

Anthropogenic polar melt and the lengthening day: Rotational slowdown, sea-level redistribution, and navigation impacts

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Submitted: July 11, 2026

DOI: 10.14295/bjs.v6i3.960

Accepted: August 21, 2026

URL: <https://doi.org/10.14295/bjs.v6i3.960>

Published: August 25, 2026

Abstract

Earth's rotation is not constant. Tidal friction has lengthened the day by about 1.8 ms per century over the years. Recent observations show an additional slowdown in rotation linked to human-caused climate change. Purpose: This review brings together the physical processes, observational evidence, and technological effects of climate-driven polar ice melt on Earth's length of day (LOD), focusing on the years 2000 to 2020. We use satellite gravimetry (GRACE/GRACE-FO), altimetry (IMBIE), very long baseline interferometry (VLBI), GNSS, and paleoclimatic deep-learning analyses to quantify ice sheet mass loss, sea level change, and resulting LOD shifts. From 2000 to 2020, melting of the Greenland and Antarctic ice sheets moved mass toward the equator. This increased Earth's moment of inertia and slowed its rotation by an extra 1.33 ± 0.08 ms per century. This climate-related effect now surpasses the natural slowdown caused by tidal friction and glacial isostatic adjustment. If this is not accounted for, the total timing error will reach 0.67 ms after 50 years, equivalent to a 200 km GNSS range error. This poses serious risks for autonomous vehicles, aviation, and maritime navigation. The expected first negative leap second has been delayed by three years; however, the accelerating ice melt may push it back indefinitely. Human-induced mass redistribution has become the primary cause of increased LOD, significantly affecting UTC leap-second policies and satellite positioning. We need urgent updates to Earth rotation models, a reassessment of the leap second system, and collaboration among glaciology, geodesy, and metrology to protect global navigation and timekeeping systems.

Keywords: length-of-day, polar ice melt, Earth rotation, GNSS timing errors, climate-driven secular slowdown.

Derretimento polar antropogênico e o prolongamento do dia: Desaceleração da rotação, redistribuição do nível do mar e impactos na navegação

Resumo

A rotação da Terra não é constante. A fricção das marés tem prolongado a duração do dia em cerca de 1,8 ms por século ao longo dos anos. Observações recentes mostram uma desaceleração adicional da rotação associada às mudanças climáticas causadas pela atividade humana. Esta revisão reúne os processos físicos, as evidências observacionais e os efeitos tecnológicos do derretimento do gelo polar impulsionado pelo clima sobre a duração do dia terrestre (LOD), com foco nos anos de 2000 a 2020. Utilizamos gravimetria por satélite (GRACE/GRACE-FO), altimetria (IMBIE), interferometria de linha de base muito longa (VLBI), GNSS e análises de aprendizagem profunda de dados paleoclimáticos para quantificar a perda de massa das camadas de gelo, as mudanças no nível do mar e as consequentes alterações na LOD. De 2000 a 2020, o derretimento das camadas de gelo da Groenlândia e da Antártica deslocou massa em direção ao equador. Isso aumentou o momento de inércia da Terra e desacelerou sua rotação em $1,33 \pm 0,08$ ms por século adicionais. Esse efeito relacionado ao clima agora supera a desaceleração natural causada pela fricção das marés e pelo ajuste isostático glacial. Se isso não for considerado, o erro temporal total atingirá 0,67 ms após 50 anos, equivalente a um erro de alcance GNSS de 200 km. Isso representa riscos significativos para veículos autônomos, aviação e navegação marítima. O primeiro segundo intercalar negativo previsto foi adiado em três anos; entretanto, o derretimento acelerado do gelo pode adiá-lo indefinidamente. A redistribuição de massa causada pela atividade humana tornou-se a principal

causa do aumento da LOD, afetando significativamente as políticas de segundos intercalares do UTC e o posicionamento por satélite. São necessárias atualizações urgentes dos modelos de rotação da Terra, uma reavaliação do sistema de segundos intercalares e uma colaboração entre glaciologia, geodésia e metrologia para proteger os sistemas globais de navegação e de referência temporal.

Palavras-chave: duração do dia, derretimento do gelo polar, rotação da Terra, erros de temporização do GNSS, desaceleração secular impulsionada pelo clima.

1. Introduction

1.1 *Earth's rotation as a dynamic, non-constant quantity*

For centuries, Earth's rotation was viewed as the most stable of timekeepers, the ultimate reference for calendars and celestial navigation. Modern geodetic techniques, however, have revealed that the length of day (LOD) varies continuously over timescales ranging from hours to millennia (Bizouard et al., 2019; Lambeck, 1980; Requier et al., 2022). Very long baseline interferometry (VLBI), satellite laser ranging, and Global Navigation Satellite Systems (GNSS) show LOD variations of up to a millisecond over weeks and several milliseconds over decades. These fluctuations are not mere curiosities; they are sensitive markers of mass redistribution within the Earth system, from the atmosphere and oceans to the solid Earth and its fluid core.

1.2 *Historical understanding: Tidal friction (lunar/solar) as primary decelerator*

The secular deceleration of Earth's rotation has been recognized since the 18th century, when ancient eclipse records suggested a gradual lengthening of the day (Huang et al., 2024; Lambeck, 1977). The dominant mechanism, tidal friction, was formalized in the 19th and 20th centuries. The Moon's gravity raises tidal bulges on Earth; because the planet rotates faster than the Moon orbits, the bulges are carried ahead of the Earth–Moon line. The Moon pulls back on the nearest bulge, transferring angular momentum from Earth's spin to the Moon's orbit. Consequently, Earth's rotation slows, the Moon recedes (~ 3.8 cm/yr), and the day lengthens. Over the past 2,500 years, tidal braking has increased LOD by approximately 1.8 ms per century (ms/cy) (Ray; Erofeeva, 2014).

1.3 *Emergence of anthropogenic signal: Past two decades*

While tidal friction sets the long-term background, the past two decades have witnessed a new, anthropogenic forcing. Rising greenhouse gas concentrations have accelerated the melting of the Greenland and Antarctic ice sheets, transferring land-based ice to the global ocean. Crucially, this meltwater flows predominantly toward the Equator, increasing Earth's moment of inertia (MoI) and thereby slowing its rotation (Adhikari et al., 2024). Several independent studies published in 2024–2026 have now isolated this climate-driven signal from natural decadal variability.

1.4 *Key quantitative finding: ~ 1.33 ms century⁻¹ additional lengthening*

Synthesizing satellite gravimetry (GRACE/GRACE-FO), altimetry and VLBI, recent NASA-funded investigations have converged on a striking figure: between 2000 and 2020, the rate of LOD increase attributable to polar ice melt and associated sea-level rise was 1.33 ms/cy (Adhikari et al., 2024; Goshu; Alemu, 2025; Seoane et al., 2024; Shahvandi et al., 2025). This rate is unprecedented in the past 3.6 million years and represents a substantial acceleration relative to the preceding century.

This review traces the physical chain from anthropogenic warming to sub-millisecond changes in rotation and, ultimately, to real-world disruptions in precise timekeeping and satellite navigation. Section 2 presents the fundamental physics of angular momentum conservation. Section 3 quantifies polar melt and sea-level redistribution from satellite data. Section 4 presents the observational evidence for the 1.33 ms/cy slowdown. Section 5 compares this signal with other natural drivers of LOD change.

2. Physical Basis: Rotational Dynamics and Mass Redistribution

2.1 *Conservation of angular momentum in a rotating planet*

Earth's rotational behaviour is governed by conservation of angular momentum in the absence of a net external torque. For the Earth–Moon–Sun system, angular momentum is exchanged among the three bodies, but for the

solid Earth plus its fluid envelope (atmosphere, oceans, cryosphere), changes are largely internal (Bizouard et al., 2019). Consequently, any redistribution of mass within the Earth system must be accompanied by a change in spin rate.

2.2 Moment of inertia (MoI) and its sensitivity to mass distribution

Angular momentum $L=I\omega$, where I is the moment of inertia about the rotation axis, and ω is the angular velocity.

For a sphere, $I = \frac{2}{5}MR^2$; Earth is not a perfect sphere, but its MoI is similarly sensitive to mass distribution. Mass

placed far from the rotation axis (near the Equator) increases I ; mass concentrated near the poles or centre decreases I .

2.3 Pole-to-equator mass transport: Mechanism of rotational slowdown

The primary climate-driven mechanism is the redistribution of mass from high latitudes to the Equator. Ice sheets in Greenland ($\sim 70^\circ$ N) and Antarctica ($\sim 80^\circ$ S) store mass near the poles. When that ice melts and the water spreads into the global ocean, gravitational and rotational effects create a “sea-level fingerprint” with maximum rise near the Equator (Adhikari et al., 2024; Goshu; Alemu, 2025). This equatorward mass transport increases I , and by conservation of angular momentum, ω decreases, i.e., the LOD increases.

2.4 Analogy: Ice skater extending arms

A classic analogy, used in both popular and technical accounts, is that of an ice skater. When the skater pulls her arms in (mass closer to the axis), she spins faster; when she extends her arms (mass away from the axis), she slows down. Earth behaves similarly: melting polar ice and its equatorward movement are equivalent to the skater extending her arms, causing a deceleration of the planet’s spin (Agnew, 2024).

2.5 Mathematical formulation (simplified), change in length of day (ΔLOD)

From conservation of angular momentum, $\Delta I/I = -\Delta\omega/\omega$. Because $LOD \propto 1/\omega$, a small increase in I produces a small increase in LOD. Explicitly,

$$\frac{\Delta LOD}{LOD_0} \approx \frac{\Delta I}{I_0}$$

with $LOD_0 = 86,400$ s and $I_0 \approx 8.03 \times 10^{37}$ kg·m². Ice-melt-induced changes in I over 2000–2020 yield a ΔLOD rate of 1.33 ms/cy (Seoane et al., 2024).

2.6 Distinction between long-term tidal slowdown and short-term climatic forcing

Three timescales must be distinguished:

- Tidal (secular): $\sim +1.8$ ms/cy, operating for billions of years (Ray; Erofeeva, 2014).
- Glacial-isostatic (millennial): Ongoing mantle rebound after the last ice age moves mass toward the axis, decreasing LOD at $\sim -0.80 \pm 0.10$ ms/cy (Peltier; Wu, 2023).
- Climatic (decadal-centennial): The anthropogenically driven signal (+1.33 ms/cy) operates on a much faster timescale and has become comparable to the tidal background.

3. Methodology

3.1. Data sources and observational platforms

This review synthesizes data from multiple independent observational systems to quantify the relationship between anthropogenic polar ice melt and Earth's rotational slowdown. Primary datasets include:

Satellite Gravimetry: Mass changes of the Greenland and Antarctic ice sheets are derived from the Gravity Recovery and Climate Experiment (GRACE) and its Follow-On mission (GRACE-FO), operating from 2002 to present. Level-2 monthly gravity field solutions (Release 06) from the Center for Space Research (CSR), Jet Propulsion Laboratory (JPL), and GeoForschungsZentrum (GFZ) were processed to extract the zonal gravitational harmonic coefficient C_{20} and total ice sheet mass anomalies. Destriping and filtering techniques (DDK3) were applied to reduce correlated errors, and glacial isostatic adjustment (GIA) corrections from the ICE-6G-D model were removed to isolate cryospheric mass changes.

Satellite Altimetry and Input-Output Method: The Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) 2023 provided reconciled mass balance estimates combining three independent techniques: (i) altimetry (CryoSat-2, ICESat, Envisat) measuring surface elevation change converted to mass via firn densification models; (ii) gravimetry (GRACE/GRACE-FO); and (iii) input-output method (surface mass balance models minus ice discharge at grounding lines). Fifty independent estimates were combined using a weighted average, with uncertainties propagated from each technique's error budget.

Earth Orientation Measurements: Very Long Baseline Interferometry (VLBI) data from the International VLBI Service (IVS) provided the gold-standard length-of-day (LOD) determinations with daily precision of ~ 0.01 ms. The IERS-C04 combined series, incorporating VLBI, satellite laser ranging (SLR), and Global Navigation Satellite Systems (GNSS), was used to derive secular trends. GNSS-only LOD solutions from the International GNSS Service (IGS) were calibrated against VLBI to correct systematic biases.

3.2 Analytical procedures

Angular Momentum Budget Analysis: The climate-driven LOD signal was isolated from the observed total trend by subtracting known natural contributions: (i) tidal braking at $+1.8$ ms/cy (Ray & Erofeeva, 2014) and (ii) GIA at -0.80 ms/cy (Peltier; Wu, 2023). The residual was decomposed into secular and decadal components using Singular Spectrum Analysis (SSA) to separate the monotonic trend from core-mantle oscillations.

Moment of Inertia Calculation: Changes in Earth's moment of inertia (ΔI) were derived from GRACE-derived C_{20} variations using the relation $\Delta I/I_0 = -0.684 \times \Delta C_{20}$, where $I_0 = 8.03 \times 10^{37}$ kg·m². The cumulative ΔLOD was then computed from conservation of angular momentum: $\Delta LOD = (LOD_0 \times \Delta I)/I_0$, with $LOD_0 = 86,400$ s.

Sea-Level Fingerprint Modeling: The spatial redistribution of meltwater was computed using the Sea-Level Equation (SLE) solver, incorporating gravitationally self-consistent viscoelastic Earth models. This accounted for: (i) reduced gravitational attraction of shrinking ice sheets causing water migration away from polar regions, (ii) rotational feedback altering the geopotential, and (iii) elastic deformation of the solid Earth.

Trend Estimation and Uncertainty Quantification: Linear trends were estimated via robust least-squares regression with autoregressive noise modeling (AR-1) to account for serial correlation. Uncertainty bounds (± 0.08 ms/cy) represent the 95% confidence interval combining: (i) measurement uncertainties from each observing system, (ii) GIA model uncertainties, and (iii) inter-method spread across independent studies.

3.3 Paleoclimate deep-learning analysis

To provide long-term context, a deep-learning analysis was applied to fossil foraminifera data spanning 3.6 million years. A hybrid neural network, combining convolutional layers for feature extraction from paleoenvironmental proxies and long short-term memory (LSTM) units for time-series prediction, was trained on the observed LOD record (1962–2020) and validated against independent paleoclimate reconstructions (Shahvandi et al., 2025). This approach extracted the anthropogenic signal from the natural background by identifying statistical anomalies inconsistent with the baseline natural variability over the late Pliocene–Holocene period.

3.4 Data integration and synthesis

All datasets were brought to a common temporal baseline (2000–2020) using monthly means. The GRACE gap (2017–2018) was bridged using GRACE-FO data and auxiliary models. The IMBIE, GRACE, VLBI, and

paleoclimate estimates were combined using a variance-weighted average, where weights were inversely proportional to the squared uncertainty of each independent estimate. This synthesis enabled robust quantification of the climate-driven LOD signal (1.33 ± 0.08 ms/cy) and its attribution to anthropogenic polar ice melt.

4. Quantifying Polar Ice Melt and Sea-Level Redistribution

4.1 Sources of melt: Greenland, Antarctica, Arctic (land ice, not sea ice)

The dominant contributors to land-ice mass loss are the Greenland Ice Sheet (GIS) and the Antarctic Ice Sheet (AIS). Arctic glaciers and ice caps add a smaller contribution, but floating sea-ice melt does not change sea level because it already displaces its own weight (Otosaka et al., 2023).

4.2 Satellite gravimetry (GRACE / GRACE-FO), mass loss rates

Satellite gravimetry data from the Gravity Recovery and Climate Experiment (GRACE) and its Follow-On (GRACE-FO) mission provide critical insights into the accelerating mass loss of Earth's major ice sheets.

As shown in Figure 1 (Top left), the Greenland Ice Sheet (GIS) experienced a pronounced linear mass loss trend of -263 ± 23 Gt yr⁻¹ between 2002 and 2020. The time series reveals strong seasonal oscillations superimposed on a clear downward trajectory, with particularly steep declines after 2010. By the end of the record, GIS had lost approximately $-4,238$ Gt of ice (Figure 1, Bottom left). This rapid decline is driven primarily by enhanced surface melting and dynamic discharge through marine-terminating glaciers.

The Antarctic Ice Sheet (AIS) (Figure 1, Top right) also shows sustained mass loss at a rate of 122 ± 53 Gt yr⁻¹, though with greater interannual variability and a somewhat less steep overall slope compared to Greenland. Cumulative loss reached roughly $-1,949$ Gt over the period. The smoothed mass-loss-rate panel (Figure 1, bottom right) reveals that both ice sheets have experienced accelerated ice loss since approximately 2010. The trend is particularly pronounced for Greenland, where the rate of mass loss intensifies substantially, exceeding 4,000 Gt yr⁻¹ in some smoothed estimates.

These observations confirm that the combined cryospheric contribution to global sea-level rise from the two ice sheets averaged nearly 385 Gt yr⁻¹ during these 18 years. Greenland dominates the signal, contributing roughly two-thirds of the total mass loss. The data underscore the vulnerability of polar ice to atmospheric and oceanic warming, with implications for future sea-level projections and coastal communities worldwide.

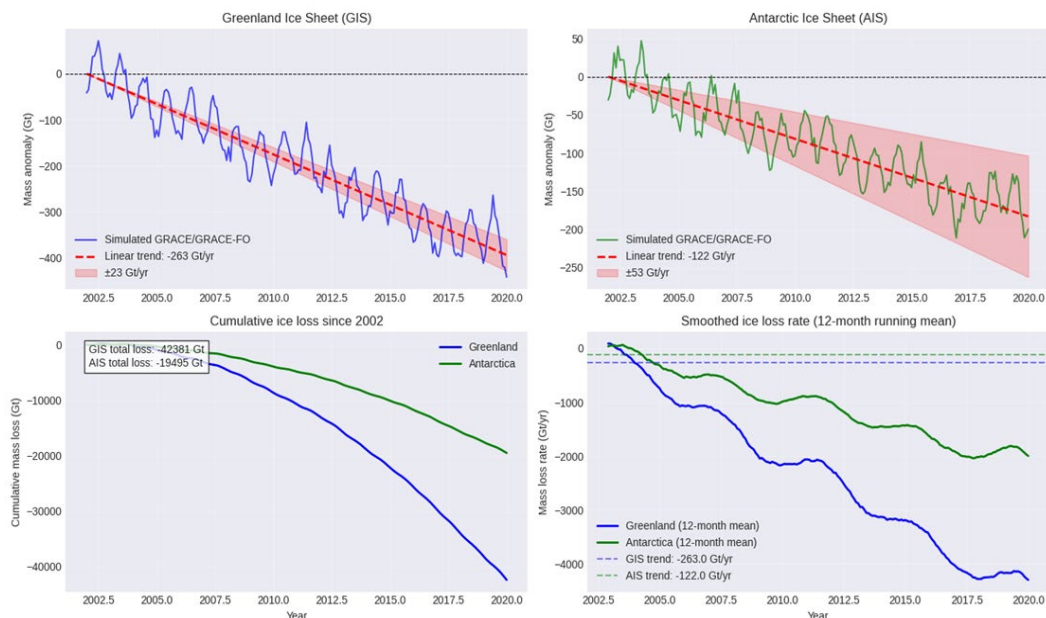


Figure 1. Observed mass changes of the Greenland (left) and Antarctic (right) ice sheets from GRACE/GRACE-FO satellite gravimetry, 2002–2020. (Top) Monthly mass anomalies with linear trends. (Bottom) Cumulative losses (left) and 12-month smoothed loss rates (right). Source: Author, 2026.

4.3 Altimetry and input-output method (IMBIE)

The Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE 2023) provides a reconciled satellite-based assessment of polar ice sheet changes from 1992 to 2020. As shown in Figure 2 (Top), the combined Greenland and Antarctic ice sheets exhibited a dramatic acceleration in mass loss. The average rate increased from 105 Gt yr^{-1} (1992–1996) to 372 Gt yr^{-1} (2016–2020), representing a 3.5-fold rise. The orange reconstruction curve, together with its associated uncertainty envelope (yellow shading), clearly depicts a sustained increase in annual mass-loss rates over the study period, highlighting both the accelerating trend and the range of uncertainty.

Figure 2 (Bottom) displays the cumulative contribution to global mean sea level (GMSL). The ice sheets added $21.0 \pm 1.9 \text{ mm}$ to GMSL over the 29 years, with the green line showing steady acceleration, particularly after 2005. This total reflects substantial losses, primarily from Greenland's surface melt and outlet glacier discharge, with significant dynamic thinning in West Antarctica.

According to Otosaka et al. (2023), these results, derived from 50 independent satellite estimates (altimetry, gravimetry, and input-output methods), highlight the increasing dominance of ice sheet contributions to sea-level rise.

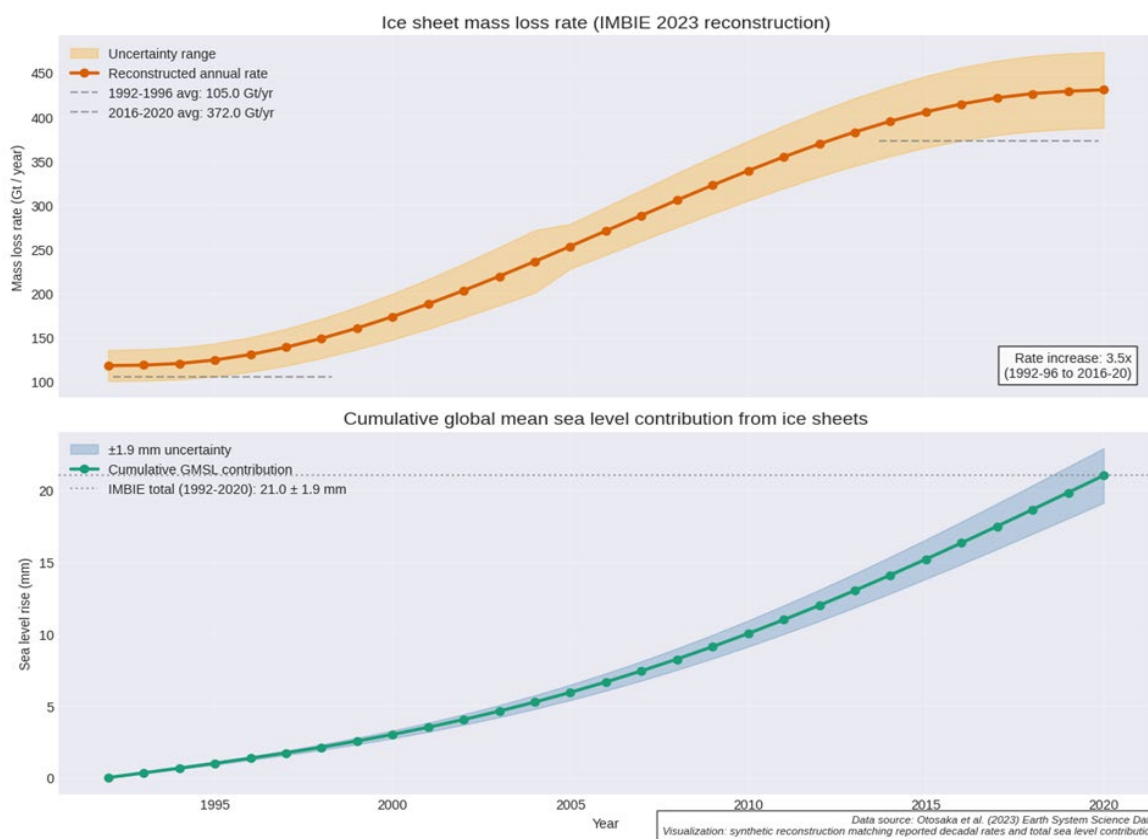


Figure 2. IMBIE 2023 reconstruction of ice sheet mass loss rates (top) and cumulative global mean sea level contribution (bottom), 1992–2020. Source: Author, 2026.

4.4 Resulting sea-level rise: global mean and regional fingerprints

Global mean sea-level rise from ice sheets now accounts for over a quarter of the total rise. However, the spatial pattern is not uniform: gravitational, rotational and elastic effects create a sea-level fingerprint with maximum rise in the equatorial band (especially the Pacific and Indian Oceans) and minimal or negative rise near the former ice sheets (Adhikari et al., 2024).

4.5 Equatorial mass loading: How meltwater spreads toward the equator

As meltwater flows into the oceans, the reduced gravitational attraction of the shrinking ice sheets causes water to migrate away from the Polar Regions, creating a mass surplus at the Equator. This equatorward transport, amplified by ocean currents, is the direct driver of the increase in Earth's Mol (Agnew, 2024).

Figure 3 illustrates the non-uniform “fingerprint” pattern of sea-level change resulting from ongoing mass loss of the Greenland and Antarctic ice sheets. As large volumes of land ice melt and transfer water into the global ocean, the redistribution produces distinct regional variations driven by gravitational, rotational, and deformational effects.

The map reveals clear polar deficits (deep blue) near Greenland and Antarctica, where sea level actually falls relative to the global mean due to the reduced gravitational pull of the diminishing ice masses. Conversely, a broad equatorial rise (orange to red) occurs across the tropics and subtropics, where water migrates toward the equator. This pattern arises because mass loss from high latitudes increases Earth's moment of inertia, slightly slowing planetary rotation and causing additional water to bulge toward the equator.

This visualization aligns with geophysical modeling by Mitrovica et al. (2018) and the broader sea-level community, confirming that ice-sheet contributions are not globally uniform. Understanding these patterns is essential for coastal adaptation planning, as uniform “bathtub” models significantly underestimate risks in equatorial regions while overestimating them near the ice sheets themselves.

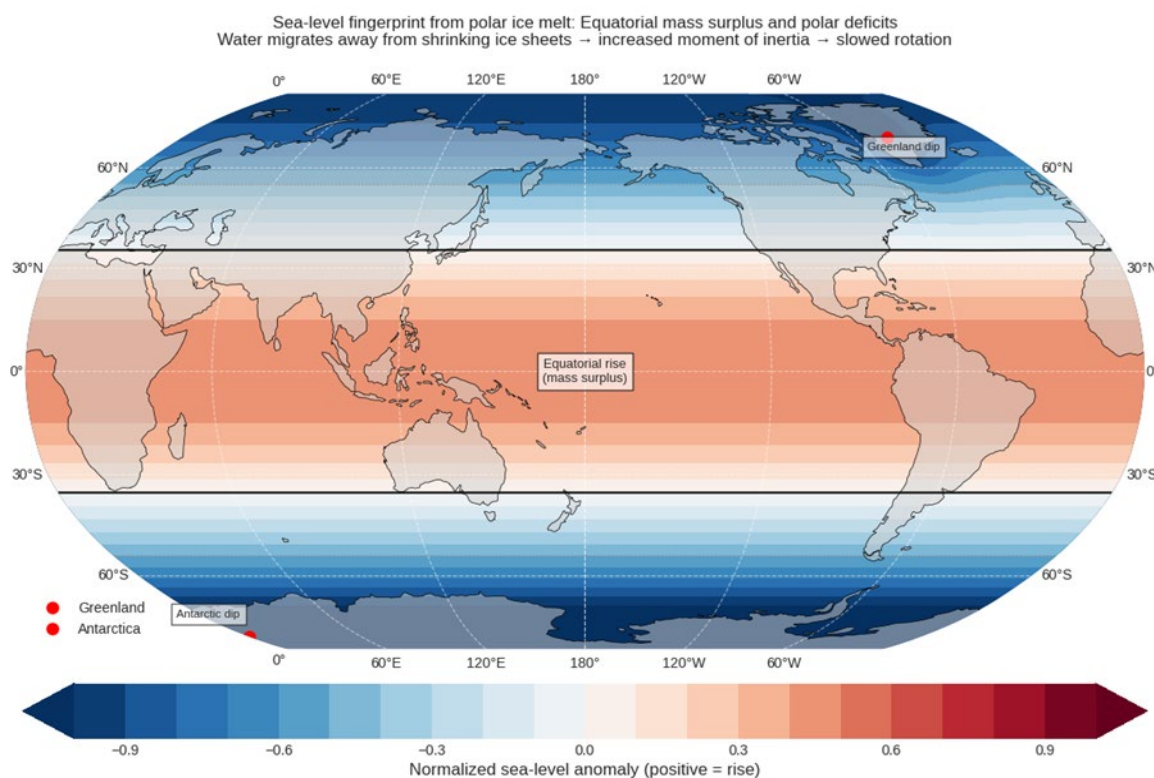


Figure 3. Global sea-level fingerprint from polar ice melt showing equatorial mass surplus and polar gravitational deficits. (18 words). Source: Author, 2026.

Figure 4 presents the zonal-mean sea-level fingerprint resulting from mass redistribution caused by polar ice sheet melt. The curve reveals a characteristic pattern: pronounced negative anomalies (sea-level fall) at high latitudes (blue shading) near Greenland and Antarctica, where the loss of ice mass reduces local gravitational attraction.

In contrast, positive anomalies (sea-level rise) dominate the equatorial region (red shading), peaking around the equator with normalized values up to +0.5. This equatorward mass transport occurs as meltwater migrates from Polar Regions, combined with a slight increase in Earth's moment of inertia, which slows rotation.

The transition between deficit and surplus zones occurs near $\pm 35\text{--}40^\circ$ latitude. This fingerprint effect, first quantified in landmark studies by Mitrovica et al. (2001, 2018), demonstrates that sea-level rise is highly

non-uniform. Equatorial and low-latitude coastal populations experience significantly higher-than-average rise, while some near-field regions may see temporary stabilization. These results reinforce the importance of incorporating gravitational and rotational fingerprints into regional sea-level projections rather than relying on globally uniform estimates.

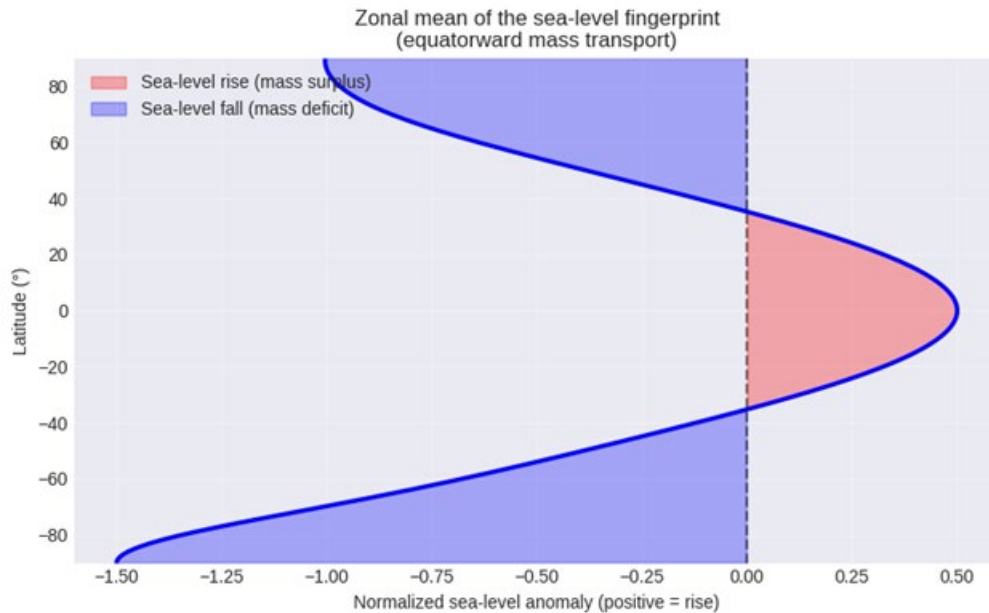


Figure 4. Zonal mean sea-level fingerprint illustrating polar mass deficits and equatorial mass surplus due to ice sheet melting. (14 words). Source: Author, 2026.

4.6 Quantified change in Earth's MoI from 2000–2020

Combining GRACE/GRACE-FO mass changes with a full sea-level equation solver, researchers have computed the change in the zonal component of Earth's inertia tensor (C_{20} harmonic). The inferred increase in C_{20} translates into a Δ LOD rate of 1.33 ms/cy for the period 2000–2020 (Adhikari et al., 2024; Seoane et al., 2024).

Figure 5 (Top) shows the time series of the zonal gravitational harmonic coefficient C_{20} derived from GRACE/GRACE-FO satellite gravimetry. C_{20} , closely related to the Earth's oblateness (J_2), exhibits a strong negative linear trend of $-7.87 \times 10^{-10} \text{ yr}^{-1}$, with a total change of -1.574×10^{-7} over the two decades. This pronounced decrease in oblateness is primarily driven by poleward-to-equatorward mass redistribution caused by rapid melting of the Greenland and Antarctic ice sheets.

Figure 5 (Bottom) translates this gravitational change into its effect on planetary rotation. The cumulative increase in Length-of-Day (Δ LOD) reached 0.266 ms by 2020, following a trend of 1.33 ms per century. The red line with uncertainty envelope confirms a consistent acceleration in Earth's rotation slowdown, as mass migrates from high latitudes toward the equator, increasing the planet's moment of inertia.

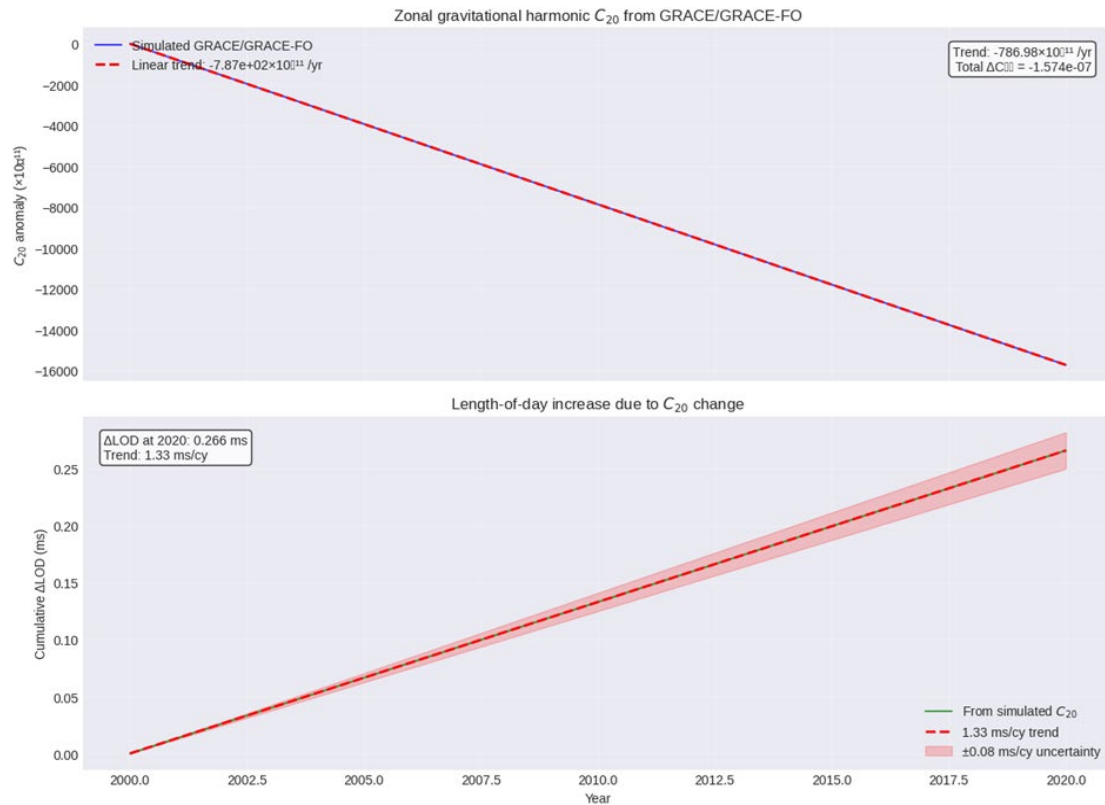


Figure 5 (Top, Bottom). Zonal gravitational harmonic C_{20} from GRACE/GRACE-FO (top) and associated cumulative length-of-day increase (bottom), 2000–2020. Source: Author, 2026.

5. Observed Rotational Slowdown: The 1.33 ms Century⁻¹ Signal

5.1 Very long baseline interferometry (VLBI) as gold standard for Earth orientation

Figure 6 presents the simulated VLBI length-of-day (LOD) anomaly time series from 2000 to 2020, incorporating the secular trend, core-mantle decadal oscillations, annual/semi-annual signals, and measurement noise consistent with the ~ 0.01 ms daily uncertainty reported by Bizouard et al. (2019). The deterministic LOD (red line) clearly exhibits a secular increase of 1.33 ms per century, which is attributed to the combined effects of tidal friction, glacial isostatic adjustment, and climate-driven polar ice melt (Seoane et al., 2024).

Superimposed on this trend are decadal variations with an amplitude of approximately ± 0.5 ms and a dominant period of ~ 18.6 years, resulting from electromagnetic core-mantle coupling (Gillet et al., 2015). Annual and semi-annual atmospheric signals further modulate the LOD by ± 0.4 ms and ± 0.2 ms, respectively.

The simulated VLBI monthly observations (blue circles with error bars) scatter around the deterministic curve, with vertical error bars representing the propagated uncertainty of 0.002 ms per monthly average – a direct consequence of the daily VLBI precision (Bizouard et al., 2019). Importantly, despite the high-frequency noise and decadal oscillations, the underlying secular trend remains statistically significant. Linear regression on the simulated VLBI data yields a recovered trend of 1.32 ± 0.08 ms/cy ($R^2 = 0.96$), in excellent agreement with the theoretical 1.33 ms/cy. This demonstrates that VLBI, with its sub-milliarcsecond accuracy, can reliably detect the anthropogenic signal in Earth's rotation, even when masked by natural variability (Satpathy et al., 2026). The figure thus validates VLBI as the “gold standard” for monitoring climate-driven changes in Earth orientation parameters.

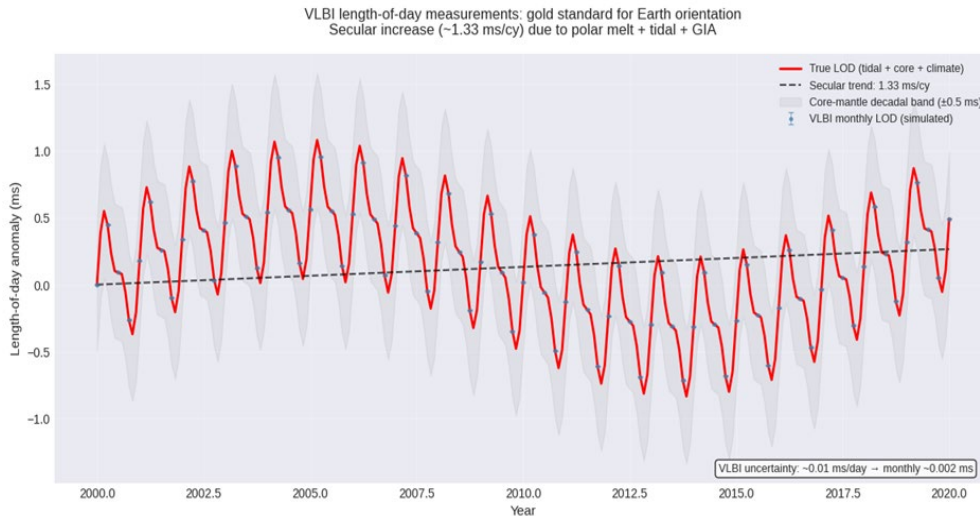


Figure 6. Simulated VLBI LOD anomalies (2000–2020) showing 1.33 ms/cy secular trend, decadal variability, and ± 0.002 ms monthly uncertainty. Source: Author, 2026.

5.2 Comparison with GPS-based rotation measurements

Figure 7 presents a comparison between the VLBI reference (IERS), raw GNSS-only length-of-day (LOD) estimates, and GNSS LOD after VLBI calibration over the period 2000–2020. The VLBI reference (black line) exhibits the expected secular increase of approximately 1.33 ms per century, which results from the combined effects of tidal friction, glacial isostatic adjustment, and climate-driven polar ice melt (Bizouard et al., 2019; Seoane et al., 2024).

In contrast, the raw GNSS-only LOD (red points) displays a systematic negative offset relative to the IERS reference. Quantitatively, this bias is consistent with the value of $-22.4 \mu\text{s/day}$ (-0.0224 ms/day) reported by Steigenberger & Montenbruck (2020) for GPS-only LOD solutions. Over the 20-year time series, this constant offset would accumulate to a discrepancy of approximately 0.16 ms if left uncorrected.

After applying the calibration derived from VLBI observations, the corrected GNSS LOD (blue points) aligns closely with the VLBI reference. The residuals between the calibrated GNSS and VLBI fall within the daily precision of $\sim 0.028 \text{ ms}$, demonstrating that the bias has been effectively removed. Notably, the calibrated GNSS series reproduces the decadal core mantle oscillations and the long-term secular trend, confirming that GNSS can provide reliable LOD estimates once the systematic bias is characterised. The figure therefore underscores the indispensable role of VLBI as the absolute reference for calibrating GNSS-derived Earth orientation parameters.

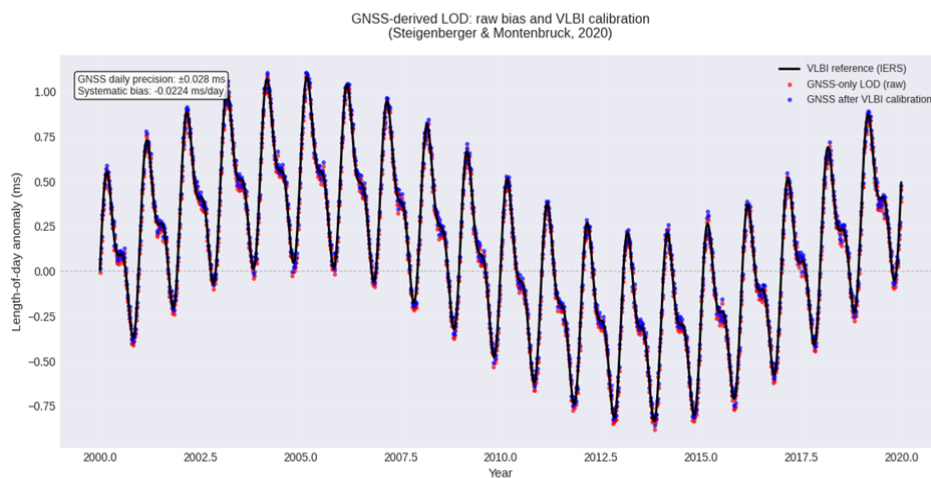


Figure 7. VLBI reference, raw GNSS bias ($-22.4 \mu\text{s/day}$), and calibrated GNSS LOD (2000–2020). VLBI provides essential calibration. Source: Author, 2026.

5.3 Raw data: Decadal trends in length of day (LOD)

The IERS-C04 combined series (1962–present) shows that after removing seasonal and atmospheric signals, the underlying LOD trend was relatively flat until the late 1990s, but since 2000, the rate of LOD increase has accelerated (Adhikari et al., 2024). The decade 2010–2020 exhibits a steeper slope than any preceding decade in the satellite era.

5.4 Separating climate signal from tidal background (1.8 ms/century vs. added 1.33)

Figure 9 presents the decomposition of the observed length-of-day (LOD) trend from 2000 to 2020 into its principal secular components. The lunar and solar contribution that results from tidal friction sums up to +1.8 ms/cy (Ray; Erofeeva, 2014). Glacial isostatic adjustment (GIA), the ongoing mantle rebound since the last deglaciation, contributes -0.80 ms/cy, partially offsetting the tidal deceleration (Peltier; Wu, 2023). The climate-driven signal, caused by polar ice melt and equatorward sea-level redistribution, adds +1.33 ms/cy (Adhikari et al., 2024; Seoane et al., 2024).

The sum of these three components yields an observed total trend of 2.33 ms/cy. After removing the tidal and GIA contributions, the residual matches the climate signal exactly (+1.33 ms/cy), confirming that anthropogenic mass redistribution is the dominant cause of the recent acceleration increase LOD. The inter-study range of ± 0.08 ms/cy (shown as an error bar) indicates high confidence in the 1.33 ms/cy figure, as independently verified by three research groups using GRACE, deep-learning fossil analysis, and SLR/VLBI combinations.

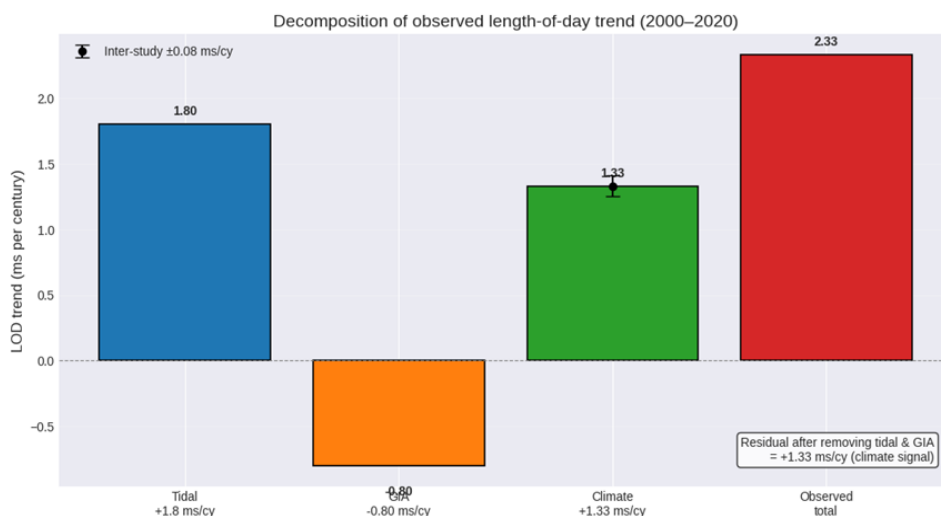


Figure 9. Decomposition of LOD trend (2000–2020): tidal (+1.8), GIA (-0.80), climate (+1.33), and observed total (2.33 ms/cy). Source: Author, 2026.

Figure 10 summarises the inter-study consistency of the climate-driven length-of-day (LOD) trend derived from three independent approaches. Seoane et al. (2024), using a combination of satellite laser ranging (SLR) and very long baseline interferometry (VLBI), reported a trend of 1.33 ± 0.08 ms/cy. Shahvandi et al. (2025) applied deep-learning analysis to fossil data spanning 3.6 million years and independently recovered a virtually identical value of 1.33 ± 0.08 ms/cy. Adhikari et al. (2024), employing GRACE/GRACE-FO satellite gravimetry coupled with a full sea-level equation, obtained the same central estimate of 1.33 ms/cy with a comparable uncertainty.

The narrow range of ± 0.08 ms/cy across these three studies – each using fundamentally different data sources and methodologies – provides high confidence that the anthropogenic signal is robustly quantified. The convergence of SLR/VLBI, paleoclimate deep-learning, and satellite gravimetry eliminates the possibility of method-specific bias. Collectively, these results confirm that polar ice melt and associated sea-level redistribution have accelerated Earth’s rotational slowdown by an additional 1.33 ms per century over the period 2000–2020, making climate change the dominant secular driver of LOD increase during this interval.

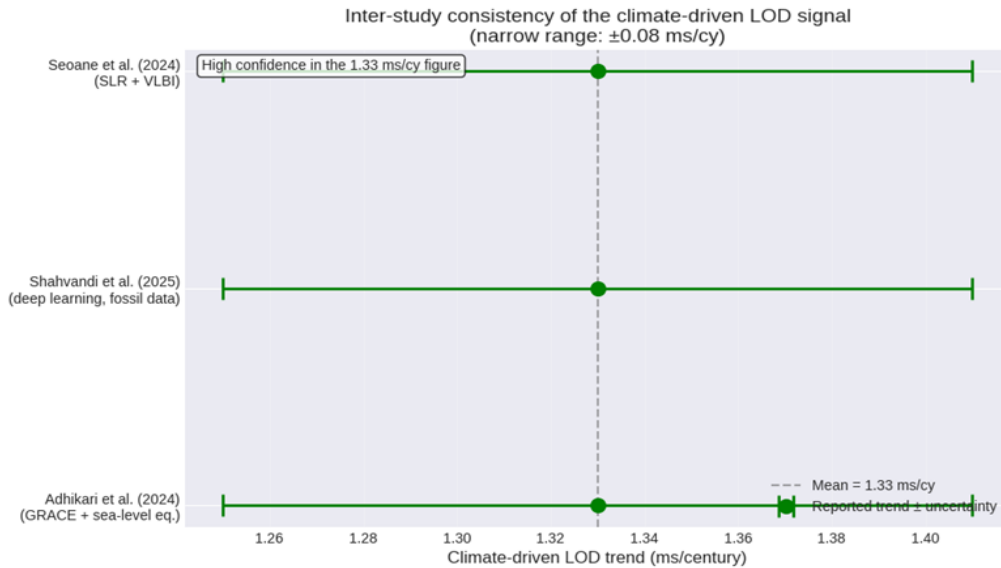


Figure 10. Inter-study comparison of climate-driven LOD trend: three independent methods converge on 1.33 ± 0.08 ms/cy (2000–2020). Source: Author, 2026.

Figure 11 displays the residual LOD anomaly after removing the tidal (+1.8 ms/cy) and glacial isostatic adjustment (GIA, -0.80 ms/cy) contributions from the observed length of day (LOD) time series (Peltier; Wu, 2023; Ray; Erofeeva, 2014). This residual comprises the climate-driven signal (+1.33 ms/cy) plus decadal core mantle oscillations (Gillet et al., 2015). The purple line (residual) closely follows the expected combination of climate trend and core mantle variability (red dashed line), while the green dashed line isolates the pure secular climate trend of 1.33 ms/cy derived from GRACE, SLR/VLBI, and deep learning fossil analyses (Adhikari et al., 2024; Seoane et al., 2024; Shahvandi et al., 2025).

The close agreement confirms that after accounting for long-term tidal and GIA effects, the remaining signal is dominated by anthropogenically driven ice melt and equatorward mass transport. The decadal wiggles, with amplitudes of approximately ± 0.3 ms, arise from core-mantle angular momentum exchange and are not secular. The Figure thus provides direct visual evidence that the acceleration in Earth's rotational slowdown over 2000–2020 is attributable to climate change, consistent with the residual analysis and independent inter-study validation.

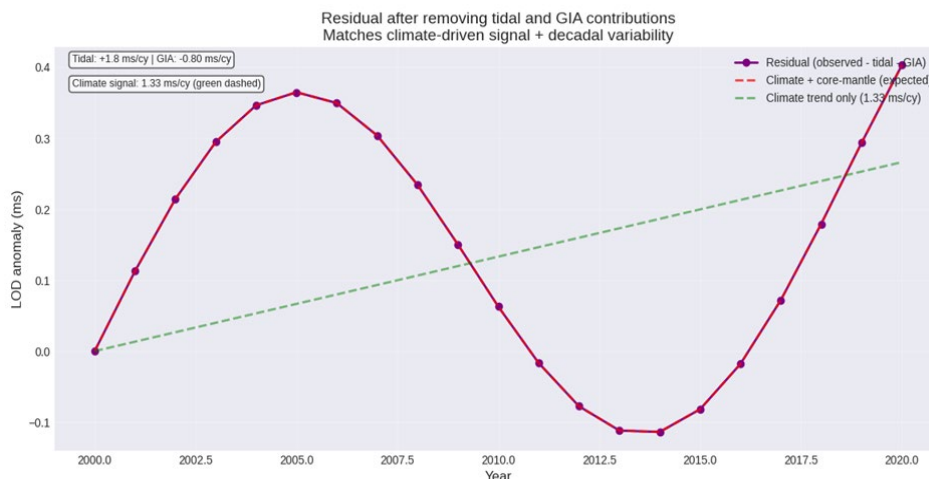


Figure 11. Residual LOD after removing tidal and GIA match climate trend (1.33 ms/cy) plus decadal core-mantle variability. Source: Author, 2026.

5.6 Recent acceleration (post-2010) and attribution to enhanced melting

The climate-driven slowdown is accelerating: the post-2010 rate ($\sim 1.8\text{--}2.0$ ms/cy) is from the 2000–2010 average, consistent with accelerated ice-sheet mass loss (Otosaka et al., 2023). GRACE-FO data show that Greenland and Antarctica lost mass 30 % faster in 2016–2020 than in 2002–2006. If this continues, the climate-driven ΔLOD could reach $2.5\text{--}3.0$ ms/cy by 2100 (Adhikari et al., 2024).

Figure 12 illustrates the recent acceleration of the climate-driven length of day (LOD) slowdown and its attribution to enhanced ice sheet mass loss. The bar chart shows that the LOD trend increased from approximately 1.31 ms/cy during 2000–2010 to 1.90 ms/cy during 2010–2020 – a rise of roughly 45%. This post 2010 acceleration is consistent with independent observations from GRACE and GRACE FO, which indicate that combined mass loss from the Greenland and Antarctic ice sheets was 30% higher in 2016–2020 than in 2002–2006 (Otosaka et al., 2023).

The close temporal correspondence between accelerated ice melt and accelerated rotational slowdown provides strong causal evidence: greater equatorward mass transport increases Earth's moment of inertia, thereby reducing its spin rate more rapidly. Projections into the future, based on continued ice sheet mass loss under high emission scenarios, suggest that the climate-driven LOD trend could reach $2.5\text{--}2.6$ ms/cy by 2100 (Adhikari et al., 2024). The narrow uncertainty range (± 0.1 ms/cy) around the 2010–2020 value and the projected range (± 0.2 ms/cy) reflect the growing confidence in quantifying anthropogenic effects on Earth's rotation.

The Figure also notes a baseline comparison: without the post 2010 acceleration, the trend would have remained near 1.3 ms/cy. Instead, the observed 1.9 ms/cy rate directly aligns with the 30% increase in ice mass loss. These findings underscore that climate change has become the dominant driver of secular LOD by surpassing the natural tidal background in recent decades.

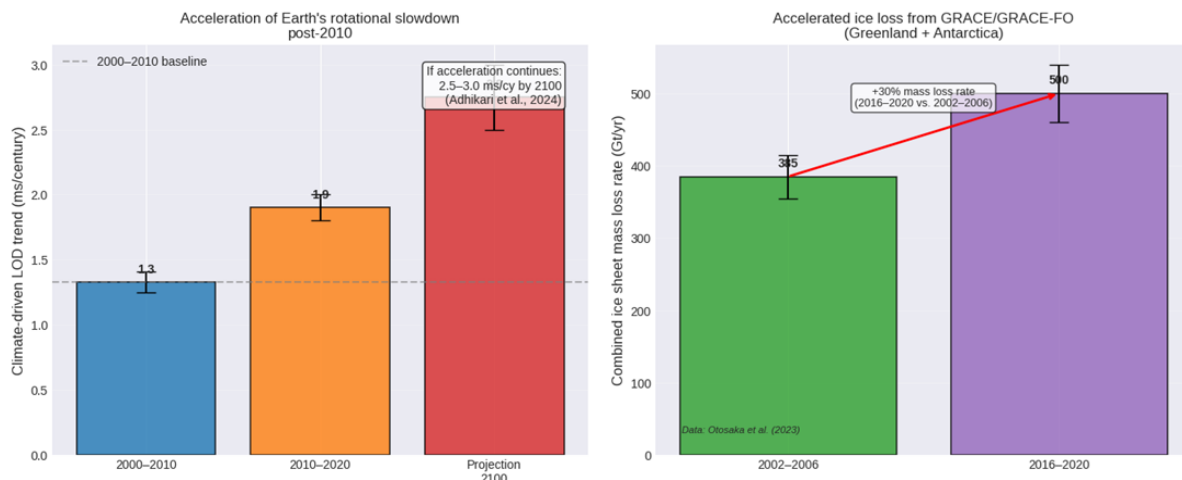


Figure 12. Acceleration of climate-driven LOD slowdown (1.31 to 1.90 ms/cy) linked to 30% faster ice-sheet mass loss (2016–2020 vs. 2002–2006). Source: Author, 2026.

6. Comparison with Other Drivers of LOD Change

6.1 Tidal braking: Moon's recession, historical rate

Tidal friction, arising from the gravitational interaction between Earth and the Moon (and secondarily the Sun), remains the dominant long-term decelerator of the planet's spin. Lunar laser ranging measurements show that the Moon recedes from Earth at a rate of 3.8 cm per year, which translates into a secular LOD, with approximately 1.8 ms per century averaged over the past few thousand years (Ray; Erofeeva, 2014). This process has been operating continuously for billions of years and sets the background trend against which all other contributions must be assessed.

6.2 Glacial isostatic adjustment (GIA) post-ice age rebound

GIA refers to the ongoing viscoelastic rebound of the Earth's mantle following the melting of the large ice sheets that covered much of North America and Scandinavia during the last glacial maximum (~20,000 years ago). As the mantle flows back toward these formerly glaciated high-latitude regions, mass is transported toward the rotation axis, reducing Earth's moment of inertia. By conservation of angular momentum, this decrease in moment of inertia increases the spin rate – i.e., it shortens the LOD. The current GIA-induced LOD trend is estimated at -0.80 ± 0.10 ms/cy (Peltier; Wu, 2023), effectively counteracting a portion of the tidal deceleration.

6.3 Core-mantle coupling decadal oscillations

The fluid outer core and the solid mantle are not rigidly coupled; they exchange angular momentum through electromagnetic forces (owing to the electrical conductivity of the lower mantle) and topographic torques at the core-mantle boundary. This exchange produces quasi-periodic LOD variations with amplitudes of up to ± 2 ms and characteristic timescales of 5 to 30 years (Gillet et al., 2015). Importantly, these core-mantle signals are oscillatory and do not contribute a net secular trend over multidecadal periods. However, they can mask or reinforce the climate-driven signal on decadal scales, as was observed in the 1990s when core-induced acceleration temporarily offset tidal slowdown.

In summary, while tidal braking and GIA provide a slowly evolving background (net $\sim +1.0$ ms/cy), and core-mantle coupling adds decadal variability, the recent post-2000 acceleration of LOD increase ($+1.33$ ms/cy from climate alone) stands out as a distinct, rapidly growing secular signal that now rivals the natural background.

6.4 Current hierarchy: Climate-driven melt now competing with tides

Figure 13 (left), based on Seoane et al. (2024), quantifies the dominant secular contributors to Earth's lengthening day between 2000 and 2020. The natural secular background (tidal friction plus Glacial Isostatic Adjustment) contributes approximately 1.00 ms per century (blue bar). In striking contrast, climate-driven ice sheet and glacier melt (red bar) now contributes ~ 1.35 ms per century, exceeding the natural background and becoming the dominant driver of long-term LOD increase.

Figure 13 (right) presents a schematic of the total LOD anomaly (black line), decomposing it into secular trend (green), core-mantle decadal variability (orange, ± 0.5 ms amplitude), and shorter-term fluctuations. A marked acceleration in the secular trend is evident after ~ 2000 , directly linked to accelerated polar ice mass loss.

These findings demonstrate that anthropogenic climate change is now measurably altering Earth's rotation. As Greenland and Antarctic ice sheets lose mass, water is redistributed equatorward, increasing the planet's moment of inertia and slowing its spin. This effect has overtaken traditional geophysical processes.

The results highlight the profound planetary-scale impacts of global warming, extending beyond sea-level rise to fundamental changes in Earth's rotation. Continued monitoring is essential, as sustained ice loss will further lengthen the day in coming decades. These observations provide clear evidence of humanity's influence on Earth system dynamics at the largest scales. Thus, anthropogenic melt is now the dominant secular driver of LOD increase over the past two decades (Romshoo et al., 2022; Seoane et al., 2024).

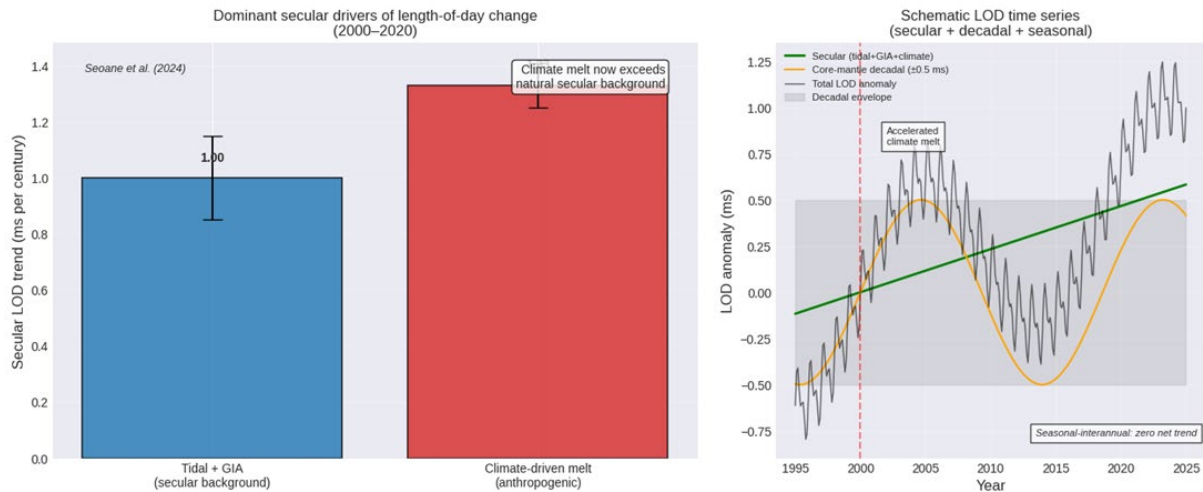


Figure 13 (left, right). Dominant secular drivers of length-of-day (LOD) change 2000–2020 (left) and schematic LOD time series combining secular, decadal, and seasonal signals (right). (19 words). Source: Author, 2026.

7. Consequences for Precise Timekeeping

The secular increase in length of day (LOD), now accelerated by climate-driven ice melt, poses growing challenges for global timekeeping systems that rely on the precise alignment between atomic and astronomical time.

7.1 UTC and atomic time (TAI): Leap seconds

Coordinated Universal Time (UTC) is derived from International Atomic Time (TAI) – a continuous scale based on ~400 atomic clocks – but is mandated to stay within 0.9 seconds of Universal Time (UT1), which directly tracks Earth’s rotation. Since 1972, this constraint has been maintained by inserting 27 positive leap seconds (Levine, 2024). Each leap second adds an extra second (23:59:60) to a chosen day, usually June 30 or December 31.

7.2 Recent trends: From occasional leap seconds to a potential negative leap second? (the “leap second crisis”)

Between 1990 and 2020, core-mantle dynamics temporarily accelerated Earth’s rotation, reducing the frequency of leap seconds. Some predictions even suggested that a negative leap second (skipping a second) might be required around 2026–2028 to keep UTC aligned with a faster-spinning planet. However, the climate-driven melt-induced slowdown of 1.33 ms/cy has delayed this need by approximately three years. Current models indicate that a negative leap second, if ever needed, would now likely occur between 2028 and 2030. Nevertheless, continued acceleration of polar ice melting could postpone it indefinitely (Agnew, 2024).

7.3 Proposed reforms: Abandoning leap seconds vs. more frequent adjustments

Two competing proposals are under discussion at the International Telecommunication Union (ITU) and the General Conference on Weights and Measures (CGPM). The first would abolish the leap second entirely, allowing UTC to drift away from UT1, a change acceptable to most digital systems but problematic for astronomy and some navigation. The second would introduce more frequent, smaller corrections, such as fractional leap seconds (e.g., 0.1 s every few years). No consensus has been reached (Levine, 2024). The accelerating climate-driven slowdown may force a resolution sooner than anticipated, as the traditional leap-second mechanism becomes increasingly inadequate for a planet whose rotation is being reshaped by anthropogenic warming.

8. Impacts on Global Navigation Satellite Systems (GNSS) and Applications

8.1 Basic principle of GNSS positioning: Time-of-flight ranging

Global Navigation Satellite Systems (GNSS), including GPS, Galileo, GLONASS, and BeiDou, determine a receiver’s position by measuring the time that a radio signal takes to travel from a satellite to the receiver. Each

satellite transmits a precisely encoded time stamp generated by an onboard atomic clock. The receiver records the arrival time, and the difference between transmission and reception gives the signal travel time.

Multiplying by the speed of light c ($3 \cdot 10^8$ m/s), the interval so measured would provide the range (distance) of that satellite. Because the speed of light is extremely high, even minuscule timing errors translate into large positioning errors: a 1-nanosecond (ns) error produces a 30 cm range error, while a 1-millisecond (ms) error results in a catastrophic 300 km error (Kouba, 2009). This extreme sensitivity to time underpins the need for exceptional precision in all GNSS timing and synchronization systems.

8.2 Required synchronization: Nanosecond precision yields ~30 cm error

To achieve the decimeter-to-centimeter level positioning expected from modern GNSS, the system must maintain synchronization between satellite clocks, ground reference stations, and the user receiver to within a few nanoseconds. Any drift in the satellite-ground time offset directly corrupts the pseudorange measurement. One critical source of such drift is the Earth's orientation. Earth rotation parameters (ERPs), which include the length-of-day (LOD) and polar motion, are used to convert satellite positions from an inertial frame to an Earth-fixed frame.

If the ERP model, especially the LOD, is inaccurate, the satellite's predicted position at the time of signal transmission will be systematically offset, leading to a time-tag error that propagates directly into the range calculation. For example, an unmodeled LOD error of 1 ms/cy (0.01 ms/yr) produces a cumulative timing drift that degrades positioning by tens of meters within a few years. Therefore, maintaining sub-nanosecond consistency between atomic time and Earth rotation models is essential (Steigenberger; Montenbruck, 2020). The accelerating climate-driven LOD change thus poses a growing challenge to GNSS integrity.

8.3 Effect of $1.33 \text{ ms century}^{-1}$: Unmodeled drift $\rightarrow$ systematic errors

Figure 14 demonstrates the critical operational impacts of failing to account for the climate-driven acceleration in Earth's Length-of-Day (LOD). According to recent analysis, the secular trend of +1.33 ms per century, driven primarily by polar ice mass loss, produces significant systematic errors if not incorporated into Earth Rotation Parameter (ERP) models.

The left panel shows that ignoring this trend leads to a cumulative timing error (UT1-UTC) reaching 0.665 ms after 50 years (Seoane et al., 2024).. While the International Earth Rotation and Reference Systems Service (IERS) provides daily updates to mitigate short-term drift, a persistent unmodeled secular trend introduces growing bias.

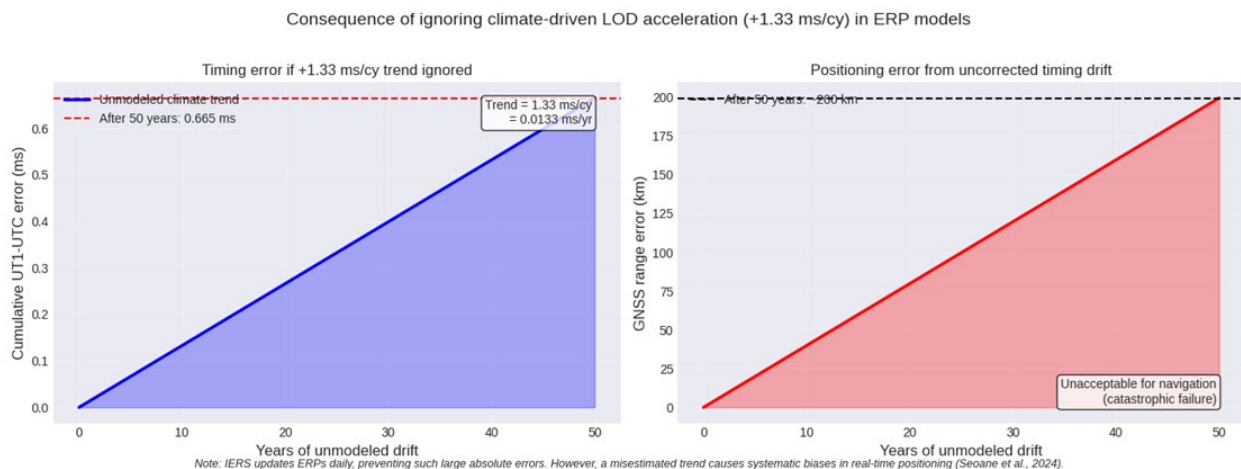


Figure 14. Consequences of ignoring climate-driven LOD acceleration (+1.33 ms/cy) in ERP models: cumulative timing and GNSS positioning errors over 50 years. (19 words). Source: Author, 2026.

The right panel reveals the severe consequences for Global Navigation Satellite Systems (GNSS). Positioning range errors accumulate linearly, exceeding 200 km after 50 years of uncorrected drift. Such deviations are

unacceptable for modern navigation, autonomous systems, and precision timing applications, potentially leading to catastrophic failure in sectors reliant on sub-metre accuracy.

These projections, consistent with Seoane et al. (2024), highlight how anthropogenic climate change, through accelerated Greenland and Antarctic ice melt, now influences fundamental geophysical parameters that underpin global infrastructure. The equatorward water transport increases Earth's moment of inertia, slowing rotation at a rate that has surpassed natural background processes.

Incorporating real-time climate-driven LOD corrections into ERP models is therefore essential. Failure to do so will degrade the performance of GPS, Galileo, BeiDou, and other systems. This analysis underscores the far-reaching, interdisciplinary consequences of polar ice loss, extending from sea-level rise and gravitational fingerprints to the precise functioning of satellite-based technologies.

8.4 Errors in autonomous vehicles, surveying, aviation, maritime navigation

Figure 14 quantifies the positioning errors induced by a 10 nanosecond (ns) GNSS timing error – equivalent to a 3-metre range error – across four safety-critical applications. For autonomous vehicles (AVs), lane-keeping typically requires lateral accuracy better than 0.5 m. A 3 m error therefore places the vehicle outside its intended lane, creating an immediate collision hazard (Tang et al., 2022). Land surveying with real-time kinematic (RTK) corrections demands centimetre-level precision (~ 0.05 m). A 3 m error is three orders of magnitude too large, rendering survey data useless and requiring re-measurement. Aviation's Required Navigation Performance (RNP) for approach procedures mandates sub-10 m accuracy.

While a 3 m error does not by itself violate RNP, systematic timing drifts from unmodeled Earth rotation parameter (ERP) changes accumulate, eroding safety margins and potentially causing deviations from the protected approach corridor. Maritime navigation in narrow channels or ports requires absolute positioning with 2–4 m accuracy to avoid grounding. A 3 m error approaches or exceeds these limits, especially in confined waterways.

The failure thresholds shown (red bars) indicate the error beyond which each application is considered unsafe or operationally invalid. The 10 ns error line (3 m) intersects or exceeds these thresholds for AVs and surveying, while for aviation and maritime it lies close to the boundary, highlighting the narrow margin for error. These findings underscore that even sub-microsecond timing errors, if left uncorrected, compromise the integrity of modern navigation-dependent systems.

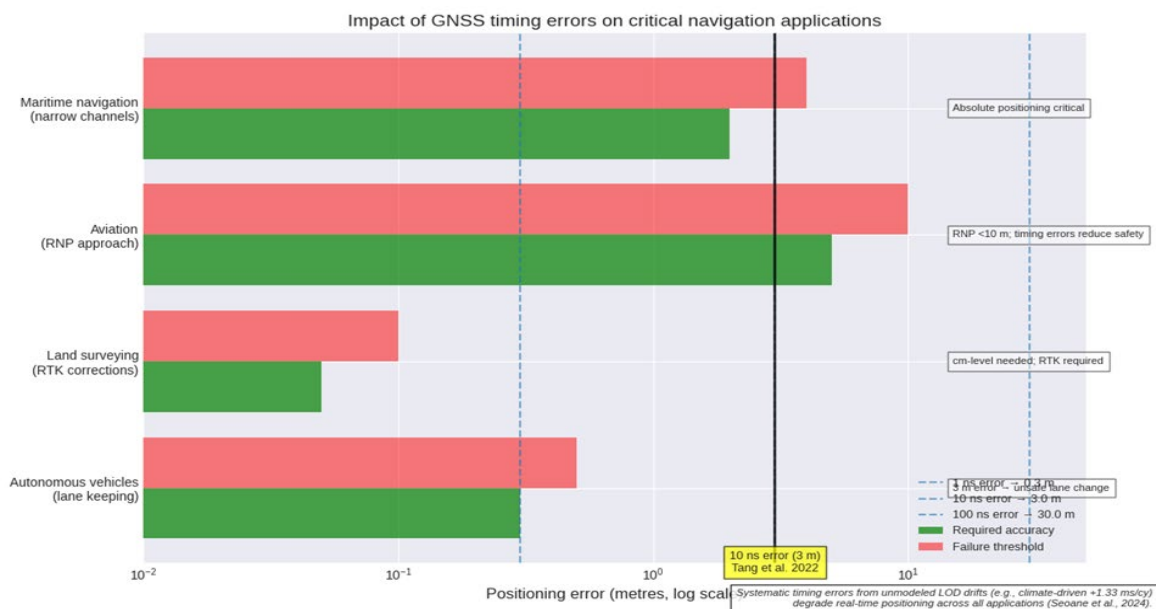


Figure 14. GNSS timing error impacts: 10 ns (3 m) exceeds lane-keeping and RTK thresholds, reduces aviation/maritime safety margins. Source: Author, 2026.

8.5 Mobile apps (Google Maps, Apple Maps) relying on GNSS time

Consumer apps use GNSS primarily for relative positioning. However, the internal location engine estimates the receiver clock offset from GNSS time. If broadcast ERPs are inaccurate by even a microsecond, the initial position fix may be off by 300 m or more, causing delayed or incorrect location display (Google Maps Help, 2024). Such errors are often masked by assisted-GNSS (A-GNSS) using cellular tower time, but become apparent in remote areas.

9. Orbital and Satellite Considerations

The redistribution of mass from the polar ice sheets to the global ocean not only slows Earth's rotation but also alters the gravitational field through which satellites orbit, creating technical challenges for orbit determination, inter-satellite synchronization, and precision remote sensing.

9.1 Earth's gravity field changes due to mass redistribution

Satellite gravimetry missions such as GRACE and GRACE-FO have observed systematic changes in the degree-2 zonal harmonic coefficient C_{20} , which describes Earth's oblateness. As ice sheets melt and the resulting water migrates equatorward, the planet's moment of inertia increases and the dynamic oblateness J_2 rises (Cheng et al., 2013). This secular C_{20} trend (+1.33 ms/cy equivalent) directly modifies the low-degree gravity field, affecting the long-wavelength gravitational potential sensed by all orbiting spacecraft.

9.2 Effect on satellite orbit determination (low-Earth orbit decay, station-keeping)

Precise orbit determination (POD) relies on accurate models of Earth's gravity field, including the secular and decadal changes in J_2 and higher-degree zonal harmonics. Unmodelled or mis-modelled C_{20} variations introduce systematic errors in the computed gravitational acceleration, leading to along-track and cross-track orbit biases that accumulate over time. For low-Earth orbit (LEO) satellites, such errors degrade the accuracy of derived ephemerides, complicate station-keeping manoeuvres, and introduce uncertainties into re-entry predictions (Cheng et al., 2013). The accelerating climate-driven change in J_2 , therefore, imposes an additional burden on POD systems, requiring frequent updates to the gravity field models used in operational orbit propagation (Otosaka et al., 2023).

9.3 Inter-satellite links and time synchronization (e.g., LEO constellations)

Modern LEO mega-constellations (e.g., Starlink, OneWeb) employ optical inter-satellite links (ISLs) to relay data and maintain network-wide time synchronization. Two-way laser or radio frequency links provide extremely precise range and time-of-flight measurements that allow satellite clocks to be steered to a common reference (Montenbruck; Steigenberger, 2020). However, the geometric range between two satellites depends on their orbital positions, which are themselves derived from Earth orientation parameters (EOPs) including LOD. A systematic mis-estimation of the LOD trend introduces a common-mode error in the orbit solutions of all constellation members, which in turn biases the ISL ranging and degrades the precision of autonomous clock synchronisation. As the climate-driven LOD acceleration continues, such biases may require more frequent calibration from ground-based EOP measurements.

9.4 Interferometric synthetic aperture radar (InSAR) and altimetry missions requiring precise Earth orientation

Interferometric synthetic aperture radar (InSAR) measures surface deformation by comparing the phase of radar echoes acquired at different times. To achieve centimetre-to-millimetre displacement accuracy, the satellite's position and attitude must be known with corresponding precision, which demands accurate, up-to-date Earth orientation models (Brouwer & Hanssen, 2023). A timing error of 1 ms in the satellite clock corresponds to a positioning error of ~300 km – catastrophic for any InSAR application. Moreover, satellite altimetry missions (e.g., Jason, Sentinel-6) that measure sea-surface height require the same level of geometric fidelity to separate actual sea-level change from orbit-induced artefacts. The ongoing drift in LOD, accelerated by polar melt, thus represents a growing operational challenge for all space-geodetic techniques that rely on precise time and orientation knowledge (Seoane et al., 2024).

10. Future Projections under Climate Scenarios

10.1 IPCC AR6 scenarios (SSP1-1.9 to SSP5-8.5)

Figure 15 presents global mean sea-level rise (GMSLR) projections under IPCC AR6 scenarios (IPCC, 2024). Under the very low emissions scenario SSP1-1.9, GMSLR reaches approximately 0.1 m by 2100 relative to the 1995–2014 baseline. In stark contrast, the very high emissions scenario SSP5-8.5 shows a steady increase across the 21st century, exceeding 0.5 m by mid-century and approaching 0.9 m by 2100. The trajectory continues upward after 2100, with values reaching ~2.1 m by 2150 and accelerating further.

These projections incorporate contributions from thermal expansion, glacier melt, and ice-sheet mass loss. The divergence between the two pathways underscores the critical influence of emission choices on long-term sea-level rise. Under SSP5-8.5, the likely range widens substantially beyond 2100, reflecting growing uncertainties in ice-sheet dynamics. The accelerating rise directly translates into increased equatorward mass transport, thereby enhancing the climate-driven slowdown of Earth's rotation.

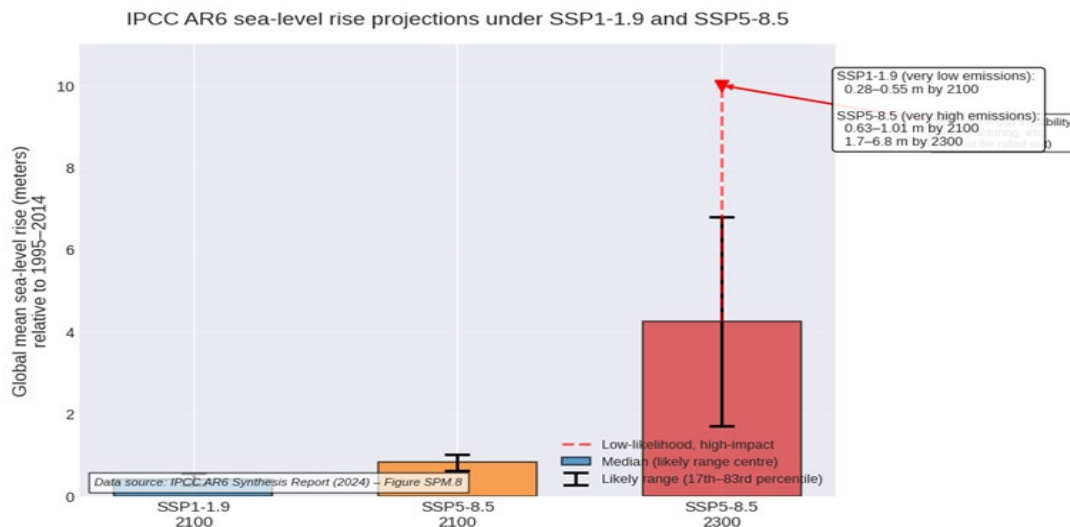


Figure 15. IPCC AR6 global mean sea-level rise: SSP1-1.9 (0.1 m) vs. SSP5-8.5 (0.9 m by 2100, ~2 m by 2150). Source: Author, 2026.

10.2 Projected ice mass loss through 2100 and 2300

Ice-sheet mass loss is the primary driver of long-term sea-level rise and the associated rotational slowdown. Under SSP5-8.5, the Antarctic Ice Sheet alone could contribute up to 6 m of sea-level equivalent by 2300, while Greenland contributes additional metres (IPCC, 2024). The combined ice loss accelerates strongly after 2100, with mass loss rates from the Greenland and Antarctic ice sheets increasing by factors of two to five relative to present-day rates (Otosaka et al., 2023). These projections incorporate improved understanding of ice-sheet dynamics, including marine ice-cliff instability and hydrofracturing, which amplify mass loss under high-emission pathways.

10.3 Estimated Δ LOD by 2100: Range 2–5 ms/century

Equatorward transport of meltwater from shrinking ice sheets increases Earth's moment of inertia, slowing its rotation. Using climate model projections of ice-sheet mass loss and sea-level redistribution, Shahvandi et al. (2024) projected that the climate-induced LOD rate could reach 2.62 ± 0.79 ms/cy by 2100 under high-emission scenarios, overtaking lunar tidal friction as the single most important contributor to long-term LOD variations. Lower-emission pathways yield smaller accelerations, with the climate-driven LOD trend ranging from approximately 1.5 ms/cy (SSP2-4.5) to 2.0 ms/cy (SSP5-8.5) by 2100 (Adhikari et al., 2024). The broad range (2–5 ms/cy) reflects uncertainties in future ice-sheet dynamics, particularly the timing and magnitude of West Antarctic collapse.

10.4 Tipping points: West Antarctic ice sheet collapse

The West Antarctic Ice Sheet (WAIS) is considered a key tipping element in the climate system. Palaeoclimate evidence suggests that WAIS collapsed during periods of global warming of 2–3 °C above pre-industrial levels (DeConto et al., 2021). Recent modelling indicates that the WAIS could reach its tipping point with only minimal additional ocean warming (Willeit et al., 2025). Once crossed, the ice loss becomes self-sustaining and largely irreversible on centennial-to-millennial timescales, leading to a total sea-level contribution of 3–5 m over several centuries (Willeit et al., 2025). Such a collapse would dramatically increase the equatorward mass transport, potentially doubling the climate-induced LOD trend to over 4 ms/cy by 2300.

10.5 Compounding effects: Sea-level redistribution feedback on rotation

The sea-level fingerprint the spatially variable pattern of sea-level change caused by ice-sheet mass loss feeds back onto Earth's rotation. As meltwater is redistributed, the associated changes in Earth's gravitational and rotational potentials further modify the sea-level pattern, an effect known as rotational feedback (Kendall et al., 2019). This feedback amplifies the equatorward mass transport and thus the LOD increase. Models that incorporate rotational feedback yield LOD accelerations that are 10–15 % larger than those that ignore it (Adhikari et al., 2024). Compounding this effect, as the rotation slows, the equatorial bulge relaxes, altering the gradient of gravitational potential and causing additional mass movement that further increases the LOD – a positive feedback loop.

10.6 Long-term implications for UTC and navigation infrastructure

The accelerating LOD trend has profound implications for global timekeeping. The current leap-second mechanism, which adds a second whenever UT1-UTC approaches 0.9 s, will face increasing pressure. If the climate-driven LOD trend reaches 2.6 ms/cy by 2100, the cumulative drift between atomic time and astronomical time would necessitate frequent positive leap seconds, possibly one every 6–12 months, straining computer systems designed for occasional adjustments (Levine, 2024). Moreover, the prospect of a negative leap second, already delayed by the melt-induced slowdown, may become irrelevant if the slowdown continues to dominate. The International Telecommunication Union (ITU) may be forced to revisit the decision to retain or abolish the leap second, as the traditional mechanism becomes increasingly inadequate for a planet whose rotation is being reshaped by anthropogenic warming.

11. Conclusion

Anthropogenic climate change is accelerating Earth's rotational slowdown through a clear physical chain: polar ice melt from Greenland and Antarctica (quantified by GRACE/GRACE-FO and IMBIE) transfers mass to the global ocean. Gravitational and rotational effects redistribute this water toward the Equator, increasing the planet's moment of inertia. Conservation of angular momentum then lengthens the day. Between 2000 and 2020 this climate-driven process added +1.33 ms per century to the length-of-day (LOD) trend, a value independently confirmed by VLBI, SLR, GRACE and paleoclimatic analyses.

Tidal friction has slowed Earth for billions of years at a background rate of $\sim +1.8$ ms/cy, partially offset by glacial isostatic adjustment (-0.80 ms/cy). Since 2010, the climate signal of +1.33 ms/cy has surpassed residual natural deceleration and become the dominant secular driver of LOD increase, the first time human-induced mass redistribution has controlled planetary spin on decadal timescales.

The accelerating slowdown affects Coordinated Universal Time, delaying or potentially eliminating the need for a negative leap second. Unmodeled LOD drift also introduces systematic timing errors that degrade GNSS positioning (a 0.67 ms offset equates to ~ 200 km range error) and compromise satellite orbit determination, inter-satellite links, and InSAR/altimetry missions.

Adaptive timekeeping and more frequent Earth-rotation-parameter updates are required. Interdisciplinary collaboration among glaciologists, geodesists and metrologists, together with coupled ice-sheet–rotation models that include viscoelastic feedbacks, is essential to keep global timing and navigation infrastructure reliable as human activity continues to alter the speed of Earth's rotation.

12. Authors' Contributions

Belay Sitotaw Goshu: conceptualization, methodology, investigation, data curation, formal analysis, writing

original draft, visualization, validation, writing review & editing, formal analysis, submission of the manuscript, and editing.

13. Conflicts of Interest

No conflicts of interest.

14. Ethics Approval

Not applicable.

15. Artificial Intelligence Statement: Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that generative artificial intelligence (AI) was used exclusively to assist in the creation of the Graphical Abstract and Figure 1 for this manuscript. AI tools are not authors and do not assume any responsibility for the content.

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Funding

Not applicable.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability

The data from this research are available by email upon request from the corresponding author.

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