Human–Climate Interactions and the Changing Water Cycle

Monitoring and modeling the water cycle using isotope tracers

Subimal Ghosh
subimal@iitb.ac.in

The climate system comprises the coupled dynamics of the atmosphere, hydrosphere, geosphere, and biosphere. These systems interact through the energy, water, and carbon cycles, enabling the Earth to maintain a thermodynamic state far from equilibrium (Kleidon, 2010). Anthropogenic activities—including greenhouse gas emissions, deforestation, and large-scale water abstractions—have drastically altered this balance. As global temperatures rise, these interconnected cycles face systemic disruptions, with the water cycle being especially sensitive to climate perturbations.

Recent assessments from the Inter-Governmental Panel on Climate Change (IPCC AR6) report an unequivocal intensification of the global hydrological cycle. This includes heightened frequency and severity of both droughts and floods due to greater variability in precipitation (IPCC, 2021a). Glaciers in the Himalayas, which supply water to over a billion people across Asia, are melting at accelerated rates, contributing to shifting seasonal flows and downstream water uncertainty (IPCC, 2021b). These changes present direct threats to disaster preparedness, the water-food-energy nexus, and long-term urban resilience strategies. Vulnerable regions in the Global South, particularly South Asia, are disproportionately affected due to high population densities and limited adaptive infrastructure. Moreover, because carbon dioxide has a centennial-scale atmospheric lifetime, adaptation in the water sector becomes crucial for resilience even if mitigation efforts succeed.

The water cycle does not operate in isolation from human activity. Human interventions—such as dam construction, irrigation, inter-basin transfers, and groundwater extraction—have profoundly modified the water cycle, often surpassing the impacts of climatic variability at regional scales (Wada et al., 2014). Yet, this anthropogenic component remains difficult to monitor and even harder to predict. A core challenge in understanding human impacts on the hydrological cycle lies in the spatial and temporal heterogeneity of water usage patterns. Unlike atmospheric processes, human water use is driven by a confluence of economic, cultural, and political factors, which vary from village to village and season to season. Data on irrigation, particularly in countries like India, is sparse, outdated, or politically contested. In India, unmonitored irrigation and groundwater abstraction are especially problematic to understand their impacts on water cycle. According to Jha et al. (2022), human water management activities like irrigation show limited influence on mitigating pre-monsoon heat stress in the Indo-Gangetic Plain, challenging previous literature that irrigation alone buffers climatic extremes in pre-monsoon summer, which is not a major crop season. However, irrigation has impacts on monsoon as found by Devanand et al. (2019), revealing a feedback loop: irrigation practices affect land-atmosphere coupling, thereby distorting regional rainfall patterns.

Controversy persists in literature over the extent of groundwater extraction, particularly due to inconsistencies in satellite-derived versus in-situ measurements. Disagreements also stem from the political sensitivity of declaring groundwater "over-exploited," which has economic ramifications for agricultural subsidies and resource access. Recent studies have attempted to reconcile this gap through high-resolution modeling and remote sensing techniques (Jha et al., 2022; Famiglietti et al., 2011). Literature also emphasizes the limitations of current irrigation datasets.

The findings expose the blind spots in India's irrigation governance, where state-level water usage is either unreported or not correctly estimated. This inadequacy impedes regional modeling efforts and leads to miscalibrated climate adaptation strategies. Moreover, the dynamic nature of human decisions—e.g., switching crops, sudden abstraction during heatwaves, or farmer-led water-sharing—introduces non-stationarity into water demand models. This makes the modeling of water flows as difficult as weather prediction itself. Unlike precipitation or temperature, which follow physical laws, water use decisions are socio-politically governed, making them inherently unpredictable and poorly captured in Earth system models. In sum, the "human component" of the water cycle is both vital and opaque. Without adequate monitoring and modeling of irrigation practices, abstraction trends, and infrastructure impacts, any climate adaptation strategy risks being both incomplete and ineffective, especially in South Asia's rapidly changing hydrosocial landscapes.

Water management practices, though essential for sustaining human society, do not merely respond to climate variability—they actively reshape it. In regions like India, large-scale water diversions, inter-basin transfers, and intensive irrigation systems generate land-atmosphere feedbacks that alter precipitation patterns, soil moisture dynamics, and monsoon variability (Chauhan et al., 2023). This anthropogenic modification of hydroclimatology represents a secondary, human-driven layer of climate forcing. One of the most profound illustrations of this comes from India's proposed river interlinking projects. According to Chauhan et al. (2023), simulations using Earth system models demonstrate that the interlinking of river basins leads to major changes in the spatial structure of Indian Summer Monsoon (ISM) rainfall (in September).

The altered water availability and evapotranspiration patterns from irrigation expansion generate regional imbalances in heat fluxes, suppressing rainfall in some areas while enhancing it in others. Devanand et al. (2019) earlier emphasized that such irrigation-induced modifications in surface energy fluxes influence the intensity of the monsoon in September. Their work shows that irrigation shifts regional soil moisture availability, which acts as a boundary condition for atmospheric circulation. Overall, irrigation introduces large uncertainty into seasonal forecasts, complicating both water planning and agricultural decisions. Joseph et al. (2021) adds another dimension to this understanding by examining how water management interfaces with the water-food-energy nexus.

In some of the water-stressed regions of India, groundwater extraction for irrigation has surged, supported often by subsidized electricity (Joseph et al., 2021). This coupling of energy and water sectors creates feedback loops where excessive water abstraction necessitates more energy input, leading to greater emissions—ironically reinforcing the climate change problem. These findings point to the importance of integrating hydrological feedbacks into infrastructure planning to ensure that short-term adaptation does not undermine long-term resilience. Taken together, these studies underscore the complex, bidirectional relationship between water management and the climate system. Instead of viewing human activity as merely reactive to climate signals, these insights compel us to consider humans as active geomorphic agents whose decisions reshape the climate-water landscape.

The Indian monsoon system is a product of complex feedbacks among oceanic, atmospheric, and terrestrial systems. While global models offer broad projections, regional monsoon dynamics often diverge due to localized land–atmosphere interactions, land use changes, and soil moisture variability. The critical challenge lies in accurately modeling these regional processes, which govern a significant portion of water availability in South Asia. Roxy et al. (2017) have shown that the frequency of extreme rainfall events over Central India has tripled over the past six decades, largely due to intensified moisture flux convergence from the Arabian Sea (Roxy et al., 2017). Their work identifies the weakening of large-scale monsoon circulation coupled with increased mid-tropospheric humidity—both consequences of warming oceans—as primary drivers.

More importantly, the study underscores that regional land surface processes, including precipitation recycling and vegetation feedback, modulate the spatial extent and intensity of monsoon rainfall, a feature not well captured in coarser global models. These findings reflect a shift in the understanding of monsoons—not merely as ocean-driven phenomena but as tightly coupled land-ocean systems. Recent work by Chandel et al. (2024) further expands this understanding by exploring the role of land-to-land water transport within India. The model, based on Lagrangian moisture source tracking, identifies that during monsoon breaks, recycled moisture from the Indo-Gangetic Plains and central Indian forests contributes significantly to rainfall in downwind regions such as Odisha and Telangana. This intra-continental moisture recycling is sensitive to soil moisture anomalies and irrigation intensity, reinforcing the importance of regional land management in shaping rainfall.

Chandel et al.(2020) also examined the uncertainty associated with Himalayan glacier melt and downstream runoff in the context of warming scenarios. His results highlight that poorly constrained subsurface hydrology and sparse glacier monitoring contribute to wide uncertainty bands in runoff projections. Since a significant portion of India's dry season flow comes from snow and ice melt, this gap in data poses a serious challenge to water resource planning in northern India. Together, these studies highlight the importance of integrating regional land-ocean interactions into hydroclimatic models. Failure to do so risks missing critical tipping points in rainfall patterns, particularly in monsoon-dependent regions like South Asia.

Despite significant advances in climate modeling, gaps in hydrological data—especially concerning groundwater abstraction, recharge rates, and regional runoff—continue to hinder water-related climate adaptation. Conventional observational systems fall short in characterizing sub-surface and atmospheric moisture fluxes, particularly in complex terrains like the Himalayas and semi-arid agricultural zones. In this context, water isotope analysis offers a powerful and increasingly indispensable approach for monitoring and modeling the water cycle at multiple scales. Stable water isotopes act as natural tracers within the hydrological cycle. Since isotope ratios in precipitation, runoff, soil water, and groundwater vary with evaporation, altitude, and moisture source, they provide a fingerprint of water's history. This makes isotopes uniquely suited for quantifying partitioning processes such as evapotranspiration vs. percolation, snowmelt vs. rainfall runoff, and natural recharge vs. artificial irrigation (Gat, 1996). A study by Wen et al. (2024) highlights how isotope-enabled modeling can resolve key ambiguities in Asian monsoon hydrology.

Using isotope records in conjunction with general circulation models, they reconstructed moisture pathways and rainfall intensities with high spatial fidelity, capturing previously unresolved dipole responses in South Asia. Their results also reveal how past climate changes manifest in isotope signals, helping to validate projections under future warming. Water isotope studies have also proven vital in glacier-fed systems. Zhao et al. (2025) used isotopic tracing to determine the contribution of snow, glacier, and groundwater sources to river flow in the Tibetan Plateau. Their findings confirmed that groundwater-fed baseflows, long thought to be negligible in alpine systems, are actually critical during dry seasons—particularly when glacial melt alone cannot sustain discharge. These insights call for better integration of isotopic data into river basin management and climate resilience strategies.

In India, such methods can directly address uncertainties around unmonitored irrigation and groundwater dynamics. For example, isotopic mapping can differentiate between canal-fed and groundwater-fed irrigation, offering insights into human water management even in data-scarce regions. This approach is particularly valuable where socio-political constraints limit access to abstraction records. From a modeling perspective, isotope-enabled hydrological models offer a more nuanced understanding of water residence time, flow paths, and recharge-discharge dynamics. When paired with remote sensing (e.g., GRACE satellite mass anomalies) and machine learning, these models can inform early warning systems for floods, droughts, and aquifer depletion. Critically, isotopic data also offer a common calibration metric for integrating disparate hydrological datasets—such as rainfall, river discharge, and groundwater levels—into coherent models. This synthesis is essential for operational climate adaptation, where decisions rely on predictive reliability. In summary, water isotope science bridges critical data gaps in the hydrological cycle. By enabling better monitoring, enhancing model accuracy, and uncovering hidden water pathways, isotopes support robust design of early warning systems and long-term adaptation strategies in South Asia and beyond.

References for this article have been consolidated and are available upon request.

Prof. Subimal Ghosh is currently serving as the Head of the Centre for Climate Studies and Institute Chair Professor in Engineering Sciences and Design in the Department of Civil Engineering, IIT Bombay. His research interests include hydro-climatology, regional climate modelling, understanding of the Indian Monsoon and its variability, mesoscale hydrological modelling, water resources systems, urban climate and simulating land surface feedback to climate. He has around 150 publications in journals, including Nature Climate Change, Nature Communications, Nature Water, Science Advances, Geophysical Research Letters, Water Resources Research, etc. He is the conferred fellow of the American Geophysical Union (AGU) and the recipient of the AGU D L Memorial Medal, European Geosciences Union Humboldt Medal, Shanti Swarup Bhatnagar Prize, Swarnajayanti Fellowship, PRL Award, Dr A P J Abdul Kalam Cray HPC Award, and many more.