https://doi.org/10.5194/egusphere-2026-5546
Preprint. Discussion started: 24 September 2026
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Anti-phased steric and mass cycles and an unresolved dynamic trend in Arabian Gulf sea level

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Abstract

The Arabian Gulf is a shallow, evaporative marginal sea whose sea level has been characterised almost entirely from tide gauges and satellite altimetry; its steric and ocean-mass components have never been separated observationally, because the basin has no continuous hydrographic record. I combine DUACS satellite altimetry with CSR and JPL GRACE/GRACE-FO mascon solutions over April 2002 to December 2025 to close the Gulf sea-level budget at seasonal and multi-year timescales. The seasonal cycle of total sea level (annual amplitude 4.3 ± 0.3 cm, maximum in November) is shown to be the residual of two larger, nearly anti-phased components: an ocean-mass cycle of 3.9 ± 0.4 cm with a climatological maximum in January and a steric cycle of 7.0 ± 0.3 cm with a climatological maximum in October. The inferred steric cycle is confirmed by two further estimates: a fully independent thermal-expansion calculation from ERA5 sea-surface temperature (7.2 cm, August) and the full-column steric height from the GLORYS12 reanalysis (5.3 cm, August; halosteric contribution 0.6 cm). GLORYS12 assimilates altimetry, so it is independent for the seasonal cycle but not for the trend. These bracket the budget value and bound its systematic uncertainty at about 1.5 cm. For the long-term trend I show that regional gravimetry cannot be used directly: leakage from groundwater depletion in the adjacent Arabian Peninsula and Iran imprints −2.2 ± 0.3 mm yr^{-1} on Gulf mascon cells, and the two mascon products diverge by 10–15 cm after 2021. Using instead the global barystatic rate (2.1 mm yr^{-1}) and a steric trend of 0.3–0.9 mm yr^{-1}, 2.1–3.2 mm yr^{-1} of the observed 5.2–5.6 mm yr^{-1} rise — roughly two-fifths to just over half, depending on the end date (2002–2021 or 2002–2025) and the steric route — is accounted for by neither ocean-mass nor steric change. This implies a Gulf-mean manometric trend of order 4–5 mm yr^{-1} that regional GRACE cannot independently confirm or refute; I weigh a dynamic, remotely forced origin against two alternatives in the Discussion. Gulf sea level rose in the year following each of the four strong positive Indian Ocean Dipole events of the record, consistent with remote forcing through the Strait of Hormuz.

1 Introduction

The Arabian Gulf (hereafter the Gulf) is a semi-enclosed marginal sea of about 240 000 km² with a mean depth near 35 m, connected to the Indian Ocean only through the Strait of Hormuz. Evaporation far exceeds precipitation and river inflow, so the basin is an inverse estuary in which dense, saline water forms in winter and exits at depth through Hormuz while surface water enters from the Gulf of Oman (Swift and Bower, 2003). Its coasts host a large and rapidly growing population and much critical infrastructure at low elevation, so the magnitude and causes of sea-level change in the Gulf are of direct practical concern.

Existing knowledge of Gulf sea level rests on tide gauges and satellite altimetry. Long-term rates of 2.3–3.6 mm yr^{-1} have been reported from gauges and altimetry over various windows (Hosseinibalam

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et al., 2007; Siddig et al., 2019; Al-Subhi and Abdulla, 2021), with a suggestion of acceleration after about 2005. The seasonal cycle has a maximum in November and a minimum in April (Al-Subhi and Abdulla, 2021), and regression studies attribute a large fraction — roughly three quarters — of its variance to the inverse-barometer response to atmospheric pressure, with thermal expansion as a secondary contributor (Sultan et al., 1995; Hosseinibalam et al., 2007). The only published thermosteric estimate for the basin (Hosseinibalam et al., 2007) was derived from temperature profiles at 1° spacing and gave a monthly range of about ±2 cm. Separately, from a geodetic perspective, I have recently shown that this seasonal Gulf mass signal is large enough to drive detectable winter crustal subsidence at GNSS stations around the Arabian Peninsula, using a single representative CSR mascon point (Usman and Heki, 2025); that analysis characterised neither the spatial structure of the Gulf's mass cycle nor its relationship to the much larger cycle recorded by altimetry.

What has not been done — in either the tide-gauge and altimetry literature above or my own point-based geodetic analysis — is the observational partition of Gulf sea level into its ocean-mass and steric components. The obstacle is the absence of any continuous hydrographic record: the Argo array does not enter the Gulf, and the sparse profiles that exist cannot resolve the basin's seasonal heat content. Piecuch et al. (2021) combined satellite altimetry with GRACE gravimetry to characterise intraseasonal sea-level variability in the Gulf over 2002–2015, demonstrated that GRACE resolves a coherent basin-wide mass signal, and stated explicitly that steric changes could not be estimated, suggesting that future work compare the difference between altimetry and GRACE with the sea-level response expected from local surface heat flux. The neighbouring Red Sea has since received a full thermosteric and halosteric decomposition (Wahr et al., 2014, and later work); the Gulf has not.

The principle is simple. Altimetry measures total sea level; satellite gravimetry measures the ocean-bottom-pressure, or manometric, component; their difference is the steric component. Applying it to the Gulf, however, raises three difficulties that a global or open-ocean budget does not face. The basin is small — near the resolution limit of GRACE mascon solutions — and lies beside one of the largest groundwater-depletion signals on Earth (Voss et al., 2013; Joodaki et al., 2014), so leakage of continental mass change into the ocean cells must be assessed rather than assumed negligible. The inverse-barometer signal in a shallow semi-enclosed sea is large, and the way altimetry and gravimetry products treat the ocean's response to atmospheric forcing must be shown to be consistent. And with no in situ hydrography, the inferred steric component can only be validated by independent estimates built from other data.

This paper addresses four questions. (1) Can the seasonal sea-level cycle of the Gulf be closed observationally as the sum of an ocean-mass and a steric component, and what are the amplitude and phase of each? (2) Is the steric cycle so inferred consistent with independent estimates that use neither altimetry nor gravimetry? (3) What fraction of the 2002–2021 sea-level rise in the Gulf is accounted for by ocean-mass and steric change? (4) Can satellite gravimetry be used directly to estimate the ocean-mass trend of a small marginal sea bordered by a region of large groundwater depletion? Section 2 describes the data, Sect. 3 the methods including the leakage and consistency tests, Sect. 4 the results in the order of the four questions, and Sects. 5 and 6 the discussion and conclusions.

2 Data

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2.1 Satellite altimetry

Total sea level is taken from the Copernicus Marine reprocessed DUACS level-4 gridded sea-level anomaly (SLA) product (product SEALEVEL$_{GLO}$PHY$_{L4}$MY$_{008}$047, dataset cmems$_{obs\text{-}sl}$glo$_{phy\text{-}ssh}$my$_{allsat\text{-}l4\text{-}duacs\text{-}0.125deg}$P1M-m; Taburet et al., 2019), monthly on a 0.125° grid, referenced to the 1993–2012 mean. The product has the dynamic atmospheric correction (DAC) applied, which at monthly and longer timescales is essentially the inverse-barometer response to atmospheric pressure (Carrère and Lyard, 2003); its treatment relative to gravimetry is examined in Sect. 3.4. I use April 2002 to December 2025 (285 months), the interval of overlap with gravimetry; the reprocessed stream lags real time by roughly nine months.

2.2 Satellite gravimetry

Ocean mass is taken from two GRACE/GRACE-FO mascon solutions: the CSR RL06.3 0.25° mascon product with all corrections applied (Save et al., 2016), and the JPL RL06.3Mv04 coastline-resolution-improvement (CRI) product (Watkins et al., 2015; Wiese et al., 2016); mascon solutions of this kind substantially reduce, though as Sects. 3.3 and 4.4 show do not eliminate, the land-to-ocean leakage that affects spherical-harmonic GRACE products (Scanlon et al., 2016). Both remove the non-tidal atmospheric and oceanic mass variability model AOD1B RL06 (Dobslaw et al., 2017) during processing and restore its ocean component (GAD) so that values over the ocean represent ocean bottom pressure; both are corrected for glacial isostatic adjustment with ICE-6G_D (Peltier et al., 2018). The CSR GAD component grid and the CSR land and ocean masks are used separately. The record spans April 2002 to June 2026 with the eleven-month gap between the GRACE and GRACE-FO missions (July 2017 to May 2018), which is treated as missing throughout.

2.3 Reanalyses and indices

ERA5 monthly means (Hersbach et al., 2020) of sea-surface temperature, the four surface heat-flux components (net shortwave and longwave radiation, sensible and latent heat flux) and surface pressure were obtained over 46–58° E, 23–31° N for 2002–2025. Full-column temperature and salinity were taken from the GLORYS12V1 global ocean reanalysis (Lellouche et al., 2021; product GLOBAL$_{MULTIYEAR}$PHY$_{001}$030), monthly at 1/12°, on 24 levels between the surface and 131 m, for 2002–2025. GLORYS12 assimilates satellite altimetry, so its interannual and trend behaviour is not fully independent of my altimetry term; its seasonal cycle, dominated by the model's surface forcing and sea-surface-temperature assimilation, is much less affected. The Dipole Mode Index (DMI; Saji et al., 1999) from HadISST was obtained from NOAA PSL.

2.4 Gulf domain

The Gulf is defined as the ocean cells of the CSR ocean mask within 47–57° E, 23.5–30.5° N, excluding the Gulf of Oman side of the Strait of Hormuz (longitude greater than 56.5° E and latitude below 26.5° N). On the mascon grid this gives 331 cells and an area of about 227 000 km²; on the altimetry grid 1259 cells; on the GLORYS12 grid 2732 cells with an area-mean wet depth of 35 m, matching the known mean depth of the basin. Figure 1 shows the domain over the GRACE mass trend of the surrounding region.

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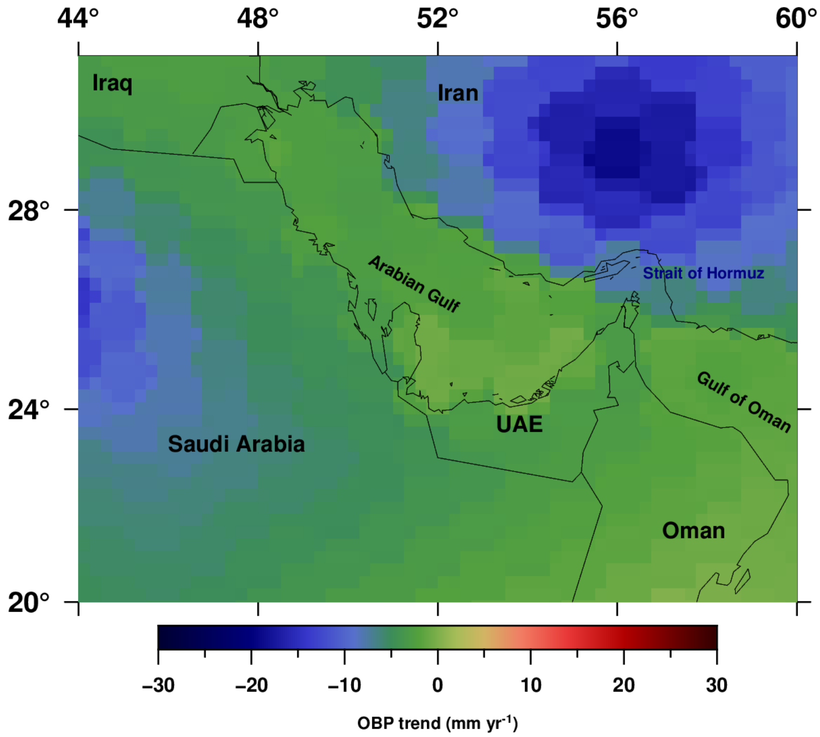

Figure 1. Linear trend of GRACE ocean-bottom pressure (OBP; CSR RL06.3, 2002–2021) around the Gulf, on a non-linear colour scale that gives finer visual resolution to the small trend affecting the Gulf itself (of order a few mm yr^{-1}; Table 3) than to the much larger land signal at the scale's extremes (tens of mm yr^{-1}), which saturates rather than being resolved precisely at this contrast. Coastlines and national borders are shown for geographic orientation only, not the exact ocean-mask boundary used to compute the Gulf mean (Sect. 3.3). Continental mass loss from groundwater depletion in the Arabian Peninsula and southern Iran borders the domain and is clearly distinguishable from the near-zero trend over the open Gulf, illustrating why the leakage correction of Sect. 3.3 is necessary.

3 Methods

3.1 Basin-mean series and baseline

All fields are averaged over the Gulf domain with cosine-of-latitude weights, using only cells with finite values in each month. This last point matters for ERA5 sea-surface temperature, which is undefined over the reanalysis's land cells; weighting by all mask cells would dilute the basin-mean anomaly by about half. Every series is expressed relative to its 2004–2009 mean, the reference period of the mascon products.

3.2 Harmonic and trend fitting

Each basin-mean series $y(t)$ is fitted by ordinary least squares with a linear trend and annual and semi-annual harmonics,

$$y(t) = a + b\,t + A\cos 2\pi t + B\sin 2\pi t + C\cos 4\pi t + D\sin 4\pi t, \quad (1)$$

with t in decimal years. Fits use observed months only: the GRACE mission gap is excluded rather than interpolated, because interpolating across it and then smoothing creates a spurious minimum at the gap

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(Sect. 4.4). Standard errors are heteroskedasticity- and autocorrelation-consistent (Newey and West, 1987) with a 12-month bandwidth; the error of the annual amplitude $A_1 = (A^2 + B^2)^{1/2}$ follows by the delta method. The month of the annual-harmonic maximum is reported as the phase; where a series also carries a substantial semi-annual amplitude (A2 comparable to A1), the empirical monthly-climatological maximum can fall one to two months later than this phase, and both are given where this matters (Sect. 4.1). Trends are quoted for 2002–2021 unless stated. This is forced by the Gulf-regional mascon series, which diverge between products after 2021 (Sect. 4.4); it is not required by the altimetry or the global barystatic series, both of which are available and considered reliable through 2025, and I adopt the common 2002–2021 window across all trend terms for comparability rather than because every term needs it. The altimetry trend itself is insensitive to this choice (5.16 ± 0.39 mm yr^{-1} over the full 2002–2025 record against 5.56 ± 0.72 mm yr^{-1} over 2002–2021), so the truncation does not bias the headline rate.

3.3 Leakage from continental mass change

The Gulf domain is roughly 250 km wide and lies beside continental mass loss of 10–20 mm yr^{-1} (Fig. 1), attributed to groundwater depletion in Saudi Arabia, Iraq and Iran (Voss et al., 2013; Joodaki et al., 2014). To estimate how much of that signal reaches the ocean cells I forward-model the leakage: the CSR mascon field over 30–70° E, 12–42° N is set to zero over ocean cells, filtered with a Gaussian kernel of 300 km full width at half maximum as a proxy for the effective resolution of the mascon solution, and averaged over the Gulf domain. The result is subtracted from the raw Gulf series to give a leakage-corrected mass series. The sensitivity of this correction, and the fact that it is insufficient for the trend, are examined in Sect. 4.4.

3.4 Consistency of atmospheric corrections

In the budget $\eta_{\mathrm{alt}} = \eta_{\mathrm{mass}} + \eta_{\mathrm{steric}}$, the altimetry term must represent the same physical quantity as the gravimetry term. DUACS altimetry has the DAC removed, so it excludes the ocean's response to atmospheric pressure and to high-frequency wind forcing. GRACE mascons have the atmosphere removed and the modelled ocean response to atmospheric forcing (GAD) restored. For a purely isostatic inverse-barometer response the two treatments coincide, because an isostatic response changes sea level but not bottom pressure. Any non-isostatic seasonal response would appear in GAD but be removed by the DAC. I therefore compute the seasonal inverse-barometer amplitude over the Gulf from ERA5 surface pressure, the seasonal cycle of the GAD component over the Gulf, and the budget with and without GAD, and use the independent steric estimates of Sect. 3.5 to decide which formulation is physically consistent (Sect. 4.3).

3.5 Independent estimates of the steric component

Two estimates of the steric cycle are built from data that enter neither the altimetry nor the gravimetry term. The first treats the Gulf as a column of depth $H = 35$ m whose temperature follows the sea surface, giving a thermosteric height $\alpha H(\mathrm{SST} - \langle \mathrm{SST} \rangle)$ with a thermal-expansion coefficient $\alpha = 3 \times 10^{-4}$ K^{-1} appropriate to 25–30 °C and 40 psu. No parameter is tuned; this estimate is an upper bound because it assumes the whole column follows the surface. A related estimate integrates the passive response to net surface heat flux, $\mathrm{d}\eta/\mathrm{d}t = \alpha Q_{\mathrm{net}}/(\rho c_{\mathrm{p}})$, as proposed by Piecuch et al. (2021). The second estimate integrates the GLORYS12 temperature and salinity profiles: the steric height of each column is $-(1/\rho_0)\int[\rho(T,S,p) - \rho(T_{\mathrm{c}},S_{\mathrm{c}},p)]\mathrm{d}z$ with TEOS-10 density (McDougall and Barker, 2011), where T_{c} and S_{c}

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Preprint. Discussion started: 24 September 2026
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are the long-term mean profiles. Thermosteric and halosteric parts are obtained by holding salinity, respectively temperature, at its long-term mean profile.

3.6 Trend budget

Because regional gravimetry proves unusable for the Gulf trend (Sect. 4.4), the mass contribution to the trend is taken from the global barystatic rate, computed as the area-weighted mean of the CSR mascon field over open-ocean cells more than two grid cells from any land cell and equatorward of 66°. A basin connected to the global ocean through a strait must carry the global ocean-mass rise, since mass adjusts through Hormuz on timescales of days; regional dynamic departures from it are part of the residual I seek to quantify. The steric trend is taken from the full-column GLORYS12 estimate, with the SST-based thermosteric trend as a check. The unexplained residual is the altimetry trend minus these two terms, with errors combined in quadrature.

4 Results

4.1 The seasonal budget

Table 1 gives the harmonic fits over 2002–2021 and Fig. 2 the series and climatologies. Total sea level from altimetry has an annual amplitude of 4.33 ± 0.33 cm. Its fitted annual harmonic (Eq. 1) is phased to the September/October boundary, but because total sea level also carries a significant semi-annual component (A2 = 1.63 cm), the full monthly climatology peaks later, in November (+9.6 cm), with a minimum of −2.0 cm in April (Fig. 2b) — reproducing the pattern reported by Al-Subhi and Abdulla (2021) and providing an external check on the altimetry processing. Ocean mass from the leakage-corrected CSR product has an amplitude of 3.88 ± 0.37 cm, peaking in late January in both the annual harmonic and the monthly climatology; the JPL CRI product gives 4.73 ± 0.40 cm with a closely matching phase (early February), so the seasonal mass cycle is robust to the choice of solution. Over the full record to 2025 the values change by less than 0.2 cm.

The steric component, obtained as altimetry minus mass, has an amplitude of 7.03 ± 0.27 cm and a semi-annual amplitude of 2.0 cm, larger than for any other term in the budget. Its fitted annual harmonic is phased to late August, but as for total sea level the semi-annual term shifts the monthly climatological maximum later, to October (+8.7 cm, with November essentially tied at +8.67 cm), against a minimum of −5.3 cm in March. The mass and steric cycles are nearly in antiphase — a January mass maximum against an autumn steric maximum — and the observed 4.3 cm cycle of total sea level is their residual. This is the central result of the paper: the modest seasonal range of Gulf sea level conceals two opposing cycles each larger than the total.

Component	n	A_1 (cm)	Peak month	A_2 (cm)	Residual (cm)
Total sea level (altimetry)	237	4.33 ± 0.33	Nov†	1.63	3.38
Ocean mass (CSR, leakage-corrected)	202	3.88 ± 0.37	late Jan (1.7)	0.71	3.02
Ocean mass (JPL CRI)	202	4.73 ± 0.40	early Feb (2.1)	0.86	3.60
Steric (altimetry − mass, CSR)	202	7.03 ± 0.27	Oct†	2.00	2.48
Steric (altimetry − mass, JPL)	202	8.20 ± 0.39	early Sep (9.0)	1.90	3.10

Table 1. Harmonic fits (Eq. 1) to Gulf-mean series over April 2002 – December 2021, observed months only. A_1 and A_2 are the annual and semi-annual amplitudes; errors are Newey–West; series referenced to 2004–2009. †

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marks the empirical monthly-climatological maximum, which falls one to two months after the fitted annual-harmonic phase for series with a substantial semi-annual term (Sect. 4.1); other entries give the annual-harmonic phase, with the fitted decimal month in parentheses.

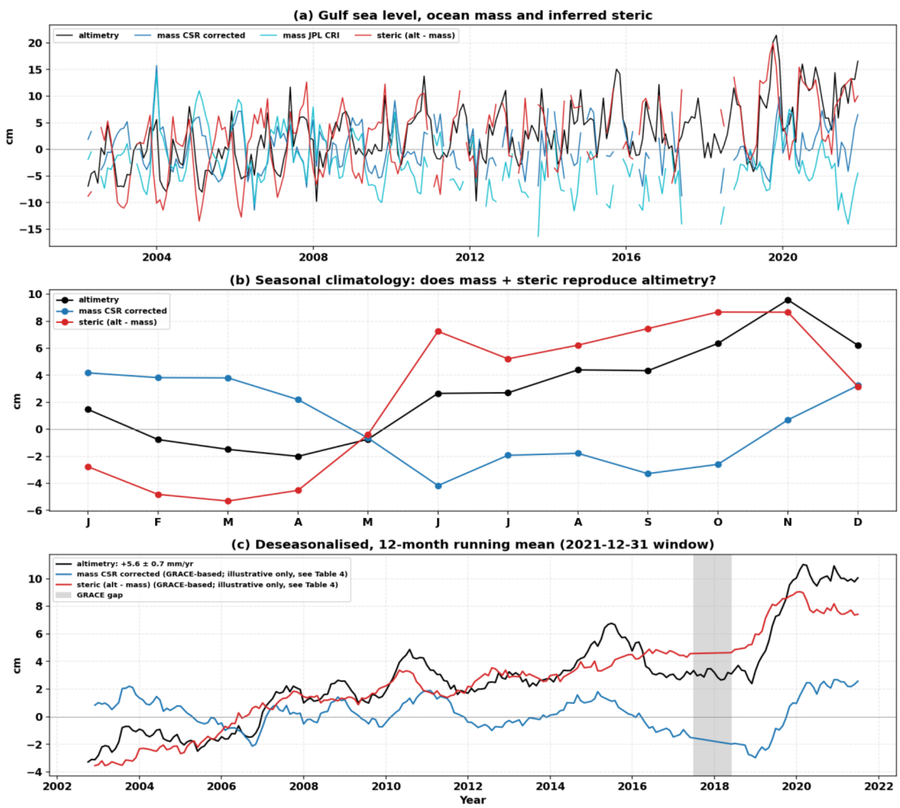

Figure 2. (a) Gulf-mean sea level from altimetry (black), ocean mass from the leakage-corrected CSR (blue) and JPL CRI (cyan) mascons, and the inferred steric component (red), relative to 2004–2009, over 2002–2021, matching Table 4. (b) Monthly climatologies over the same window: the steric and mass cycles are nearly anti-phased and total sea level is their residual, reproducing the values quoted in Sect. 4.1 exactly. (c) Deseasonalised series, 12-month running mean, over the same window; the GRACE mission gap is shaded. Only the altimetry trend is annotated, since it is the one directly measured quantity; the mass and steric lines are the GRACE-based decomposition, shown for shape only — Sect. 4.4 gives the reasons this decomposition is not used for the adopted trend budget of Table 4.

4.2 Validation of the steric cycle

Table 2 and Fig. 3 compare the budget-derived steric cycle with the two independent estimates. Thermal expansion of a 35 m column following ERA5 sea-surface temperature has an amplitude of 7.23 ± 0.07 cm with its maximum in August, matching the budget value to within 5 % with no adjustable parameter; the climatologies correlate at 0.84 and the monthly series at 0.70. The one-month lag of the budget steric behind the SST-based estimate is expected, since the column-mean temperature of a 35 m water column lags the surface as heat penetrates downward. The passive response to ERA5 net surface heat flux gives the same August phase but an amplitude of 4.2 cm, about 60 % of the budget value; this estimate omits the advective heat exchange through Hormuz and accumulates reanalysis flux biases under integration, so it supports the phase of the cycle rather than its amplitude.

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The GLORYS12 column integral gives a total steric amplitude of 5.26 ± 0.07 cm peaking in August, of which the thermosteric part is 4.84 cm and the halosteric part 0.57 cm, peaking in July. The climatologies correlate with the budget at 0.91 and the monthly series at 0.78. The halosteric term is therefore small in the seasonal cycle, and the difference between the GLORYS12 and SST-based thermosteric estimates — 4.8 against 7.2 cm — arises from stratification: the reanalysis resolves a bottom layer that remains cooler than the surface through summer, so the column-mean temperature range is about 4.6 K rather than the 7 K range of the surface. The SST-based value is an upper bound, and the three estimates together span 5.3–7.2 cm.

The budget value of 7.0 cm lies at the upper end of that range. Its formal error of 0.3 cm understates the true uncertainty, which is dominated by the mass term: the seasonal leakage correction is 1.3 cm, and the mass cycle in the mascon products is largely the restored dealiasing model (Sect. 4.3). I therefore report the seasonal steric amplitude of the Gulf as 7.0 cm with a systematic uncertainty of about 1.5 cm (annual-harmonic phase in late August; climatological maximum in October, Sect. 4.1), and note that whether the true value is nearer 7 or 5 cm depends on whether the modelled winter mass gain is slightly overstated. Both the phase and the order of magnitude are established beyond doubt by three estimates from independent data.

These values are larger than the only previous thermosteric estimate for the basin. Hosseinibalam et al. (2007) integrated one-degree-gridded temperature profiles, obtained from the Pacific Fisheries Environmental Laboratory, over a fixed 100 m reference depth — chosen for the Gulf's roughly 110 m maximum rather than its 35 m mean depth — using the same general vertically integrated density-anomaly formulation as ours, and reported a monthly thermosteric range of +2.2 cm (July) to −2.1 cm (February): an amplitude of about 2.2 cm, under half my GLORYS12 estimate and roughly a third of my budget and SST-based estimates, peaking several weeks earlier. Because the calculation is directly comparable in form to ours, the gap more plausibly reflects the input temperature data than the method of integration: a global 1° profile product from the mid-2000s is unlikely to resolve the Gulf's genuinely large (order 15 K) seasonal temperature range with more than a handful of independent points across a basin only 200–300 km wide, and the authors themselves note that the thermosteric signal is less pronounced in the Gulf than in other parts of the world ocean. The closer agreement among my three independent, higher-resolution estimates (Sect. 4.2) is the more reliable characterisation of the Gulf's thermosteric cycle. The two studies agree, however, on the dominant role of atmospheric pressure: Hosseinibalam et al. (2007) attribute 62–90 % of tide-gauge seasonal variance to pressure alone, consistent with the 10.6 cm inverse-barometer amplitude I independently derive from ERA5 in Sect. 4.3.

Estimate	**Inputs**	**A_1 (cm)**	**Peak month**	**r (climatology)**
Budget: altimetry − GRACE mass	DUACS, CSR	7.03 ± 0.27	Oct†	—
Column expansion from SST	ERA5 SST; α, H fixed	7.23 ± 0.07	Aug	0.84
GLORYS12 total steric	GLORYS12 T, S	5.26 ± 0.07	Aug	0.91
thermosteric		4.84 ± 0.07	Aug	
halosteric		0.57 ± 0.02	Jul	
Passive heat-flux response	ERA5 fluxes	4.25 ± 0.10	Aug	—

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Table 2. The seasonal steric cycle of the Gulf from the budget and from independent estimates, 2002–2021. r is the correlation of the monthly climatology with that of the budget steric. † empirical climatological maximum; the annual-harmonic phase alone is in late August, matching the other rows (Table 1).

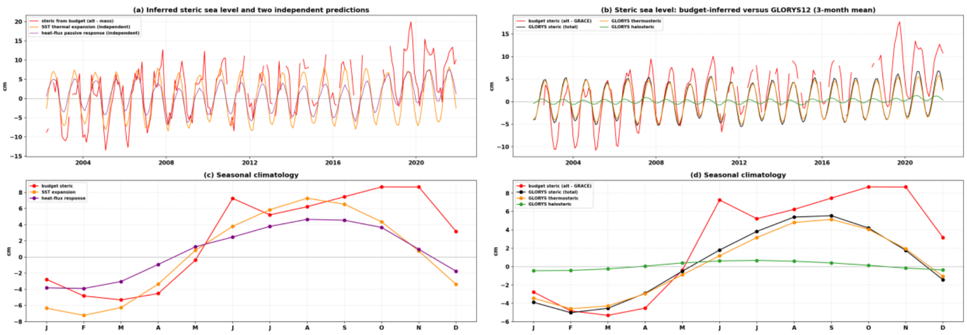

Figure 3. Validation of the budget-inferred steric cycle (red in both panel pairs) against two independent estimates, over 2002–2021, matching Table 2 and Sect. 4.2. Left: SST-based column thermal expansion (orange) and the passive heat-flux response (purple), with (a) the full series and (c) the monthly climatology. Right: the GLORYS12 reanalysis, showing its total steric height (black) and thermosteric and halosteric parts (orange, green), with (b) the full series and (d) the monthly climatology. Both independent routes reproduce the budget's phase and order of magnitude; see Sect. 4.2 for the amplitude comparison.

4.3 Atmospheric pressure and the nature of the mass term

The seasonal inverse-barometer signal over the Gulf, from ERA5 surface pressure, has an amplitude of 10.6 cm with sea level depressed in winter under the seasonal high. This exceeds every term in Table 1 and is consistent with earlier attributions of most of the uncorrected seasonal sea-level cycle to atmospheric pressure (Sultan et al., 1995; Hosseinibalam et al., 2007). It is removed from the altimetry by the DAC and never enters gravimetry, so the budget of Sect. 4.1 is a budget of the pressure-corrected sea level. The question is whether the residual, non-isostatic response is treated consistently.

The GAD component over the Gulf has a seasonal amplitude of 3.94 ± 0.39 cm peaking in late February — essentially the whole of the mass cycle in Table 1. The mass series with GAD removed retains only 1.72 ± 0.12 cm, peaking in November. In other words, the seasonal ocean-mass cycle in the mascon products over this basin is dominated by the restored AOD1B ocean model, and GRACE itself measures the departure from that model. Physically the modelled signal is the wind- and pressure-driven exchange through Hormuz, which altimetry with the DAC removed retains, so the formulation with GAD is the consistent one. The independent estimates decide the question empirically: the steric cycle from the budget with GAD (7.0 cm) agrees with the SST-based estimate (7.2 cm), whereas the budget without GAD gives 3.2 cm and agrees with nothing. Because the budget closes against two independent steric estimates, the closure in turn validates the mass term: the seasonal ocean-mass cycle of the AOD1B model in this small marginal sea is consistent, to within the uncertainties of Sect. 4.2, with altimetry minus thermosteric height.

4.4 Regional gravimetry and the Gulf mass trend

Table 3 summarises the trend diagnostics. The raw CSR series over the Gulf has a trend of −2.0 ± 0.8 mm yr^{-1} over 2002–2021 and the JPL CRI series −3.0 ± 1.1 mm yr^{-1}. Both are unphysical: a basin open to the Indian Ocean through a strait cannot lose mass over two decades while the global ocean gains it at more than 2 mm yr^{-1}. The forward-modelled leakage from continental mass loss is −2.2 ± 0.3 mm

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yr^{-1}, with a seasonal amplitude of only 1.3 cm, so it affects the trend far more than the seasonal cycle. After correction the CSR trend is +0.2 ± 0.6 mm yr^{-1}, still below the barystatic rate, indicating that the Gaussian forward model under-corrects: the aquifer's true imprint on the Gulf cells is nearer −4 mm yr^{-1}. The GAD component over the Gulf also carries a drift of +1.61 ± 0.63 mm yr^{-1}. I do not take this as evidence of a real trend: AOD1B's skill is established here only for the seasonal wind- and pressure-driven cycle (Sect. 4.3), and there is no reason to expect a de-aliasing product of that kind, with limited resolution at a strait as narrow as Hormuz, to capture a two-decade secular drift in exchange reliably. Its sign is at least directionally consistent with the dynamic-trend hypothesis explored in Sect. 4.5, but I treat it as suggestive at most, not as independent confirmation.

Two further features confirm that regional gravimetry cannot supply the Gulf trend (Fig. S1). Smoothing the series after interpolating across the 2017–2018 mission gap produces an apparent minimum in Gulf mass at exactly the gap, because the last GRACE month and the first GRACE-FO month both fall in the seasonal trough; a supplementary Hodrick–Prescott/piecewise-linear analysis of this gap-interpolated series — distinct from the harmonic model of Eq. (1) used elsewhere in this study — places a breakpoint at 2017.9, which is an artefact of the interpolation rather than a change in the basin. And after 2021 the CSR and JPL solutions diverge over the Gulf by 10–15 cm, with CSR rising and JPL falling, so no trend claim can be supported beyond that date. The seasonal cycle is unaffected by any of this: it agrees between products to 0.3 cm and is insensitive to the leakage correction. I conclude that for a basin of this size next to a large continental mass trend, mascon products yield a reliable seasonal ocean-mass cycle but not a reliable trend.

Series	**Trend 2002–2021 (mm yr^{-1})**	**A_1 (cm)**	**Peak**
CSR raw, ocean mask	−2.04 ± 0.78	5.11 ± 0.41	late Jan
Leakage model (land only, filtered)	−2.22 ± 0.30	1.31 ± 0.09	mid-Feb
CSR leakage-corrected	+0.18 ± 0.64	3.88 ± 0.37	late Jan
GAD component over Gulf	+1.61 ± 0.63	3.94 ± 0.39	late Feb
CSR corrected, GAD removed	−1.43 ± 0.19	1.72 ± 0.12	early Nov
JPL CRI, ocean mask	−2.97 ± 1.13	4.73 ± 0.40	early Feb
Global barystatic (open ocean)	+2.11 ± 0.07	—	—

Table 3. Trend and seasonal diagnostics of the gravimetric series over the Gulf, 2002–2021. Negative Gulf mass trends are unphysical for a basin connected to the global ocean and reflect leakage of continental mass loss.

4.5 The trend budget

Table 4 gives the trend budget for 2002–2021. Total sea level from altimetry rose at 5.56 ± 0.72 mm yr^{-1}, above the 2.3–3.6 mm yr^{-1} reported for windows beginning in 1993 (Siddig et al., 2019; Al-Subhi and Abdulla, 2021) and consistent with the acceleration after about 2005 noted in those studies. The global barystatic rate from the CSR mascons over the open ocean is 2.11 ± 0.07 mm yr^{-1} (Fig. 4), close to independent estimates of the global ocean-mass trend for the GRACE era (e.g. Frederikse et al., 2020), which serves as a check on the calculation. For the steric term, both the GLORYS12 and ERA5-SST thermosteric trends are confirmed at 2002–2021 from window-matched fits (Sect. 3.2). The fully independent SST-based estimate (0.31 mm yr^{-1}) agrees closely with the GLORYS12 thermosteric trend (0.28 mm yr^{-1}), a tighter match than the full-record comparison (0.35 vs 0.43 mm yr^{-1}, Table 4); GLORYS12 is not independent of altimetry for the trend (Sect. 2.2), so a thermosteric contribution

https://doi.org/10.5194/egusphere-2026-5546
Preprint. Discussion started: 24 September 2026
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below 0.4 mm yr^{-1} rests on the SST route, corroborated rather than independently duplicated by GLORYS12's agreement. The GLORYS12 halosteric trend (0.30 mm yr^{-1} at 2002–2021, confirmed by the same re-run) has no independent check, implies a freshening I cannot explain in a net-evaporative basin, and rests on a reanalysis with essentially no in-situ salinity constraint in the Gulf, so I do not take it at face value. Spanning a plausible steric trend of 0.3–0.9 mm yr^{-1} — thermosteric alone (0.28) to thermosteric plus the full GLORYS12 halosteric term (0.58), with margin either side for the halosteric term's own uncertainty — against the 2002–2021 barystatic rate leaves a residual of 2.55–3.15 mm yr^{-1}, or 46–57 % of the observed rise, over that window. Repeating the full calculation — altimetry, global barystatic, and GLORYS12 full steric all re-fitted on the full 2002–2025 record (5.16 ± 0.39, 2.14 ± 0.07, and 0.78 ± 0.14 mm yr^{-1} respectively, the last split 0.43 ± 0.11 thermosteric and 0.35 ± 0.05 halosteric) — gives a smaller but still substantial residual of 2.24 ± 0.42 mm yr^{-1}, or 43 % of the trend. The residual's share of the total therefore falls from 52 % at the shorter window to 43 % at the longer one; the specific claim that it exceeds half the observed rise holds at 2002–2021 but not, at its central estimate, at 2002–2025. Combining both windows with the full steric sensitivity gives an overall range of 2.1–3.2 mm yr^{-1}, or 41–57 % of the trend (Table 4). I therefore report the residual as a large, robustly positive fraction of order two-fifths to one-half of the observed rise, rather than as reliably exceeding half.

Equivalently, because total sea level is identically the sum of the manometric (mass) and steric heights, this residual implies a Gulf-mean manometric trend of order 4–5 mm yr^{-1} (2.11 + 2.87 ≈ 5.0 mm yr^{-1} at 2002–2021; 2.14 + 2.24 ≈ 4.4 mm yr^{-1} at 2002–2025) — the barystatic rate plus a Gulf-specific dynamic mass trend comparable in size to the residual itself. Regional GRACE cannot adjudicate this: even after leakage correction the Gulf mascon trend is only +0.18 ± 0.64 mm yr^{-1} (Table 3), and matching it to the barystatic floor alone already implies a leakage correction nearer −4 mm yr^{-1} than my forward model's −2.2 mm yr^{-1} (Sect. 4.4); reconciling it with a true manometric trend of +4 to +5 mm yr^{-1} would require a correction of about −6 to −7 mm yr^{-1}, which I have no basis to exclude given how poorly constrained that correction already is. Regional gravimetry can therefore neither confirm nor refute a dynamic origin for the residual; Sect. 5 weighs it against two alternatives. Panel (c) of Fig. 2 shows that much of the residual is concentrated in a rise of about 7 cm between 2018 and 2020, which the altimetry — continuous through the gravimetry gap — records unambiguously and which the steric estimates follow; the mass and steric curves there are the GRACE-based decomposition, shown for shape only, not the adopted budget (Sect. 4.4).

Term	**Source**	**2002–2021 (mm yr^{-1})**	**2002–2025 (mm yr^{-1})**
Total sea level	DUACS altimetry	+5.56 ± 0.72	+5.16 ± 0.39
Ocean mass	Global barystatic, CSR mascons	+2.11 ± 0.07	+2.14 ± 0.07
Steric	GLORYS12 full column (T and S)	+0.58 ± 0.20	+0.78 ± 0.14
thermosteric	GLORYS12 / ERA5 SST	+0.28 / +0.31	+0.43 / +0.35
halosteric	GLORYS12	+0.30 ± 0.08	+0.35 ± 0.05
Unexplained residual	Total − mass − steric	+2.87 ± 0.75	+2.24 ± 0.42

Table 4. Sea-level trend budget of the Gulf, over both the primary 2002–2021 window and the full 2002–2025 record as a robustness check. Regional gravimetry is not used for the mass term in either column (Sect. 4.4); all GLORYS12 and ERA5-SST values are from window-matched fits (Sect. 3.2). The unexplained residual is 52 % of the observed rise at 2002–2021 and 43 % at 2002–2025 (Sect. 4.5).

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4.6 Interannual variability and the Indian Ocean Dipole

Piecuch et al. (2021) showed that intraseasonal sea level in the Gulf is set by its boundary condition in the Gulf of Oman and thereby by coastal and equatorial waves from the wider Indian Ocean. I test whether the same pathway operates at interannual timescales by correlating the deseasonalised altimetry and steric series with the Dipole Mode Index (Fig. 5). The correlations are weak: a maximum of +0.31 at a lag of nine months (DMI leading) for altimetry and +0.39 at five months for the steric series, together explaining 10–15 % of the variance. A composite is more suggestive. In each of the four strong positive dipole events of the record (September–November DMI above 0.5 °C in 2006, 2018, 2019 and 2023) Gulf annual-mean sea level was higher in the following year than in the event year, by 2.9, 3.9, 2.2 and 0.7 cm respectively; the step of 2018–2020 in Fig. 2c coincides with the consecutive events of 2018 and 2019, the second of which was the strongest on record. With four events this is consistent with, but not evidence for, remote forcing through Hormuz, and I report it as such.

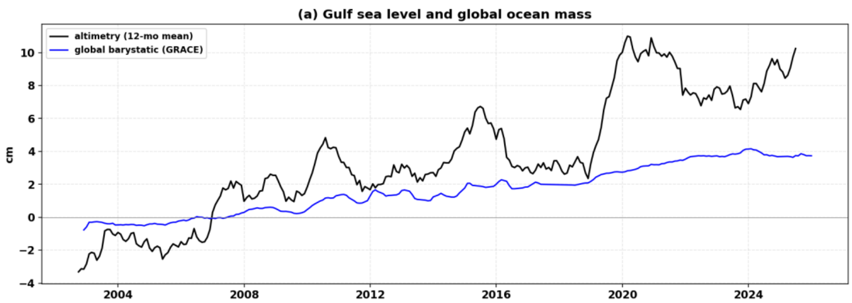

Figure 4. Gulf sea level from altimetry (black, 12-month mean) and global barystatic sea level from GRACE (blue), relative to 2004–2009.

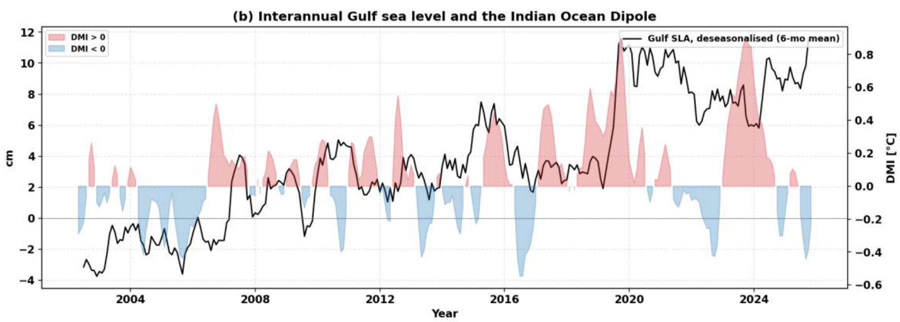

Figure 5. Deseasonalised Gulf sea level (black, 6-month mean) with the Dipole Mode Index shaded (red positive, blue negative).

5 Discussion

The seasonal sea-level cycle of the Gulf has been described for decades as modest and pressure-dominated (Sultan et al., 1995; Hosseinibalam et al., 2007). In answer to my first research question, the budget shows both descriptions to be true only of the uncorrected signal: the 10.6 cm inverse-barometer amplitude found here (Sect. 4.3) accounts for most of that variance, but the pressure-corrected cycle, though itself small, is the residual of two much larger and opposing components. A 7 cm steric cycle, driven by the 15 K seasonal range of the basin's temperature and reaching its climatological maximum

https://doi.org/10.5194/egusphere-2026-5546
Preprint. Discussion started: 24 September 2026
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in October, is offset by a 4 cm mass cycle peaking in January, when winter cooling and evaporation drive dense-water formation and the wind- and pressure-driven exchange through Hormuz is at its seasonal maximum. Any account of Gulf sea level that attributes the seasonal cycle to a single mechanism — pressure, thermal expansion or exchange — is therefore incomplete. The phase relations are physically coherent throughout: the steric maximum lags the sea-surface temperature maximum by a month as heat penetrates the column, and the mass maximum coincides with the winter regime documented by Swift and Bower (2003).

This picture also refines my own earlier, geodetically motivated estimate of the Gulf's seasonal mass cycle. Usman and Heki (2025) inferred a peak-to-peak range of order 15 cm from a single representative mascon cell, used there to explain winter GNSS subsidence around the basin; the area-mean, leakage-corrected cycle constructed here is about half that (3.9 cm annual amplitude, roughly 8 cm peak-to-trough with the semi-annual term included), which is the more appropriate quantity for basin-integrated loading and for the elastic corrections that such GNSS studies require. More fundamentally, in partial answer to my second question, the GAD/AOD1B finding of Sect. 4.3 deserves emphasis because it bears on every use of GRACE over small marginal seas. Over the open ocean the de-aliasing model and the GRACE-observed departure from it are both small and the distinction is academic; over the Gulf the model contributes 4 cm of the seasonal cycle and the measured departure only 1.7 cm, so the 'observed' seasonal mass cycle is in practice a hybrid whose reliability rests on the model's skill in the basin. The budget closure against two independent steric estimates constitutes, as far as I am aware, the first such check of AOD1B's seasonal ocean-mass response in a semi-enclosed sea, and here the model passes it to within the uncertainty of the steric term — a result that should not be assumed to generalise, since the same de-aliasing product has elsewhere been identified as a dominant source of budget-residual variance rather than a validated signal (see below). Conversely, the same closure identifies the mass term as the dominant source of systematic uncertainty in my own steric estimate, and a single moored temperature record in the central Gulf would collapse that uncertainty substantially.

The trend residual of 2.9 ± 0.8 mm yr^{-1} answers my third question only partially, and it is worth situating within the wider literature on regional sea-level budgets before interpreting it further. The global mean budget is now considered closed to within a few tenths of a millimetre per year (WCRP Global Sea Level Budget Group, 2018), but this closure has repeatedly been shown not to extend to individual ocean regions: Royston et al. (2020) found that as much as a third of the regional trend signal in the Indian–South Pacific cannot be attributed to a known component, and the most recent basin-by-basin reassessment finds significant, unexplained residuals concentrated in the North Atlantic regardless of whether the manometric term comes from GRACE or from ocean reanalyses (Bouih et al., 2025; see also Camargo et al., 2023). Non-closure at the regional or marginal-sea scale is therefore closer to the expectation than the exception, and the Gulf's residual — 41–57 % of the observed rise across the windows and steric estimates considered (Table 4) — sits within the higher part of that spread rather than being anomalous in kind. Its sign and magnitude are nonetheless robust here: the altimetry trend is measured directly, the barystatic rate reproduces independent estimates of the global GRACE-era ocean-mass trend (Sect. 4.5), and the steric trend is small by two independent routes, one of them (ERA5 SST) fully independent of both altimetry and gravimetry. The residual's concentration in a single step between 2018 and 2020, which the altimetry — continuous through the gravimetry gap — records unambiguously, and its coincidence with the two strongest recent positive Indian Ocean Dipole events, both favour a dynamic, remotely forced origin over the alternative that it reflects GRACE-FO's

https://doi.org/10.5194/egusphere-2026-5546
Preprint. Discussion started: 24 September 2026
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documented post-2016 degradation relative to steric-corrected altimetry elsewhere in the ocean (Ludwigsen et al., 2024). A third possibility is altimetry error specific to a shallow, semi-enclosed, highly saline basin: wet-troposphere and tide corrections are known to degrade close to complex coastlines (Vignudelli et al., 2011), and the Gulf's coastline, with the Qatar peninsula and numerous small islands, is more convoluted than most of the open-ocean settings in which DUACS is validated. I do not attempt to adjudicate among these three candidates here: doing so would require independent validation data or a regional ocean model forced at Hormuz, and the choice among them is the principal open problem raised by this study.

Finally, in answer to my fourth question, regional gravimetry alone cannot supply the Gulf's mass trend, and this is not a peculiarity of the Gulf. Mascon solutions substantially reduce land-to-ocean leakage relative to spherical-harmonic GRACE products (Scanlon et al., 2016), but for a basin small enough and adjacent to a strong enough continental signal, leakage still dominates: an almost identical situation has been documented for the Bohai Sea, a semi-enclosed basin of comparable size next to North China's groundwater depletion, where a leakage-in trend of about −2.9 mm yr^{-1} — closely matching the −2.2 to −4 mm yr^{-1} inferred here for the Gulf — and correspondingly large CSR/JPL disagreement were both found (Mu et al., 2020). The combination of leakage, a restored de-aliasing component with its own drift, and post-2021 divergence between mascon products means that, over such basins, mascon products should be used for seasonal cycles, where they are demonstrably robust, and not for trends, unless a leakage inversion is performed with the specific continental signal as an explicit basis function. The budget approach used here, which takes the mass trend from the global barystatic rate rather than from the region itself, sidesteps the problem for any basin in free connection with the global ocean, and is the more general recommendation I draw from this study.

Together these results show that a combined geodetic and oceanographic treatment of a small, data-sparse marginal sea can extract more from GRACE and altimetry than either observing system offers alone: the seasonal budget refines the ocean-mass loading signal that motivated my earlier geodetic study (Usman and Heki, 2025), while a geophysically informed treatment of the AOD1B and leakage terms lets the trend be estimated at all, in a setting where a naive regional-GRACE calculation fails outright. Given the Gulf's exposure — its coasts carry a large and rapidly growing population and extensive low-lying infrastructure — even the small, well-quantified fraction of sea-level rise attributed here provides a firmer basis for regional projections than has previously been available, while the larger, unattributed fraction is the more urgent target for future work.

6 Conclusions

I have closed the sea-level budget of the Arabian Gulf from satellite altimetry and gravimetry over 2002–2025 and answered the four questions posed in the Introduction.

(1) The seasonal cycle closes. Total sea level has an annual amplitude of 4.3 ± 0.3 cm with a climatological maximum in November; it is the residual of an ocean-mass cycle of 3.9 ± 0.4 cm peaking in January and a steric cycle of 7.0 cm with a climatological maximum in October, the two being nearly anti-phased. The mass cycle agrees between the CSR and JPL solutions to 0.3 cm.

(2) The steric cycle is confirmed by two further estimates. Column thermal expansion from ERA5 sea-surface temperature — fully independent of both altimetry and gravimetry — gives 7.2 cm, and the

https://doi.org/10.5194/egusphere-2026-5546
Preprint. Discussion started: 24 September 2026
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GLORYS12 reanalysis gives 5.3 cm, both peaking in August, with the expected one-month lag of the column behind the surface; because GLORYS12 assimilates altimetry, this second agreement is independent for the seasonal cycle specifically, not for the trend estimates in (3) below. The halosteric contribution to the seasonal cycle is 0.6 cm. The three estimates span 5.3–7.2 cm; I report 7.0 cm with a systematic uncertainty of 1.5 cm dominated by the mass term.

(3) Over 2002–2021 sea level rose at 5.6 ± 0.7 mm yr^{-1}, of which 2.1 ± 0.1 mm yr^{-1} is the global addition of ocean mass and 0.3–0.9 mm yr^{-1} is steric, depending on how much weight is given to an uncertain halosteric term. The remaining 2.1–3.2 mm yr^{-1} — roughly two-fifths to just over half of the total, depending on the end date (2002–2021 or 2002–2025) and the steric estimate used — implies a Gulf-mean manometric trend of order 4–5 mm yr^{-1} that regional gravimetry, given its own leakage-driven uncertainty here, can neither confirm nor refute. A dynamic, remotely forced trend in the Hormuz exchange is one of three candidates weighed in the Discussion, alongside GRACE-era barystatic uncertainty and coastal altimetry error; the year-after-IOD sea-level rises documented here are consistent with, though not proof of, the first.

(4) Regional gravimetry cannot supply the Gulf's mass trend. Leakage from groundwater depletion in the Arabian Peninsula and Iran imprints at least −2.2 mm yr^{-1} on the ocean cells, the restored dealiasing model carries its own drift, and the CSR and JPL solutions diverge by 10–15 cm after 2021. The seasonal mass cycle, by contrast, is robust, and is itself largely the restored AOD1B ocean model — which the budget closure validates in this basin.

The steric cycle reported here is the first altimetry–gravimetry partition of the Gulf's seasonal cycle, and the approach can be applied to any marginal sea without hydrography. The principal open question is the origin of the dynamic component of the trend.

Data availability

All data are publicly available: DUACS altimetry and GLORYS12 from the Copernicus Marine Service (https://marine.copernicus.eu), CSR mascons and component grids from https://download.csr.utexas.edu/outgoing/grace/RL0603_mascons/, JPL mascons from PO.DAAC, ERA5 from the Copernicus Climate Data Store, and the DMI from NOAA PSL.

Author contributions

M.U. conceived the study, developed the methodology, built the software and performed the formal analysis, carried out the investigation and data curation, validated the results, and wrote the original draft and reviewed and edited the manuscript.

Financial support

Grant no. RIF 23021 (Zayed University, UAE)

Competing interests

The author declares that he has no conflict of interest.

https://doi.org/10.5194/egusphere-2026-5546
Preprint. Discussion started: 24 September 2026
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Acknowledgements

I thank the Center for Space Research at the University of Texas at Austin and NASA's Jet Propulsion Laboratory for the GRACE/GRACE-FO mascon solutions and associated component and mask grids; the Copernicus Marine Service for the DUACS altimetry and GLORYS12 reanalysis products; the Copernicus Climate Change Service for ERA5; and NOAA's Physical Sciences Laboratory for the Dipole Mode Index. I am grateful to all of these data providers for making their products freely available.

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