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Where is the Water Coming From? Reconciling Decades of Sea Level Data

Environment * Climate Change * Energy

1. Introduction: Planetary Equilibrium and the Sea Level Budget

Global mean sea level (GMSL) serves as one of the most integrative physical indicators of anthropogenic climate change. As rising concentrations of atmospheric greenhouse gases increase positive radiative forcing, the global ocean absorbs over 90 percent of the resulting Earth Energy Imbalance (EEI, currently estimated near 0.77 W m-2).[11,12] Proxy and instrumental records confirm that modern sea level rise has broken a 4,000-year baseline of Holocene stability, threatening coastal megacities and marine infrastructure worldwide.[1]

In physical oceanography and climate science, attribution relies on closing the "sea level budget": total observed volumetric GMSL change must equal the sum of steric changes (volume alterations driven by water temperature and salinity) and barystatic changes (ocean mass additions from land-based ice loss and terrestrial water storage).[2] For decades, assessments by the Intergovernmental Panel on Climate Change (IPCC) contended with a persistent "budget gap" between top-down satellite altimetry measurements and bottom-up sums of steric (Argo profiling floats) and barystatic (GRACE/GRACE-FO satellite gravimetry) components -- a divergence that widened noticeably after 2015.[2,4,6,8,9]

Milestone research published in Science Advances in May 2026 has now mathematically closed the global mean sea level budget from 1960 to 2023.[4] By correcting subtle instrumental drifts, assimilating sparse mid-twentieth-century hydrographic records, and decoupling vertical land motion from coastal tide gauges, researchers have reconciled six decades of sea level data and quantified the physical drivers of its modern acceleration.[4,14]

2. Resolving the Budget Gap: Four Observational Breakthroughs

Closing the post-2015 and historical budget discrepancies required identifying and correcting four distinct sources of instrumental and structural bias across the global ocean observing system:[4,14]

* Satellite Altimetry Wet-Path Calibration: Radar altimeters (from TOPEX/Poseidon through the Jason series) calculate sea surface height from radar pulse return times, relying on onboard microwave radiometers to correct for the "wet path delay" caused by atmospheric water vapor in the troposphere.[8] Researchers discovered a post-2015 calibration drift in the Jason-3 microwave radiometer that overestimated wet path delay and biased GMSL trends downward by ~ 0.05 mm yr-1.[4,8] Recalibrating the radiometer and refining coastal, high-latitude, and seismic ocean masks realigned the altimetric record.[15]

* Argo Conductivity and Halosteric Drift Correction: Beginning around 2016, conductivity sensors on a subset of autonomous Argo floats drifted toward

artificially high salinity readings, producing spurious halosteric sea level drops of up to 15 mm in the Atlantic Ocean and 10 mm in the Southern Ocean and skewing 0-1,000 m regional steric rates by 3-8%.[10,16] Bias-correcting these conductivity profiles restored accurate steric expansion estimates.[10]

* Historical Ocean Heat Reconstruction (IAPv4): Prior to global Argo coverage in 2005, subsurface temperature records relied on shipboard mechanical and expendable bathythermographs (XBTs) concentrated along Northern Hemisphere shipping lanes.[17,18] The Institute of Atmospheric Physics version 4 (IAPv4) dataset bridged this gap back to 1940 across 119 vertical levels down to 6,000 meters (1 deg x 1 deg monthly resolution) using kernel-smoothing bias corrections and spatial covariances trained on Earth System Model hindcasts to quantify ocean heat content and thermosteric expansion since 1960.[14,18,19]

* Decoupling Vertical Land Motion (VLM): Coastal tide gauges measure sea level relative to the local crust, which deforms continuously due to millennial Glacial Isostatic Adjustment (GIA), tectonics, deltaic compaction, and localized anthropogenic groundwater and hydrocarbon extraction (e.g., Galveston, Texas).[14,25,27] Unaccounted non-linear VLM previously distorted twentieth-century acceleration estimates by over 50%.[24] Probabilistic Monte Carlo reconstructions integrated with Global Navigation Satellite System (GNSS) data isolated true climate signals, showing that early twentieth-century rise was slower -- and modern acceleration sharper -- than previously estimated.[4,24,29]

3. Partitioning Physical Drivers (1960-2023) and the Acceleration Budget

With the budget closed, the 1960-2023 record partitions total GMSL rise across five physical contributors.[2,4] Thermosteric expansion -- driven by thermal uptake across the upper 2,000 meters and slow warming in abyssal plains below 2,000 meters -- accounts for 43% of total rise.[2,5,21] Barystatic mass additions from the cryosphere account for 54%, led historically by lower-latitude mountain glaciers (27%), followed by surface melt and dynamic calving from the Greenland Ice Sheet (15%) and basal shelf melting and marine-terminating glacier retreat (such as Thwaites Glacier) across the Antarctic Ice Sheet (12%).[2,7,32] Net terrestrial land water storage accounts for the remaining 3%.[2]

| Component Driver | | Percentage of Total GMSL Rise (1960-2023) | | Primary Physical Mechanism |

| Thermosteric Expansion | | 43% | | Volume expansion of seawater due to the absorption of excess anthropogenic atmospheric heat. |

| Mountain Glaciers | | 27% | | Addition of freshwater mass from the melting of high-altitude and high-latitude terrestrial glaciers. |

| Greenland Ice Sheet | | 15% | | Surface mass balance reduction, summer melt, and dynamic ice discharge into the North Atlantic. |

| Antarctic Ice Sheet | | 12% | | Basal melting of floating ice shelves and dynamic loss from marine-terminating glaciers. |

| Land Water Storage | | 3% | | Net addition of mass to the oceans via groundwater

depletion, offset historically by terrestrial reservoir impoundment. |

Crucially, the rate of GMSL rise nearly doubled from a long-term average of 2.06 mm yr-1 (1960-2023) to 3.94 mm yr-1 (2005-2023).[4]

| Time Period | | Average Rate of GMSL Rise | | Contextual Significance |

| 1960 - 2023 | | 2.06 millimeters per year | | The long-term historical baseline for the modern anthropogenic era. |

| 2005 - 2023 | | 3.94 millimeters per year | | A near-doubling of the long-term historical rate, indicating rapid systemic acceleration. |

Decomposing this twenty-first-century "acceleration budget" reveals a major structural shift in barystatic forcing.[14] While thermosteric expansion drives 41% of the acceleration, terrestrial land water storage drives 21% -- reflecting the late-twentieth-century slowdown in mega-dam reservoir impoundment combined with surging agricultural and municipal aquifer depletion.[2,5,14] Simultaneously, polar ice sheets in Greenland (16%) and Antarctica (13%) have overtaken diminishing mountain glaciers (9%) as the primary cryospheric engine of acceleration.[4,14]

| Component Contributor | | Proportional Contribution to GMSL Acceleration |

| Thermosteric Expansion | | 41% |

| Land Water Storage | | 21% |

| Greenland Ice Sheet | | 16% |

| Antarctic Ice Sheet | | 13% |

| Mountain Glaciers | | 9% |

4. Cascading Impacts on Circulation, Meteorology, and Coastlines

The thermal and freshwater fluxes quantified in the sea level budget drive severe secondary disruptions across Earth systems. Subsurface ocean heat content fuels the rapid intensification of tropical cyclones, governs South and Southeast Asian monsoon timing for over two billion people, drives multi-year East African droughts via Indian Ocean thermal anomalies, and impacts naval acoustics and port logistics in global meteorology and maritime trade.[12]

In the North Atlantic, buoyant freshwater discharge from Greenland dilutes surface salinity and inhibits deep convective sinking, weakening the Atlantic Meridional Overturning Circulation (AMOC) -- the vital northern branch of global thermohaline circulation.[17,34] Meanwhile, compound hazards of accelerating sea level rise and urban land subsidence threaten southeastern Chinese megacities, while marine heatwaves trigger widespread coral bleaching, degrading natural reef breakwaters that buffer coastal storm surges.[1,35]

5. Conclusion: Geophysical Inertia and Multi-Century Commitment

Reconciling the 1960-2023 global mean sea level budget validates the physical fidelity of modern climate models and eliminates a long-standing source of projection uncertainty.[4] Because deep-ocean heat diffusion and polar ice-sheet mass-balance adjustments operate over multi-century to millennial timescales,

substantial future sea level rise is already locked into the Earth system regardless of near-term emissions trajectories -- underscoring the urgent mandate to sustain global ocean observing networks and engineer resilient coastal adaptations.[4,5,12]

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