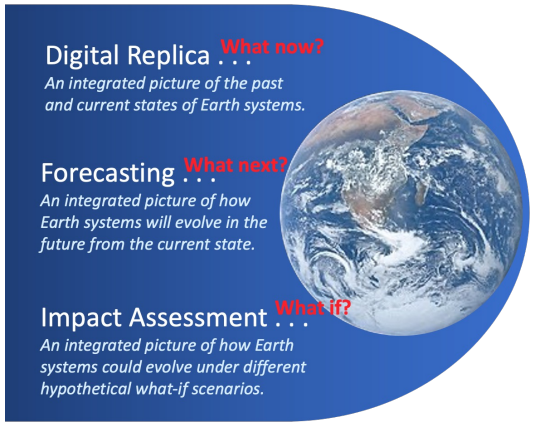
TIE02. IGARSS'2024 Townhall on "Digital Twins for Earth Science"

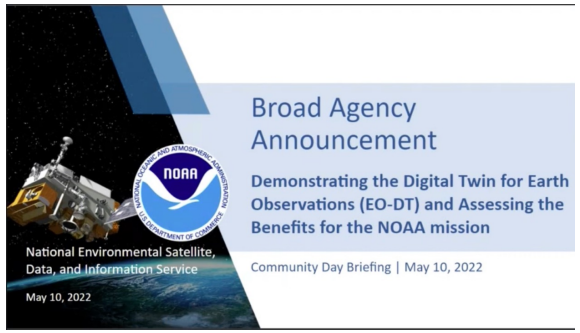


Jacqueline Le Moigne/NASA

Claudia Vitolo/ESA

Simon Baillarin/CNES

Sean Helfrich/NOAA



Townhall Objectives

NASA, ESA, NOAA, CNES and other international organizations have started programs to design and develop Digital Twins of the Earth and/or Earth systems.

We all have slightly different definitions of what these Digital Twins are, but all of them share **three main objectives**:

1. Monitor and understand the Earth
2. Anticipate the future and especially extreme events
3. Explore various scenarios to prevent or mitigate the effects of these events and of climate change.

This Townhall will:

- Provide a status of Destination Earth
- Provide a status of ESA's, NASA's, CNES's and NOAA's current independent and common efforts in Digital Twins
- Provide information about community building
- Engage in a dialogue about Digital Twins of the Earth with the IGARSS community.

Townhall Agenda

- **Claudia Vitolo/ESA (13:45-13:55)**
  "Status – Destination Earth (DestinE) and ESA Digital Twins of the Earth (DTE) Programs"
- **Jacqueline Le Moigne/NASA (13:55-14:05)**
  "Status – NASA AIST Earth System Digital Twins (ESDT) Program"
- **Simon Baillarin/CNES (14:05-14:15)**
  "Status CNES Data Campus Digital Twin Factory"
- **Sean Helfrich/NOAA (14:15-14:25)**
  "Status NOAA's EO-DT Program"
- **Thomas Geenen/ECMWF (14:25-14:35)**
  "DestinE Status and Latest Developments"
- **Sid Boukabara/NASA (14:35-14:45)**
  "Future NASA Digital Twin Developments "
- **NASA + NOAA + CNES (14:45-14:55)**
  "Coastal Zone Digital Twin"
- **Jacqueline Le Moigne, Claudia Vitolo, Simon Baillarin and Sean Helfrich (14:55-15:05)**
  "Community Building"
- **GENERAL DISCUSSION (15:05-15:20)**

Jacqueline Le Moigne/NASA

Status – AIST Earth Systems Digital Twins (ESDT)

Earth Systems 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 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 Earth System Digital Twin or ESDT is a dynamic and interactive information system that first provides a digital replica of the past and current states of the Earth or Earth system, as accurately and timely as possible, second allows for computing forecasts of future states under nominal assumptions and based on the current replica, and third offers the capability to investigate many hypothetical scenarios under varying impact assumptions.

=> What Now? What Next? What If?

An ESDT includes:

- Continuous observations of interacting Earth & human systems
- From many disparate sources
- Driving inter-connected models
- At many physical and temporal scales
- With fast, powerful and integrated prediction, analysis & 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

What is Different about ESDTs?

1. **Continuous integration** of timely data (real- or near-real-time for some applications, “timely for others)

2. **Interactivity** with users => “playing with the models and the data” for policy/decision making and conjecturing/planning

3. Integration of anthropomorphic forcing and **impact models**

4. Heavy use of **Machine Learning**
   - Data Fusion and Data Assimilation
   - Super-Resolution/Downscaling
   - Speeding up models => higher spatial and temporal resolution possible
   - Causal Reasoning

NASA Earth Science to Action (ES2A)

NASA's Earth Science to Action strategy aligns our assets to provide actionable information for a wide range of actors and decision-makers, and to do so for a variety of impactful areas identified for their strategic importance to national and international priorities.

https://science.nasa.gov/earth-science/earth-science-to-action/

Objectives:

Objective 1: Holistically Observe, Monitor, and Understand the Earth System

Objective 2: Deliver Trusted Information to Drive Earth Resilience Activities

NASA ESDT Activities

- **2022:** AIST-21 => 16 ESDT Projects
- **2022:** ESDT Workshop and Report
- **2023:** ESDT Architecture Framework Document
- **2023:** ESDT Standards for Interoperable Digital Twins Workshop
- **2023:** 6 Use Cases (2 additional in development)
- **2023 – 2025:** Inter-agency/International Coastal Zone Digital Twin pathfinder activity
- **2024 – 2027:** AIST-23 => Advanced technologies + 2 or 3 end-to-end prototypes
- **Collaboration** with NOAA, ESA, DestinE/ECMWF and EUMETSAT, CNES
- **Community Outreach:** Invited Sessions at AGU and IGARSS; IGARSS multi-org townhalls

ESDT Initial 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 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 Digital Twin	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.

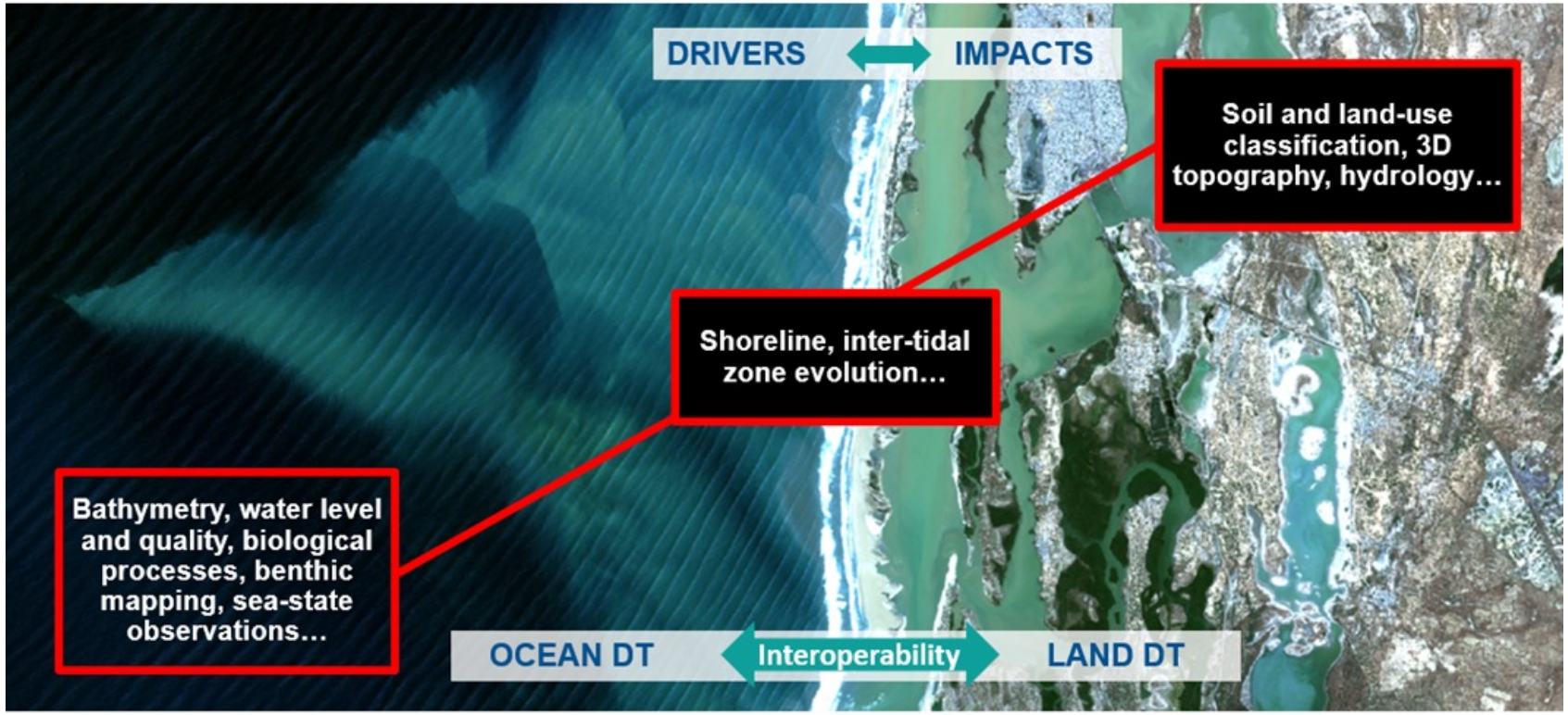
Coastal Zone Digital Twin (CZ-DT)

SCOPE: An Earth System Digital Twin of local and regional coastal zones considering 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.

What is the effect/impact of changing climate on coastal environment under various sea level and storminess scenarios?

What would be the economic health changes if flood risks were lowered? Increased?

What are the shifts in phytoplankton types under different natural/human forcings with improved HAB forecasting?



What would be the water quality changes under different water management structures/policies?

What are the impacts of management on blue carbon ecosystems to support climate mitigation and adaptation and improve resiliency to climate impacts?

What would be the changes in ecological makeup if cities reacted to increased flood risk?

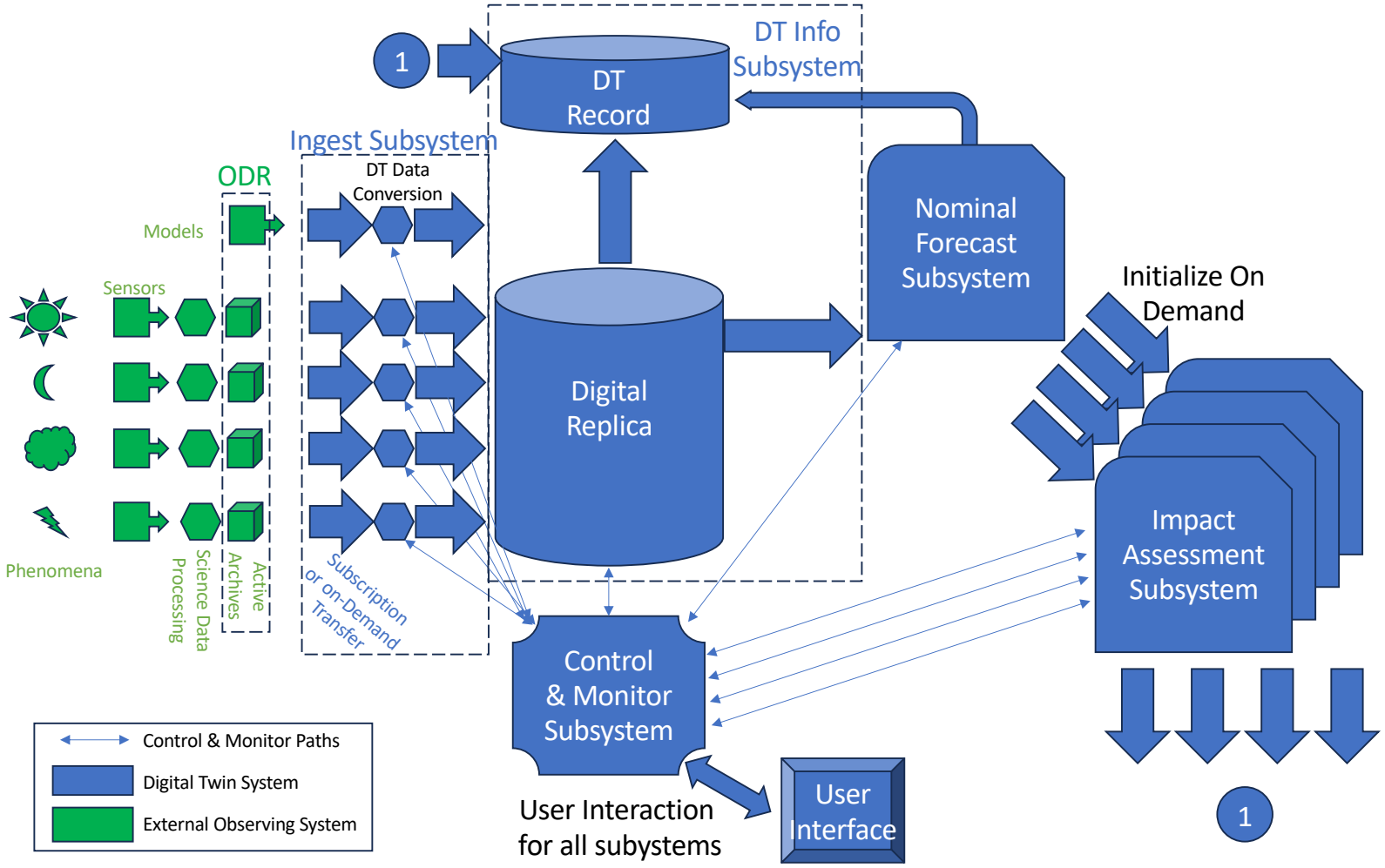
What would the economic outlook be if biodiversity changed as a result of city or industry change?

How can we support cities to mitigation if flood risk increased?

What would be the flood risk changes if global temperature goals were met? Not met ?

ESDT Architecture Framework

An ESDT architecture must consider the full range of components and their relationships

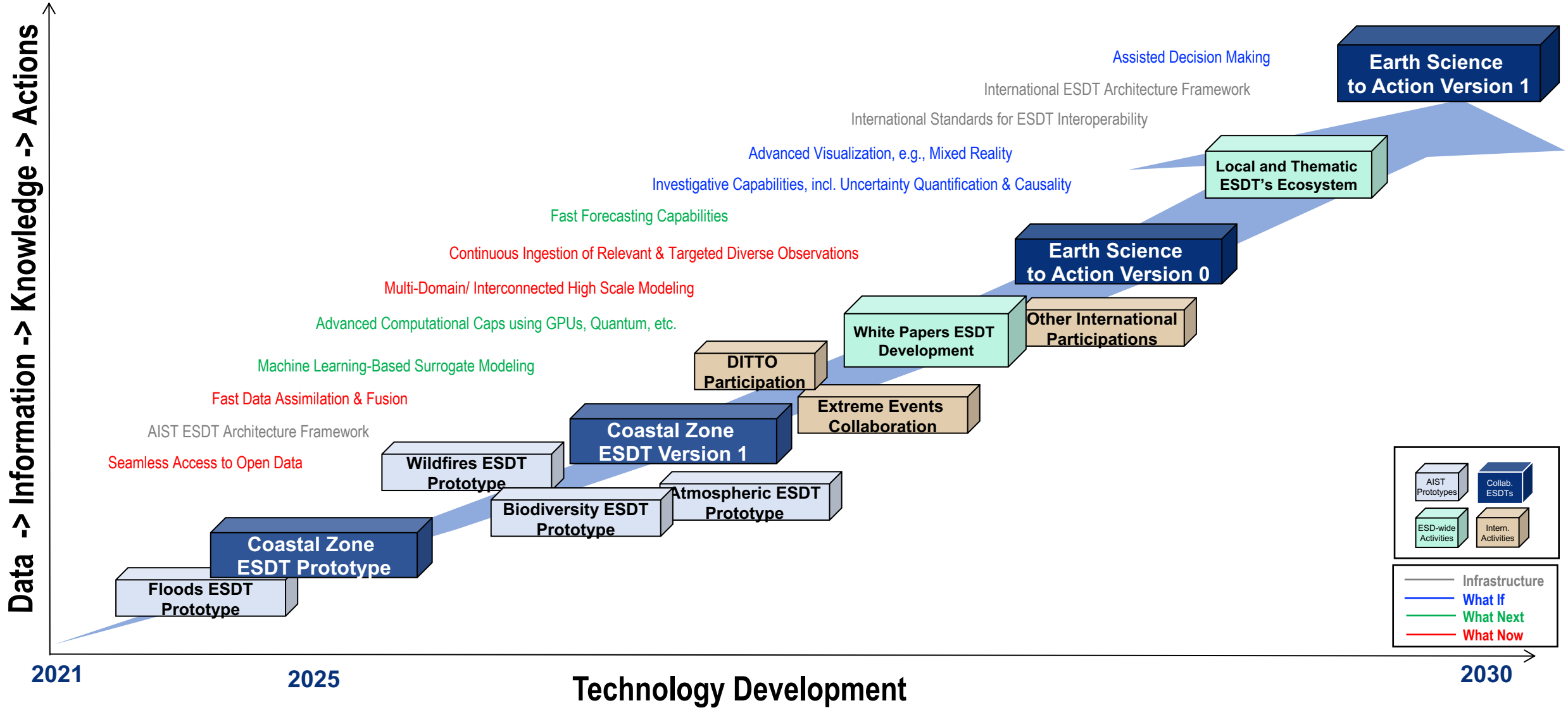


Functional components:

- Observational Data Repository (ODR)
- Ingest Subsystem (ISS)
- DT Information Subsystem (DISS)
- Nominal Forecast Subsystem (NFSS)
- Impact Assessment Subsystem (IASS)
- Control and Monitor Subsystem (CMSS)
- User Interface Subsystem (UISS)

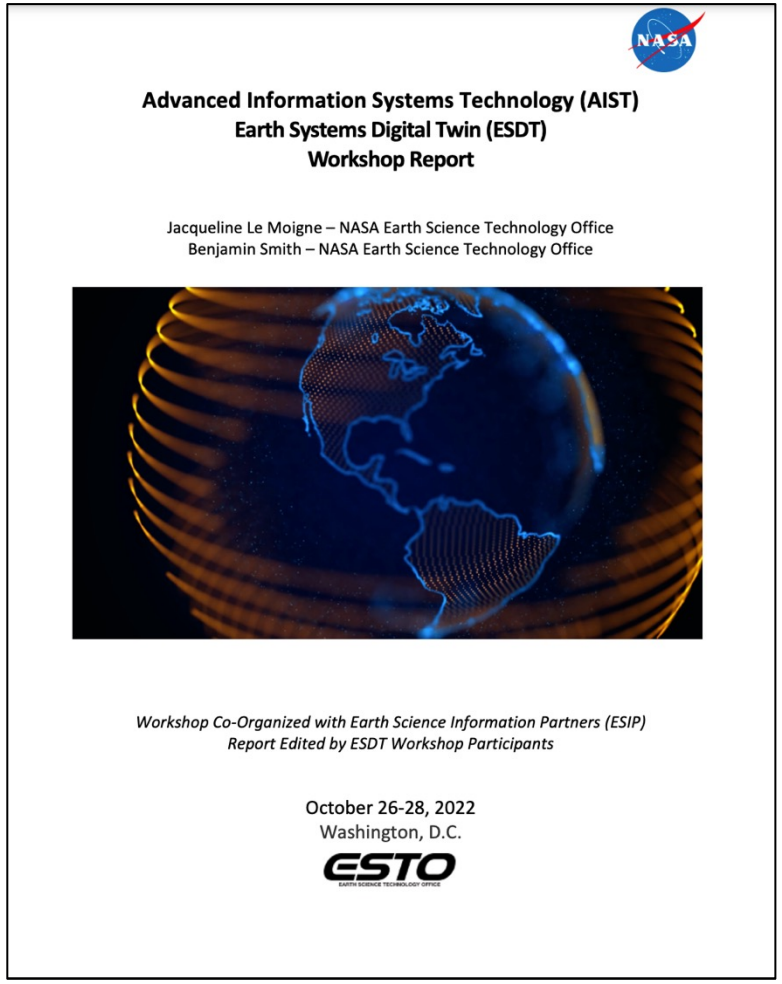
Architecture design may combine components or group them differently

AIST ESDT Roadmap



NASA AIST ESDT Reference Documents

ESDT Workshop 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

Jacqueline Le Moigne – NASA Earth Science Technology Office
Benjamin Smith – NASA Earth Science Technology Office

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

October 26-28, 2022
Washington, D.C.

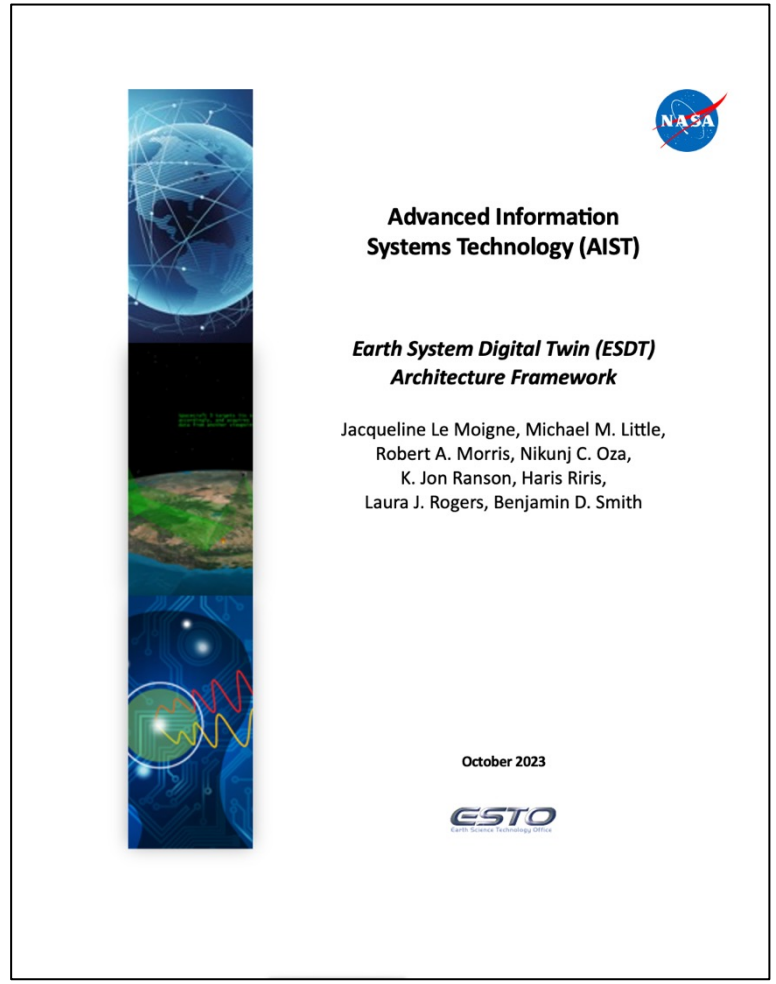
ESTO

Standards for Interoperable Digital Twins Workshop

September 18, 2023

- Presentations: https://esto.nasa.gov/files/AIST/ESDT%20Standards%202023.pdf
- Video: https://www.youtube.com/watch?v=qdpL0Ui-jqc

Document available
on AIST Website:
https://esto.nasa.gov/files/AIST/ESDT_ArchitectureFramework.pdf



Advanced Information Systems Technology (AIST)

Earth System Digital Twin (ESDT) Architecture Framework

Jacqueline Le Moigne, Michael M. Little,
Robert A. Morris, Nikunj C. Oza,
K. Jon Ranson, Haris Riris,
Laura J. Rogers, Benjamin D. Smith

October 2023

ESTO

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Coastal Zone Digital Twin (CZ-DT)

Historical Background

NASA/AIST

NOAA

CNES/JPL Collaboration as a data science technical exchange

FloodDAM as a generalization of FloodML

Developed under the SCO umbrella

Extending FloodDAM to a joint CNES/AIST Earth System Digital Twin (ESDT)

Coastal Zone Digital Twin (CZ-DT), tri-organization – NOAA/CNES/AIST

2017 – 2019
FloodML

Algorithms for Flood Detection using Machine Learning (ML) on satellite and in-situ data.

2020
FloodDAM

Augmenting FloodML with new, higher resolution data sources and better interconnecting the French and US systems. Demonstrated high potential for using space data to monitor floods.

2022-2024
IDEAS / FloodDAM DT

Federated Digital Twins – AIST-funded Integrated Digital Earth Analysis System (IDEAS) + CNES-funded FloodDAM DT. Dynamically connecting existing models and data from both organizations for large-scale flood understanding and prediction with local-scale simulations.

2023
CZ-DT

Initially developing a comprehensive science use case summarizing the objectives of a Coastal Zone Digital Twin. Will be followed by architecture design and implementation plan, including roles and responsibilities of the 3 organizations.

Funded independently by (1) CNES& SCO (2) NASA and (3) NOAA

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Coastal Zone Digital Twin (CZ-DT) "Grand Vision"

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?

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Coastal Zone Digital Twin (CZ-DT) "Grand Vision"

Earth Systems	• Hydrodynamics (e.g. water levels, waves, river run-off), nearshore bathymetry and topography, landuse and cover in three-dimensions. • Water color and quality, bathymetry, seabed, algae, foreshore vegetation, biodiversity, land use and cover 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, LULC, and shoreline change) • Ecology; Climate; Weather; Hydrology; Socioeconomic
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 : Land cover/land use (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)

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CZ-DT Grand Vision Main Elements

Coastal zones → **Local and regional** → **Land and marine** → **Natural and human systems**

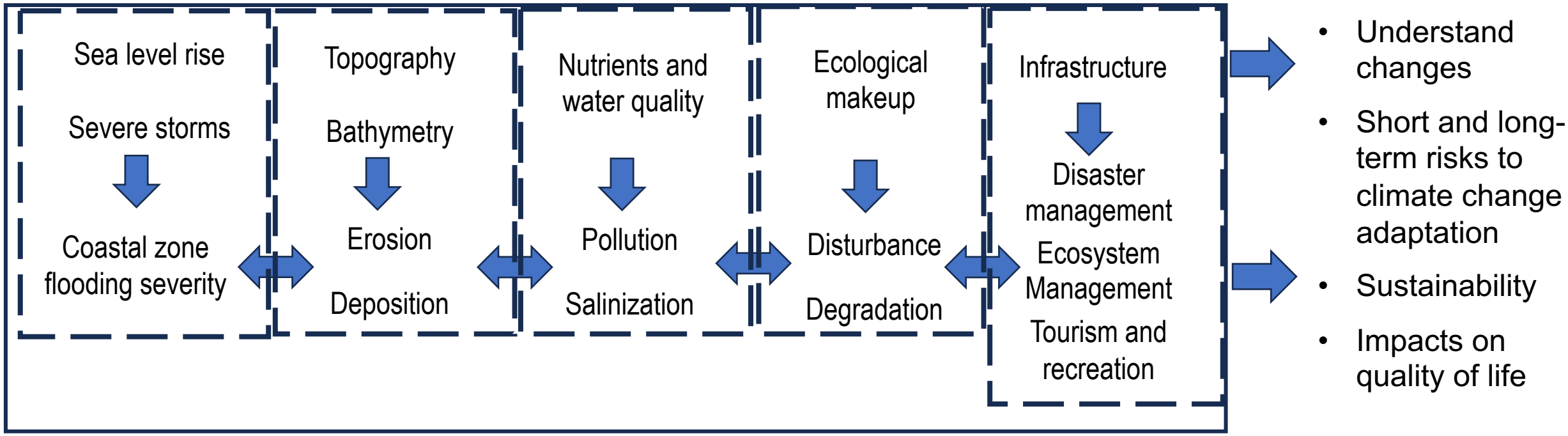

Diagram of Essential Elements of the Coastal Zone Digital Twin Use Case

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CZ-DT Personas

Use cases envision how users will interact with the CZDT from the perspective of these three user personas.

Farmer (Aquaculture)

City Planner/ Resource Manager

Scientist

	Concerns		Concerns		Concerns
What now	Growing conditions		Monitor impact of events on city/facilities, effect of responses.		Monitor events from multiple sources.
What next	Forecasts, crop yield predictions		Understand predicted risks and actions in the near to medium term.		Understand causes, predict events, improve models.
What if	Planting choices, field interventions		What are longer term risks, and how will mitigation options reduce them?		Understand causes, effectiveness of mitigations.

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CZ-DT Use Cases

Credit: USGS ERROS, Landsat 8

https://landsat.gsfc.nasa.gov/article/satellites-on-toxic-algae-patrol/

Harmful Algal Blooms (HABs)

Credits: U.S. Department of Defense, Air Force Senior Master Sgt. Michael Davis

https://appliedsciences.nasa.gov/what-we-do/disasters/disasters-activations/vermont-flooding-july-2023

Urban Flooding

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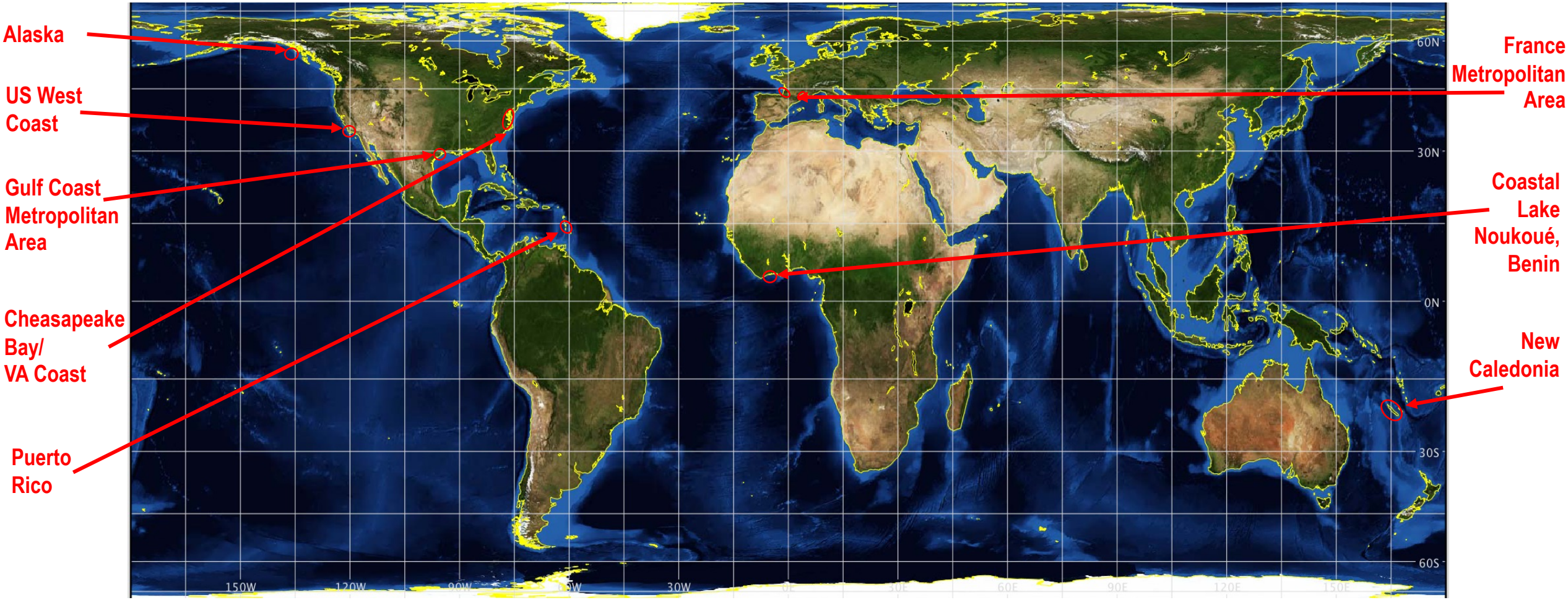
CZ-DT Potential Regions of Interest



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CZ-DT Current Timeline

- 01/06/2023: Study Start
- January to March 2023: Review of relevant projects from the 3 organizations
- March to June 2023: Identification of Science Use Cases and Definition of CZ-DT Scope
- July to October 2023:
  - Selection of appropriate study sites (“Regions of Interest (ROI’s)”)
  - Identification of data and models relevant to initial prototypes
- November 2023 to February 2024:
  - Architecture Framework development (report)
  - Preliminary use cases and personas defined
  - February 25, 2024: CZ-DT Architecture Workshop
- March to July 2024: Digital Replica/Ingest Subsystem White Papers
  - White Papers Review; implementation steps identified
  - Definition of project organization
  - Selection of Technical PI, Science PI and Technical Leads
- Next Steps:
  - August 2024: Project Kick-off
  - August 2025: First prototype implementation and demonstration with limited capabilities
  - 2027: First CZ-DT beta version

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Community Building: How to get involved?

(1) IGARSS'24 DEDICATED EVENTS:

In response to SP.4: Leveraging the Destination Earth and Digital Twins paradigms Leveraging the big multi-sensor data and cloud platforms using the paradigms of Destination Earth and Digital Twins, to deploy scalable applications in the support of science and markets across sectors.

- **Data Fusion Subcommittee – Data Fusion Contest** Proposal by CNES and AIST (Fusion for Digital Replicas):
  - https://ieee-dataport.org/competitions/2024-ieee-grss-data-fusion-contest-flood-rapid-mapping
  - IGARSS'24 Sessions:
    - CCS.55: IEEE GRSS Data Fusion Contest - Track 1
    - CCS.56: IEEE GRSS Data Fusion Contest - Track 2

- **Digital Twin Sessions:**
  - CCS.10: Advancing Earth System Digital Twins for Informed Decision Making (FRI1.R11 & FRPA.PA)
  - CCS.33: Digital Twins in Europe, looking at challenges and opportunities in interoperability
  - CCS.5: Advanced Strategies for Measurement- and Event-Driven Earth Observations (TU1.R15)
  - *CCS.37: Explainable, Physics-aware, and Trustworthy AI for SAR: Towards Digital Twin Earth (TH3&TH4.R11)*

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Community Building: How to get involved?

(2) OTHER DEDICATED EVENTS:

- **AGU - December 2024 – Washington, DC (USA)**
  Digital Twins- Related Sessions:
  - ***Advanced Digital Twin Information Systems and Earth Action***
    Session IN003 or Session ID: 228347
  - ***Novel Observing Strategies for a Changing Planet***
    Session IN034 or Session ID: 227386

- **EGU – April 2025 – Vienna (Austria)**
  Digital Twins- Related Sessions (proposals to be submitted)

- **Future Topics** for Data Fusion Contest or Other Hackathons or Challenges?

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Community Building: How to get involved?

(2) INTEROPERABILITY AND STANDARDS (Coordinating with these consortia):

- ESIP – January 2025 meeting (virtual) & July 2025 (Seattle, US): https://www.esipfed.org/meetings
- OGC – OGC Member Meeting/November 2024 (South Korea/hybrid): https://www.ogc.org/events/
- Digital Twin Consortium – https://www.digitaltwinconsortium.org/
- **IEEE –** Newly established Industry Connections Group "**Digital Twin of the Earth – Tools and Resources for Interoperable Development and Operations**"

(3) FUNDING OPPORTUNITIES:

- **NASA:**
  - **Solicitation** AIST-23 (Being Selected) => Next Solicitation AIST-25 or -26; AMT-25?
  - **Joint Solicitation** with Land Cover Land Use Change Program: LCLUC-24
  - Other future **Solicitations related to the Earth Action Initiative**
  - **See ROSES** website: **https://nspires.nasaprs.com/external/** for current open solicitations

  - **NASA Small Business Innovation Research (SBIR)**
    - **SBIR TOPIC S17 on Crosscutting Information Technologies** – Titles might change in 2025:
      - **S17.01** "Technologies for Large Scale Simulations"
      - **S17.04** "Application of Artificial Intelligence for Science Modeling and Instrumentation"
    - **New solicitation release in January 2025**: https://sbir.nasa.gov/

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IGARSS Community

Dialogue – Questions and Answers

- What are the benefits of Earth System Digital Twins (ESDT) to Earth Science?
- How do we effectively translate ESDT data into actionable information?
- How will interoperability work? Which kind of interoperability? Data? Models? Outputs of ESDT? How will we federate future ESDT?
- How do we ensure long-term sustainability of ESDT, given the ever-growing demand of resources and variety of approaches?
- How to best engage with the various community? What is the role of industry in shaping ESDT?
- How do we ensure the complexity of the system does not hinder use by less-technical users?
- What is the role of Machine Learning for ESDT?
- What is the role of Open Science for ESDT?
- How do we validate ESDT (e.g., using historical data, etc.)? How to quantify uncertainty?


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