

What's next in Geoscience?

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Geoscience is undergoing a fundamental paradigm shift toward an Earth system science framework.¹ The accelerating environmental change, the growing prevalence of extremes, and the pervasive influence of human activities are exposing the inherent limitations of traditional, component-based, and stationarity-driven approaches to understanding the Earth system. The

central challenge we face is no longer merely describing the isolated states of Earth's spheres, but building an integrated scientific framework that links mechanistic understanding, predictive capability, and actionable decision support under deep nonlinearity and non-stationarity. Advancing Earth system science requires a leap from "explaining Earth's functions, to "antici-

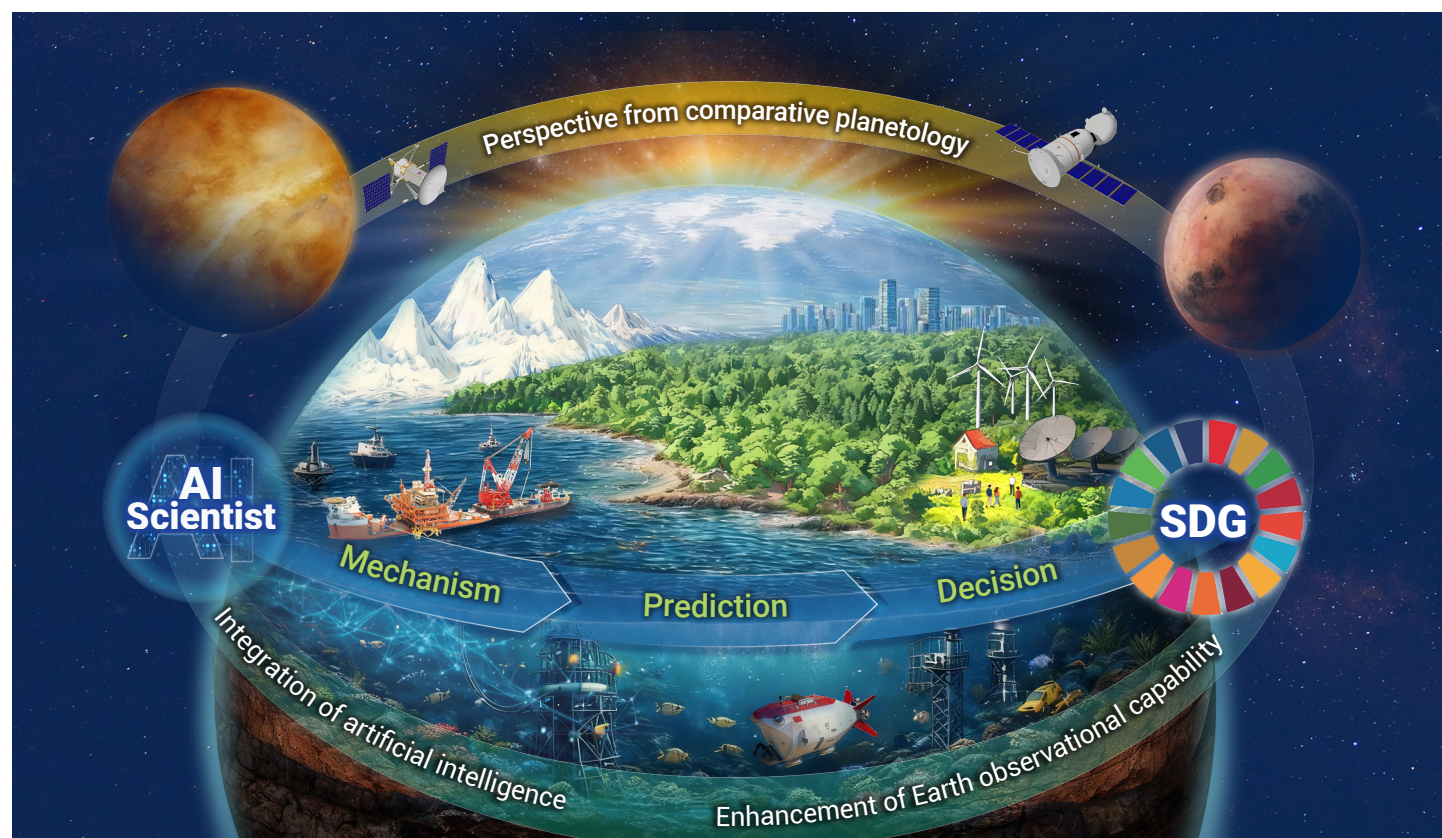


Figure 1. The next paradigm shift in Geoscience toward an Earth system science framework.

pating global changes", and ultimately to "guiding societies toward a sustainable transition" (Figure 1).

First, geoscience needs to deepen mechanistic understanding of Earth system nonlinearity and tipping behavior, and cascading feedbacks. As human forcing pushes the Earth system beyond its historical envelope, we must move beyond linear assumptions to systematically resolve the strong coupling between the lithosphere, atmosphere, cryosphere, biosphere, and anthroposphere. A primary priority is identifying the key thresholds and amplifiers that govern system resilience and vulnerability. Process-level researches into abrupt transitions and compound extremes will provide the predictive physical foundation necessary for society to act before crossing dangerous "planetary boundaries".

Second, the capacity for prediction in a non-stationary world must be strengthened by translating mechanistic insights into robust predictive skills. This demands a new generation of Earth system models that are high resolution, strongly constrained by observations, and capable of learning from data while respecting physical principles. The future lies in hybrid approaches that integrate physics-based modeling with artificial intelligence, data assimilation, and deep learning diagnostics, culminating in adaptive Digital Twin Earth systems. Such frameworks can substantially improve forecasts of extreme

events, cascading risks, and critical transitions across societally relevant timescales. Crucially, predictive progress must be evaluated with transparent benchmarks, explicit uncertainty quantification, and careful assessment of generalization to futures that fall outside historical training distributions. Probabilistic forecasting and uncertainty propagation across the full chain from observations to models to decisions are necessary to ensure that improved prediction translates into improved risk management.

Third, geoscience must more effectively translate Earth system knowledge into decision support and risk governance. In an era of escalating risks, the discipline's role extends beyond explaining past changes or projecting future trajectories. It now requires tighter coupling between natural and social systems and the conversion of complex scientific understanding into accessible, region specific, and operational tools for risk assessment, early warning, and scenario planning. This translation is most effective when knowledge products are co-produced with stakeholders so that indicators, thresholds, spatial resolution, and response timescales match real decision contexts. By helping to define "safe and just" Earth system boundaries using measurable metrics, geoscience can provide an essential evidence base for climate adaptation, disaster risk reduction, and sustainable development at both regional and global scales.²

ENHANCEMENT OF EARTH OBSERVATIONAL CAPABILITY

The rapid advancement of Earth observation technologies has broadened detection methodologies, transitioning from conventional two dimensional surface remote sensing toward integrated, multidimensional, and penetrative approaches (e.g., electromagnetic, microwave, laser, and gravity).³ In parallel, the proliferation of small and low-cost satellite constellations is fundamentally reshaping geoscience by shifting the focus from mapping static features to monitoring dynamic Earth processes in near real time. Coordinated observations from airborne, ground-based, and ocean-based platforms, combined with the fusion of these diverse datasets, now make it possible to study the atmosphere, hydrosphere, biosphere, lithosphere, and other spheres as an interconnected system with unprecedented precision and depth. These capabilities enable retrieval of fine scale structures and dynamic processes within each sphere, and more importantly, they facilitate direct observation and diagnosis of key interactions and feedbacks across spheres through cross platform, multi-scale, and multi-sphere coordinated measurements.

This observational transformation will have its greatest impact when it strengthens the observation and data foundation needed for attribution, prediction, and decision support. The value of big data lies not only in volume but in comparability, provenance, and quantified uncertainty. Progress therefore depends on building analysis ready and interoperable data products through cross sensor harmonization, rigorous quality control, traceable validation, and explicit uncertainty propagation.

At the same time, this revolution faces significant challenges, including barriers to data sharing and standardization, high technological costs, growing demand for advanced analytical expertise, and concerns over data security and ethics. Future progress will increasingly depend on international cooperation, open-source tools and standards, interdisciplinary collaboration, and inclusive data-governance frameworks.

INTEGRATION OF ARTIFICIAL INTELLIGENCE (AI)

The unprecedented volume and diversity of Earth system observations, combined with the intrinsic complexity of cross sphere interactions, have created computational and analytical challenges beyond the capacity of traditional methods. AI's ability to learn from massive observations and bridge data with physical understanding is driving a paradigm shift from physics-based modeling toward hybrid frameworks that fuse data driven learning with mechanistic knowledge. This transformation enables comprehensive integration of observations, models, and domain expertise into unified analytical frameworks.⁴

Comprehending the underlying mechanisms that govern the interactions among Earth system components is a central goal in Earth system science. Interpretability thus forms the foundation for AI's meaningful contribution to the field. By embedding physical constraints into model architectures and leveraging explainable AI techniques together with causal discovery methods, AI can help identify plausible causal pathways, disentangle driver response relationships, and generate testable hypotheses that can be evaluated with targeted observations and experiments.

The increasing complexity of Earth system interactions and nonlinear dynamics demands enhanced predictive capabilities for extreme events and critical transitions. Earth foundation models are emerging as a unifying paradigm to deliver these advances. Trained on vast multimodal observations and simulations, such models can develop rich representations of cross sphere dynamics that enable skillful forecasting across diverse spatiotemporal scales. When combined with physical constraints, data assimilation, and ensemble strategies, they can strengthen robustness and uncertainty awareness, particularly for rare and high impact events.

Earth system science must ultimately translate knowledge into actionable guidance. The fusion of AI with this field opens new pathways toward this goal. AI can enable exploration of complex decision spaces through policy scenario simulation and optimization, including reinforcement learning interacting with digital twin environments. However, effective application requires human expert oversight, transparent objectives, explicit uncertainty communication, and responsible AI practices that address robustness, bias, reproducibility, and governance. A human and AI collaborative framework will give rise to a new generation of intelligent tools, such as Human-AI collaborative

modeling platform, open Earth system simulators and AI scientists, for the adaptive governance of climate risks, ecosystem dynamics, and natural hazards in an era of accelerating change.

PERSPECTIVE FROM COMPARATIVE PLANETOLOGY

Recent advancements in the field of deep space exploration have significantly accelerated the pace of human expansion beyond Earth. The methodologies of geoscience have provided a foundational framework for the study of terrestrial planets, thereby greatly deepening our understanding of their evolution, environments, and resources. The wealth of data acquired from neighboring planets such as Venus and Mars enables reliable and detailed comparisons with the sophisticated dataset available for Earth. This comparative planetology approach, in turn, profoundly refines our comprehension of the Earth system. For example, the planets Venus, Earth and Mars all had oceans and extensive volcanism in their early histories. They currently have climates determined by energy balance relationships involving carbon dioxide, water and aerosols, regulated by solar energy deposition, atmospheric and ocean circulation, composition, and cloud physics and chemistry.⁵

The comparative planetology method treats the solar system as a planetary evolution laboratory. Its core strength lies in providing natural experiments with distinct control variables. Venus and Mars showcase the divergent climatic fates of terrestrial planets resulting from variations in key parameters such as core mass, magnetic field strength, water inventory, and distance from the Sun. By studying these "failed" or "stagnant" cases, we can identify the critical thresholds and vulnerable nodes that sustain Earth's long-term habitability—revealing, for example, the delicate synergy between moderate mass and orbital position, active internal and external dynamic systems, and robust magnetospheric protection.

Consequently, the perspective of comparative planetology holds the potential to foster the development of a conceptual framework capable of consistently explaining the climatic evolution of terrestrial planets. This framework aims not to replace, but to refine and validate our existing climate models for Earth. Currently, policy-relevant science, as embodied in assessment reports like those from the IPCC, relies heavily on precise observation and modeling of the Earth system. However, uncertainties remain regarding long-term projections involving Earth system stability. By employing Venus and Mars as extreme boundary conditions for "stress-testing", we can substantially strengthen scientific confidence in assessing Earth's climate tipping points and long-term evolutionary pathways. This approach would ground strategies for addressing global change upon a more robust and expansive foundation of knowledge.

CONCLUSION

Ultimately, the enhancement of Earth observational capability, the integration of artificial intelligence, and the adoption of a comparative planetology approach, together with the continued development and stable operation of major scientific infrastructure, there is potential to build the resilience needed to safeguard our collective future.

REFERENCES

1. Reid, W. V., Chen, D., Goldfarb, L., et al. (2010). Earth system science for global sustainability: Grand challenges. *Science* **330**:916–917. DOI:10.1126/science.1196263
2. Rockström J., Gupta J., Qin D. et al. (2023). Safe and just Earth system boundaries. *Nature* **619**:102–111. DOI:10.1038/s41586-023-06083-8
3. Wang, L., Zuo, B., Le, Y., et al. (2023). Penetrating remote sensing: Next-generation remote sensing for transparent earth. *The Innovation* **4**:100519. DOI:10.1016/j.xinn.2023.100519
4. Chen, M., Qian, Z., Boers, N., et al. (2024). Collaboration between artificial intelligence and Earth science communities for mutual benefit. *Nat. Geosci.* **17**:949–952. DOI:10.1038/s41561-024-01550-x
5. Taylor, F. W. (2011). Comparative planetology, climatology and biology of Venus, Earth and Mars. *Planetary and Space Sci.* **59**:889–899. DOI:10.1016/j.pss.2010.11.009
6. Kidd C., Becker A., Huffman G. J., et al. (2017). So, how much of the Earth's surface is covered by rain gauges. *Bull. Am. Meteorol. Soc.* **98**:69–78. DOI:10.1175/BAMS-D-14-00283.1

DECLARATION OF INTERESTS

The author declares no competing interests.