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Short Communication

Natural lakes dominate global water storage variability

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Although land surface water only covers a small portion (∼3.7 %) of our planet, it plays many essential roles: e.g., freshwater storage, industrial consumption, agricultural irrigation, and biodiversity maintenance [1,2]. Water storage variability is associated with various natural processes and human activities on the Earth [3,4] and it is well known that reservoir regulation is the most widely distributed and fundamental human activity capable of altering the global water cycle. In recent years, through reservoir regulation, humans have been able to obtain more freshwater from the Earth's surface, with great benefits to human wellbeing. Currently, however, the extent to which human activities affect the global water cycle remains unknown. As a result, there is an urgent need to quantify and understand the role of human activities in the global water cycle to ensure that freshwater resources are managed sustainably at the global scale.

Traditional *in situ* measurement can only record water storage variability for a very limited number of lakes and reservoirs at a local scale, and fails to provide water storage information in many remote and sparsely populated areas without gauging stations. Fortunately, satellite remote sensing offers repeatable observation of the earth at the global scale, and has a great potential to track global surface water storage dynamics. In particular, the Advanced Topographic Laser Altimeter System (ATLAS), carried on the Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2), is able to accurately measure the water levels of lakes and reservoirs. It has a high vertical accuracy of about a few tens of centimeters, which has been widely validated against in-situ measurements in many previous studies [5,6]. Moreover, the small footprint of ICESat-2 (i.e., with a diameter <17 m) gives it a unique advantage over other satellite sensors of being able to monitor the water levels of small water bodies.

Since the launch of ICESat-2, its products have been widely used to track water body storage variability from local to global scales [7,8]. In one recent study, which used the ICESat-2 data from October 2018 to July 2020, Cooley et al. [9] reported the water storage variability of global lakes (including natural lakes and human-managed reservoirs) to be 2048 km^3, with 61% of this variability occurring in human-managed reservoirs. Globally, south of 45°N, reservoirs make up 67% of surface water storage variability (arid and semi-arid regions heavily influence this figure), an indication of intensive water resource management in these regions [9]. Cooley et al. [9] highlight the dominant role of human-managed reservoirs in altering global lake water storage variability. They binarized the Global Surface Water Occurrence (GWSO) product by counting only pixels with >75% water occurrence to derive a global water body mask. This mask hides many natural lakes and reservoirs which are covered by surface water during the ICESat-2 period but have water occurrence <25% during the Landsat period (1984–present). Cooley et al. [9] further discarded water bodies without ICESat-2 observations during the period 14 October 2018 to 16 July 2020 to obtain their global lake product, thus losing many natural lakes and reservoirs. As a result, a large number of lakes across the globe were not considered, undoubtedly affecting their estimate of global lake water storage variability, which is associated with the area and number of global lakes. Specifically, Cooley et al. included only 227,386 lakes across the globe in their study, and further identified 8964 reservoirs based on GRanD (Global Reservoir and Dam) and GOODD (GlObal geOreferenced Database of Dams).

We compared the dataset by Cooley et al. with GLAKES (Pi et al.) [10], the most comprehensive lake dataset, which is derived from

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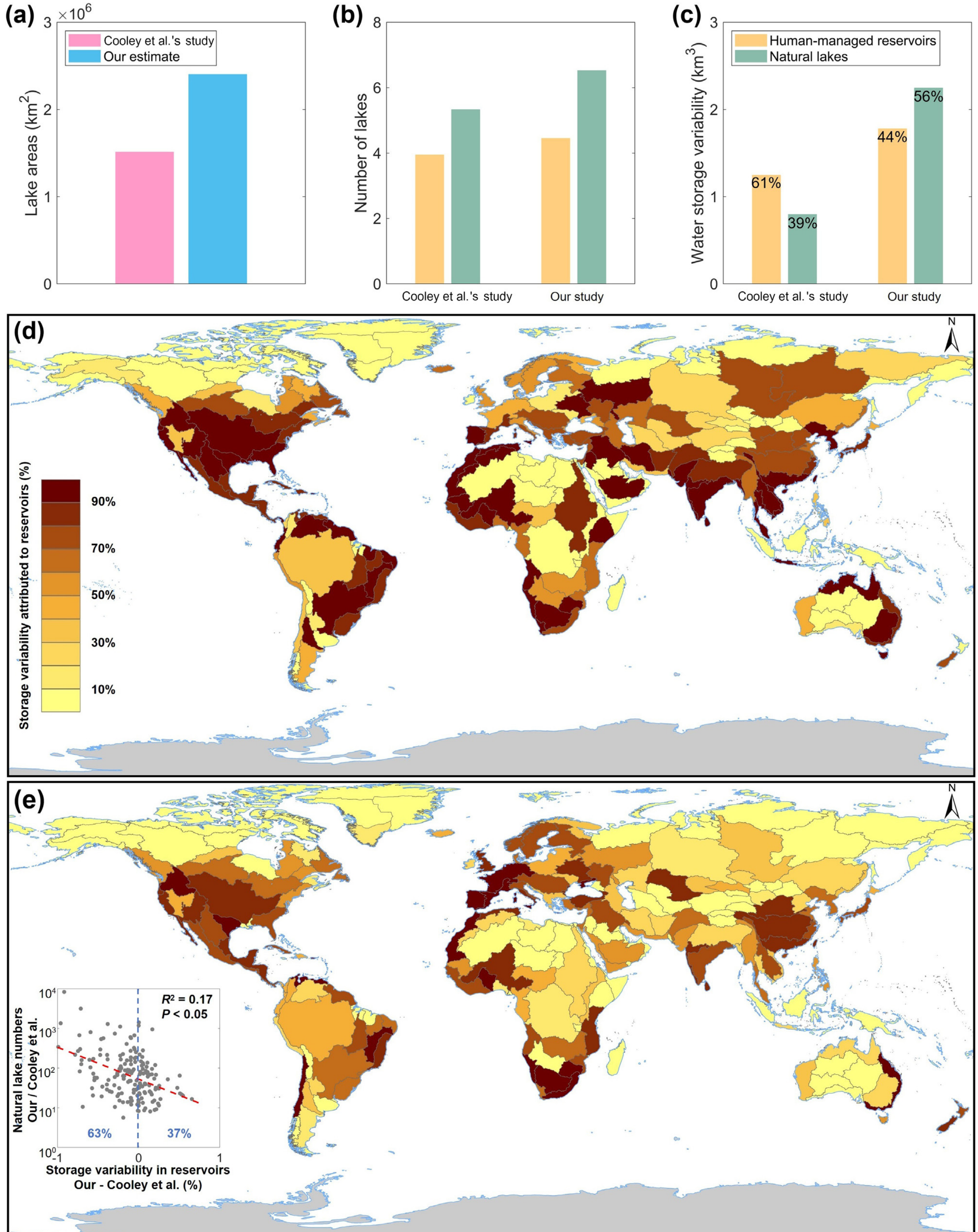

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Fig. 1. Comparison of our estimate of water storage variability with that from Cooley et al. [9]. (a) Lake area. (b, c) Number and water storage variability in human-managed reservoirs and natural lakes. Both panels share the same legend. (d, e) Proportion of seasonal surface water storage variability associated with reservoirs at the basin scale derived from the estimate of Cooley et al. (d) and our estimate (e), which share the same legend. In (d) and (e), darker colours represent a greater influence of reservoirs on surface water storage, while lighter colours represent less influence. In (e), the inset shows the relationship between the percentage difference of reservoir storage variability derived in our study and that from Cooley et al. and the ratio of natural lake numbers in our study to that from Cooley et al.

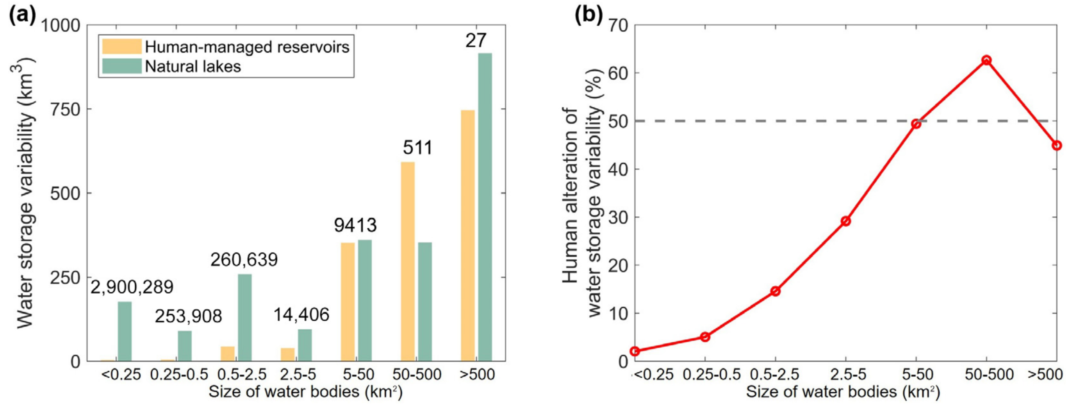

Fig. 2. Variation of the estimate of water storage variability with the water body size. (a) Water storage variability in human-managed reservoirs and natural lakes of various sizes. (b) How the human alteration of water storage variability varies for different sizes of water bodies. In both (a) and (b), the size of the water bodies is given in km^2.

the 30 m spatial-resolution GSWO dataset by using a deep learning classification algorithm. The GLAKES dataset makes it possible to detect lakes as small as 0.03 km^2 (corresponding to ~33 Landsat image pixels) and, hence, can greatly improve the minimum mapping unit and mitigate issues of mis-accounted small lakes in previous publicly-accessible lake datasets. Although, Pi et al. [10] also adopted the GSWO dataset, the global lake product they used was more complete than that used by Cooley et al. [9] for three reasons. First, they used GSWO data, containing all potential lakes, for the period 1984–2019. Second, they used a well-trained U-Net model, which is significantly better at detecting lakes than a thresholding method. Third, all the lakes, with or without ICESat-2 observations, are in their global lake product. Additionally, Pi et al. [10] used the more complete Georeferenced Global Dam And Reservoir Database (GeoDAR) to distinguish reservoirs from natural lakes. In our study, based on the water bodies from Cooley et al. [9], we obtained additional human-managed reservoirs and natural lakes from GLAKES, and merged the two data sources in our analysis. We find that, globally, the number of derived lakes in Cooley et al. [9] (227386) is significantly lower than the number in GLAKES (3426389).

Here, we used five steps to derive the water storage variability of global lakes. Firstly, it must be realized that ICESat-2 is unlikely to capture the true maximum or minimum water levels of any particular lake, because most lakes are not observed every month. It is therefore necessary to correct the observed ICESat-2 water level variability values (i.e., the maximum minus minimum lake water levels). By comparing with USGS/G-REALM data, we binned the percentage values of water level variability observed by ICESat-2 by lake areas (<1 km^2, 1–2.5 km^2, 2.5–5 km^2, 5–50 km^2, 50–500 km^2, >500 km^2). For each lake-area interval, we extracted the ICESat-2 water level variability from Cooley et al. [9] and applied the corresponding percentage to make the correction. Secondly, we obtained the area for the lakes in Cooley et al. [9], and combined the data from GLAKES with the dataset developed by Cooley et al. [9]. This combined dataset contains 28,868 human-managed reservoirs and 3,412,779 natural lakes. Thirdly, following Luo et al. [11], we calculated the area-weighted average water level variability for human-managed reservoirs and natural lakes for each of the seven lake-area groups in Cooley et al. [9]. Finally, we obtained the water storage variability in human-managed reservoirs and natural lakes across the globe by multiplying the water level variability by the lake area. The ratio of the water storage variability in human-managed reservoirs to the water storage variability in global lakes then gives us an estimate of the human alteration effect on the global water storage variability. We derived the uncertainties in the estimate following the method of Cooley et al. [9] and further compared our estimate of water storage variability with that from Cooley et al. [9].

According to our calculations, both the area of the derived lakes (Fig. 1a) and the number of lakes (Fig. 1b) is significantly higher than the values given in Cooley et al. [9]. Furthermore, we find that, globally, the lake water storage variability from October 2018 to July 2020 is 4032 (3685–4635) km^3, with human-managed reservoirs making a relatively low contribution (44%: 1782 km^3) compared with the contribution from natural lakes (56%: 2250 km^3). Specifically, for the 227,386 lakes (average area: 6.66 km^2) in Cooley et al. [9] and the supplemental 3,214,261 lakes (average area: 0.28 km^2) provided by GLAKES, 61% and 16% of the lake water storage variability occurs in human-managed reservoirs, respectively. For the total global lakes (average area: 0.70 km^2), the contribution from human-managed reservoirs is 44% (39%–50%). This result is not consistent with the finding in Cooley et al. [9] that the Earth's water storage variability is 2048 km^3 and the contribution of human-managed reservoirs is 61% (Fig. 1c). We also present a comparison of the proportions of seasonal surface water storage variability associated with reservoirs at the basin scale derived from our estimate (Fig. 1d) and those from Cooley et al. [9] (Fig. 1e). From the inset in the figure, it is clearly apparent that most basins (63%) exhibit an overestimation in the proportion of water storage variability associated with reservoirs, especially those with numerous small natural lakes, such as North America, South America, and northern Asia. Additionally, Fig. 2a shows the water storage variability in the differently sized human-managed reservoirs and natural lakes, and Fig. 2b implies that human alteration of water storage variability varies for different sizes of water bodies. Fig. 2b illustrates a general increasing trend between the human alteration of water storage variability and water body size, which highlights the fact that small lakes play a non-negligible role in reducing the human alteration of water storage variability.

In this study, we re-evaluated the human alteration of global water storage variability, and conclude that natural lakes play a dominant role in altering global water storage variability, despite extensive worldwide reservoir regulation operations involving damming. Furthermore, our results suggest that the study of Cooley et al. [9] largely underestimates the water storage variability in global lakes from October 2018 to July 2020, while overestimating the contribution of human-managed reservoirs to water storage variability in lakes across the globe. It should be noted that GLAKES may still omit some small lakes (especially natural lakes), meaning that the ratio of the global reservoir water storage variability to the global lake water storage variability may actually be smaller than our estimate (i.e., 44%). Additionally, Cooley et al. [9] considered that the water storage variability of human-managed reservoirs is the result of human alteration, however, in reality this variability is controlled by both human activities and natural processes (e.g., precipitation, evaporation, discharge, or infiltration). The human influence on water storage variability should be defined as the increment in water storage variability caused by human activities, rather than simply the water storage variability in human-managed reservoirs. However, it is difficult to disentangle the contribution of human activities to global lake water storage variability by using satellite observations alone. Note that our study still has two limitations: one is that some small lakes are still not included, and the second is that water storage variability in human-managed reservoirs can be induced by various natural processes as well as human activities. In the future, it is urgently required to combine satellite observations, hydrological models [12], and *in situ* gauge data to separate the contributions of human activities and natural forces, in order to better understand the human impact on global surface water storage variability, evaluate its ecological-environmental impacts [13,14] and guide reservoir management strategies [15].

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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