Terrestrial Water Storage in 2023

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Standfirst: Global terrestrial water storage (TWS) anomalies reached a record low of -9.94 cm in 2023, decreasing 0.80 cm from 2022. These reductions largely reflect ongoing TWS losses from glacial melt and groundwater use for irrigation, offset by gains in central and eastern Antarctica and La Niña-related tropical wetting.

Key points:

1. Of the -9.94 cm TWS anomaly in 2023, -10.20 cm is contributed by anthropogenic factors, offset by +0.26 cm from natural factors.
2. La Niña-associated tropical wetting led to multi-year natural gains in global TWS, slowing the rate of TWS loss since 2020.
3. TWS exhibited natural drying trends across northern mid-high latitudes and pockets of strong negative anomalies in southwestern North America and South America.

Terrestrial water storage (TWS) is the sum of soil moisture, groundwater, snow and ice, and surface water. Sustained TWS reductions have been observed, driven by a combination of anthropogenic and natural factors. Anthropogenic factors can be direct (intentional human activities)[], including groundwater consumption or construction of dams) or indirect (global warming), including warming-induced glacial melt or drying up of inland seas), and dominate total TWS losses[1]. However, natural variability in the climate system, including that of precipitation temperature and modes of oceanic signals such as the El Niño-Southern Oscillation are also important, driving fluctuations of TWS around its long-term mean; extreme TWS anomalies, for example, are often accompanied by floods and droughts[2].

Here, we investigate TWS variations in 2023 using Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow On[3-4](GRACE/FO) observations, separating them into anthropogenic (averages over regions dominated by anthropogenic effects [hatches in Fig.1]) and natural (the remainder of the terrestrial surface) contributions. While GRACE/FO cannot determine the total amount of water in storage at a given time, they offer anomalies relative to the long term (2002-2023) mean or changes relative to the previous month. Herein, the seasonal cycle was removed prior to computing annual mean anomalies, and missing values were not filled (with a substantial impact only during the long gap period, July 2017-May 2018).

[H1] Global TWS changes

From 2022 to 2023, global mean TWS anomalies (relative to 2002-2023) decreased from -9.14 cm to -9.94 cm equivalent height of water, representing a further loss of 0.80 cm (**Fig. 1a**). This reduction reflects a continuation of the long-term negative trend observed since GRACE records began (**Fig. 1a**). However, the rate of decreases slowed compared to -1.02 cm yr^{-1} over 2002-2023, reflecting reduced TWS declines in 2020-2023 (**Fig. 1a**).

Consistent with the entire record, anthropogenic-induced changes dominate. Their contributions went from -9.50 cm to -10.20 cm between 2022 and 2023, a reduction of 0.70 cm Anthropogenic changes thus account for ~90% of the total 2022-2023 TWS decline (0.75 cm of 0.80 cm). Long-term annual mean trends are, thus, nearly identical for global total (-1.02 cm yr^{-1}) and global anthropogenic (-1.00 cm yr^{-1}) TWS changes.

However, natural TWS changes were also important. In 2023 they reached +0.26 cm, continuing the positive streak that started in 2020 (albeit 0.10 cm lower than in the 2022 total of 0.36 cm) that is attributable to a triple-dip La Niña[5] (**Fig. 1a**). Given that the anomaly is still positive, these natural changes offset the anthropogenic contributions somewhat. The long-term trend of global natural changes over the GRACE/FO period, is statistically insignificant, reflecting the fact that periodical gains and losses associated with climate variability tend to cancel out worldwide and in the long run.

[H1] Regional TWS changes

While the global mean TWS anomaly for 2023 was negative, regional anomalies exhibited a far more complicated pattern of change (**Fig. 1b**).

[H2] North America

Negative TWS anomalies encompassed much of North America in 2023 (**Fig. 1b**). In particular, severe droughts were observed over western and central Canada owing to low snowfall (especially in southern British Columbia), causing TWS anomalies exceeding -20 cm relative to 2002-2023. Negative TWS anomalies of a similar magnitude were also apparent throughout much of Mexico, where 75% of the country was in drought by September 2023-- the worst drought in a decade. Severe droughts also persisted for months in the US southern Great Plains, notably in Texas and Oklahoma where TWS anomalies lower than -30 cm were observed. More extreme TWS losses occurred in the Canadian Archipelagoes and Gulf of Alaska, where anomalies up to -600 cm reflect ongoing accelerated melt of glaciers and perennial ice.

While negative anomalies dominate, pockets of increased TWS were also apparent. In association with above average precipitation, positive TWS anomalies of 5-10 cm were observed across the Atlantic coast, the Great Lakes region, and parts of western and northern Canada and Alaska (**Fig. 1b**). In the groundwater-depleted California Central Valley, record precipitation and associated flooding during the winter/spring season also raised TWS anomalies substantially to ~5 cm.

[H2] South America

Annual TWS anomalies across South America largely reflect the typical La Niña-induced rainfall pattern--a dipole of anomalies between the north-east and south-west. Positive TWS anomalies exceeding 5 cm occurred throughout northeastern Brazil and French Guiana. In contrast, anomalies below -15 cm were observed in Uruguay, southwestern Argentina and the central Amazon. As such, water levels in some Amazon rivers reached their lowest levels in over 100 years[6] and Uruguay experienced the driest summer in 42 years.

[H2] Europe

Below average TWS emerged across much of Europe in 2023. This continental-scale picture arises from widespread drought, repeated heatwaves and low snowfall, representative of 2023 being the second-warmest year for Europe. In the Alps, TWS anomalies exceeding -20 cm emerged because of severe snow drought and rapid heat wave-induced snow and glacier melt[7]. In Moldova, TWS anomalies reached -20 cm after continued droughts and heat waves since 2021. Against this overarching water loss are positive TWS anomalies from Scandinavia to the northwestern Caspian Sea (**Fig. 1b**). Here, heavy rainfall—including from the low-pressure system, Hans—brought relief to dry conditions including long-term droughts. .

[H2] Asia and the Middle East

2023 TWS anomalies across Asia were very mixed (**Fig. 1b**). Much of the region encompasses negative anomalies, consistent with above average temperatures, heatwaves and drought. For instance, anomalies of -20 cm were observed in central and northern Russia, as well as similar magnitude pockets in northeastern Afghanistan, northeastern India and the Middle East. Indeed, extreme droughts lowered major reservoir levels in Turkey and Afghanistan suffered the worst drought in 30 years. Ongoing TWS declines are also evident in more anthropogenically-dominated regions. Anomalies reaching below -30 cm are apparent in northern India, northwestern China and large areas surrounding the Caspian Sea (**Fig. 1b**). A noticeable exception is the North China Plain where a reduced TWS deficit was observed in 2023 (anomalies of -2 cm) owing to the north-south water diversion project and increases in precipitation since 2016 (ref [8]).

Yet, regions of intense positive TWS were present. Anomalies that exceed 15 cm were observed in southern India, southwestern China and the Angara River of Russia (northwest of Lake Baikal), each associated with intense precipitation and flooding. Positive TWS anomalies of ~ 5 cm are also evident along the coastal area from the Korean Peninsula to Russian Far East, reflecting the impact of Typhoon Khanun.

[H2] Africa

TWS anomalies in Africa were dominantly positive in 2023, continuing the intense wet regime that started in 2019 across a large swath of sub-Saharan Africa[2]. Anomalies exceeding 30 cm in some cases spread across most of sub-Saharan Africa, highlighting heavy rainfall and flooding. These wet conditions reflect various processes: the presence of La Niña and El Niño, causing wetter conditions in the Sahel and southern Africa, and the Horn of Africa, respectively; the shift to a positive Indian Ocean Dipole that causes wetter conditions in eastern Africa; and anthropogenically-exacerbated rainfall across many Intertropical Convergence Zone regions. Some pockets of enhanced TWS also occur in the north, namely at Lake Nassar in southern Egypt where anomalies reached 30 cm, reflecting elevated water levels filled by substantial rainfall in Sudan since 2020.

In contrast, moderate negative TWS anomalies generally dominate the north, particularly in the Sahara Desert. However, much stronger anomalies reaching -30 cm occurred elsewhere, including northern Algeria and Tunisia, reflecting persistent droughts and heat waves since 2022.

[H2] Australia

The most notable TWS anomalies in Australia were the wet conditions that dominated northern and southeastern regions. In these locations, TWS anomalies reached 15 cm, reflecting wetter precipitation patterns associated with La Niña. In the Northern Territory, for example, days of downpours from a tropical low in early March caused rivers to overflow. In other parts of the country, TWS anomalies were negligible or slightly negative..

[H2] Greenland and Antarctica

Generally, strong TWS losses characterize the polar regions. TWS anomalies as low as -1,000 cm occurred across coastal Greenland and western Antarctica, consistent with ongoing ice loss. However, positive anomalies were observed in other areas, namely central and eastern Antarctica, given precipitation increases abetted by a warmer atmosphere. Indeed, while Antarctica has lost nearly 150 GT of ice per year on average since 2002, gains in central and eastern Antarctica have outpaced losses in western Antarctica since 2021.

[H1] Summary

Global TWS decreased by 0.80 cm from 2022 to 2023. Of these losses, 90% can be attributed to direct and indirect anthropogenic effects (ice sheet and glacier ablation, and groundwater withdrawals for irrigation), with natural climate variability having a relatively minor role. Total losses during 2023 were slightly below the long-term trend (-1.02 cm yr^{-1}), mainly because of TWS gains in the tropics and central and eastern Antarctica. This deceleration in total TWS loss is unlikely to persist given emerging signs of ice shelf destabilization in eastern Antarctica[9]. Accelerated water fluxes in a warmer climate demand enhanced tracking of all forms of TWS in order to mitigate the impacts of water resources depletion and hydrological extremes[2,10].

References

1. Rodell et al. . 2018. Emerging trends in global freshwater availability. *Nature* **557 (7707)**: 651-659 [10.1038/s41586-018-0123-1]
2. Li, B., and Rodell, M. 2023. How have hydrological extremes changed over the past 20 years? *Journal of Climate,* **36**(24): 8581-8599 [10.1175/jcli-d-23-0199.1].
3. Landerer et al, 2020. Extending the global mass change data record: GRACE Follow‐On instrument and science data performance. *Geophysical Research Letters*, **47**(12), [10.1029/2020GL088306].
4. Save, H., Bettadpur, S. & Tapley, B. D. (2016). High resolution CSR GRACE RL05 mascons. *J. Geophys. Res. Solid Earth*, 121, 7547–7569, doi: 10.1002/2016JB013007.
5. Rodell, M., and Wiese, D. 2023. Groundwater and terrestrial water storage [in "State of the Climate in 2022"] *Bulletin of the American Meteorological Society* 104 (9): S63-S64, doi:10.1175/BAMS-D-23-0090.1.
6. NOAA National Centers for Environmental Information (NCEI), 2023b, Global Drought Narrative for October 2023, published online November 2023, retrieved on December 17, 2023 from https://www.ncei.noaa.gov/access/monitoring/monthly-report/global-drought/202310.
7. NOAA National Centers for Environmental Information (NCEI), 2023a, Global Drought Narrative for February 2023, published online March 2023, retrieved on February 5, 2024, from https://www.ncei.noaa.gov/access/monitoring/monthly-report/global-drought/202302.
8. Long et al. South-to-North Water Diversion stabilizing Beijing's groundwater levels. *Nat Commun,* **11**, 3665 (2020). https://doi.org/10.1038/s41467-020-17428-6.
9. NASA Earth Observatory, accessed Feb. 16, 2024, https://earthobservatory.nasa.gov/images/149640/ice-shelf-collapse-in-east-antarctica.
10. Li et al. 2019. Global GRACE data assimilation for groundwater and drought monitoring: Advances and challenges. *Water Resour. Res.* **55,** 7564-7586 [10.1029/2018wr024618].

Acknowledgements

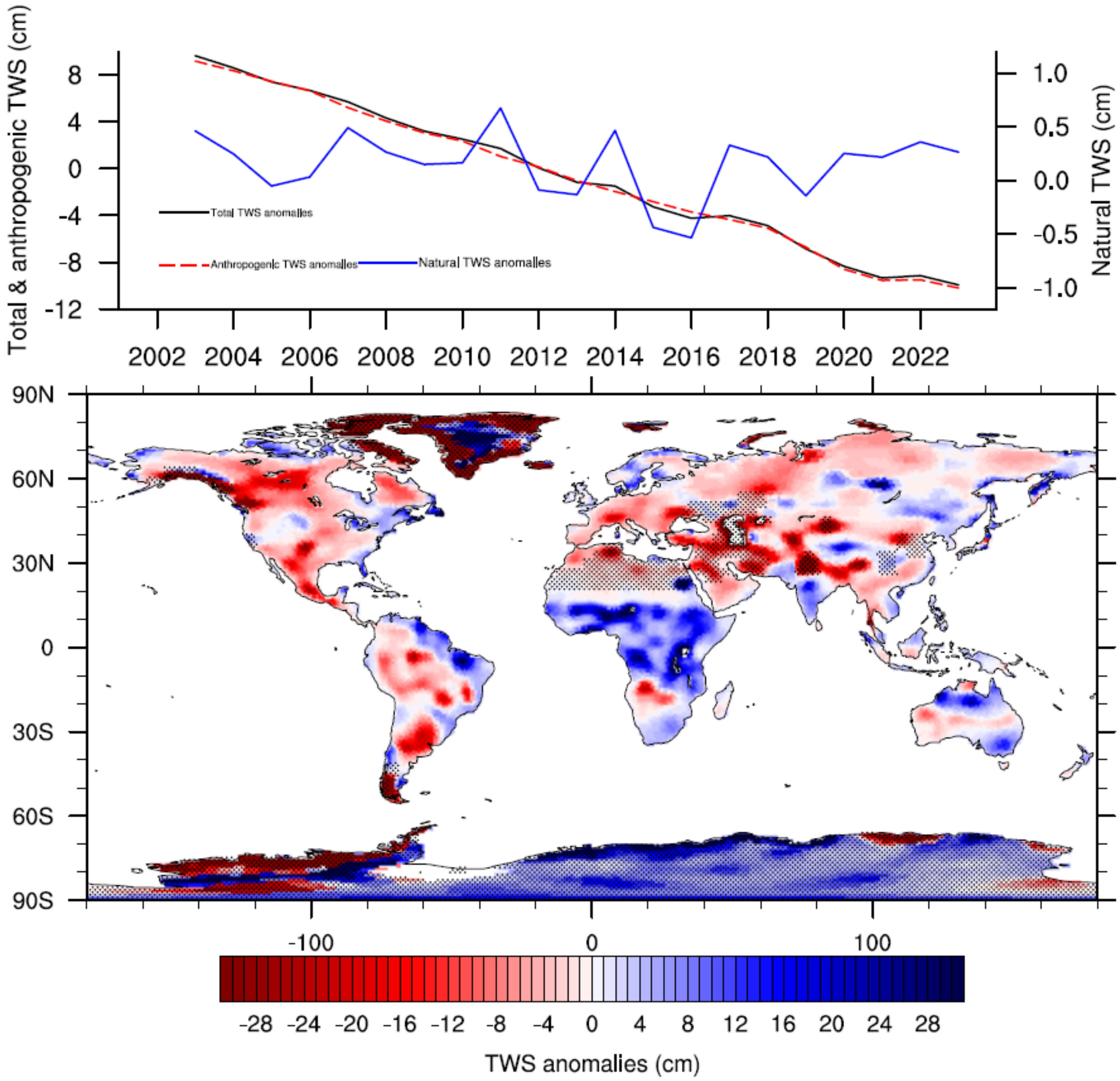
The authors were supported by the NASA GRACE-FO Science Team and the NASA Western Water Application Office.

Publisher's note

Data availability

The GRACE/FO TWS data, developed by the Center for Space Research (CSR) at the University of Texas, Austin[5], can be downloaded at the GRACE Tellus website (https://www2.csr.utexas.edu/grace/RL06_mascons.html).

Figure 1. Terrestrial water storage anomalies. **a**| Time series of annual mean GRACE/FO[5] total TWS anomalies (black), and their natural- (blue) and anthropogenic (red) components. **B**| Map of annual mean GRACE/FO TWS anomalies for 2023. Hatching indicates regions where sustained TWS declines are linked to ice sheet and glacier losses (Antarctica, Greenland, the Canadian Archipelago, the Gulf coast of Alaska and Patagonia), human-induced groundwater depletion (the Middle East, the Sahara Desert, northwestern China, the North China Plain, northern India and California's Central Valley) and water impoundment (the Three Gorges dam in China) after ref[1]. TWS losses associated with ice melt and groundwater depletion drive global total TWS decreases, while natural changes are modulated by climate variability.


Total & anthropogenic TWS (cm)
Natural TWS (cm)
Total TWS anomalies
Anthropogenic TWS anomalies
Natural TWS anomalies
TWS anomalies (cm)