Earth System Digital Twins (ESDT) Workshop

Jacqueline Le Moigne
Earth Science Technology Office (ESTO)
Advanced Information Systems Technology (AIST)

October 26, 2022

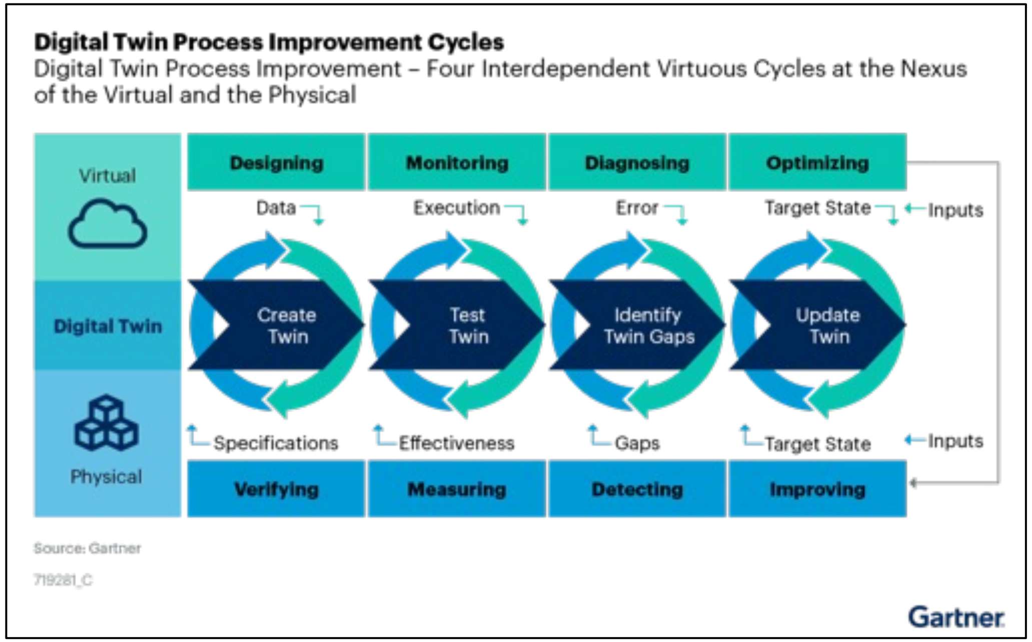
"Digital Twin" is not a new concept

- **2002:** Digital Twin concept introduced by Michael Grieves et al. at a *Society of Manufacturing Engineers* conference as a conceptual model underlying Product Lifecycle Management (PLM).

- **2010:** Digital Twin introduced to NASA by John Vickers in a *2010 Technology Roadmap*.
  A Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin.

- **2020:** IBM definition –
  A Digital Twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making.

- Adopted and used by aerospace and automotive industry



Evolution of Digital Twins

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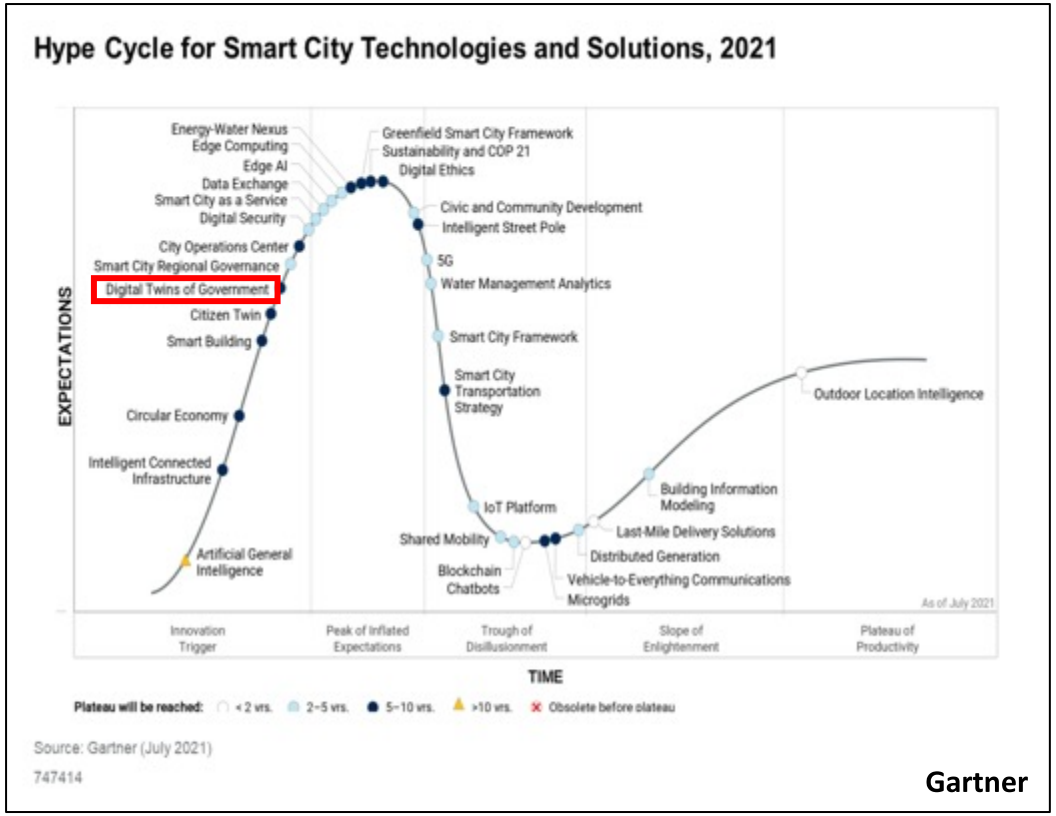
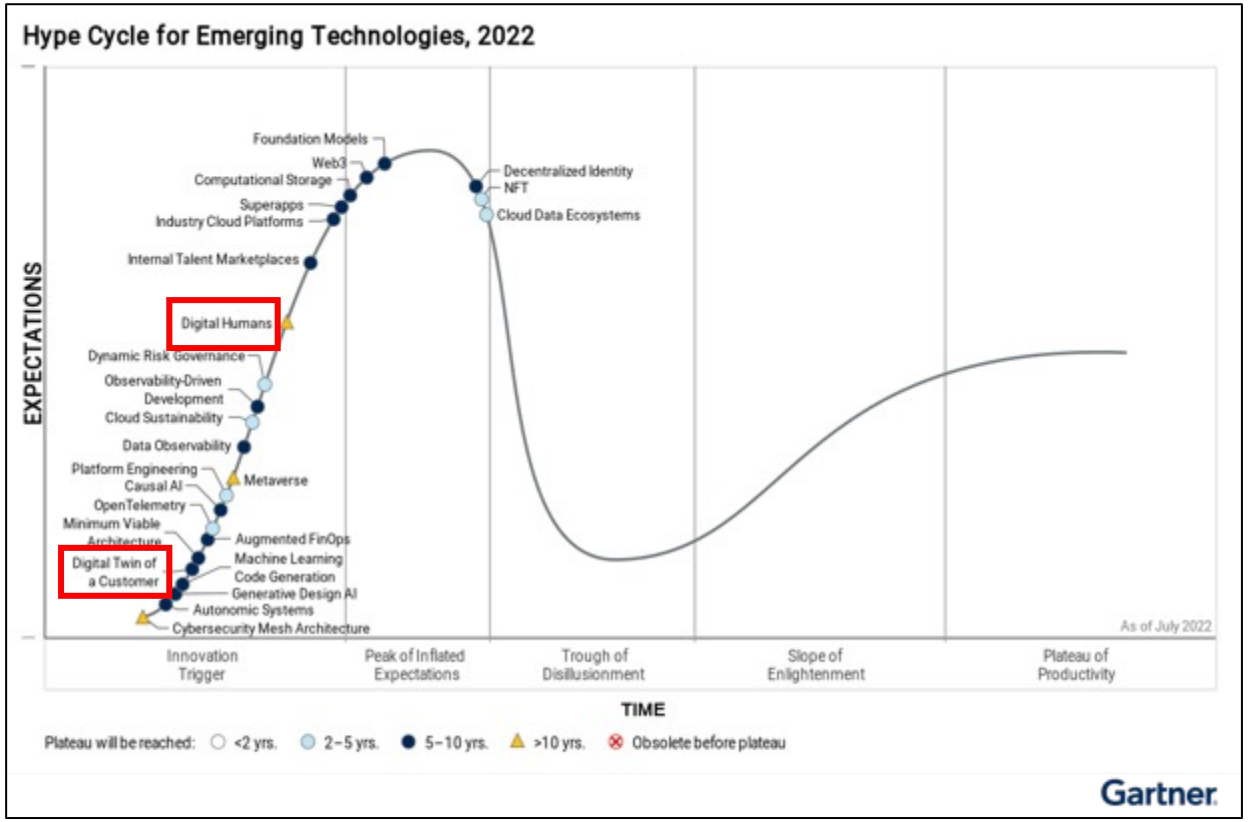
- **2018 + :** Digital Twins move from manufacturing to other domains, e.g., Infrastructure & Urban Development and Health





Digital Twins in Earth Science

- **2020/Loekken, Le Saux & Aparicio-ESA**
  A dynamic interactive replica of the past, present and future of our planet in the digital domain based on an effective integration of observations (satellite, in-situ, IoT and socioeconomic data), Earth-system science and simulations, the bridge to impact sectors science and simulations and artificial intelligence methodologies

- **2020/Bauer-ESA**
  A digital twin of Earth is an information system that exposes users to a digital replication of the state and temporal evolution of the Earth system constrained by available observations and the laws of physics.

- **2021/ECMWF-DestE Position**
  A digital twin is a digital replica of a living or non-living physical entity. The digital twins created in DestinE will give expert and non-expert users tailored access to high-quality information, services, models, scenarios, forecasts and visualisations. This includes models of the climate, weather forecasting, hurricane evolution and more. Digital twins rely on the integration of continuous observation, modelling and high-performance simulation, resulting in highly accurate predictions of future developments.

- **2022/**https://www.esa.int/Applications/Observing_the_Earth/ESA_moves_forward_with_Destination_Earth
  Constantly fed with Earth observation data, combined with *in situ* measurements and artificial intelligence, the digital twins provide us with highly accurate representation of the past, present and future changes of our world.

Earth System Digital Twins (ESDT) in the AIST-21 Solicitation

AIST defines an Earth System Digital Twin (ESDT) as an interactive and integrated multidomain, multiscale, digital replica of the state and temporal evolution of Earth systems that dynamically integrates:

- Relevant Earth system models and simulations
- Other relevant models (e.g., related to the world's infrastructure); continuous and timely (including near real time and direct readout) observations (e.g., space, air, ground, over/underwater, Internet of Things (IoT), socioeconomic)
- Long-time records
- Analytics and artificial intelligence tools.

Effective ESDTs enable users to run hypothetical scenarios to improve the understanding, prediction of and mitigation/response to Earth system processes, natural phenomena and human activities as well as their many interactions.
An ESDT is a type of integrated information system that, for example, enables continuous assessment of impact from naturally occurring and/or human activities on physical and natural environments.

AIST ESDT strategic goals are to:

- Develop information system frameworks to provide continuous and accurate representations of systems as they change over time;
- Mirror various Earth Science systems and utilize the combination of Data Analytics, Artificial Intelligence, Digital Thread*, and state-of-the-art models to help predict the Earth's response to various phenomena;
- Provide the tools to conduct "what if" investigations that can result in actionable predictions.

* The digital thread designates the communication framework that links all digital twin data flow throughout its lifecycle.

Why a Workshop on Earth Systems Digital Twins (ESDT)?

- Bring together science and technology communities to explore the use and benefits of ESDT and their enabling technologies.
- Develop ESDT reference use cases and corresponding technology needs to guide the development of ESDT technologies that will be needed by NASA Earth Science within the next five to ten years.

WORKSHOP GOALS:

1. Identify driving Earth science use cases that will benefit from unique ESDT capabilities
2. Identify emerging technologies that will enable such ESDT systems within the next five to ten years
3. Understand opportunities and technologies for federating ESDTs and creating more capable systems

Earth System Digital Twins Components

Digital Replica . . .

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

Forecasting . . .

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

Impact Assessment . . .

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

- **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**

Earth System Digital Twins Components

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Digital Replica . . . What now?

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

Forecasting . . . What next?

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

Impact Assessment . . . What if?

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

- **Continuous observations** of interacting Earth systems and human systems
- From many **disparate sources**
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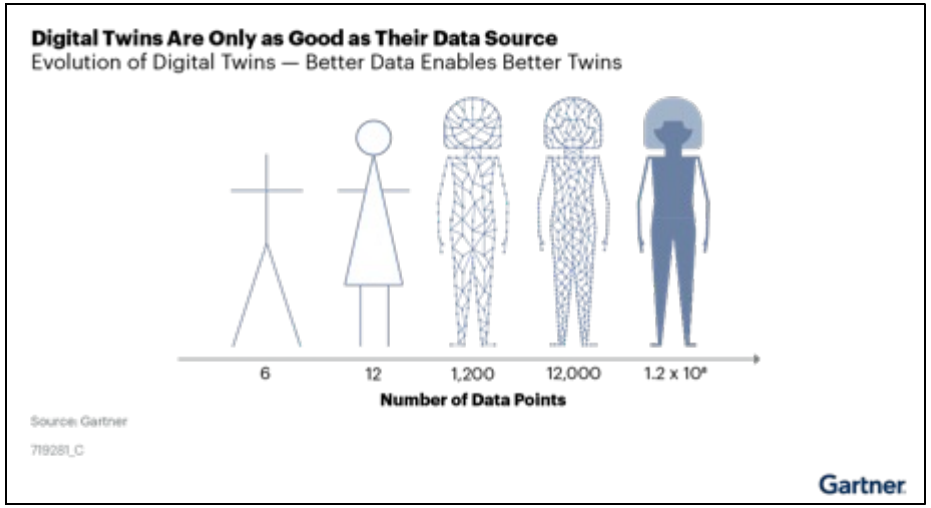
AIST ESDT Description

Multi-Domain/
Interconnected
High Scale
Modeling

AIST ESDT Description



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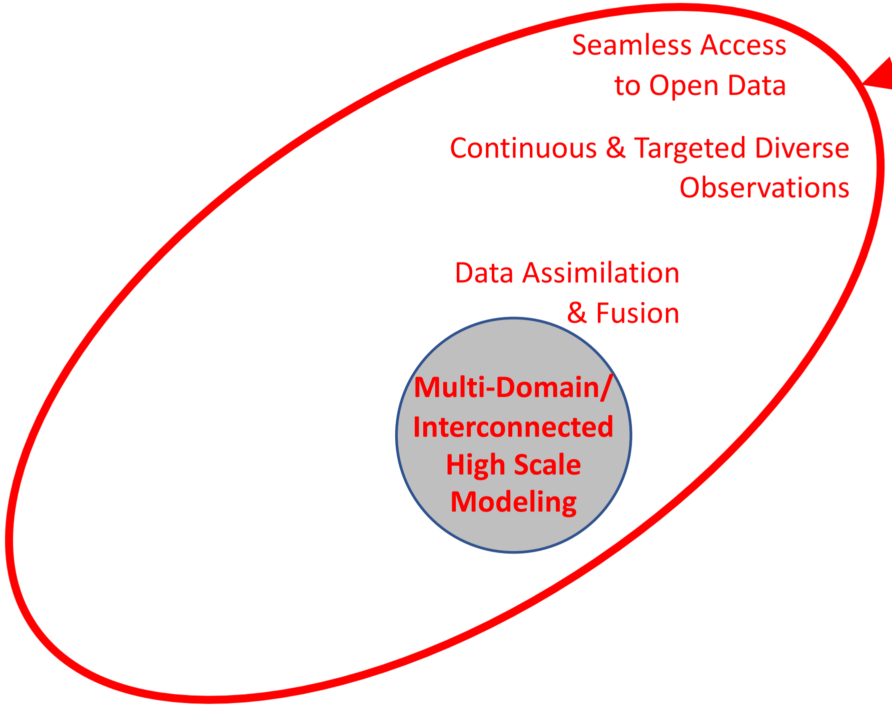
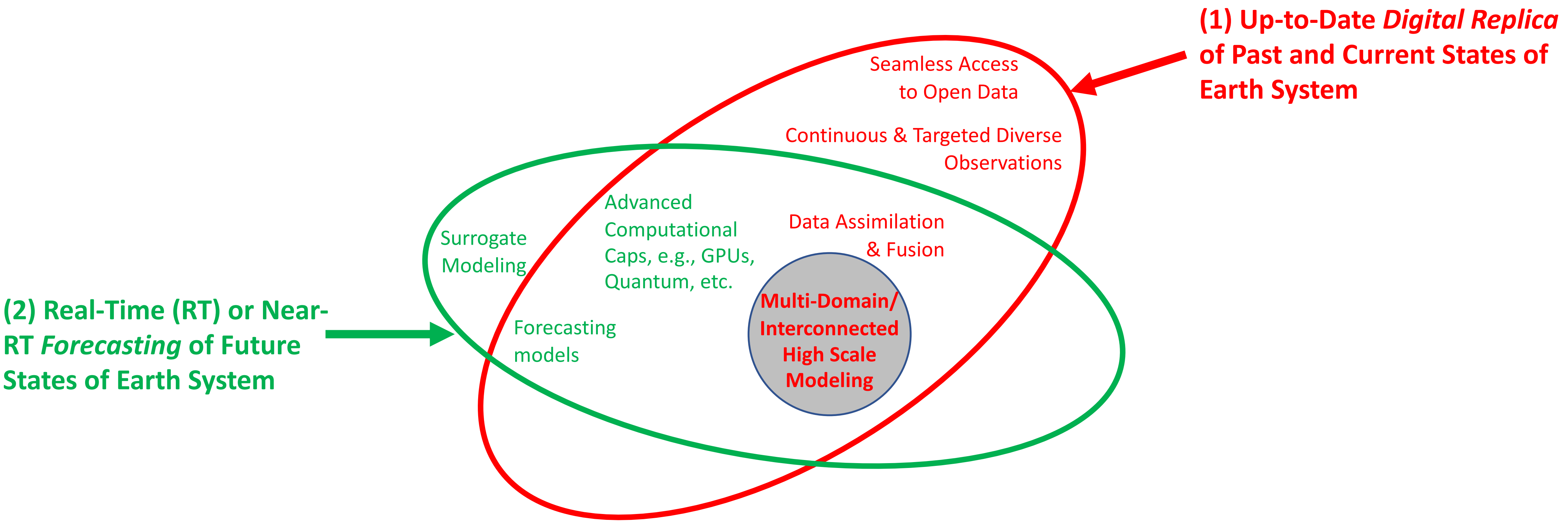


(1) Up-to-Date *Digital Replica* of Past and Current States of Earth System

AIST ESDT Description



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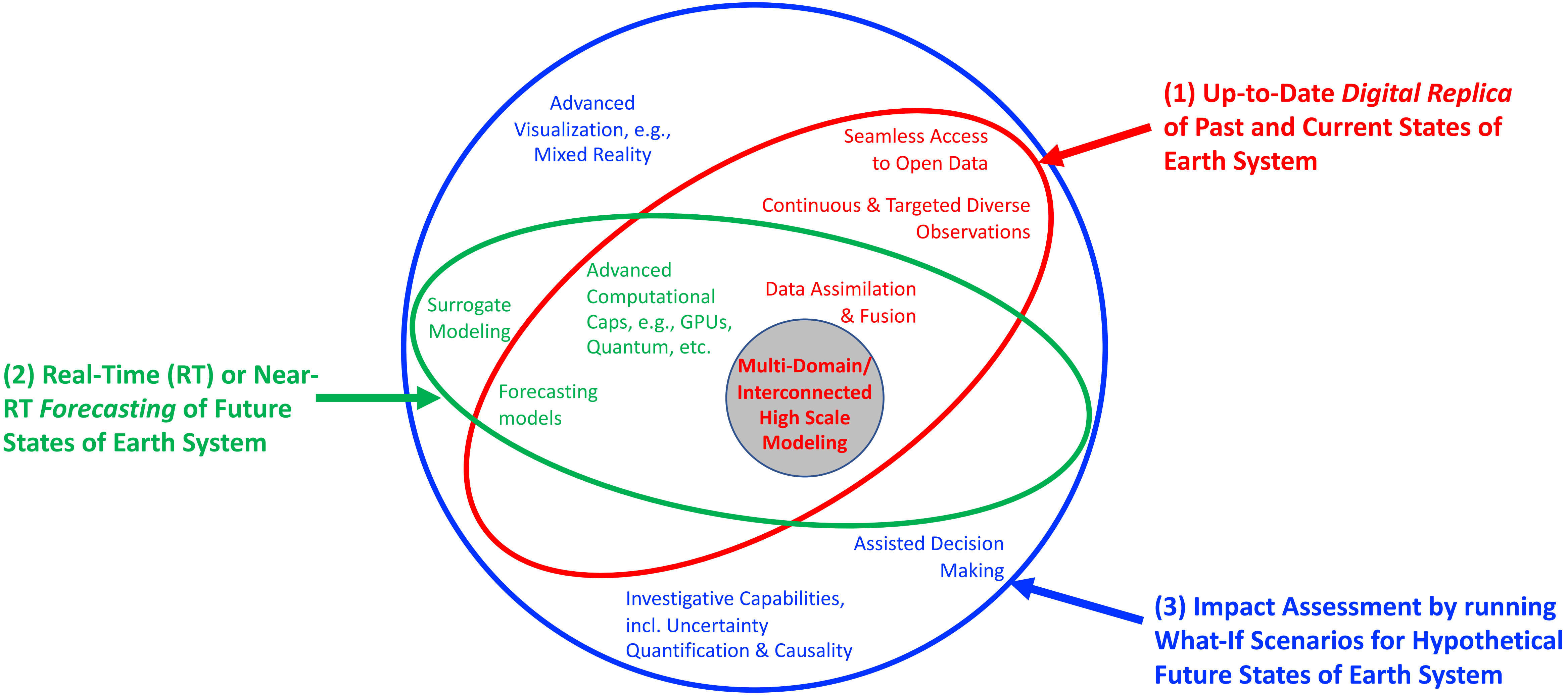

AIST ESDT Technologies

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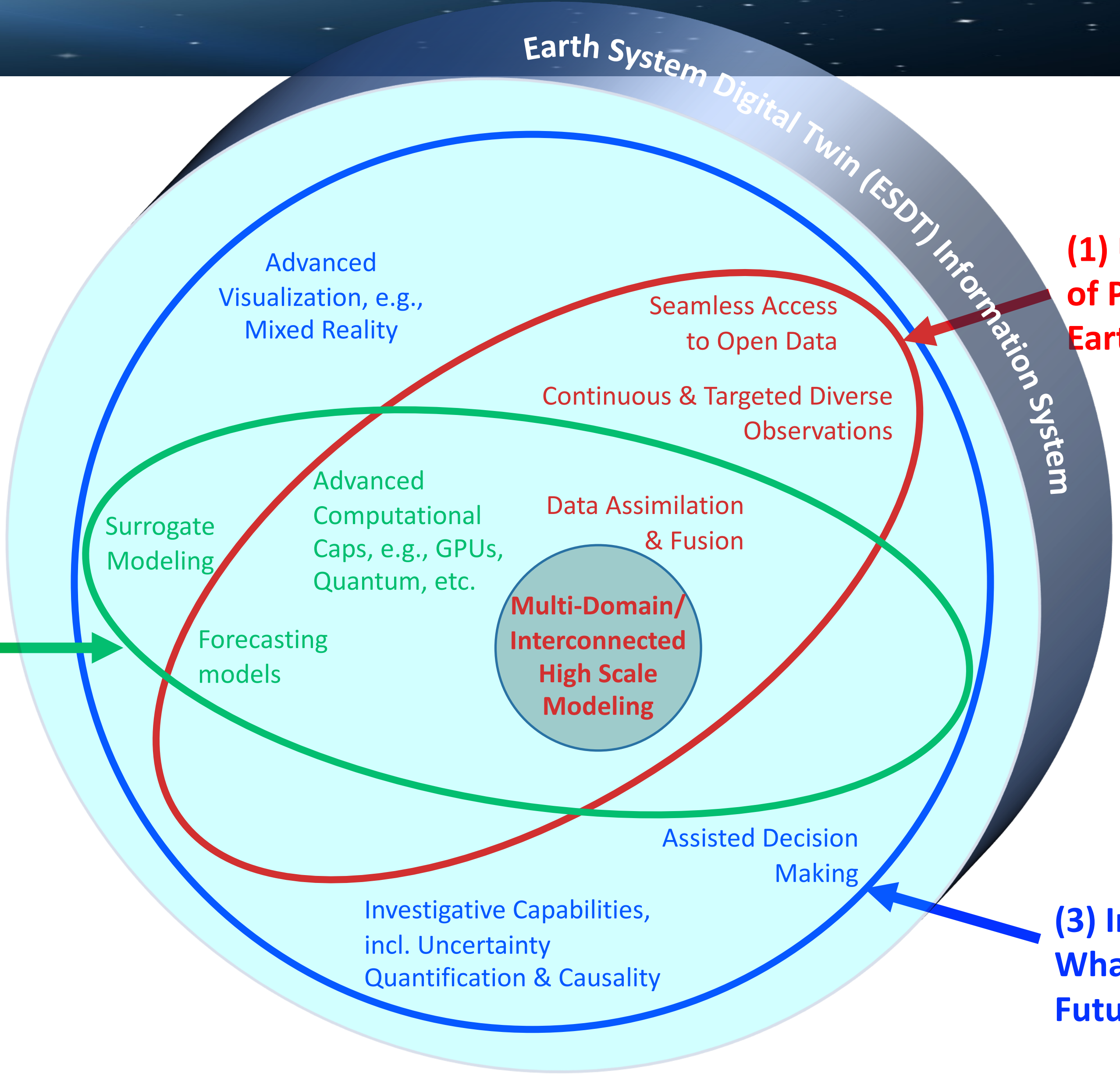


(1) Up-to-Date *Digital Replica* of Past and Current States of Earth System

(2) Real-Time (RT) or Near-RT *Forecasting* of Future States of Earth System

(3) Impact Assessment by running What-If Scenarios for Hypothetical Future States of Earth System

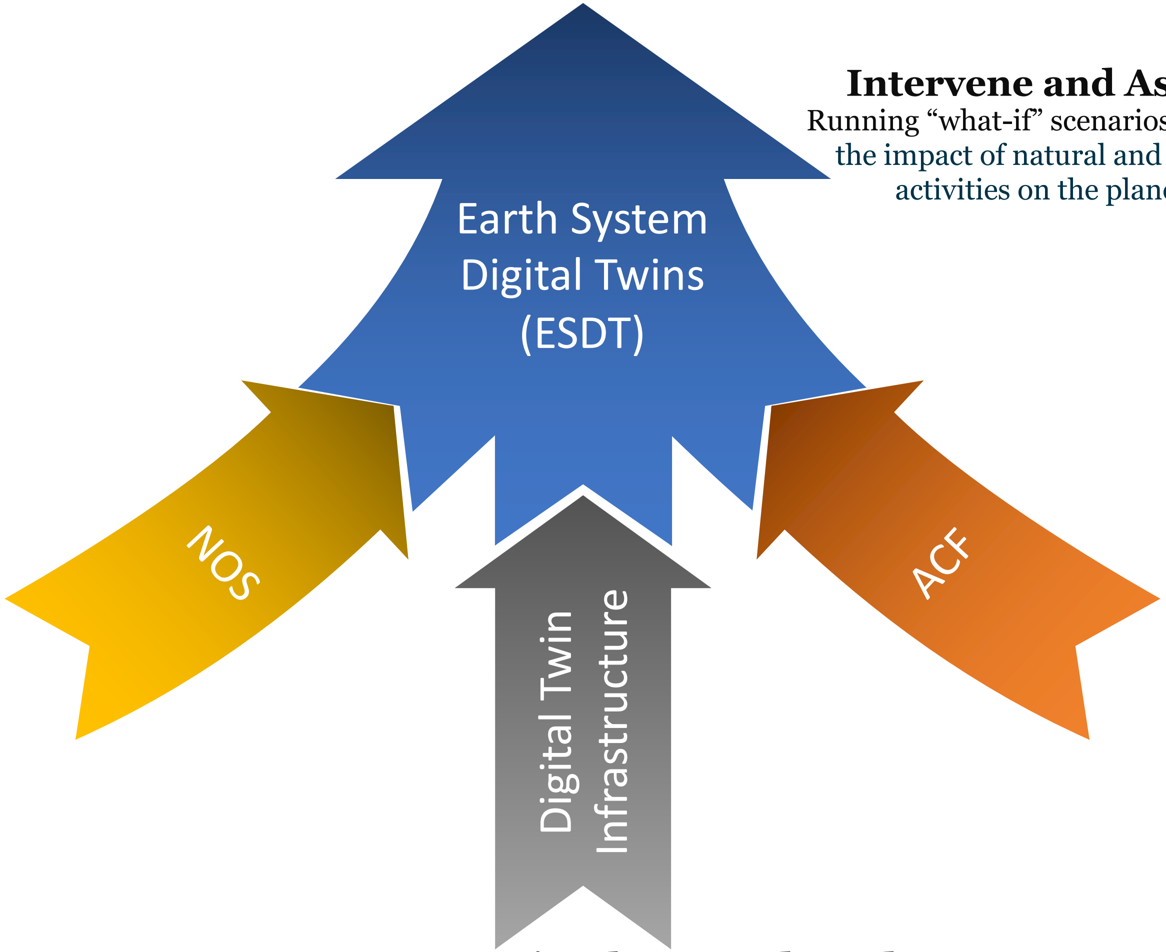
ESDT Technologies Requested in AIST-21

- Technologies for agile interaction and interoperability between measurement acquisition and science investigations
- Frameworks that enable data ingest from multiple, integrated models, and/or moving from mono-discipline to multi-discipline inter-related systems
- Leveraging of Model-Based System Engineering (MBSE) frameworks for the development and sustainment of ESDTs
- Digital Thread developments to link all digital twin capabilities (design, performance data, product data, operational status data, event status data), to enable design requirements, records, provenance, and system reorientations to be easily reviewed and address issues within the digital twin system
- Concepts and technologies for developing "federated ESDTs" in which multiple individual ESDTs interact and can be integrated as the layers of broader ESDTs
- Novel AI (not limited to ML) techniques enabling ESDTs
- Investigative technologies to facilitate "what-if" investigations inherent to ESDT systems

➔ 14 ESDT-Related Projects Selected:

- ESDT Infrastructure
- AI=Surrogate Modeling for ESDT
- Analytic Frameworks Development towards ESDT
- ESDT Prototypes

ESDT one of 3 AIST Thrusts



Intervene and Assess
Running "what-if" scenarios to assess the impact of natural and human activities on the planet.

Observe, Target and Coordinate
Edge and on-the-ground intelligent planning, evaluating, coordinating and operating collections of diverse and distributed observing assets

Fuse, Analyze, Share and Collaborate
Simplify access to diverse and large amounts of data, analytics & modeling tools and advanced computational resources for collaborative science

Interrogate, Simulate, Trade and Visualize
Robust tools for interrogating, assessing uncertainties & causality, and for visualization, leveraging diverse data, models and products

NOS = Novel Observing Strategies

ACF = Analytic Collaborative Frameworks

Workshop Goals:
Some Overarching Questions

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- What are Digital Twins?
- What are the benefits of ESDT to NASA Earth Science?
- What are the main differences between Earth System Models (ESMs) and Earth System Digital Twins (ESDT) (e.g., model resolutions, connection to impact models, overall interactive information system, others)? How can we integrate/coordinate ESMs with ESDT?
- What are the main architecture components of an ESDT? What could various ESDT architectures look like?
- Should we develop a common Digital Twin Engine?
- What are the AIST Technologies that need to be enhanced or developed?
- What is the role of Machine Learning for ESDT? What is the role of Open Science for ESDT?
- Which computational resources will be required? Cloud, GPU’s, Quantum, Neuromorphic, etc.?
- How will various data, models, ESDT interoperate? Which basic interfaces and standards will be required?
- How to prioritize “quick wins” (short-term prototypes) and incrementally enhance digital twin investments over time?
- How do we validate ESDT (e.g., using historical data, etc.)? How to quantify uncertainty?
- How will we federate future ESDT?
- Which sustainable digital twin governance model should be adopted to address software configuration changes, security and full life cycle management?

Workshop Agenda

https://esdt2022.sched.com/

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OCTOBER 26–28, 2022

WEDNESDAY October 26, 2022

9:30	10:00	Gathering	
10:00	10:30	Welcome Plenary	Jacqueline Le Moigne, AIST Susan Shingledecker, ESIP
10:30	11:30	Panel: Digital Twins for NASA Earth Science	
11:30	Noon	Interactive discussion	
NOON	1pm	LUNCH	
1:00	1:30	Earth system digital twins and the European Destination Earth initiative	Peter Bauer, ECMWF
1:30	2:30	Panel: Federating Earth System Digital Twins	
2:30	3:00	BREAK	
3:00	3:30	Global Digital Twin of the Earth System Environment in NOAA - for Monitoring and Prediction	Sid Boukabarra, NOAA
3:30	4:30	Panel: Technologies for Earth System Digital Twins	
4:30	5:00	Wrap up discussion	

THURSDAY Oct 27, 2022

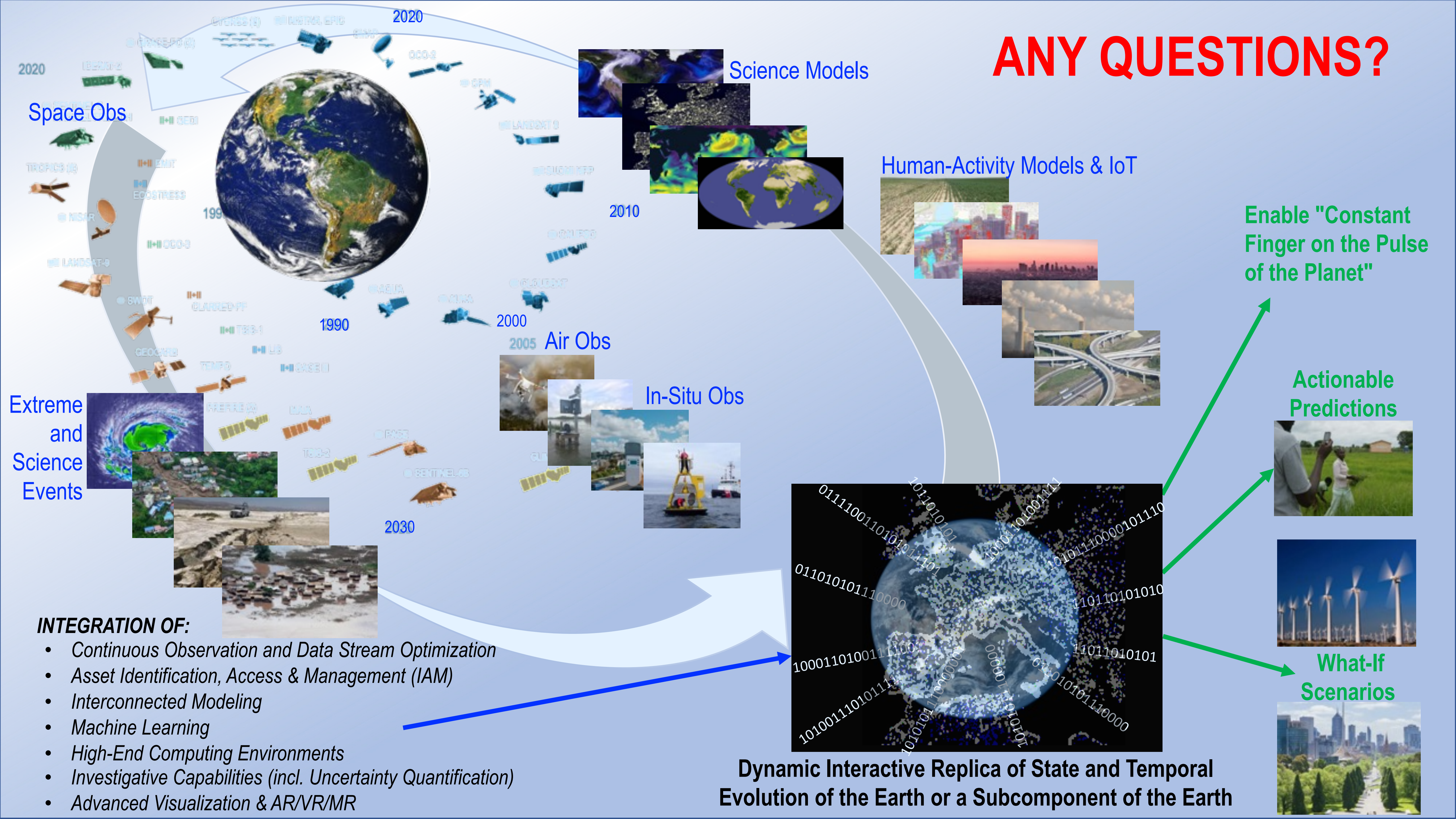
8a	8:30	GATHERING and Welcome
8:45	9:40	Lightning talks I
9:40	10:00	Science reference scenarios overview
10:00	10:30	BREAK
10:30	Noon	Breakout Session A: Science Use Cases
NOON	1pm	LUNCH
1:00	1:30	Session A Brief-outs
1:30	3:00	Lightning talks II
3:00	3:30	BREAK
3:30	5:00	Breakout Session B: Technologies and gaps
5:00	5:30	Session B Brief-outs
5:30		Adjourn for the day

FRIDAY Oct 28, 2022 (Half Day)

8a	8:30	Welcome/plan for the day
8:30	10:00	Breakout Session C: ESDT Systems Vision & Federation
10:00	10:30	BREAK
10:30	Noon	Session C Brief-outs
12:00	12:15	Wrap up
12:15		LUNCH / Adjourn

ESDT Science Use Cases/Scenarios

ESDT Domain	Abstract
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 (e.g., urbanization, land use change), to understand coastal ecological changes and impacts to ecosystem services; ocean, land, and atmospheric system to understand feedback processes, such as storm intensification and sea level rise, and their impact on coastal communities and the blue economy; assessing feasibility and impacts of the 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 the underlying processes and their relationship to climate and air quality, and 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.


ANY QUESTIONS?
Space Obs
2020
2020
2010
2000
1990
2005
2030
Science Models
Human-Activity Models & IoT
Air Obs
In-Situ Obs
Extreme and Science Events
Enable "Constant Finger on the Pulse of the Planet"
Actionable Predictions
What-If Scenarios
INTEGRATION OF:
• Continuous Observation and Data Stream Optimization
• Asset Identification, Access & Management (IAM)
• Interconnected Modeling
• Machine Learning
• High-End Computing Environments
• Investigative Capabilities (incl. Uncertainty Quantification)
• Advanced Visualization & AR/VR/MR
Dynamic Interactive Replica of State and Temporal Evolution of the Earth or a Subcomponent of the Earth

Backup

AIST-21 ESTD Awards

https://esto.nasa.gov/project-selections-for-aist-21

- **ESDT Infrastructure**

PI's Name	Organization	Title	Synopsis
Tanu Malik	De Paul University	Reproducible Containers for Advancing Process-oriented Collaborative Analytics	Aims to establish reproducible scientific containers that are easy-to-use and are lightweight. Reproducible containers will transparently encapsulate complex, data-intensive, process-oriented model analytics, will be easy and efficient to share between collaborators, and will enable reproducibility in heterogeneous environments.
Thomas Grubb	NASA Goddard Space Flight Center (GSFC)	Goddard Earth Observing System (GEOS) Visualization And Lagrangian dynamics Immersive eXtended Reality Tool (VALIXR) for Scientific Discovery	Proposes to develop a scientific exploration and analysis mixed augmented and virtual reality tool with integrated Lagrangian Dynamics (LD) to help scientists identify, track, and understand the evolution of Earth Science phenomena in the NASA GEOS model. It will provide both a scientific discovery tool and a model analysis and improvement tool.
Matthias Katzfuss	Texas A&M University (TAMU)	A scalable probabilistic emulation and uncertainty quantification tool for Earth-system models	Proposes to develop a fully automated toolbox for uncertainty quantification in Earth-system models, to provide insight into the largest and most critical information gaps and identify where potential future observations would be most valuable. It would allow interpolation between observed covariate values and running extensive what-if scenarios.
Thomas Clune	NASA Goddard Space Flight Center (GSFC)	A Framework for Global Cloud Resolving OSSEs	Will enable global, cloud-resolving Observing System Simulation Experiments (OSSEs) by addressing key computational challenges to enable existing technologies to scale to the spatial resolutions needed by the end of decade, e.g., extending parallel I/O capabilities, adopting a 2-phase Nature Run approach and a flexible API for customization.

AIST-21 ESTD Awards (cont.)

https://esto.nasa.gov/project-selections-for-aist-21

- **AI-Surrogate Modeling for ESDT**

PI's Name	Organization	Title	Synopsis
Allison Gray	Univ. of Washington, Seattle	A prototype Digital Twin of Air-Sea Interactions	Proposes to develop hybrid physics-informed AI model that ingests several existing flux estimates and observation data products and train against simultaneous ocean-atmosphere data from Saildrones. This will ascertain uncertainty of existing flux measurements and optimize combination of near-real-time existing flux data and observational data => This represents the first step towards a Digital Twin for the Planetary Boundary Layer.
Christopher Keller	Morgan State University (MSU)	Development of a next-generation ensemble prediction system for atmospheric composition	Proposes to develop a next-generation modeling framework for the real-time simulation of reactive gases and aerosols in the atmosphere. Will deploy computationally efficient parameterizations of atmospheric chemistry and transport and will develop generative models based on machine learning (ML) to predict model uncertainties.
Jouni Susiluoto	NASA Jet Propulsion Laboratory (JPL)	Kernel Flows: emulating complex models for massive data sets	Proposes a general-purpose, versatile emulation tool to provide fast, accurate emulation with little tuning, to scale up to very large training sets, and to provide uncertainties associated with outputs. This tool set will facilitate large-scale implementation of forward modeling and retrievals, and of UQ at production scales. To be applied to SBG radiative transfer emulation & convective storm nowcasting.

AIST-21 ESTD Awards (cont.)

https://esto.nasa.gov/project-selections-for-aist-21

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- **ACF Towards ESDT**

PI's Name	Organization	Title	Synopsis
Arlindo Da Silva	NASA Goddard Space Flight Center (GSFC)	An Analytic Collaborative Framework for the Earth System Observatory (ESO) Designated Observables	Will develop an Analytic Collaborative Framework for the Earth System Observatory (ESO) missions, based on realistic, science-based observing system simulations and the Program of Record (PoR), tied together in a cloud-based cyberinfrastructure. Create a 3D, holistic view of Earth with all ESO unique satellites.
Thomas Allen	Old Dominion University	Pixels for Public Health: Analytic Collaborative Framework to Enhance Coastal Resiliency of Vulnerable Populations in Hampton Roads, Virginia (VA)	Proposes to design and operationally demonstrate a system linking the VA Open Data Cube, a socio-spatial-health information “Digital Neighborhood” (Hampton Roads Biomedical Research Cons.), hydrodynamic models, and in-situ flood sensor network. Will connect observational and physical environmental domains with human vulnerability.
Thomas Huang	NASA Jet Propulsion Laboratory (JPL)	Fire Alarm: Science Data Platform for Wildfire and Air Quality	Proposes to advance AIST's Air Quality Analytics Collaborative Framework (AQACF) to establish a wildfire and air quality ACF, Fire Alarm, focusing on the prediction and analysis of wildfire, burned area and the air quality as an integrated platform to guide decision-makers, science researchers, and first-responders.

AIST-21 ESTD Awards (cont.)

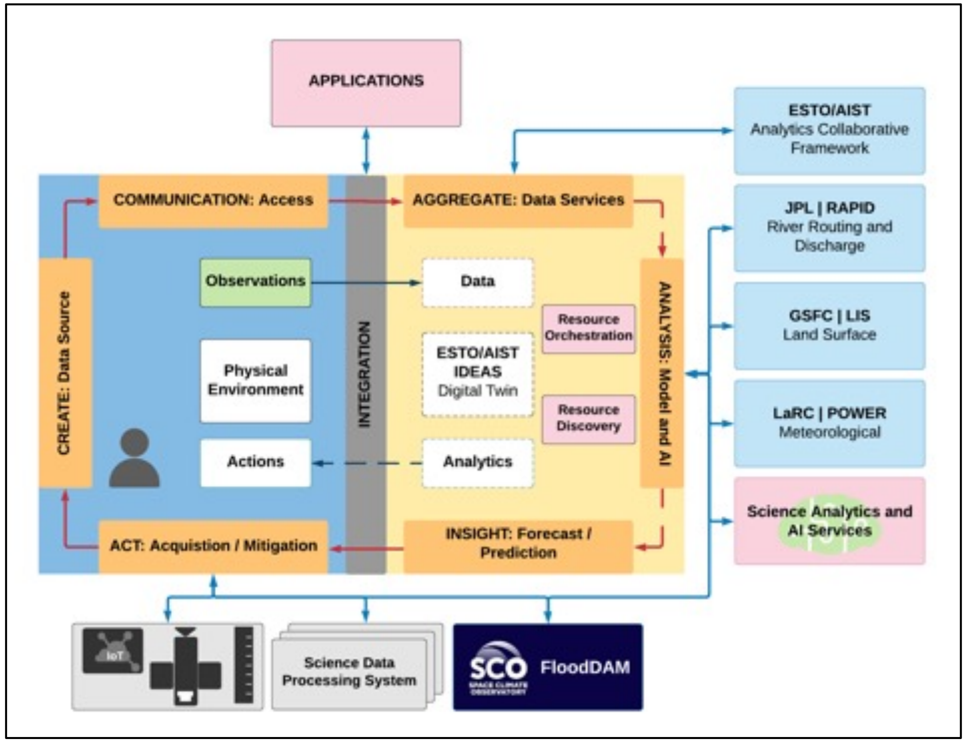
https://esto.nasa.gov/project-selections-for-aist-21

- **ESDT Prototypes**

PI's Name	Organization	Title	Synopsis
Milton Halem	University of Maryland, Baltimore County (UMBC)	Towards a NU-WRF based Mega Wildfire Digital Twin: Smoke Transport Impact Scenarios on Air Quality, Cardiopulmonary Disease and Regional Deforestation	Will develop and implement a Regional Wildfire Digital Twin (WDT) model with a sub-km resolution to enable the conduct of mega wildfire smoke impact scenarios at various spatial scales and arbitrary locations over N. America. WDT will provide a valuable planning tool for impact scenarios by season, location, intensity, and atmospheric state.
Rajat Bindlish	NASA Goddard Space Flight Center (GSFC)	Digital Twin Infrastructure Model for Agricultural Applications	Will develop an agriculture productivity modeling system over Continental United States as an example of incorporating representations of infrastructure-oriented process, for the understanding, prediction, and mitigation/response of Earth system process variability, with application to crop growth, yield, and agricultural production information, critical to commodity market, food security, economic stability, and government policy formulation.
Craig Pelissier	(SSAI)	Terrestrial Environmental Rapid-Replicating Assimilation Hydrometeorology (TERRAHydro) System: A machine-learning coupled water, energy, and vegetation terrestrial Earth System Digital Twin	Proposes to develop a terrestrial Earth System Digital Twin (TESDT) that couples state-of-the-art ML with NASA (and other) EO data. It will combine the best ML hydrology models with capabilities for uncertainty quantification and data assimilation to provide ensemble & probabilistic forecasting, sensitivity analyses, and counterfactual “what if'' experiments.

Integrated Digital Earth Analysis System (IDEAS) – *AIST Collaboration with CNES*

- **IDEAS is a NASA ESTO/AIST Earth System Digital Twin** project that bridges the physical environment and its virtual representation by continuously assimilating new observations to improve forecast and prediction for integrated science and decision support
- Using water cycle and flood analysis as the prototype application to integrate NASA, CNES, and Space Climate Observatory (SCO) data and science
- Multi-Agency and Multi-Center partnership
- Advanced numerical models and analysis
  - **JPL's RAPID**: Routing Application for Parallel computation of Discharge
  - **GSFC's LIS**: Land Information System
  - **LaRC's POWER**: Prediction of Worldwide Energy Resources
  - **CNES and SCO's FloodDAM:** Automated service to reliably detect, monitor and assess flood events globally
  - Integration with **NASA IPCC Sea Level Prediction** data for coastal flooding
  - Joint developed and trained flood detection and prediction machine learning algorithms
  - Promote and advance interoperable standards
- Improve the Machine Learning flood prediction model (Huang *et al.* 2020) from the JPL-CNES Joint Data Science pilot
- Scenario-based prediction for infrastructure and population impacts
- Ongoing formulation and planning with CNES and SCO's FloodDAM



IDEAS – Digital Twin for Water Cycle and Flood Detection and Monitoring

Jet Propulsion Laboratory California Institute of Technology
Goddard Space Flight Center
Langley Research Center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NASA