NASA Earth System Digital Twins (ESDT) Use Cases

J. Le Moigne, B. Smith, J. Ranson, M. Little, R. Morris, N. Oza and L. Rogers
NASA Earth Science Technology Office (ESTO)

Earth System Digital Twins:

Earth System 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?
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 …

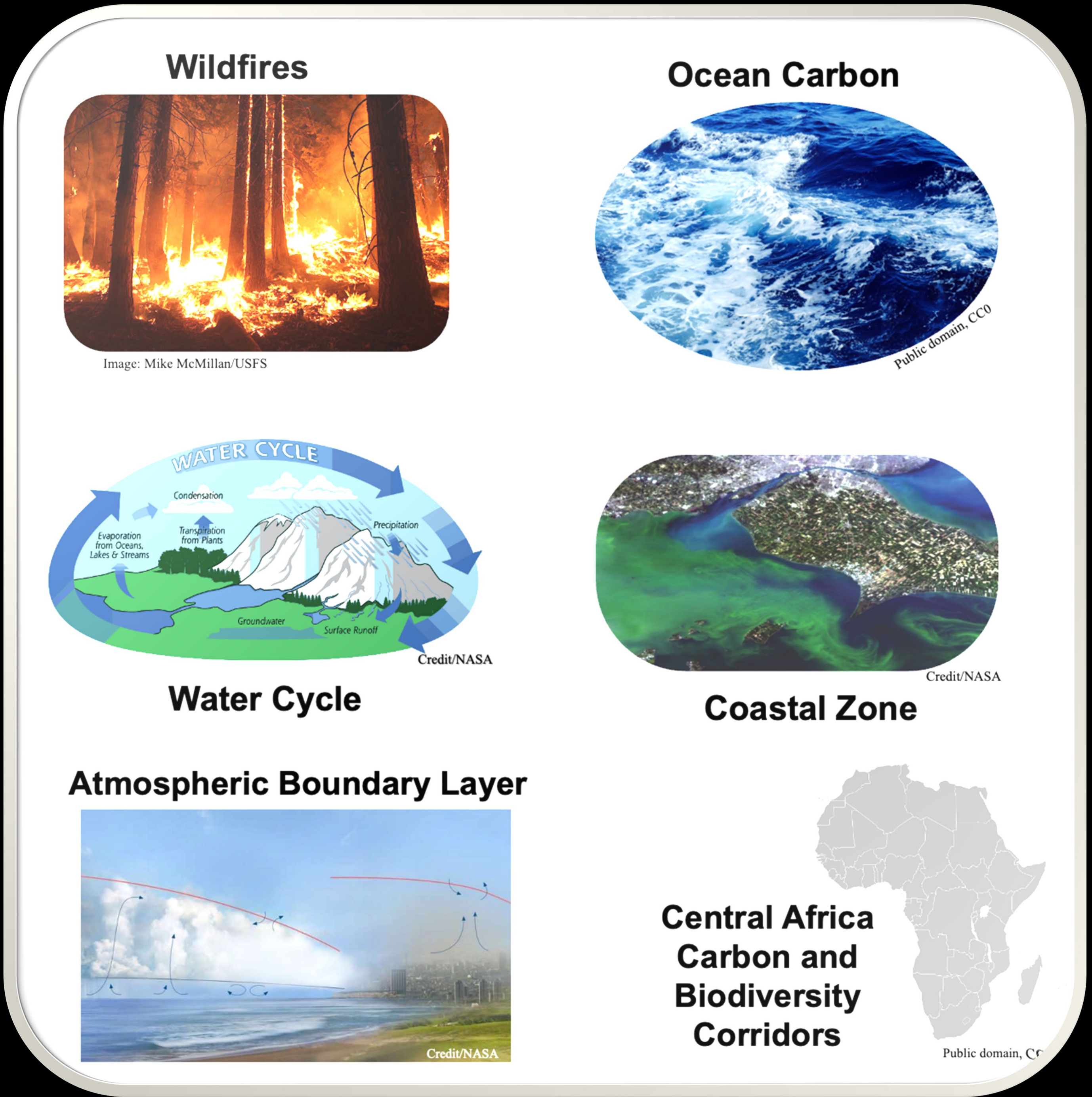
- Continuous observations of interacting Earth systems and human systems from many disparate sources driving inter-connected models at many physical and temporal scales
- Fast, powerful and integrated prediction, analysis and visualization capabilities using Machine Learning, causality and uncertainty quantification
- Models running at scale in order to improve our science understanding of those systems, their interactions and their applications

ESDT Drivers

- Fully utilize wealth of Earth Science data as well as data from policy sector
- Improve spatial and temporal resolution of Earth Science models, e.g., using Machine Learning (ML) with Physics-based models
- Provide easy-to-access and interactive actionable information to non-traditional users

6 Current ESDT Use Case Domains

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.
Coastal Zone	An Earth System digital twin of local and regional coastal zones that considers both natural and human systems to understand changes in coastal flooding severity, land and marine morphology, nutrients and water quality, ecological makeup, sea level, and the short and long-term risks to climate change adaptation, sustainable development, disaster management, tourism and recreation, quality of life, ecosystem management, and coastal infrastructure management.



Why ESDT Use Cases?

- Understand potential applications and science needs for ESDTs
- Engage the science community in motivating an ESDT Design
- Determine long-term vision for an ESDT in specific science areas
- Identify their value proposition
- Identify the technology gaps preventing the development of an ESDT in those areas

Approach

- Include representative use cases from several Earth Science domains
- Developed during October 2022 ESDT Workshop
- Continuous advancement with relevant stakeholders

Example Coastal Zone Digital Twin (CZDT) Use Case (Collaboration with NOAA and CNES)

Scope		An Earth System Digital Twin of local and regional coastal zones that considers both natural and human systems to understand changes in coastal flooding severity, land and marine morphology, nutrients and water quality, ecological makeup, sea level, and short and long-term risks to climate change adaptation, sustainable development, disaster management, tourism and recreation, quality of life, ecosystem management, and coastal infrastructure management. *The CZDT, while global in extent, will initially consider a variety of test locations (e.g., west coast of France, west coast of Africa, the east coast of the United States, selected islands) to provide a range of hydrological, ecological, and sociological conditions.*
Capabilities	Digital Replica *(What-Now)*	Digital replica of the current state of coastal systems to understand hydrological extremes and flooding; nutrient and pollutant levels including water quality parameters (physical/optical and chemical); topography and bathymetry; terrestrial and marine ecology; near-sea and in-sea infrastructure; and sea level at multiple spatiotemporal scales.
	Forecast *(What-Next)*	• Coastal morphology evolution of coastal morphology without further forced intervention. • How and at what rate will near shore vegetation and, more generally, coastal habitats evolve. • Changes in water quality, including nutrient runoff changes from natural variability and human interventions (e.g., urban, agriculture) that trigger harmful algal blooms (HAB). • Future states of tidal, storm, and combined flood events, and how they interact with human systems. How flooding, nutrient quantity or quality, water quality, ecology will change, and how coastal habitats/communities may shift.
	Impact Assessment *(What-If)*	What-if scenarios where human interventions are incorporated into responses to various environmental (sea-level and wave) forcing scenarios (e.g., relocate coastal settlements) • Effect/impact of changing climate on coastal environment under various sea level and storminess scenarios. • Water quality changes under different water management structures/policies. • Shifts in phytoplankton types under different natural/human forcings with improved HAB forecasting. • Impacts of management on blue carbon ecosystems to support climate mitigation and adaptation and improve resiliency to climate impacts. • Support cities to mitigation if flood risk increased. • Which flood risk changes if global temperature goals were met? Not met?. • Economic health changes if flood risks were lowered? Increased?. • Changes in ecological makeup if cities reacted to increased flood risk?. • Economic outlook be if biodiversity changed as a result of city or industry change?

Earth Systems	• Hydrodynamics (e.g., water levels, waves, river run-off), nearshore bathymetry and topography, 3D LCLU (land cover use) • Water color and quality, bathymetry, seabed, algae, foreshore vegetation, biodiversity, LCLU near the coast. • Land surface, hydrology, lakes, rivers, ocean, estuary, water quality models and products • Ocean (sea-level, water quality, tides), atmosphere (storms and extreme rainfall), and land (vertical land movement, LCLU, and shoreline change) • Ecology; Climate; Weather; Hydrology; Socio-economic
Human Systems	• Human systems involved in the CZDT (infrastructure, agriculture, power, etc.) • In-situ observations, socio-economic data, local/governmental data, model outputs
Resources	• Remote sensing missions/instruments : Landsat 8-9, Copernicus/Sentinel-1-2-3, Harmonized Landsat/Sentinel (HLS), SWOT, CFOSAT, Optical Very High Resolution (VHR) (Pleiades, Pleiades-NEO, MAXAR, Planet,…), ICESat 2, GEDI, VIIRS, DESIS, Airborne systems (e.g., NAIP, GLiHT, UAVSAR, AVIRIS-NG), etc. • Variables LCLU (built-up area, vegetation, natural habitat), precipitation, groundwater, streamflow, soil moisture, snow, water (quality, temperature, seabed, land surface), Bathymetry-Topography continuum (Bathymetry, shoreline, OER - topographical data, IGN LIDAR-HD, digital elevation model, digital terrain model), ecological (marine and terrestrial biodiversity, habitats), • In-situ : IoT flood sensors, tidal gages, networks, Surface truth • Socio-economic and local/governmental data : social (population), infrastructures (ports/harbors/seawalls), in situ assets, protected areas, building-parcel fabric • Models and derived data : sea level rise/change and flood models, climate/weather data and projections (precip/wind speed/temp/storm surge), oceanographic (tide, current, wave height), agriculture, forest, marsh, blue carbon ecosystem models/ changes in species, biodiversity, biomass, productivity . • Future-focused decision support systems (e.g.,Geodesign)

Reference: October 2022 ESDT Workshop Report https://esto.nasa.gov/files/ESDT_Workshop_Report.pdf