Enabling Interoperability in Earth System Digital Twins (ESDT):
Integrating Observations, Models, and AI for Actionable Insights through NASA's Intelligent Systems Technology Program

Nicole Ramberg-Pihl[1,2,3], Laura Rogers[2,4], Benjamin Smith[5], Jennifer Webster[6]
NASA Goddard Space Flight Center, [2]NASA Headquarters, [3]Science Systems and Applications, Inc., [4]NASA Langley Research Center, [5]Jet Propulsion Laboratory, [6]NOAA-nesdis Stennis Space Center, MS

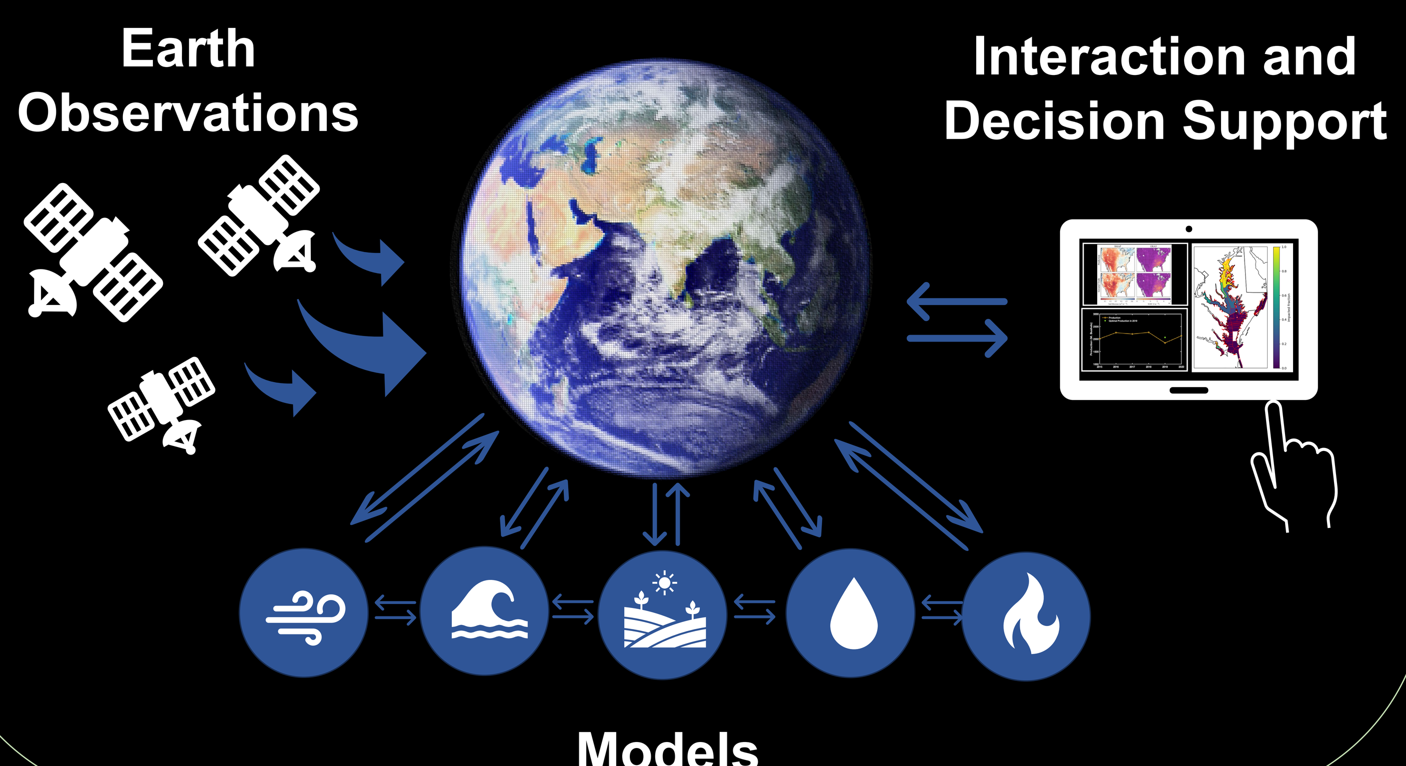
Abstract

NASA's Intelligent Systems Technology Program (IST) is driving a paradigm shift in Earth science through the development of Earth System Digital Twins (ESDT). These integrated information systems create a dynamic "digital replica" of the Earth by harmonizing continuous, multi-source observations with high-fidelity models and state-of-the-art artificial intelligence (AI) that enable "What now?", "What next?", and "What if?" scenario building. These scenarios are reflected in NASA IST's series of ESDTs, from the Coastal Zone Digital Twin that integrates complex data on the current state of the Chesapeake Bay to the Terrestrial Environmental Rapid-Replication and Assimilation Hydrometeorological (TerraHydro) AI-based ESDT that forecasts water movement across Earth's surface, to the Agriculture Land Information System (AgLIS) which can be used to assess optimal planting dates and crop yield estimates. By bridging the gap between vast data archives and actionable insights, these projects enable a system-of-systems approach to understanding complex, interacting Earth processes. This poster will highlight recent innovations and future directions from NASA's ESDT initiatives: Continuous Data Assimilation & Multi-Source Fusion. A core requirement of the ESDT work is the transition from static models to dynamic "living" replicas. This involves creating frameworks for the continual assimilation of near-real-time data from uncoordinated, heterogeneous sources, including satellite observations and airborne assets, and ground-based Internet of Things (IoT) sensors. These systems link design, operational status, and environmental data, ensuring the digital twin accurately reflects the current state of the physical Earth system. High-Fidelity Hybrid Modeling & Computational Acceleration to enable interactive "what-if" explorations, programs are moving beyond traditional, slow physical solvers by developing fast surrogate machine learning models and Deep Generative Models (DGMs). These hybrid approaches use neural networks to emulate complex physics, such as cloud feedback or ocean dynamics, at a fraction of the original computing cost, often leveraging advanced hardware like Graphics Processing Units (GPUs) to achieve the necessary scale. Federated Ecosystems & Interoperable Frameworks rather than building isolated tools, NASA IST is moving toward federated ESDTs and reusable analytic collaborative frameworks. This theme focuses on interoperability standards and common ontologies that allow specialized digital twins to interact and share data. This system-of-systems architecture supports multi-discipline investigations, such as analyzing how upstream watershed changes impact downstream urban flooding or how wildfire emissions affect regional air quality. By leveraging these advancements, ESDTs empower researchers and decision-makers to conduct real-time analysis and run complex hypothetical scenarios, ultimately improving our understanding of Earth's evolving systems and informing critical real-world applications.

More Than a Model

Elements of ESDTs in the NASA IST Portfolio

- **Continually ingest data and information from Earth observations**
- **Adaptable and scalable**
- **Integrate advanced modeling and visualization techniques**
- **Utilize cutting-edge technology including Agentic AI, ML, and LLMs**
- **Provide accurate rapid assessments**
- **Designed interoperability and federated systems**



Want to Connect?

Laura Rogers, IST Program Manager: laura.j.rogers@nasa.gov
Nicole Ramberg-Pihl, IST Deputy Program Manager, nicole.c.ramberg-pihl@nasa.gov

Technology for Today and Tomorrow

NASA's Intelligent Systems Technology Program is exploring the use of ESDTs to enable a system-of-systems approach to understanding complex interacting Earth processes.

A Planetary Blueprint

Earth System Digital Twins (ESDTs) are information systems for understanding, forecasting, and conjecturing the complex interconnections among Earth systems, including anthropomorphic forcings and impacts to humanity.

What Next?

Forecasting
An integrated picture of how Earth systems will evolve in the future from the current state.

What Now?

Digital Replica
An integrated picture of the past and current states of Earth systems.

What If?

Impact Assessment
An integrated picture of how Earth systems could evolve under different hypothetical what-if scenarios.

ESDTs enable understanding of human impact, actionable forecasting and risk management through "What-If" scenarios.

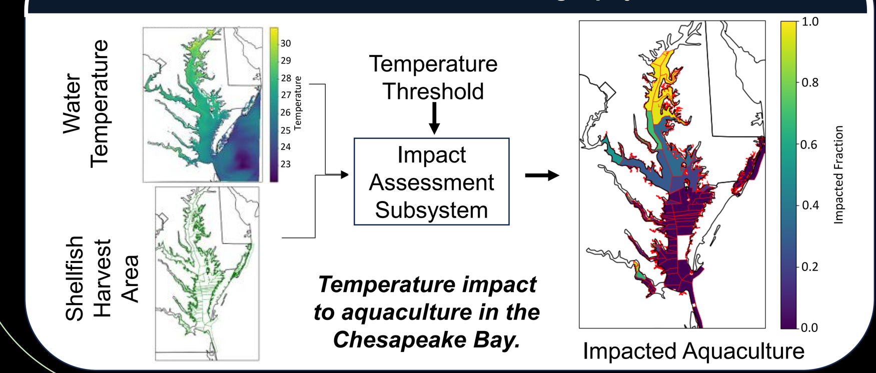
A Growing Catalog of Dynamic "Living" Replicas

Coastal Zone Digital Twin

A digital replica of the Chesapeake Bay that allows for 'what now?', 'what next?', and 'what if?' coastal flooding and water quality scenarios.

- A dynamic ESDT prototype with advanced modeling that allows for rapid forecasting:
  - Continuously updating record based on observations, model inputs, and impact assessments.
  - Provides rapid nowcasts and forecasts using ML surrogate models.
- A framework designed for scalability:
  - The architecture is modular using subsystem component roles that can be connected with domain-specific subsystems to gain new insights and build new ESDTs.

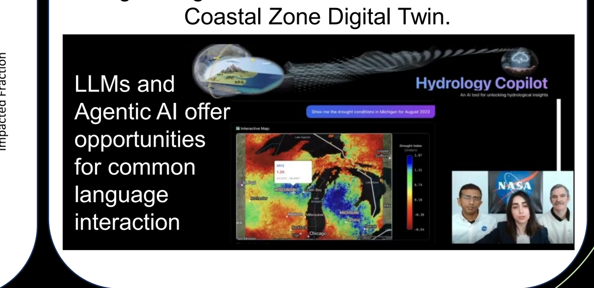
Demonstration of the Impact Assessment Subsystem that merges societal and environmental variables with geophysical variables.



Temperature impact to aquaculture in the Chesapeake Bay.

Integration of Agentic AI for enhanced user experience, delivering reliable insights faster.

The Hydrology Copilot team at NASA is working to integrate Agentic AI in the user interface of the Coastal Zone Digital Twin.

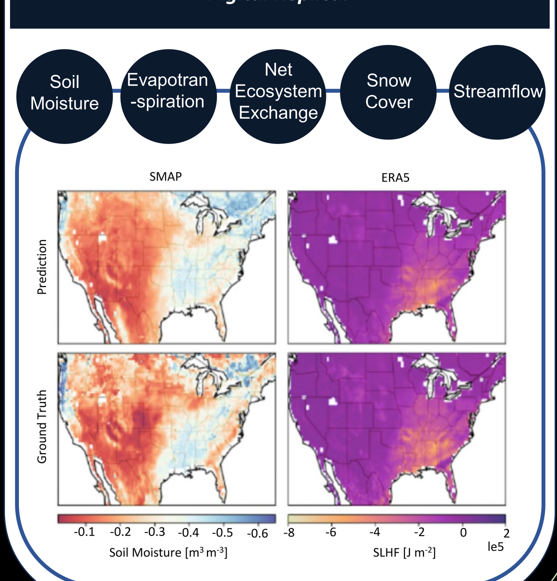


Terrestrial Environmental Rapid-Replication and Assimilation Hydrometeorological (TERRAHydro)

AI-based digital twin that simulates and monitors water movement across Earth's land surface and its impacts on human activities.

- Coupled models for deeper understanding:
  - The Coupled Reusable Earth System (CREST) framework underlies TERRAHydro. CREST provides a graph-based modeling framework built on top of tensor-based software (TBS) along with engines to support the development of community-based AI-enabled Earth Information Systems.
  - TERRAHydro combines traditional and AI/ML technologies.
- Built for interoperability and accessibility:
  - TERRAHydro supports any model that provides a gradient, tools for gradient estimation, and interoperability between TBS.
  - The system is online and available through a web-based front-end that provides users the ability to visualize, analyze, and configure the system.

TERRAHydro output of a 36 km benchmark of a coupled soil moisture and evapotranspiration Digital Replica.



Agricultural Land Assimilation System (AgLIS)

Designed to monitor, understand, and predict hydro-agricultural interactions and their implications for food security.

- The AgLIS framework enhances predictability of hydrological and crop growth conditions in croplands:
  - Tightly couples a land and hydrology model (LIS) and a crop model (Decision Support System for Agrotechnology Transfer - DSSAT) and assimilates remote sensing observations.
- Scenario Driven Impact Analysis:
  - Infrastructure allows for assessment of socio-economic impact from naturally occurring and human activities on agriculture and food security.

'What if?' Case Studies in Illinois, United States Planting date along with optimal cultivar can increase corn yield.