NASA ESTO
Advanced Information Systems Technology (AIST)



Earth System Digital Twins (ESDT)
Definition and Science Use Cases

The AIST Program
October 2023

What is an Earth System Digital Twin (ESDT)

ESDT Three Components

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

=> What Now? What Next? What If?

What now?

Digital Replica . . .

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

What next?

Forecasting . . .

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

What if?

Impact Assessment . . .

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

An ESDT includes:

- Continuous observations of interacting Earth systems and human systems
- From many disparate sources
- Driving inter-connected models
- At many physical and temporal scales
- With fast, powerful and integrated prediction, analysis and visualization capabilities
- Using Machine Learning, causality and uncertainty quantification
- Running at scale in order to improve our science understanding of those systems, their interactions and their applications

Developing ESDT Science Use Cases

Objectives:

- Understand potential applications and needs for ESDTs
  - What's the **vision** for an ESDT in this science area?
  - What's the **value proposition**?
  - Where are the technology **gaps**?
- Include representative use cases from several Earth Science domains
- Developed at the ESDT Workshop in October 2022 with follow-on discussions with stakeholders.

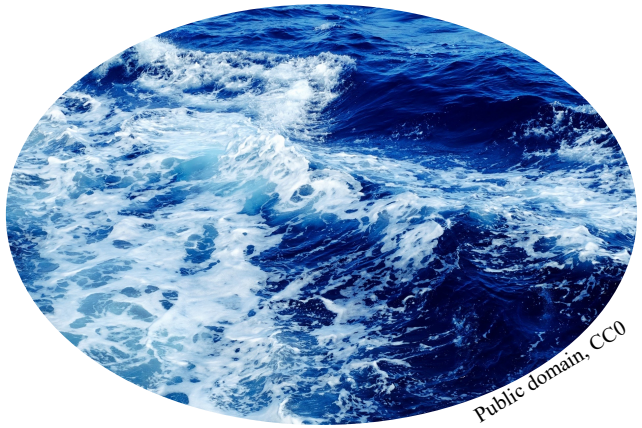
Current AIST ESDT Use Case Domains

ESTO Earth Science Technology Office
AIST

Wildfires

Image: Mike McMillan/USFS

Ocean Carbon



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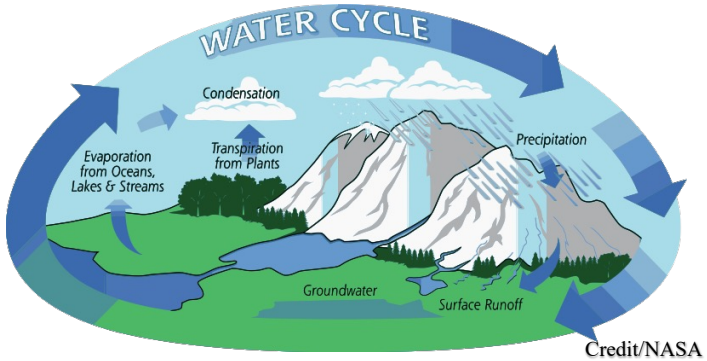
Atmospheric Boundary Layer

Credit/NASA



Credit/NASA

Water Cycle

Credit/NASA

Coastal Zone

Central Africa Carbon and Biodiversity Corridors

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Current AIST ESDT Science Use Cases

ESDT Use Case	SCOPE
Wildfires	A digital twin of Earth systems involved in wildfires to represent and understand the origins and evolution of wildfires and their impacts on ecosystem, infrastructure, and related human systems.
Ocean Carbon	An Earth system digital twin of ocean, land, atmospheric Earth systems to understand ocean carbon processes such as carbon export and ocean-atmosphere processes and coupling; land-ocean continuum and interactions with human systems; coastal ecological changes and impacts to ecosystem services; feedback processes (e.g., storm intensification and sea level rise) and impacts on coastal communities and the blue economy; assessing feasibility and impacts of various Carbon Dioxide Removal (CDR) approaches as a strategy to remove and sequester atmospheric carbon.
Water Cycle	A local or regional digital twin to understand all the complexities of the Water Cycle, how it is affected by various Earth Systems at multiple temporal and spatial scales, and how it is impacted by decision making and human influence. It would provide capabilities *such as* zooming out in time and space; helping understand water availability and origin for agriculture; how events such as floods and droughts affects life, property and infrastructure; and more generally how the effects of weather and climate variability can be mitigated under various scenarios.
Central Africa Carbon and Biodiversity Corridors	An Earth System digital twin of "Carbon Corridors" (i.e., connected regions of protected forests/vegetation. They store carbon and maintain habitat connectivity for biodiversity) in Central Africa to: understand the current conditions; assess their ability to store carbon and promote biodiversity; forecast future conditions; conduct what-if scenarios to assess the impact of policy decisions and potential climate conditions.
Atmospheric Boundary Layer	An Earth system digital twin of the atmospheric boundary layer to provide a digital replica of the lowest portions of the atmosphere and of their processes and interactions with other systems – land, ocean, and ice surfaces – and how these interactions control exchanges with materials such as trace gases, aerosols; coupled atmospheric systems to understand underlying processes and their relationship to climate and air quality, the role of these interactions on the global weather and climate system; atmospheric systems related to greenhouse gasses (GHG), sources of pollution, and their transport in the atmosphere to understand air quality and human health impacts at multiple scales from hyper local to long term global climate projections; proper characterization of the Planetary Boundary Layer (PBL) is also critically important for modeling nighttime minimum temperatures for agricultural applications, and for prediction of wildland fire risk.

Note: A 6th ESDT Use Case has been developed by AIST but is NOT Included in ROSES-23

AIST ESDT Use Case Template

Scope		The scope of science and applications questions that this Earth System Digital Twin would address.
Capabilities	Digital Replica *(what now?)*	• The kinds of "what now" questions we want the ESDT to address about the current and prior state of the earth system.
	Forecast *(what next?)*	• The kinds of "what next" questions we want the ESDT to address about how the Earth System will evolve in the forecastable future.
	Impact Assessment *(what-if?)*	• The kinds of "what if" questions we want the ESDT to address about how the Earth Systems could evolve under different assumptions, scenarios, and interventions.
Earth Systems		The key Earth Systems involved in answering the above questions
Human Systems		Human systems involved (e.g., agriculture, infrastructure, economic, …)
Resources		Observing systems, models, and other data sources that could be part of this ESDT, either directly or through federation. Consider both current and future resources.

Current AIST ESDT Use Cases – *Wildfires*

Scope		A digital twin of Earth systems involved in wildfires to assess risk (pre-fire), guide response (active fire), and understand cascading post-fire impacts (post-fire).		
	Fire Stages	Pre-fire	Active Fire	Post-fire
Capabilities	Digital Replica *(what now?)*	• *Digital replica* of current conditions to assess fire risk. What are the fuel loads, where is it dry; wind conditions; where are those near infrastructure?	• *Digital replication* of the fire evolution. • Digital replication of fire crews, air assets, infrastructure, evacuation, etc.	• *Digital replication* of post-fire systems to understand post-fire burn extent and severity. • Understand how interacting system processes change after a fire.
	Forecast *(what next?)*	• Model-derived predictions of near- and long-term ignition risks and uncertainties	• Model-derived real-time prediction of fire and smoke plume evolution and spread to guide response	• Forecast cascading impacts, such as flooding due to burn scars, impacts to air and water quality, and impacts to human health.
	Impact Assessment *(what-if?)*	• Assess risk under alternate future conditions (e.g., wet or dry winter) • Assess mitigation strategies (e.g., controlled burns).	• What-if projections to assess alternate conditions or decisions (winds; alternate strategies)	• *What-if projection* to assess possible post-fire scenarios • What if projections to improve understanding of processes: landslides, floods, impacts to watersheds.
Earth Systems		Fuel load, soil moisture, ecosystem/biodiversity, climatology, winds, smoke transport, river systems		
Human Systems		Infrastructure, crew disposition, air assets, evacuation routes		
Resources		(Current or soon) SMAP, MODIS, in situ sensors, AIRS, MAIA, NIFC systems, … (Future?) TBD Missions/Sensors/Data		

Current AIST ESDT Use Cases – *Ocean Carbon*

Scope		A digital twin of ocean, land, and atmospheric Earth systems to understand the role of ocean carbon processes such as carbon export and ocean-atmosphere-land interactions.
Capabilities	Digital Replica *(what now?)*	• Digital replica of nutrient run off following precipitation and resulting coastal algal activity. • Digital replica of carbon exchange from ocean-atmosphere coupling. • Digital replica of the effects of anthropogenic pressure on oceans (rivers, increasing atmospheric CO2, increasing temperature, etc.)
	Forecast *(what next?)*	• Where and when are we likely to get algal blooms? • Can we improve severe storm and extreme event projections?
	Impact Assessment *(what-if?)*	• How will carbon exchange from ocean-atmosphere coupling impact sea level rise under different assumptions about key climate variables? • How would sea level rise impact coastal communities under different assumptions? • Assess feasibility and impacts of various Carbon Dioxide Removal approaches.
Earth Systems		Ocean, land and atmospheric processes contributing to ocean carbon
Human Systems		Agriculture, infrastructure, tourism, health and safety
Resources		Ocean currents, SST, ocean color; ECCO; floats, gliders, and other in situ sensors (e.g., ARGO); land surface models; river flow models; ocean physical and biogeochemical models, atmospheric carbon data (OCO-2, TGO, MAIA, GOSAT)

Current AIST ESDT Use Cases – *Water Cycle*

Scope		A digital twin to understand all the complexities of the Water Cycle, its relation to weather and climate, and the impact from human influence as well and its impact onto human systems.
Capabilities	Digital Replica *(what now?)*	• What is the current state of hydrologic systems: rivers, reservoirs, snow pack, etc. • Observe current state of hydrologic systems to understand how they are interacting (rivers, snow pack, reservoirs, etc) • Understand current state of hydrologic systems following floods and droughts, including data from human systems (e.g., rivers, snow pack, aquifers, precipitation, soil moisture and their interactions with cities, agriculture, etc)
	Forecast *(what next?)*	• Under probable evolution of current conditions, what will be the future state of the water cycle in 5, 10, 20 years, considering multiple systems (snow pack, precipitation, river networks subsurface, land surface models, etc.)
	Impact Assessment *(what-if?)*	• How might hydrology systems evolve under different climate or policy assumptions, and how would that impact human activities? • Improve our understanding of the processes driving interacting hydrologic systems by conducting what-if projections under different assumptions.
Earth Systems		Evapotranspiration, river systems, snowpack, subsurface aquifers, meteorology/climatology, surface water (reservoirs/lakes), land use/land cover
Human Systems		Reservoirs, dams, agriculture, infrastructure
Resources		NISAR, SMAP, GPM, VIIRS, Landsat, SBG, PACE, GRACE/FO/MC, CYGNSS/SoOP, Sentinels, river gauge sensor network, GCMs/Reanalyses (i.e., MERRA-2), LIS

Current AIST ESDT Use Cases – *Atmospheric Boundary Layer*

Scope		**A Digital Twin of the Atmospheric Boundary Layer**
Capabilities	Digital Replica *(what now)*	• Digital replica of current lower atmospheric systems and processes including planetary boundary layer (PBL) processes that impact surface exchange of greenhouse gases and air pollutants. Of particular interest is capturing the interactions of PBL dynamics with human activities (e.g., urban and agricultural systems) and terrestrial and marine ecosystems
	Forecast *(what next)*	• Forecast evolution of these PBL processes in various environments, and for different climate scenarios • Forecast air quality and carbon cycle • Transport of wildfire smoke
	Impact Assessment *(what-if)*	• Long term climate projections and relationship to GHG under different assumptions about key variables and trends. • How would air quality evolve under different assumptions about human activity or policies, and what would the impact be on human health?
Earth Systems		Terrestrial ecosystems (forests, grasslands, etc), Marine ecosystems (coastal), precipitation, atmospheric chemistry, land/sea interactions
Human Systems		Cities, infrastructure, transportation, agriculture emissions
Resources		MODIS, AIRS, CrIS, VIIRS, CALIPSO, TROPOMI, TEMPO, GEMS, MAIA, OCO-2/3, GOSAT, MethaneSat, GHGSat, GOES-R, in situ AQ sensors

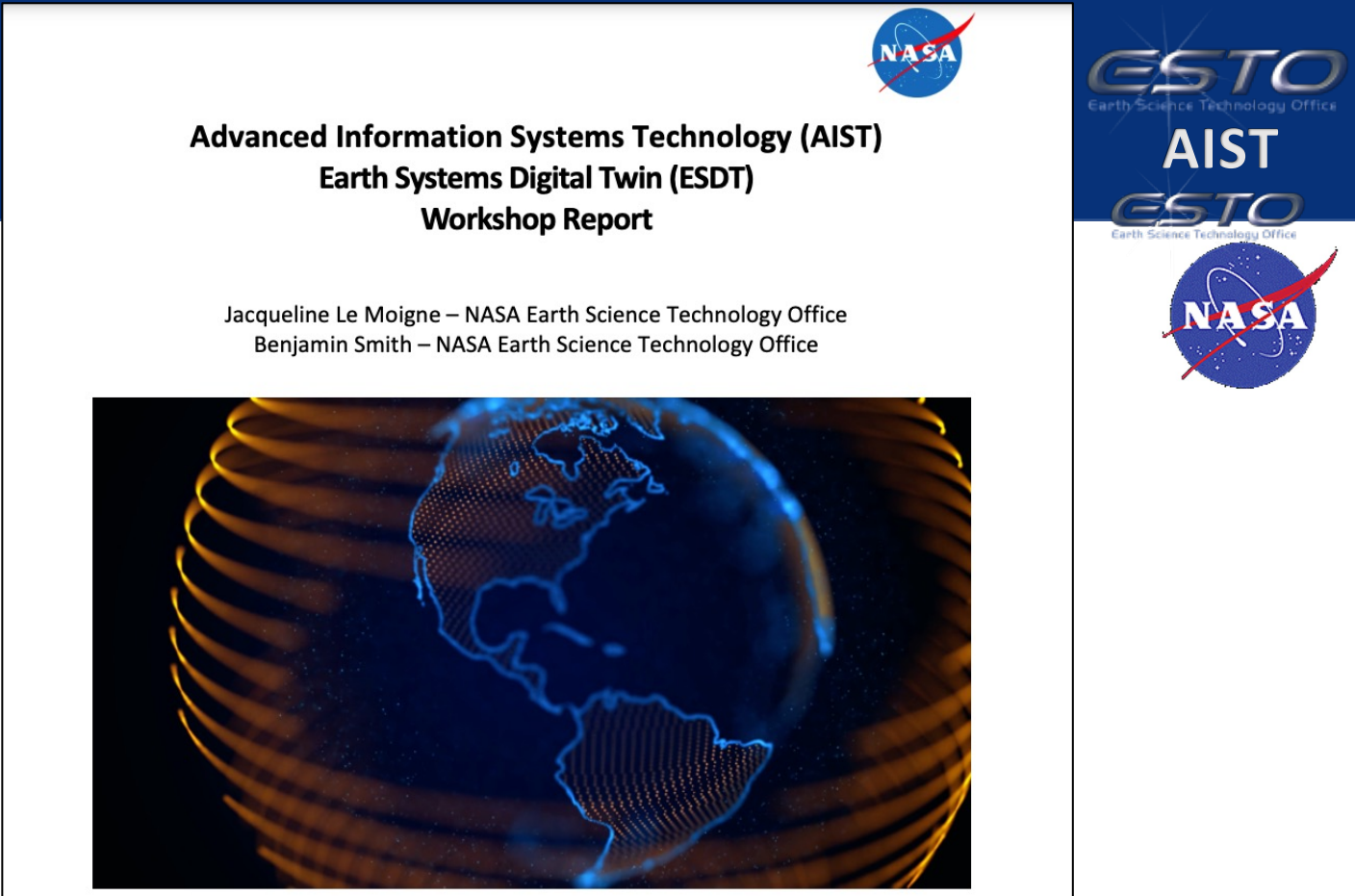
Current AIST ESDT Use Cases – *Central Africa Carbon and Biodiversity Corridors*

Scope		A digital twin of "Carbon Corridors" in Central Africa
Capabilities	Digital Replica *(what now)*	• Digital replica of carbon/biodiversity corridors to understand the current conditions. • Estimate carbon storage, biodiversity composition and abundance, and the potential for wildlife dispersal and migration • Effects/interactions with agriculture, infrastructure, and other land uses
	Forecast *(what next)*	• Forecasts of carbon storage, biodiversity conservation, and habitat connectivity • Interconnected system of systems forecasts (e.g., hydrology, vegetation, atmosphere, carbon exchange, biodiversity, and land use/land cover (LCLUC) together)
	Impact Assessment *(what-if)*	• How would carbon storage capacity and/or biodiversity composition/abundance and/or habitat connectivity change under different land use scenarios? Where would adding protected area coverage help? Which areas would have the most/least impact on the above? How would different scenarios of change impact agriculture? • How would carbon storage/biodiversity loss evolve under alternate future climate assumptions? • How would habitat corridor intactness respond to different wildfire scenarios?
Earth Systems		Forests, hydrology, atmosphere (CO2 exchange), biodiversity, fires
Human Systems		Agriculture, infrastructure, other land uses, trade in bushmeat
Resources		Landsat, MODIS, SMAP, Terra, Aqua, GEDI, NISAR, commercial high-resolution imagery, biodiversity assessments, in-situ sensors (AQ, telemetry tags, etc.)

ESDT Workshop
October 26-28, 2022

- Includes additional information about ESDT Use Cases a and projects
- Report available on AIST Website:

https://esto.nasa.gov/files/ESDT_Workshop_Report.pdf



Advanced Information Systems Technology (AIST)
Earth Systems Digital Twin (ESDT)
Workshop Report

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Workshop Co-Organized with Earth Science Information Partners (ESIP)
Report Edited by ESDT Workshop Participants

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Washington, D.C.

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