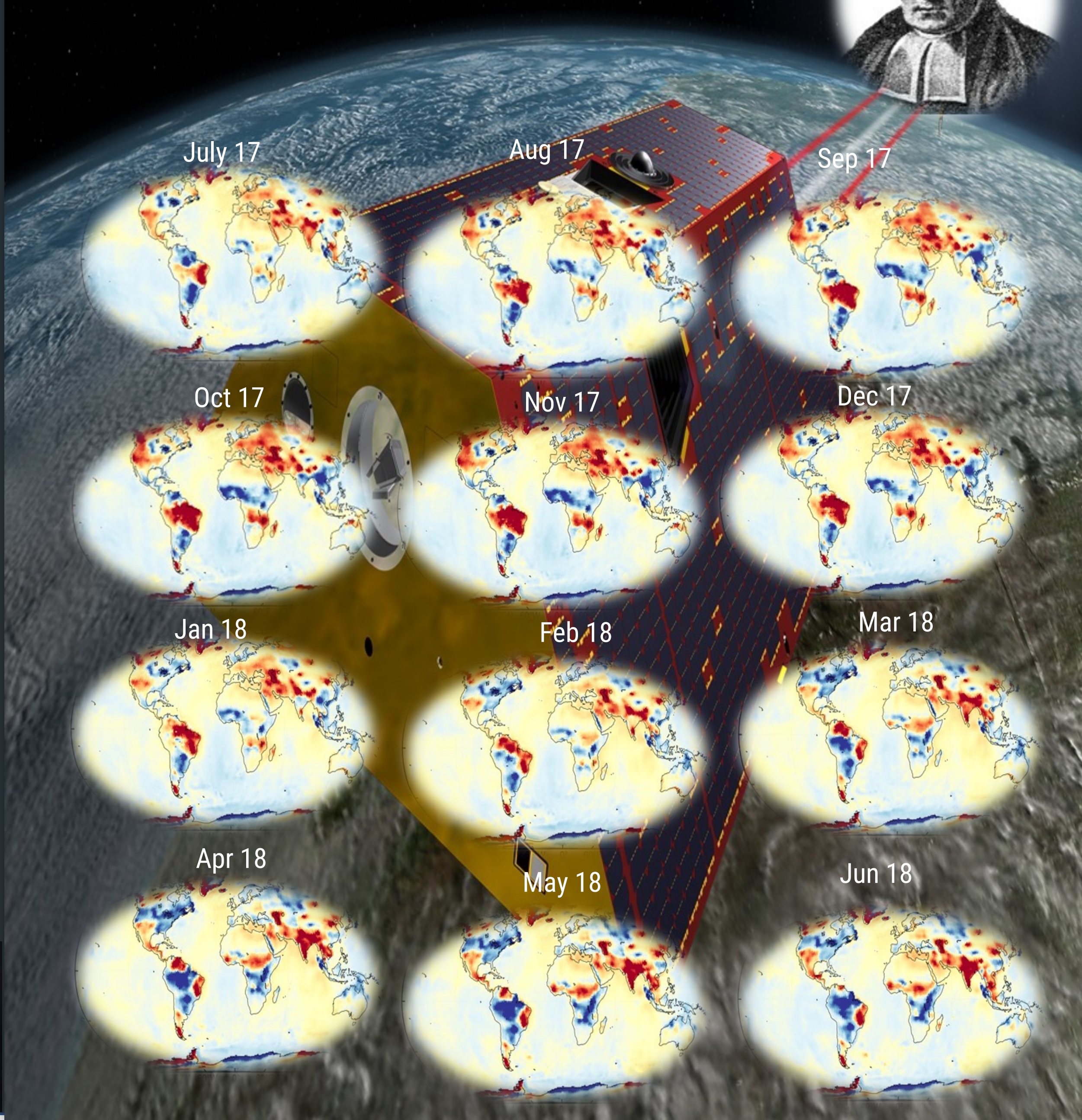
$$P(A|B) = \frac{P(B|A).P(A)}{P(B)}$$



Problem statement. 1/2

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Table 2: GRACE and GRACE-FO Level-2 product availability.

GRACE –FO SDS Newsletter No 19
Oct – Dec 2021

Level-2 (JPL)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002				1	2			3	4	5	6	7
2003	8	9	10	11	12		13	14	15	16	17	18
2004	19	20	21	22	23	24	25	26	27	28	29	30
2005	31	32	33	34	35	36	37	38	39	40	41	42
2006	43	44	45	46	47	48	49	50	51	52	53	54
2007	55	56	57	58	59	60	61	62	63	64	65	66
2008	67	68	69	70	71	72	73	74	75	76	77	78
2009	79	80	81	82	83	84	85	86	87	88	89	90
2010	91	92	93	94	95	96	97	98	99	100	101	102
2011		103	104	105	106		107	108	109	110	111	112
2012	113	114	115	116		117	118	119	120		121	122
2013	123	124		125	126	127	128			129	130	131
2014	132		133	134	135	136		137	138	139	140	
2015	141	142	143	144	145		146	147	148			149
2016	150	151	152		153	154	155	156			157*+	158*+
2017	159*+		160*+	161*+	162*	163*+						
2018						1*+	2*+			3*+	4+	5+
2019	6+	7*+	8+	9+	10+	11+	12+	13+	14+	15+	16+	17+
2020	18+*	19+*	20+	21+	22+	23+	24+	25+	26+	27+	28+	29+
2021	30+	31+	32+	33+	34+	35+	36+	37+	38+	39+	40+	41+

GRACE
- Level-2 products
- no Level-2 products available

GRACE-FO
- Level-2 products available

Current Level-2 Release: RL06

\+ Level-2 products (with ACC transplant)
* partial / overlapping calendar-months

The missing solutions within the GRACE mission (22-month) and between the GRACE and GRACE-FO missions (July 2017–May 2018; 11 months) disrupt the continuity in the observations, reducing our ability to understand the evolution of the mass changes during these times and to perform relevant hindcasting.

Problem statement. 2/2

1. Missing solutions within the missions ➔ linear or spline interpolations are performed
2. Missing solutions between the two missions (07/2017 -05/2018)

   1. Ice Sheets ➔ (Mass Balance models) [Velicogna et al., 2020];
   2. Land Hydrology
      - A. Global Positioning Systems (GPS) [Rietbroek et al., 2014]
      - B. SWARM Satellites (All masses) [Forootan et al., 2020; Lück et al., 2018; Meyer et al., 2019; Richter et al., 2021].
      - C. Statistical Learning [Li et al., 2020; Li et al., 2019c; Mo et al., 2022; Sun et al., 2021; Sun et al., 2020; Wang et al., 2021; Yang et al., 2021].
      - D. Data Assimilation [Li et al., 2019]

   3. Ocean ?

What is unique about our approach?

1. Relying only on GRACE (-FO) observations.
2. **Generating probability distributions of existing and missing solutions**, for the signal compartments (e.g., long-term trend (secular trend+ interannual variability), annual, semi-annual, and residuals) and reconstruct the full signal using medians of posterior distributions, thus accounting for uncertainties in the compartments and the full signal over the observed and missing times.
3. **Inferring missing solutions over all spheres of mass change (e.g., land, ocean, ice sheets).**

Data & Methods 1/2

Bayesian Data Analysis

$$P(\theta|D) = \frac{P(D|\theta) \times P(\theta)}{\sum P(D|\theta) \times P(\theta)} \quad [1]$$

1. GRACE (-FO) Monthly Data Generation Process

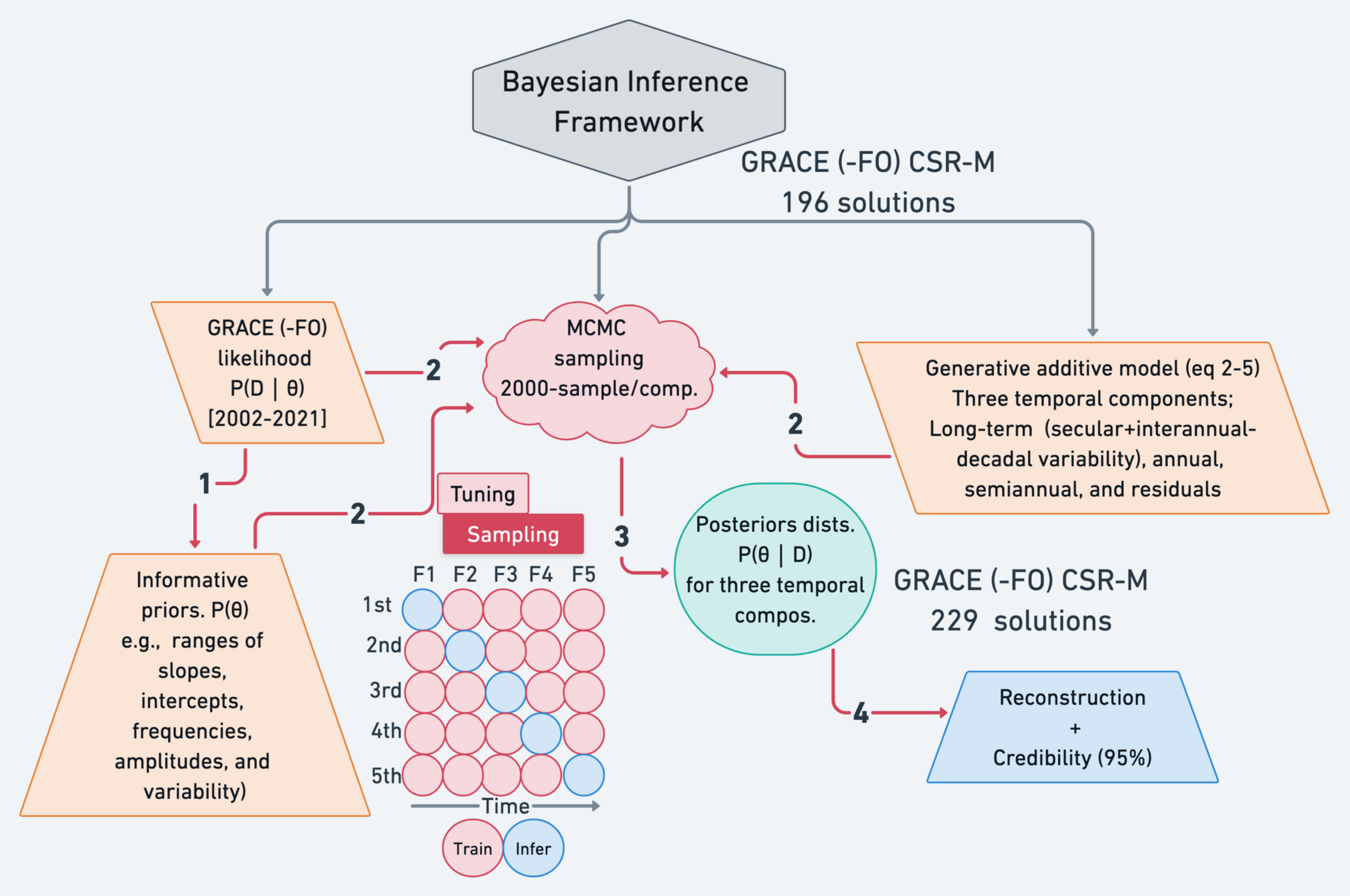
$$\textbf{GRACE (-FO) Data} = \alpha t + \beta t + \gamma_1 \cos(2\pi t) + \gamma_2 \sin(2\pi t) + \gamma_3 \cos(4\pi t) + \gamma_4 \sin(4\pi t) + \boldsymbol{\varepsilon} \quad [2]$$

- $\alpha t + \beta t$: Local Trend
- $\gamma_1 \cos(2\pi t) + \gamma_2 \sin(2\pi t)$: Annual Cycle (t=12)
- $\gamma_3 \cos(4\pi t) + \gamma_4 \sin(4\pi t)$: Semi-annual Cycle (t=6)
- ε: Residuals

$$\epsilon_t \sim N\left(0, \sigma_\mu\right),$$

Synoptic signal in GRACE (-FO) missions is small giving the monthly sampling. Here it’s left as part of the residuals, and added After the reconstruction

Data & Methods 2/2



Example 1 - Amazon

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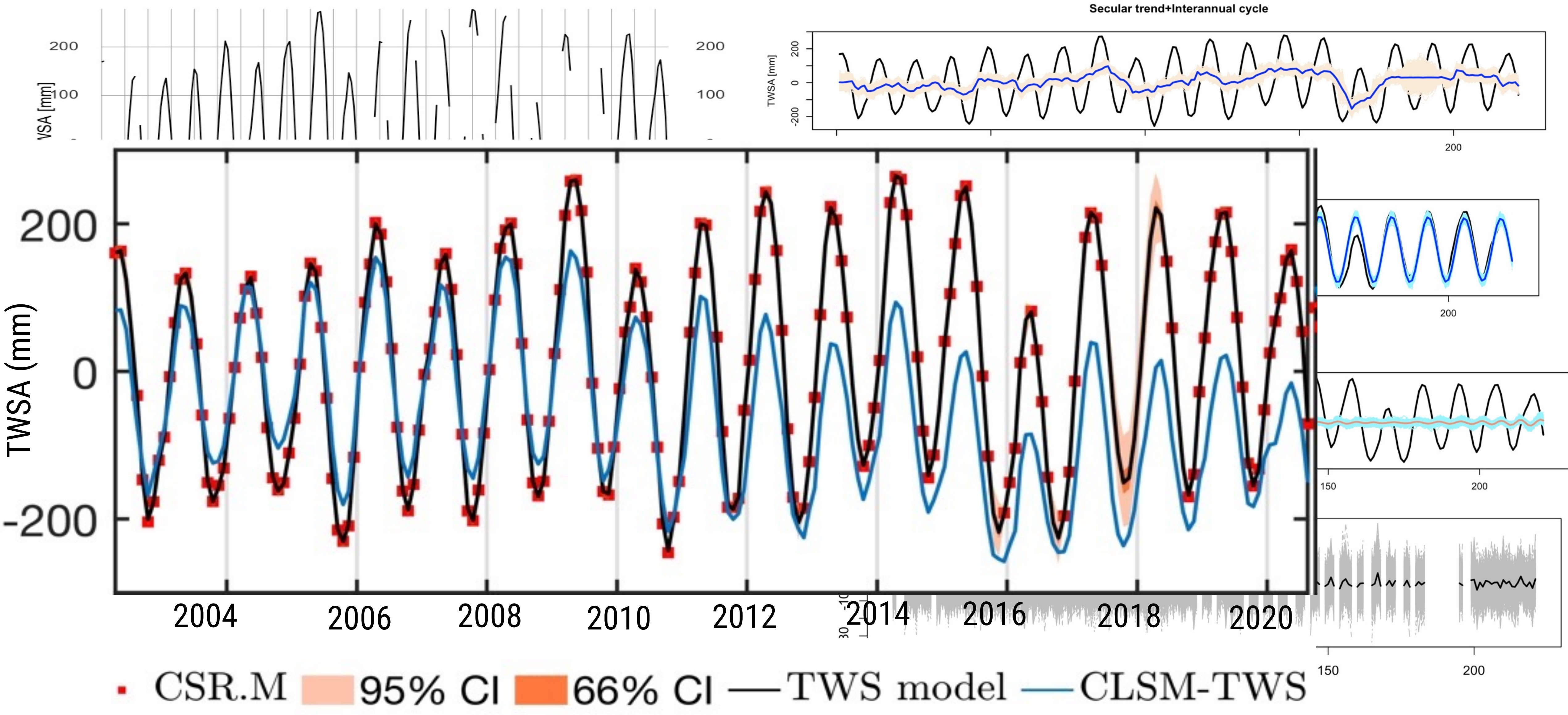

▶ Example 2 – Global Spheres

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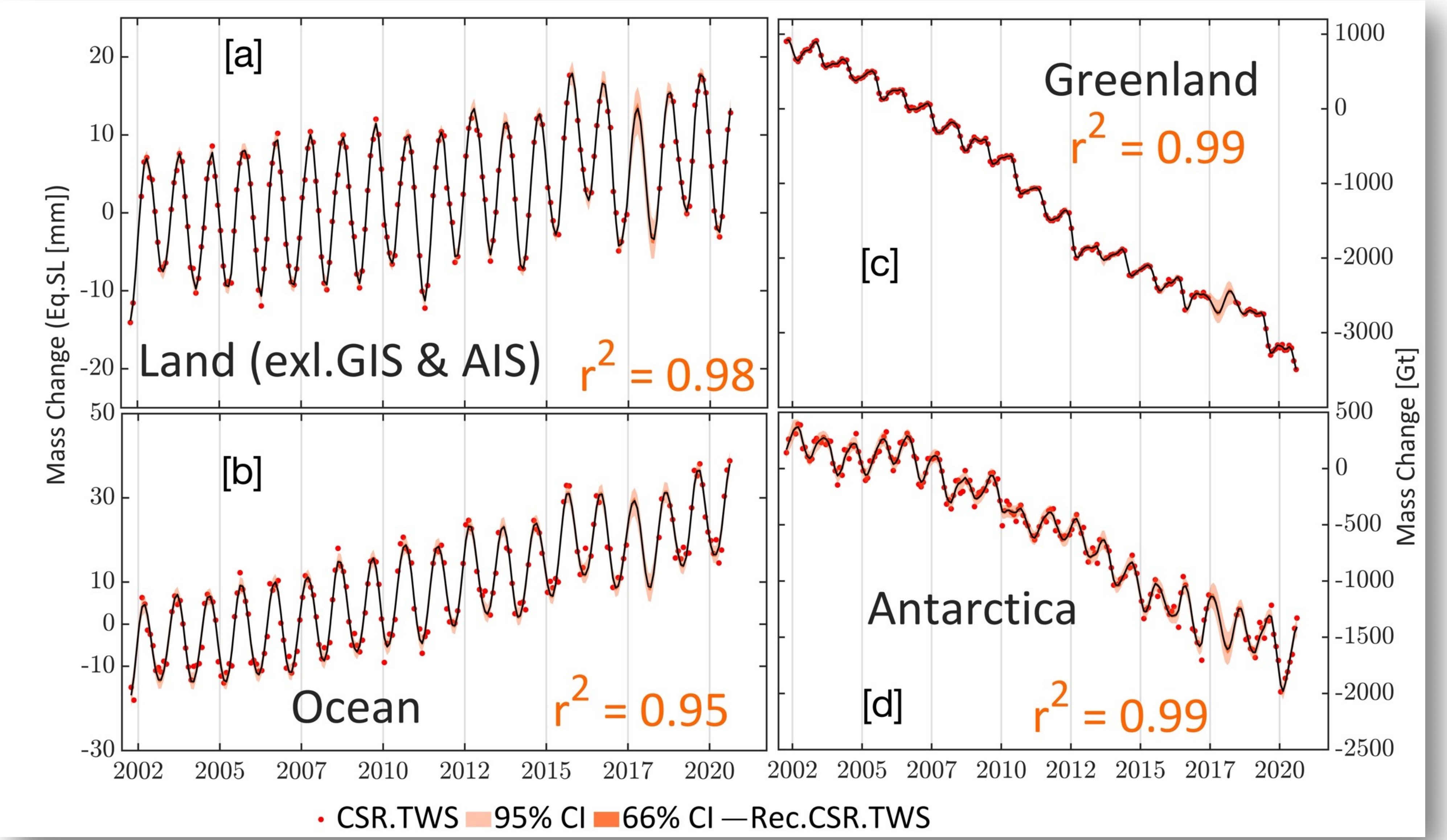
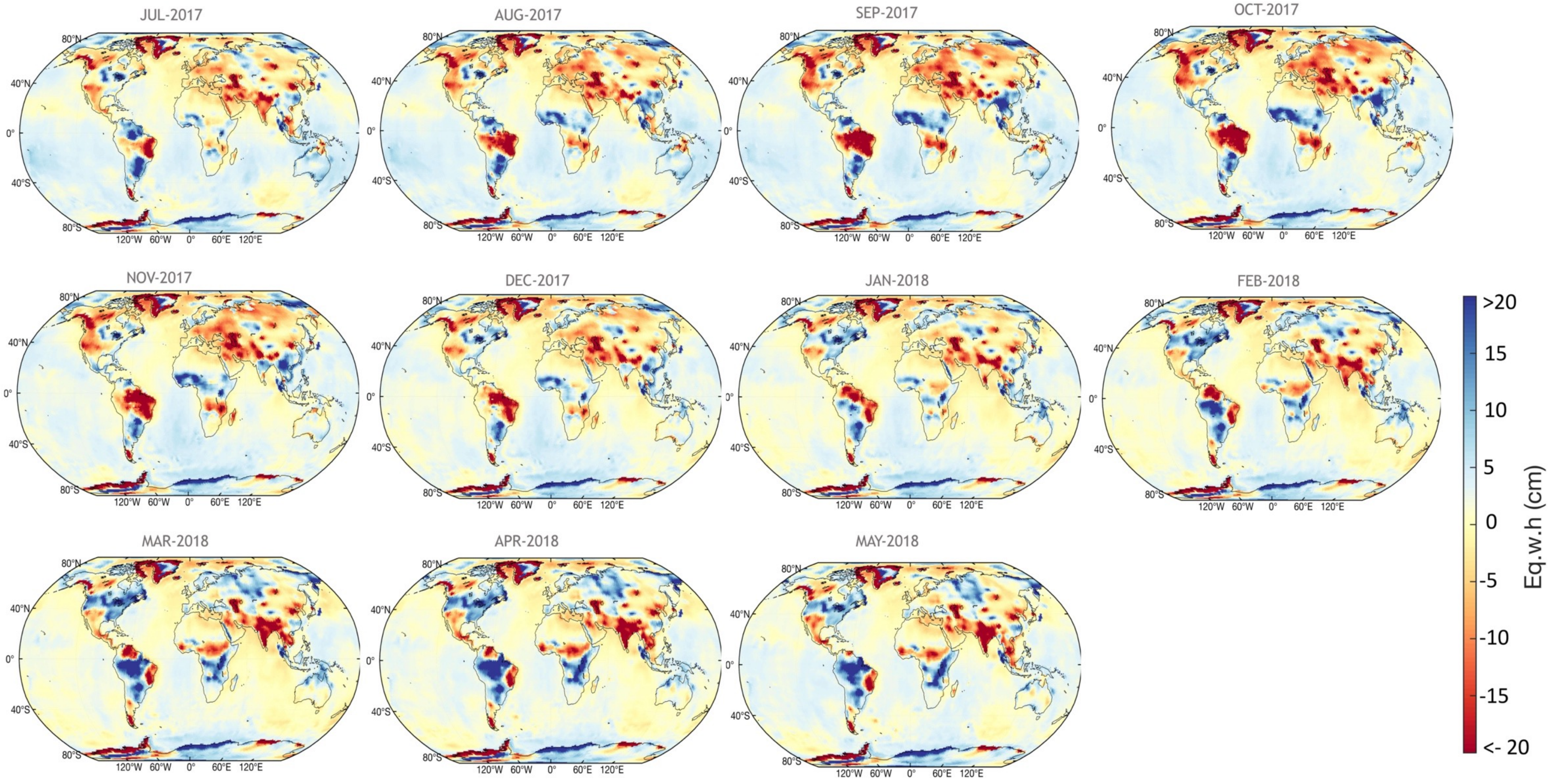


▶ Median of Posteriors Dists.

Modeled TWS during the GRACE and GRCAE-FO gap as the sum of the median posterior distribution of long-term variability (variability ≥12-month, including secular trend and interannual-decadal variations), annual and semi-annual signals between April 2002 and April 2021, sampled from 2000 steps using MCMC with the NUTS method

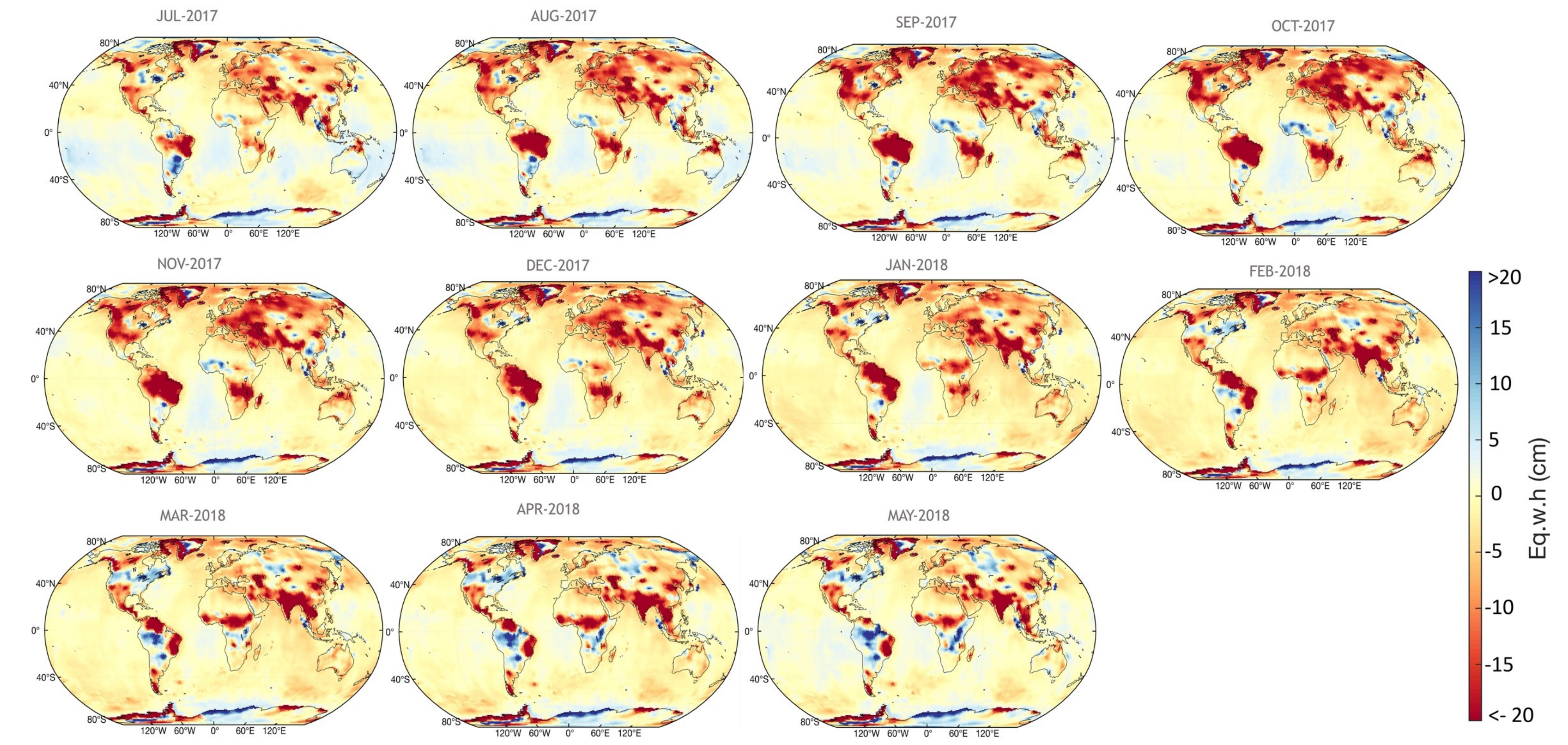


Results – Gap Months [07/2017 -05/2018]

Lower 5%

Modeled TWS during the GRACE and GRCAE-FO gap.

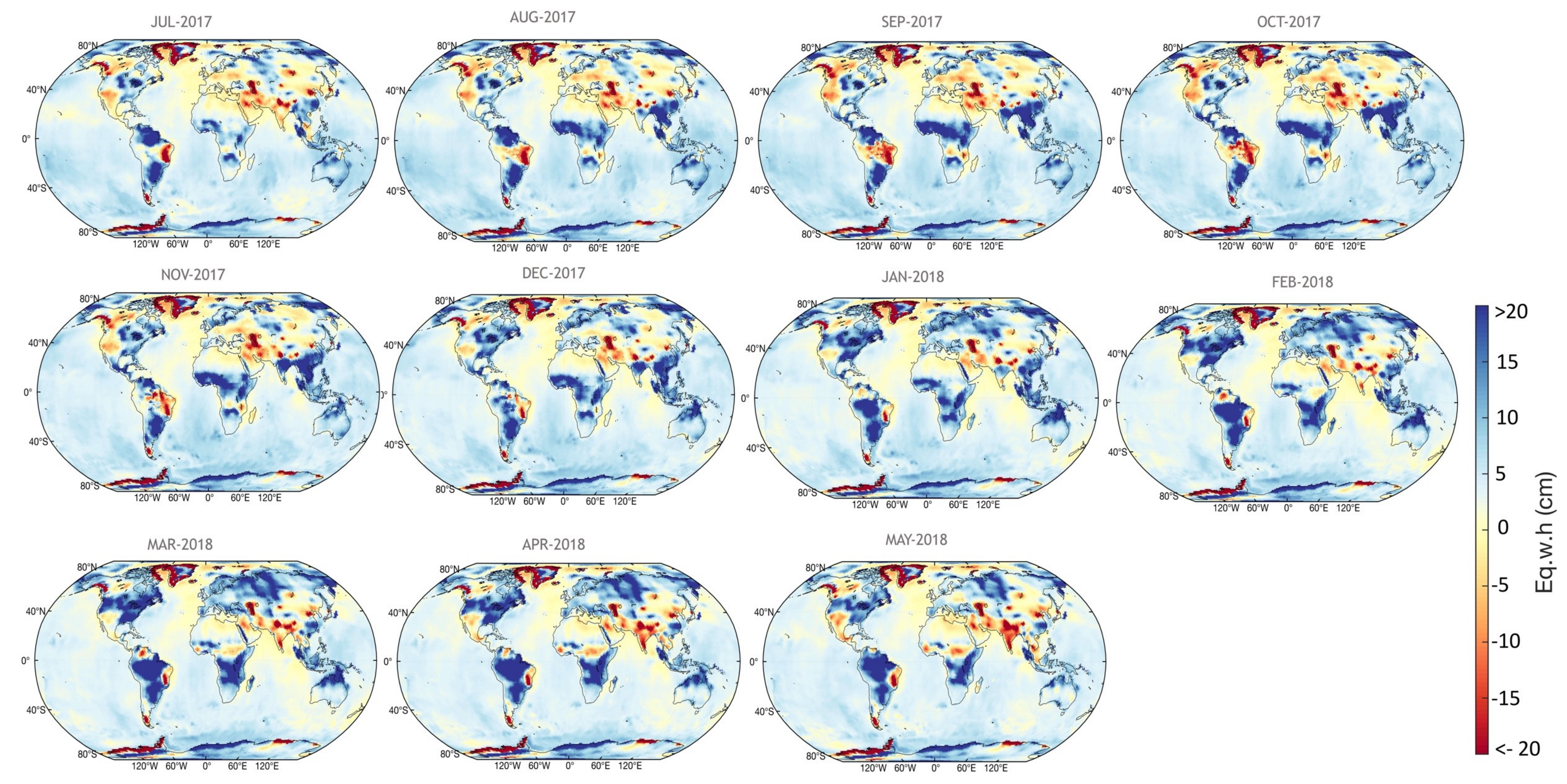
Lower 5%



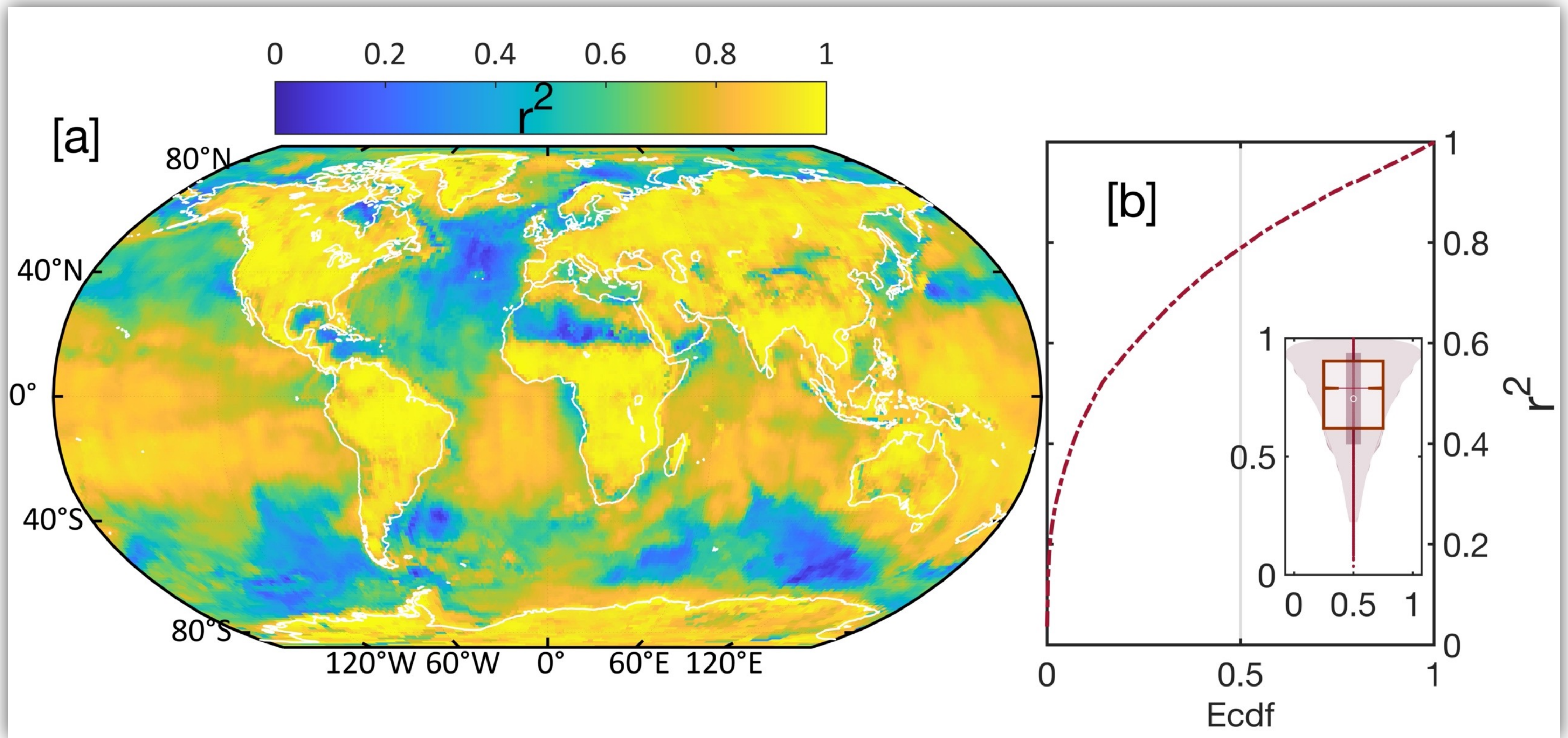
Results – Gap Months [07/2017 -05/2018]

▶ Upper 95%

Modeled TWS during the GRACE and GRCAE-FO gap. **Upper 95%**



Results – Model Performance



[a] MCMC regression model diagnostic test with coefficient of determination (r^2). [b] Empirical cumulative density function (ecdf) for r^2 showing ≥80% of the grid cells have r^2 ≥58%.

▶ Results – Model Evaluation [CLSM-F2.5]

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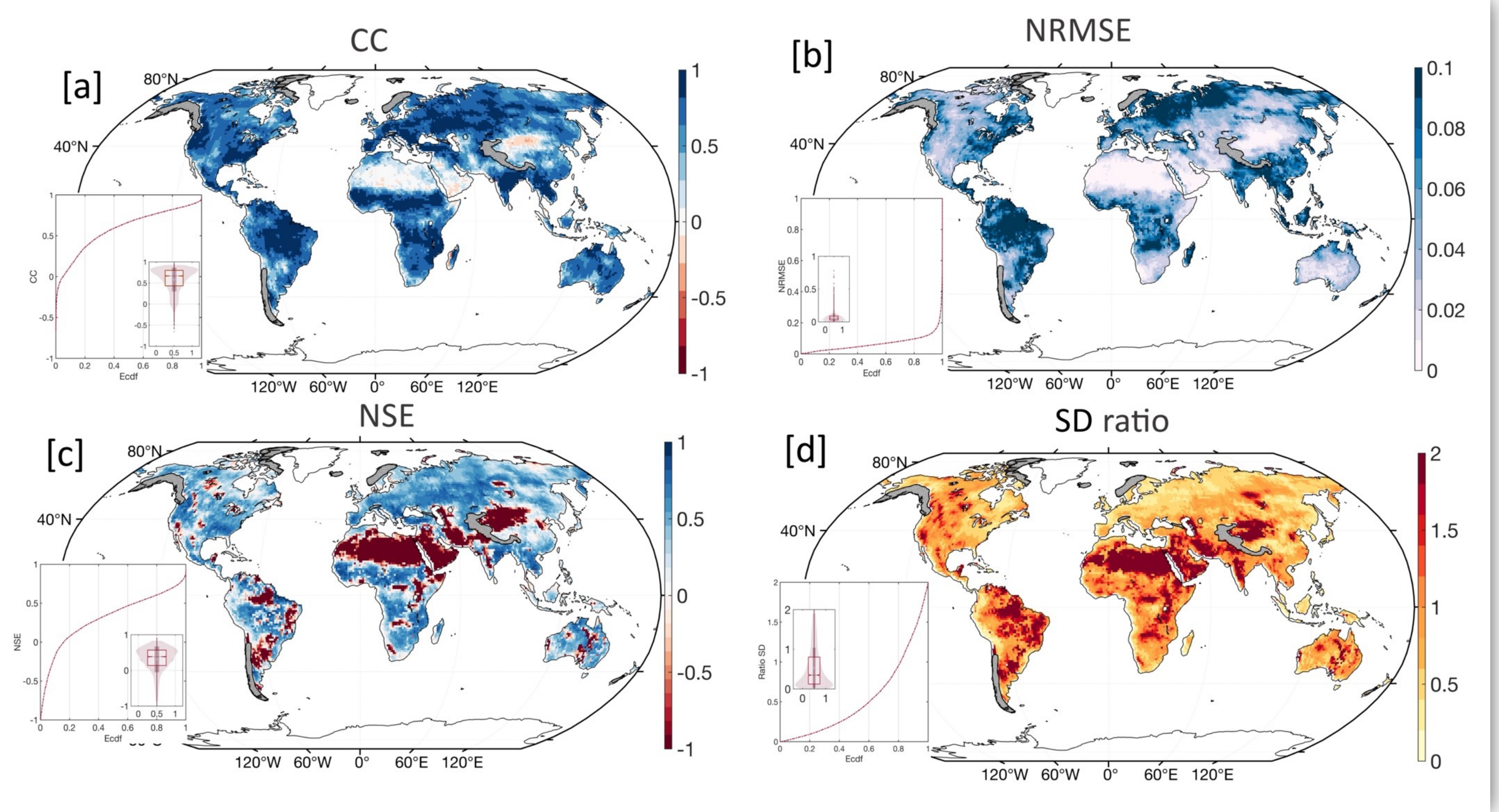

Four evaluation tests of GRACE and GRACE-FO mass change reconstructed data over land with CLSM-TWS between the April 2002 and April 2021 and the associated ecdf. **[a]** correlation coefficient, **[b]** normalized mean square error, **[c]** Nash–Sutcliffe Efficiency, **[d]** ratio of variability. *Results are hachured over 11 land glaciers for consistency because the CLSM model does not simulate permanent snow or ice.*

▶ Results – Comparison with other Reconstructed Data

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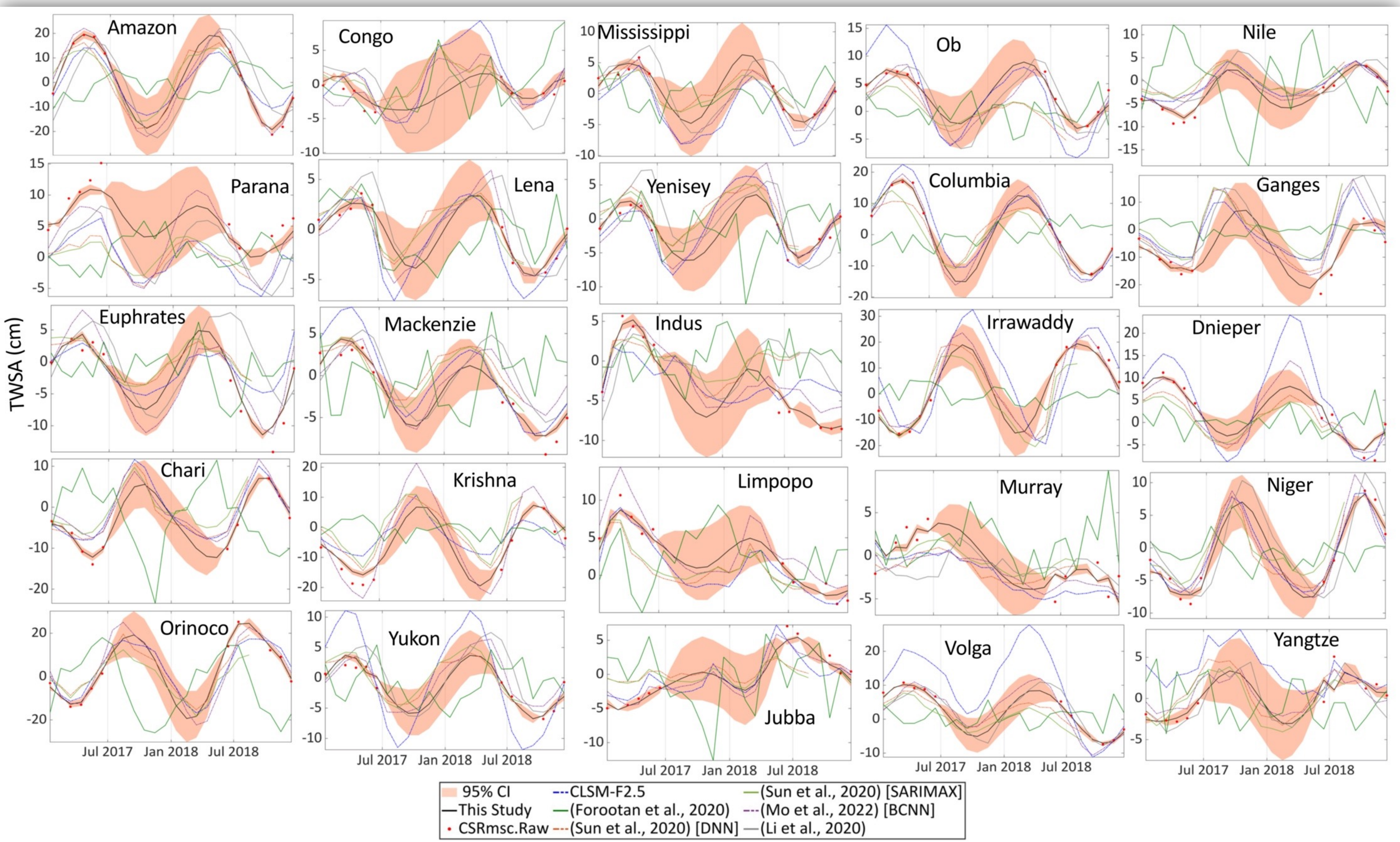
Time series for the six reconstructed data for the gap period between GRACE and GRACE-FO missions. The original data from the two missions are shown in red circles. Results from this study are plotted in black lines with the 95% of credible interval (light orange).



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Conclusions & Recommendations

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1) In this research, missing solutions within and between the two GRACE missions (33 solutions) were inferred using a probabilistic framework using GRACE (-FO) only.

2) The reconstructed data explain the variability in GRACE (-FO) data (median r^2 99%) at basin-scale and greater than 60% for ≥ 70% of the grid points. Low model performance was found in the Sahara Desert, Southeastern Indian and Pacific oceans, and North Atlantic Ocean. These areas either have low mass change at annual/semi-annual timescales and long-term variability or the meaningful signal was captured as part of the residuals as synoptic variations (e.g., southern oceans areas).

3) The results are consistent with other methods that incorporated hydroclimate indicators and applied deep learning frameworks to infer gap period and outperform them in terms of accuracy relative to land surface modeling.

4) Our method further provides a distribution over the missing and the existing observations from the perspective of the data generation processes, thus it provides total uncertainty over the GRACE missions data.

5) Given the probabilistic outcomes of this method, we generated a predictive distribution and propose to ingest it in near real-time applications of GRACE (e.g., data assimilations) to overcome GRACE data latency from the science data centers.

6) Bayesian modeling of GRACE data is a data-driven flexible approach to model the GRACE (-FO) data and infer uncertainties over the existing and missing solutions from the perspective of the data-generation processes and does not require external information.

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Thanks.....

Data

The reconstructed data are hosted by Texas data repository and freely available at https://doi.org/10.18738/T8/5MPOJU. [Rateb, 2021]

Paper

Rateb A, et al., 2022. Reconstruction of GRACE Mass Change Time Series Using a Bayesian Framework. AGU Earth and Space Science (under review)