

Global change exacerbates water cycle imbalances and intensifies water resource crises

QiuHong TANG^{1,3*} & Deliang CHEN²

¹ Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

² Department of Earth System Science, Tsinghua University, Beijing 100084, China

³ University of Chinese Academy of Sciences, Beijing 100094, China

Received April 7, 2025; revised July 26, 2025; accepted August 13, 2025; published online August 19, 2025

Citation: Tang Q, Chen D. 2025. Global change exacerbates water cycle imbalances and intensifies water resource crises. *Science China Earth Sciences*, 68(9): 3077–3080, <https://doi.org/10.1007/s11430-025-1661-5>

1. Introduction

Global change is transforming the water cycle at an unprecedented pace, pushing it beyond historical norms and threatening water security. The water cycle, which links the atmosphere, land, and oceans, depends on a delicate balance between precipitation, evaporation, runoff, and groundwater recharge. However, this balance is being disrupted. Rather than varying within the historical range to which human societies have adapted, the cycle is shifting into a new state of instability.

These imbalances are reshaping the spatial and temporal distribution of water, increasing the frequency and severity of extreme events, degrading ecosystem services, and generating widespread socio-economic impacts. What once were local or regional issues are now becoming global challenges. On one hand, extreme hydrological events can directly damage infrastructure and disrupt economic activity. On the other hand, long-term crises like cryospheric melting and groundwater overuse lead to cascading risks. Such imbalances not only disrupt natural hydrological processes but also embed water-related risks—including scarcity and disasters—within social and economic systems, complicating global water governance. Understanding the mechanisms driving water cycle imbalances and developing adaptive re-

sponses has therefore become a critical priority.

2. Global water cycle imbalances are becoming more pronounced

The global water cycle now shows dual imbalances—both in its dynamic fluxes and its structural components. In terms of flux, climate warming has intensified the global water cycle, increasing atmospheric moisture and amplifying precipitation extremes. Wet seasons have become wetter, and intense rainfall events are becoming more frequent. Observations confirm that global precipitation patterns have shifted. Evapotranspiration has also changed in response to precipitation variability and rising temperatures, altering soil moisture distribution globally.

Extreme precipitation has increased in many regions, along with more frequent hydroclimate “whiplash” events—abrupt transitions between very dry and very wet conditions. Since the mid-20th century, sub-seasonal and interannual whiplash events have increased by 31%–66% and 8%–31%, respectively (Swain et al., 2025). These changes have led to more frequent storm-induced flooding. At the same time, snowmelt-driven floods have declined due to warming (Zhang et al., 2022). Rapid shifts in evapotranspiration and rainfall deficits caused by climate change have also accelerated the onset of flash droughts, replacing the slower-

* Corresponding author (email: tangqh@igsnrr.ac.cn)

developing droughts in many regions (Yuan et al., 2023).

From a structural perspective, long-term changes in water storage on land and in oceans reflect deeper imbalances. Terrestrial water storage components—such as glaciers, snowpack, soil moisture, groundwater, rivers, and lakes—are being redistributed. Between 2000 and 2023, glaciers lost an average of 273 Gt of mass per year, with retreat rates in the Himalayas now twice as fast as in the 20th century. Some glaciers in Antarctica and Greenland are nearing irreversible tipping points. In the Northern Hemisphere, spring snow water equivalent has been declining since 1981, largely due to anthropogenic warming (Gottlieb and Mankin, 2024).

Lake expansion has occurred in some regions due to increased precipitation and ice melt—for instance, lakes on the Tibetan Plateau have grown by 24% over the past 30 years. Yet, in the Arctic, thawing permafrost has caused land subsidence and drainage, leading to the disappearance of around 35,000 lakes in the past two decades. Groundwater depletion is widespread: over the last 40 years, water levels in major aquifers have dropped rapidly, with 30% showing accelerating declines—especially in arid regions with intensive irrigation (Jasechko et al., 2024). Between 2002 and 2016, global soil moisture storage fell by about 2,623 km³, including a sharp drop of 1,614 km³ from 2000 to 2002 alone—nearly twice the mass loss of the Greenland Ice Sheet in the same period and contributing an additional 4.4 mm to sea-level rise (Seo et al., 2025).

3. Global change is driving water cycle imbalances

Global change has altered the water cycle's energy and mass exchange processes, affecting its fluxes and storage states. These changes are driven by climate change, land use and land cover changes, and direct human water use (Tang, 2020).

Rising greenhouse gas concentrations have intensified radiative forcing, leading to surface warming and shifts in the Earth's energy balance. At the same time, changes in aerosols influence the spatial variability of precipitation trends (Jiang et al., 2023). Under climate change, both the likelihood and severity of extremes—such as heavy rainfall and droughts—have increased. Compound events and abrupt transitions between wet and dry periods are becoming more common. Climate warming enhances cryospheric melt, increases evapotranspiration, and shifts water among different storage reservoirs. Between 1985 and 2018, annual evaporation from 1.42 million lakes and reservoirs was 1500±150 km³, with a 3.12 km³ yr⁻¹ upward trend, largely driven by warming and reduced ice cover (Zhao et al., 2022).

Land use and land cover changes—such as deforestation, agriculture expansion, and urbanization—directly affect

water and energy fluxes. These changes modify runoff and groundwater recharge, while also affecting downwind precipitation by altering atmospheric moisture transport (Cui et al., 2022). Vegetation-climate feedbacks, such as changes in albedo, can influence large-scale circulation patterns. For example, vegetation-driven changes in surface reflectivity may intensify the Northern Hemisphere Hadley cell, contributing to increasing aridification (Miralles et al., 2025). Urban expansion increases impervious surfaces, leading to faster runoff and higher flood peaks. While such changes may increase local water resources, they often reduce water availability and usability. The key issue is not simply more or less water, but its altered spatiotemporal distribution and the growing frequency and scale of extreme events.

Human water use—through irrigation, consumption, reservoir operation, and groundwater extraction—also drives imbalances. Globally, over 3.6 million km² are now irrigated, requiring around 2700±540 km³ of water annually. Irrigation hotspots—such as the US High Plains, the Indus-Ganges basin, and northern China—overlap strongly with regions of groundwater depletion (McDermid et al., 2023). Overuse has caused over half of medium and large lakes to shrink. At the same time, reservoir construction has expanded inland water areas by 22% globally over the past 30 years. In arid regions, water storage changes are now more influenced by climate and human management than by precipitation alone (Zhao et al., 2025).

Water cycle changes also feed back into the climate system, reinforcing imbalances. For example, Arctic sea ice loss has increased open water areas, where evaporation enhances regional water cycling and contributes to high-latitude snowfall extreme (Liu et al., 2024). Soil moisture-atmosphere feedbacks play a key role in the renewable water supply. Research shows that negative soil moisture feedback may reduce dryland surface water losses by about 60%, counteracting part of the expected decline (Zhou et al., 2021).

4. Water cycle imbalances deepen the global water crisis

One major outcome of water cycle imbalance is the increased frequency of extreme events and the faster alternation between droughts and floods. Although floods can bring abundant water in a short time, their sudden onset makes storage and use difficult. Floods also damage infrastructure, degrade water quality through overflow and contamination, and threaten water supply systems. Conversely, during dry periods, reduced rainfall and high temperatures intensify water scarcity. Hydroclimate whiplash events challenge water and food security, public health, and infrastructure. These compound events are often more destructive than

droughts or floods alone (Swain et al., 2025).

Another major outcome is the growing deviation of water fluxes and storage from natural variability, endangering long-term water sustainability. For example, on the northern slopes of China's Tianshan Mountains, a delicate "mountain-oasis-desert" system relies on mountain runoff. But climate-driven glacial retreat and the expansion of irrigated oases have increased water demand beyond what the system can provide. This has led to over-extraction of groundwater, declining river flows, shrinking lakes and wetlands, and reduced ecosystem services (Liu et al., 2024).

These imbalances also increase the risk of transboundary water conflict. In the Tibetan Plateau, hydrological changes affect the water supply for billions in East and South Asia, raising tensions between countries like India and Pakistan (Yao et al., 2022). Meanwhile, coastal areas face twin threats of falling groundwater and rising seas. Saltwater intrusion contaminates aquifers and soils, threatening water security in deltas and small islands (Richardson et al., 2024).

Extreme hydroclimatic events often degrade water quality. While high flows can dilute pollutants, floods introduce large loads of contaminants into water bodies. Droughts reduce flow, decreasing dilution and increasing salinity, algal blooms, and pollutant concentrations (van Vliet et al., 2023). These water quality challenges raise treatment costs and pose growing threats to urban water systems (Sun et al., 2025).

5. Research perspectives on addressing water cycle imbalances

Imbalances in the global water cycle span multiple scales and dimensions, presenting complex and urgent challenges for human society. Addressing these challenges requires deeper insights into the mechanisms of global change hydrology, advances in water science and technology, and the development of integrated systems that strengthen water security through interdisciplinary "One Water Cycle" research. This integrated approach can support the design of systematic solutions for global water governance.

The complexity of water cycle imbalances arises from the interactions and telecouplings among Earth's spheres—atmosphere, biosphere, hydrosphere, cryosphere, and anthroposphere. While research on the water cycle has made significant progress, substantial gaps remain in our understanding of the processes driving these changes and the feedbacks between the water cycle, climate, and socio-economic systems. In particular, the quantification of cross-system couplings remains a major challenge. Future research should address key questions about the drivers and consequences of water cycle imbalances, including: interactions between the terrestrial water cycle and climate change; telecoupling mechanisms in human-water systems; the socio-

economic impacts of water cycle disturbances; and mechanisms to enhance resilience in water security.

Technological advances are offering new capabilities for observing, modeling, and predicting the global water cycle. Tools such as remote sensing, artificial intelligence (AI), large-scale models, digital twins, and the Internet of Things (IoT) are creating new opportunities to understand and respond to water cycle imbalances. Moving forward, priority research directions include:

(1) Expanding big data resources for water science by developing spatiotemporal databases for global water fluxes (e.g., precipitation, evaporation, runoff, and streamflow) and storage components (e.g., lakes, rivers, glaciers, snowpack, soil moisture, and groundwater);

(2) Advancing real-time, high-resolution monitoring of the terrestrial water cycle by integrating AI with numerical models, and improving risk forecasting tools to better predict water cycle imbalances, associated socio-economic exposure, and potential losses;

(3) Developing optimization and scenario-based models for water allocation at transboundary, inter-basin, and cross-regional scales, to assess the multi-dimensional impacts of water cycle disturbances and identify effective strategies for enhancing basin-scale water resilience;

(4) Improving representations of human activities in land surface hydrological models, constructing regional Earth system models tailored to areas with intensive human influence, and building digital twin Earth system platforms where the water cycle forms a core component for research, education, and management.

Socio-economic systems are essential to understanding and addressing water cycle imbalances. Current studies tend to focus on natural hydrological processes, while the flows and transformations of water within human systems—urban centers, irrigated landscapes, and supply chains—receive less attention. Yet these human systems are both drivers and recipients of water cycle changes.

This paper calls for a new research paradigm, inspired by the "One Water" concept—originally developed for integrated management of drinking water, wastewater, and stormwater in urban systems. We propose extending this concept to a broader "One Water Cycle" framework that treats natural and human-influenced water cycles as inseparable components of the global water system. Research under this framework should be interdisciplinary and integrative, addressing water cycle dynamics at global, regional, basin, and urban scales. This approach can help prevent further imbalances, improve water security resilience, and support the sustainable use of water resources in tandem with socio-economic development.

Ultimately, this calls for collaborative, integrated, inclusive, and holistic governance strategies that can restore balance to the global water cycle. Doing so will strengthen

global water governance and offer new pathways for addressing the escalating global water crisis.

Acknowledgements We extend our sincere gratitude to Yin TANG, Guoyong LENG, Si'ao SUN, Gang ZHAO, Xingcai LIU, and Ximeng XU for their valuable contributions to the editing of this manuscript and for their constructive input during discussions. Special thanks go to Yin TANG for her assistance with the initial English translation. This work was supported by the National Natural Science Foundation of China (Grant No. U2243226), the Third Xinjiang Comprehensive Scientific Expedition Project (Grant No. 2021xjkk0800), and the Tsinghua University Project (Grant No. 100008001).

Conflict of interest The authors declare no conflict of interest.

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(Editorial handling: Xiaoyan LI)