Interannual Variability in Global Ocean Mass Derived from 18+ Years of GRACE and GRACE-FO Satellite Gravimetry

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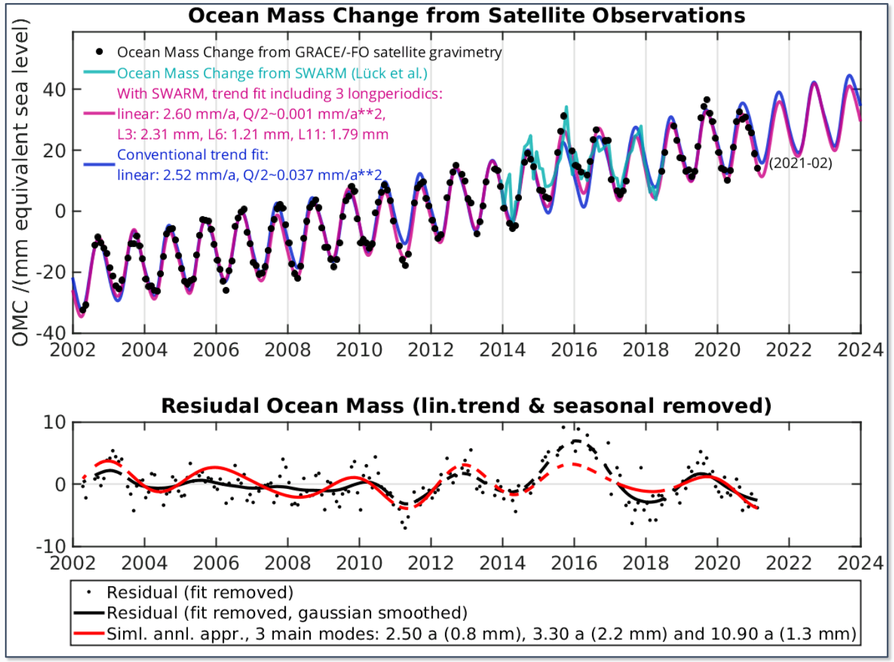
Global Ocean Mass Change from GRACE/-FO & SWARM (optional)

The combined 18+ years long time series of observations of the Earth's gravity field from the satellite missions GRACE and GRACE-FO provides us with the opportunity to **analyze water mass change and re-distribution in the Earth system**. As the mission continues, we also gain insight into those types of variability that act over time scales of multiple years.

Here, we updated the **Ocean Mass Change (OMC)** product by the **ESA CCI Sea Level Budget Closure project***, including:

- corrections for Glacial Isostatic Adjustment (Caron et al., 2018)
- restorement of GAD background field and subtraction of atmospheric mean fields (GAD mean over full ocean domain)
- replacement of dedicated low-degree coefficients for centre-of-mass, oblateness (TN14) and C30 (TN14) in the spherical harmonic gravity field solutions.

We applied least-squares minimization of the residual of a multi-parameter functional fit to the OMC series, including linear trend, semi-/annual sinusoids, and an optional quadratic fit. We analyzed the complete residual series based on the monthly unfiltered GRACE and GRACE-FO RL06 solutions by CSR/GFZ/JPL and **ITSG-Grace2018 (shown here ●)**. Recent studies have demonstrated that the ocean mass budget itself is closed within uncertainties (0.0 ± 0.3 mm/a for linear trend), but notable variability beyond annual scales remains.



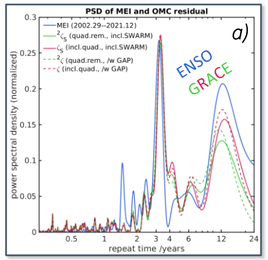
Here, we attempt to analyze additional components of the system more closely. By including SWARM data (stabilizing GRACE gap; by Lück et al., 2018) and implementing an alternative simulated-annealing approach, we find evidence for several interannual modes (frequencies, not PCA/EOF) masked by the dominant annual cycle. Their monthly correlation with ENSO is significant (>0.5; cf. Boening 2012).

The initial **STD of the residual (~3 mm) is reduced by 22% or 26%** via the inclusion of the {3,11} or {3,6,11} year main modes, respectively. Likewise, an alternative simulated annealing approach shows a residual STD reduction by 24–29% for ~{2.5,3,6,11} years.

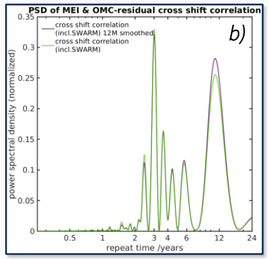
PSD Analysis & Simul. Annealing

We analyzed ocean mass residuals in several ways:

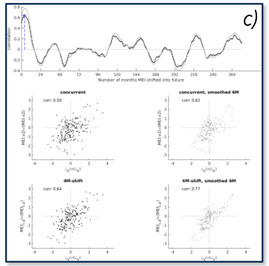
- **Classic spectral analysis (a)** (temporal interpolation required): SWARM during 2018 gap helps bridging the gap. Spectral energy peaks at ~11 a and ~3.3 a. There is notable secondary energy near 6 a and short of 3 a, the latter of which is masked by the rise of stronger primary modes.



- **Temporal cross shift correlation (b,c)** with global dominant climate index (ENSO): find frequencies at which both series agree most. There are clear and strong peaks at 3 a, 11 a and 5⅔ a, with secondary peaks at 3⅔ a, 4⅓ a and 29.5 months.



- **Multidimensional simulated annealing (d)** approximation of main mode frequencies and amplitudes. Long modes rather unstable, but ~3 and 11 a are persistent. Best results (lowest residual STD<2.08 mm) occur for heavily weighted main modes from spectral analysis while amplitudes vary freely.

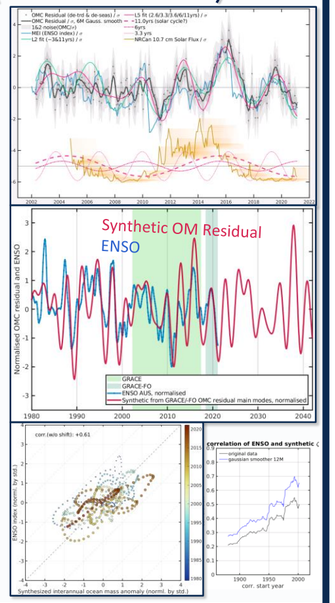


Main modes from Simulated Annealing:

	L1	L2	L3	L4	L5
T /a	2.5	3.1	3.6	5.7	11.0
A /mm	1.0	1.9	1.6	0.6	1.3

Extrapolation (back & forth)

Based on only a few main modes (frequencies), we can extrapolate the interannual ocean mass anomalies back and forth in time. This may predict significant sea level highs or lows, like the current La Niña, predominantly moderated by ENSO. In case of the back-projection, we find coincidences with multi-annual ENSO progression. These might not be highly correlated, but still notable given the fact that only a basic set of frequencies was estimated from the 2002–2021 global OM residual (not just equatorial Pacific). Hard links with teleconnections and time-lag (solar cycle, QBO?) are still under debate.



Take-home messages:

- ‘Hidden’ behind linear trend and seasonal cycles, GRACE/-FO ocean mass change contains signal from interannual variability
- Filling the gap /w SWARM ‘sharpens’ spectral peaks near 3.3/5.9 a
- 29-month oscillation (QBO?) visible in cross shift correlation of ocean mass residual and ENSO index, but not clear in classic PSD
- Reduction of quadratic trend affects multiannual periods: more exact 6 year fix and decadal component shifted from 12 to 11 a; joint fit reduces quadratic factor.
- Overall correlation of ocean mass residual and ENSO is strong
- Limited extrapolation based on main modes is possible (back and forth for index evaluation and forecast); e.g. current La Niña
- Given the 19-a span, decadal oscillation to be taken with caution
- Apparent ~8a cycle may be effect of too wide sampling window

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*) Time series of the ESA CCI Sea Level Budget Closure project are freely available from the CEDA archive at https://dx.doi.org/10.5285/1562578dd07844f19f01f0db9366106d (Horwath et al., 2021a)
Ocean mass change data presented here is based on the processing scheme as described therein in the linked data description, but with additional upgrades to degree-1 and the fit functional. The SLBC project is summarized at: https://doi.org/10.5194/essd-2021-137 (Horwath et al., 2021b)

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