The Quest for Independent Evidence of Permanent Shifts in the Global Water Cycle

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This essay explores the long-standing scientific quest across multiple geophysical disciplines to develop long-term monitoring networks, advanced climate and land surface models, and cutting-edge satellite missions. These collective efforts have enabled researchers to tackle a grand scientific challenge—providing conclusive evidence of a permanent shift in the global hydrological regime under the current climate.

Introduction

Science advances by formulating hypotheses and testing them against empirical observations (Popper, 1934). In climate science, this process began over a century ago when Arrhenius (1896) predicted that rising atmospheric carbon dioxide levels would increase global temperatures. A key question that followed was how this warming would impact Earth's hydrological cycle. Despite progress in hydrometeorology and evidence of local or regional hydrological shifts (*1, 2*), conclusive global-scale evidence has remained elusive, largely due to the absence of independent, globally reliable indicators of significant water cycle changes. Addressing this challenge has required decades of astronomical, geophysical, and oceanographic observations—tracking Earth's rotational axis and global mean sea level—alongside advanced climate and hydrological modeling. Seo et al. (*3*) mark a milestone in this scientific effort by integrating independent global geophysical datasets to demonstrate a permanent decline in terrestrial water storage. Their findings represent a major interdisciplinary breakthrough, deepening our understanding of Earth's evolving water cycle and providing robust evidence of an irreversible shift under the current climate.

To fully appreciate how the authors reached their conclusion, it is essential to examine the type of data required and the challenges that were overcome across multiple geophysical disciplines. A key element of the validation approach by Seo et al. has been the century-long monitoring of polar motion (Figure 1), measured with sufficient accuracy to establish a link with simulated soil water storage changes from a reanalysis dataset. This simulated variable, in turn, was cross-validated against terrestrial water storage anomalies obtained from the GRACE mission and global mean sea level observations. This validation would not have been possible without advancements in data assimilation techniques and refinements in Numerical Weather Prediction (NWP) systems, which have been crucial for generating high-resolution global reanalyses of essential climate variables (*4*). Equally important are advancements in global datasets, such as digital elevation models, land cover classifications, and physiographic properties, which are necessary for high-resolution land surface models. The following sections review key details of each of these components.

Understanding Polar Motion and Its Drivers

Understanding Earth's rotational dynamics requires both observational and theoretical advancements. As an irregular, deformable solid, Earth rotates around an axis misaligned with its principal figure axis, causing a wobbling motion known as Polar Motion. Euler (1765) first predicted this phenomenon, while Küstner (1885) provided the first observational evidence of latitude variations. In 1891, Chandler identified a periodic oscillation of Earth's rotational pole—now called the Chandler Wobble (Figure 1)—one of the dominant components of polar motion (*5*). Systematic monitoring of Earth's shifting poles began with the establishment of the International Latitude Service in 1899.

Jeffreys (1916, 1940) proposed meteorological factors as a potential driver of the Chandler Wobble but lacked conclusive evidence due to observational uncertainties of 300 milliarcseconds (mas) (1 mas $\approx$ 3 cm of polar motion). He also recognized Eulerian nutation as another contributing factor (*6*). Since 1900, improvements in observation techniques have exponentially reduced PM uncertainty, reaching less than 1 mas by 2020. In 1991, Kuehne and Wilson (*6*) used global precipitation, evaporation, and runoff datasets to estimate soil moisture changes at 1° spatial resolution and their impact on PM. Their estimates of polar excitation factors explained some low-frequency PM variations, but uncertainties still hindered definitive conclusions.

Eubanks (1993) (*7*) later emphasized the interdisciplinary nature of polar motion, linking it to meteorology, oceanography, geomagnetism, and hydrology, with major implications for climate change research. However, realizing this vision required advances in Earth system modeling and observational precision.

Evolution of Climate and Hydrological Modeling

A major step in addressing these challenges has been the development of Numerical Weather Prediction (NWP) models and data assimilation techniques, enabling high-resolution terrestrial reanalysis (*4*). The foundation for climate modeling dates back to Richardson's (1922) pioneering work on numerical weather forecasting (*8*), while the first operational NWP model was introduced in 1955 by the Joint Numerical Weather Prediction Unit (JNWPU).

The ECMWF Integrated Forecasting System (IFS), the backbone of ERA5 reanalysis used by Seo et al. (*3*) (Figure 1), was developed in 1975 and has undergone continuous improvements. Major milestones include the introduction of 4D-Var data assimilation in 1996 and coupling with an ocean model in 2000, significantly enhancing atmosphere-ocean interactions (*9*). The first atmospheric reanalysis, NCEP/NCAR, was released in 1996 with a 2° spatial resolution, while the first land surface reanalysis to include soil moisture, GLDAS, was introduced in 2004 at 0.25° spatial resolution (*4*). ECMWF's first atmospheric reanalysis, ERA-15 ($\approx 1^\circ$), was launched in 1999, leading to the ERA5 reanalysis (2019) with 0.25° spatial resolution, incorporating the HTESSEL land surface model (*10*).

Reanalysis datasets rely on vast amounts of satellite and in situ observations. ERA5 integrates atmospheric state variables, radiation, cloud properties, precipitation, satellite soil moisture, and ocean/sea ice data (*10*). However, terrestrial reanalyses face significantly longer development times due to the complexity of land surface processes, requiring extensive parameterization, data assimilation, and validation. This challenge is further compounded by the fact that no existing terrestrial reanalysis assimilates streamflow, leaving water balance closure at the basin level unresolved.

Estimating terrestrial water changes requires advances in hydrological and land surface models, which provide boundary conditions for climate and NWP models to solve atmospheric hydrodynamic equations. However, challenges persist, particularly in scaling hydrological processes from soil property data ($\approx 10^2$ m) to terrestrial reanalysis scales ($\approx 10^4$ m). Progress is further limited by sparse observational networks for soil moisture and groundwater, as well as insufficient knowledge of subsoil hydraulic parameters. Recognizing these limitations, Wood et al. (2010) and Bierkens et al. (2016) identified a grand challenge in hydrological modeling: developing scalable, transferable, high-resolution models that accurately represent key terrestrial climate variables, such as soil moisture and runoff, ensuring both global consistency (*11*) and local relevance (*12*).

The Gravity Recovery and Climate Experiment (GRACE) missions (2002–present) (Figure 1) have been a transformative tool in geophysical research, providing the first-ever global integrative estimate of total water storage changes on Earth's surface. By tracking gravity field variations, these missions offer unprecedented insights into groundwater depletion, ice sheet loss, sea level rise, and solid Earth processes. As a result, GRACE has significantly advanced hydrologic simulations (*13*) and played a key role in validating land surface models (*3, 14*).

The Breakthrough by Seo et al. (2025)

This overview of key geophysical challenges contextualizes the achievements of Seo et al. (*3*). Their study integrates three independent datasets—global mean sea level from satellite altimeters, terrestrial water storage anomalies from GRACE, and polar motion data—to validate the strong soil water depletion revealed by ERA5 reanalysis since 2000.

Their triple-validation approach confirms that ERA5-simulated soil water depletion aligns with global mean sea level rise and shifts in Earth's mass distribution, altering its principal moments of inertia and exciting polar motion. These findings provide compelling evidence of a permanent shift in the global hydrological regime under current climate conditions.

This approach also highlights opportunities to improve land surface model parameterization, which remains suboptimal (*15*). Developing next-generation land surface models that incorporate anthropogenic effects—large dams, irrigation, and dynamic vegetation (*3*)—is critical. ECMWF's ongoing refinement of its ECLand model (formerly HTESSEL) represents a promising step forward (*9*), helping to reduce uncertainties and improve our understanding of climate change's impact on the global water cycle.

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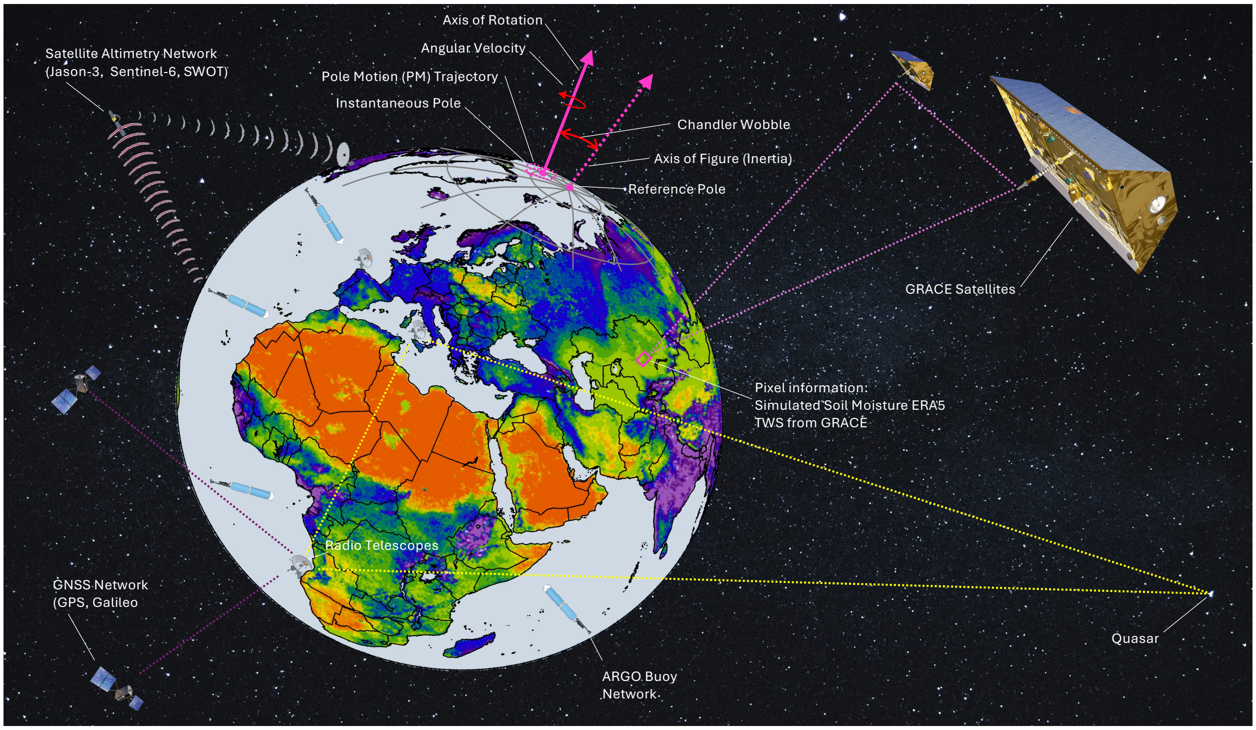

Figure 1: Earth's Water Cycle Observations and Polar Motion Tracking. This figure illustrates key geophysical datasets and observational networks used to monitor Earth's hydrological cycle and polar motion. The polar motion (PM) trajectory is shown alongside the Chandler Wobble, highlighting variations in Earth's rotational behavior. GRACE satellites estimate terrestrial water storage (TWS), while satellite altimetry missions (e.g., Jason-3, Sentinel-6, SWOT) track global mean sea level (GMSL) changes. The autonomous ARGO buoy network monitors ocean salinity and provides steric sea level estimates. High-precision geodetic measurements of Earth's rotational variations come from GNSS networks (e.g., GPS, Galileo), Satellite Laser Ranging (SLR), and Doppler Orbitography (DORIS). Meanwhile, radio telescopes using Very Long Baseline Interferometry (VLBI) refine Earth orientation parameters (EOPs) by observing distant quasars. The color-coded map represents simulated soil moisture from ERA5 at a specific point in time, with blue indicating wet conditions and red indicating dry conditions. Together, these global observation systems provide essential data for quantifying hydroclimatic-driven shifts in mass distribution and their impacts on polar motion and sea level rise.