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EDITORIAL

Convergence at the Horizon towards Predictive Resilience in a Non-Stationary World

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ABSTRACT

Climate change and technological advancement are driving a paradigm shift in the atmospheric and hydrometeorological sciences. This transformation is reflected in the complex interactions between ocean and atmospheric dynamics, the role of climate phenomena such as El Niño and La Niña, and the consequent effects on global water resources. This editorial argues that the critical task for the coming decade is to advance from hazard-focused forecasting toward the robust prediction of systemic impacts and societal resilience. We highlight three convergent frontiers of innovation: the integration of artificial intelligence and machine learning across the observational-modeling-prediction chain; the explicit coupling of human and water-energy-food systems within Earth system models; and the development of a "digital twin" framework for the Earth system. Success will require transcending disciplinary boundaries, promoting open science and data democratization, and fostering a new "convergence science" that interweaves physical dynamics, data science, socio-economics, and governance. The ultimate aim is to deliver actionable intelligence for anticipatory adaptation and enhanced climate resilience.

Keywords: AI/ML-Earth System Integration; Socio-Hydrometeorological Coupling; Predictive Resilience; Digital Twin; Convergence Science; Non-Stationarity; Climate Adaptation.

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The increasing frequency and intensity of extreme weather events, such as catastrophic flooding from atmospheric rivers and heatwaves altering the boundaries of habitability, underscore the Clausius-Clapeyron relationship's role as a significant driver of societal upheaval, rather than just a thermodynamic curiosity [1]. For decades, our fields have been dedicated to enhancing the precision and lead-time of physical forecasts, as evidenced by significant advancements in typhoon forecasting in China and the broader progress in weather forecasting technology [2]. Although never fully accomplished, this mission has seen remarkable success. Yet, a glaring disconnect persists, i.e., ever-more-skillful precipitation or temperature forecasts do not automatically translate into effective warnings, minimized loss, or resilient recovery [3]. The central thesis of this perspective is that the next great leap must be conceptual; in other words, we must shift our primary focus from predicting the atmosphere and hydrosphere to predicting the behaviour and vulnerability of the coupled human-environment system under climatic stress. This is the imperative of achieving Predictive Resilience.

This transition is being catalysed and made feasible by concurrent revolutions. The first is the pervasive integration of Artificial Intelligence and Machine Learning (AI/ML), which extends far beyond being a mere superior tool for post-processing model output or emulating parameterizations [4]. As evidenced by industry reports and real-world applications, AI/ML is a transformative force that is reshaping data quality solutions, enhancing network performance, and driving innovation across various sectors. We are witnessing the emergence of foundation models trained on petabytes of multimodal data such as satellite imagery, reanalysis, in-situ networks, and even social sensing streams. These models are not just forecasting weather patterns; they are beginning to identify precursory signals of compound extremes (e.g., coincident heatwaves and droughts) that physics-based models might miss due to incomplete representations. Furthermore, AI-driven inverse methods are revolutionizing data assimilation, optimally fusing heterogeneous observations from next-generation satellite constellations, such as COSMIC-2 and COSMO-SkyMed, GEDI) and dense, low-cost IoT sensor networks into high-resolution analyses [5,6]. The cutting-edge approach lies in the development of "hybrid" or "AI-physics" models, where deep neural networks are trained to dynamically represent sub-grid processes as functions of the resolved state, rather than relying on fixed parameterizations. This advancement could address long-standing biases in cloud microphysics and land-atmosphere interactions, thereby enhancing the precision of climate simulations. However, the inherent black-box nature of AI necessitates a renewed commitment to explainable AI (XAI) to ensure scientific trust, as evidenced by its critical role in climate research and applications. and uncover novel physical insights.

The second frontier is the explicit representation of human systems within our modeling frameworks. The era of regarding the land surface as a passive, static boundary condition has ended [7]. Socio-Hydrometeorological Coupling is now a critical research agenda. This involves two-way interactions: how changing water availability and extreme weather alter agricultural practices, urban water demand, and energy production; and conversely, how human water management (irrigation, reservoir operations, groundwater abstraction) and land-use change feed back onto local and regional climates [8]. For instance, extensive irrigation can dampen heatwave intensity but amplify atmospheric moisture, altering downwind precipitation patterns. Integrating agent-based models of farmer decision-making or water utility operations with distributed hydrological and atmospheric models presents profound computational and conceptual challenges but is essential for predicting future water scarcity and conflict hotspots [9]. The goal is to move beyond scenarios of climate impact on a static society to projections of co-evolution in a dynamic feedback loop.

These advances coalesce under the ambitious vision of a High-Resolution Earth System Digital Twin. This surpasses a traditional model operating at higher speeds; it represents a continuously updating, data-assimilative replica of the Earth system, integrating the AI-physics hybrids and human-system couplings as previously described [10]. Its purpose is not just simulation but exploration: running "what-if" scenarios in near-real-time to test the efficacy of proposed adaptation interventions from the release rules of a specific reservoir ahead of a forecast flood to the large-scale climate consequences of regional geoengineering proposals. Digital twin technology, as the ultimate integration platform, necessitates advanced computational infrastructure, robust data governance, and a novel ethical framework to support its applications.

Underpinning all these technical advances is the foundational challenge of non-stationarity. The assumption that past hydrological and climatic statistics are a reliable guide to the future has been definitively falsified. Non-stationarity in hydrological processes fundamentally challenges the validity of traditional infrastructure design, water resource planning, and risk assessment [11]. Our theoretical framework must now address the evolving nature of extreme events, as described by the Extreme Value Theory (EVT), which is crucial for understanding the time-evolving probability distributions of such events. Concepts like "stationary" vs "non-stationary" return periods need operational definitions. We must develop dynamical frameworks that can attribute changes in hazard likelihood not just to anthropogenic forcing in a broad sense, but to specific mechanisms, changing atmospheric dynamics (e.g., jet stream meandering, blocking persistence), land-atmosphere feedbacks, and oceanic modes of variability. This profound theoretical endeavour is pivotal in integrating climate science into actionable strategies for urban planners and engineers.

To navigate this complex future, we advocate for a culture of Convergence Science. Addressing the multifaceted challenges we face, such as equitable adaptation, resilient food-water-energy nexuses, and disaster-risk finance, necessitates a collaborative approach that transcends the expertise of atmospheric physicists or hydrologists alone. They necessitate sustained and in-depth collaboration with computer scientists, social scientists, economists, ecologists, and policymakers from the outset of research questions. Journals like ours must actively foster this by valuing interdisciplinary scholarship, publishing on novel methodologies for coupling disparate systems, and highlighting studies that successfully bridge the science-policy divide, such as the establishment of ONAC in Spain, which aims to provide timely scientific advice to government and test potential policy impacts.

Consequently, public investment should be channeled towards the foundational elements of digital twin technology, including high-performance computing, cloud analytics, and seamless data pipelines, as these are critical for advancing the capabilities of digital twins across various sectors. The global adoption of FAIR data principles, which ensure data is Findable, Accessible, Interoperable, and Reusable, is essential for both environmental and socio-economic datasets. Moreover, graduate programs must transcend disciplinary boundaries in both remote sensing and institutional analysis, and train scientists who are fluent in both differential equations and deep learning. Meanwhile, funding agencies should create programs specifically for high-risk, high-reward convergence research aimed at predictive resilience and move beyond incremental model improvements, fostering use-inspired fundamental research. Moreover, International consortia must be formed to develop standards, ethical guidelines, and access protocols for national and regional Digital Twins to ensure they serve the global public good.

The trajectory of our science is clear. We are moving from observers and forecasters of a natural system to architects of understanding for a deeply intertwined planetary social-ecological system. The concepts of AI-physics integration, socio-hydrometeorological coupling, and the Earth Digital Twin are not mere buzzwords [10]; they are the pillars of a new research architecture aimed squarely at the grand challenge of predictive resilience. This odyssey demands intellectual fortitude, institutional ingenuity, and a reinvigorated dedication to science for the betterment of society. As the Journal of Atmospheric Science Research enters this new era, we vow to serve as a crucible for audacious ideas, rigorous discourse, and groundbreaking scholarship that will illuminate the path ahead. The atmosphere and hydrosphere heed not our disciplinary confines; likewise, our science must transcend all bounds.

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Conflicts of Interest

The author declares no conflict of interest.

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