Professional Open-Source Framework for Earth System Digital Twins and Applications

Clearance: CL#23-1745

Thomas Huang

NASA Jet Propulsion Laboratory

California Institute of Technology

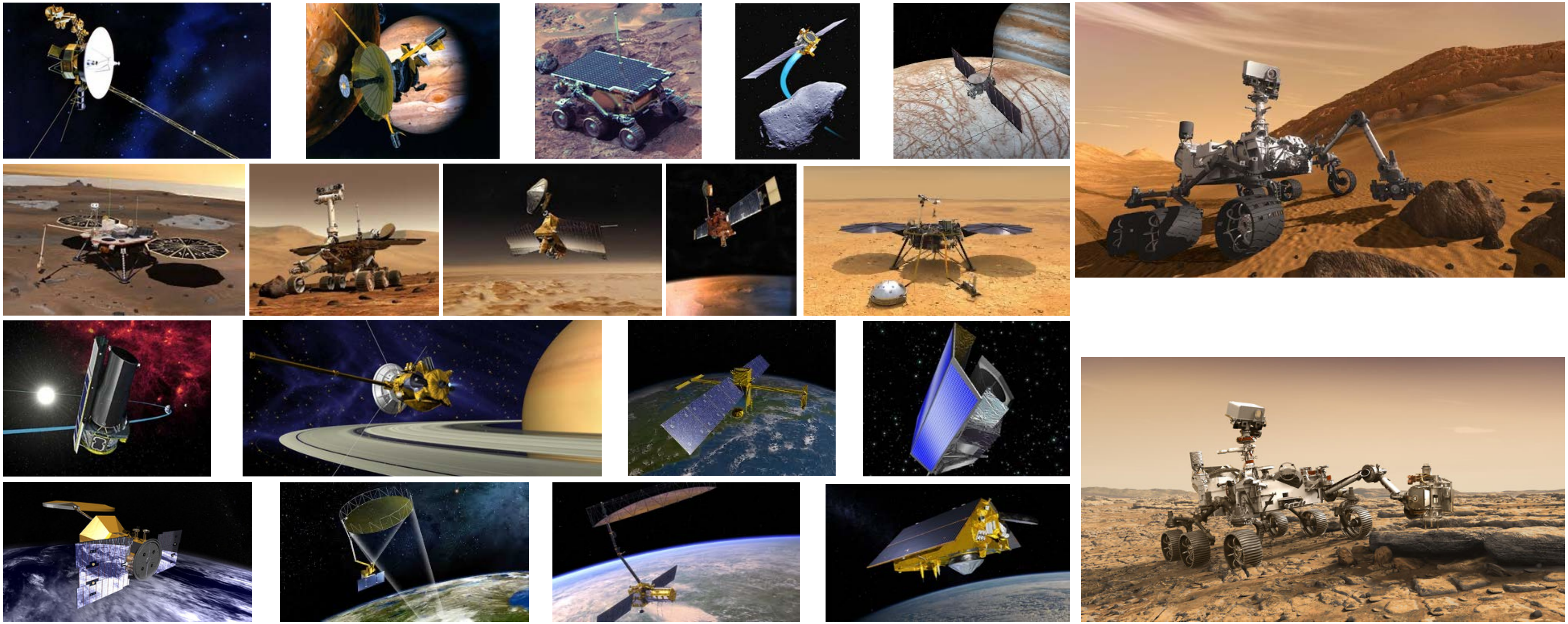
Agenda ID: 2023.04.18_11.00

WGISS-55

Cordoba, Argentina (CONAE)

18-20 April 2023

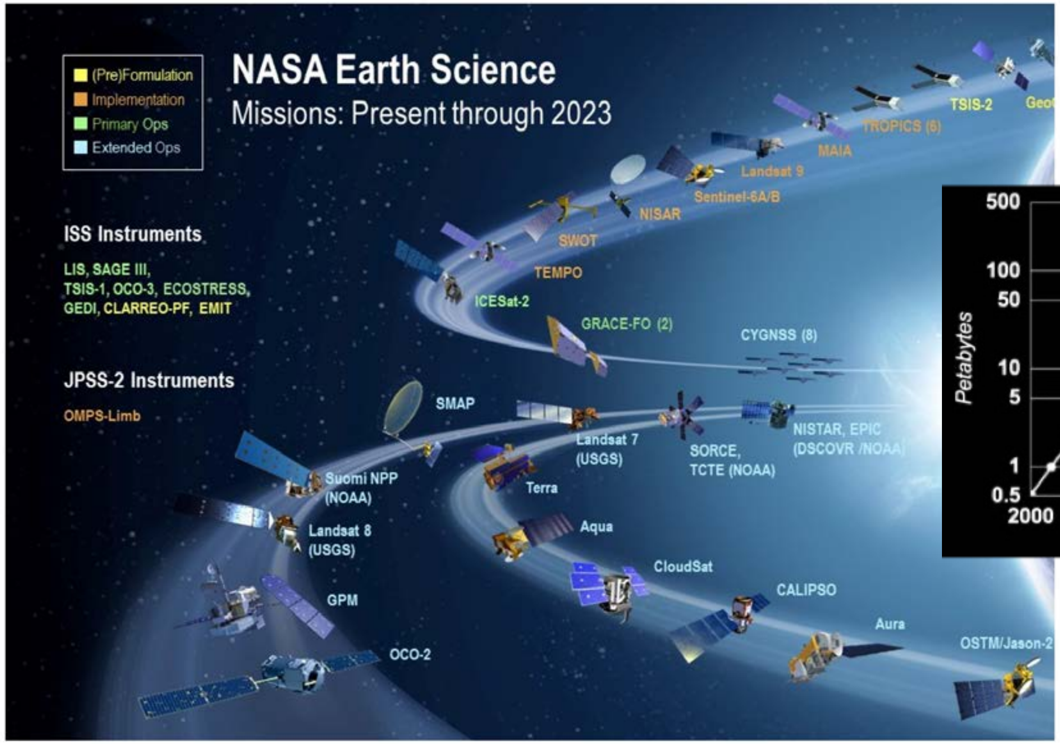
Committee on Earth Observation Satellites

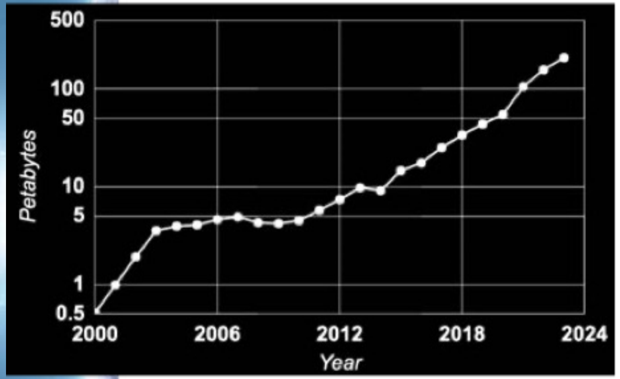


Product Generation | Data Management | Data Access | Data Distribution | Instrument Operation Technology

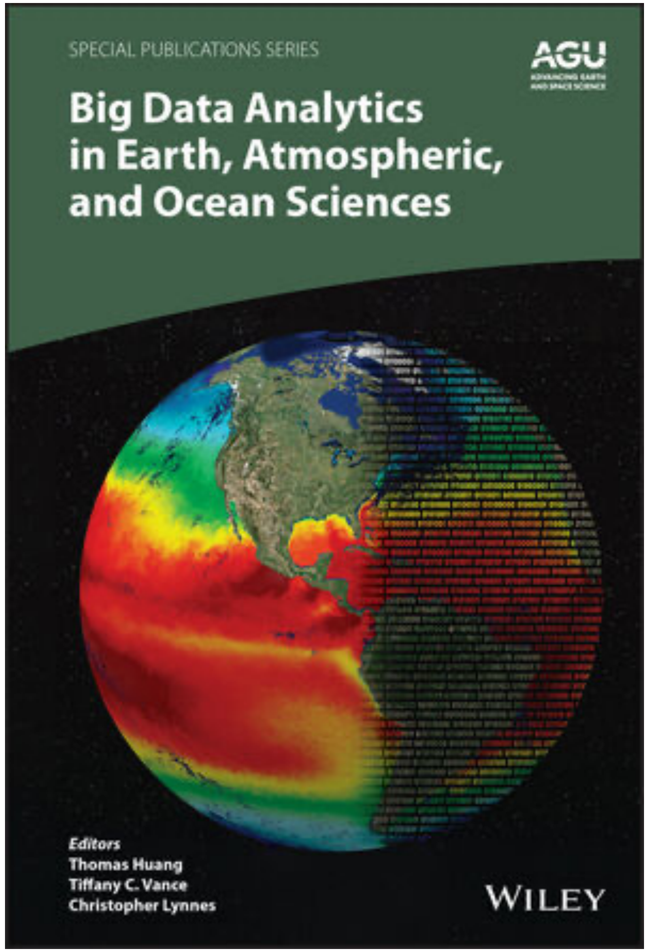
Big Data is about being Smarter about Data

Agility | Relevancy | Sustainability





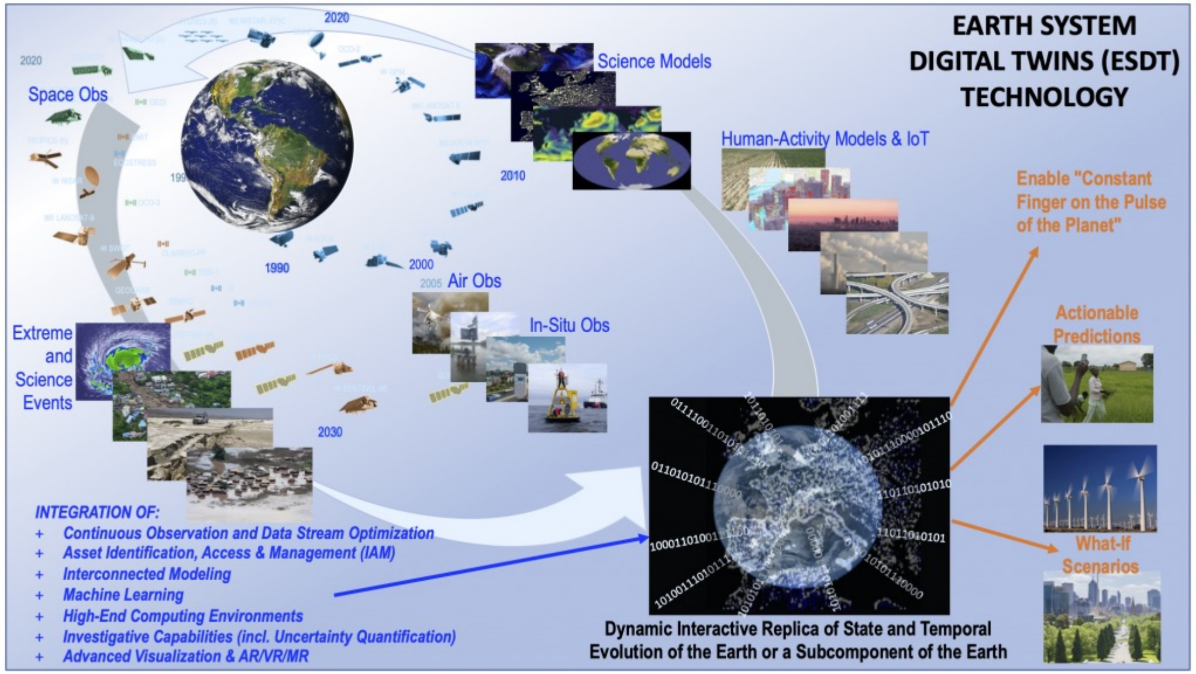
NASA Earth Science Archive Growth



AVAILABLE NOW!

Earth System Digital Twins

- An Earth System Digital Twin (ESDT) – an interactive and integrated multidomain, multiscale, digital replica of the state and temporal evolution of Earth systems
- It dynamically integrates
  - Relevant Earth system models and simulations
  - Other relevant models (e.g., related to 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
- 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



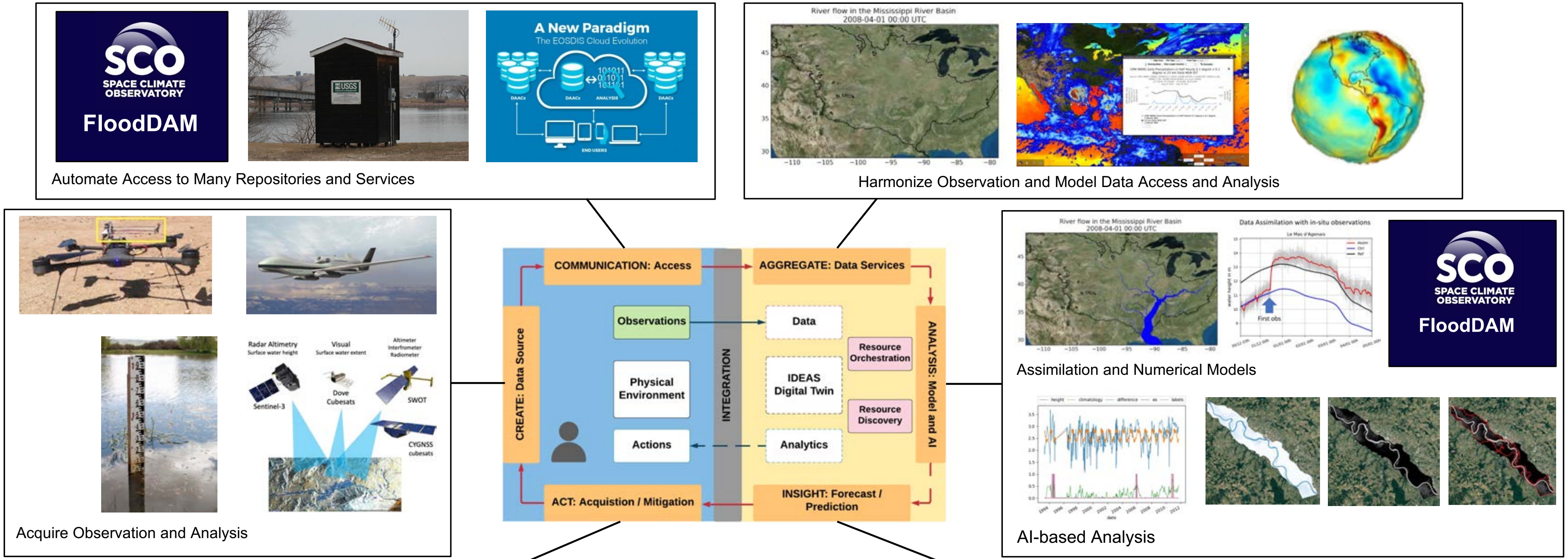
An integrated information system that, for example, enables continuous assessment of impact from naturally occurring and/or human activities or physical and natural environments

ESTO Earth Science Technology Office

Source: https://esto.nasa.gov/aist/

The Vision: Toward Earth System Digital Twin

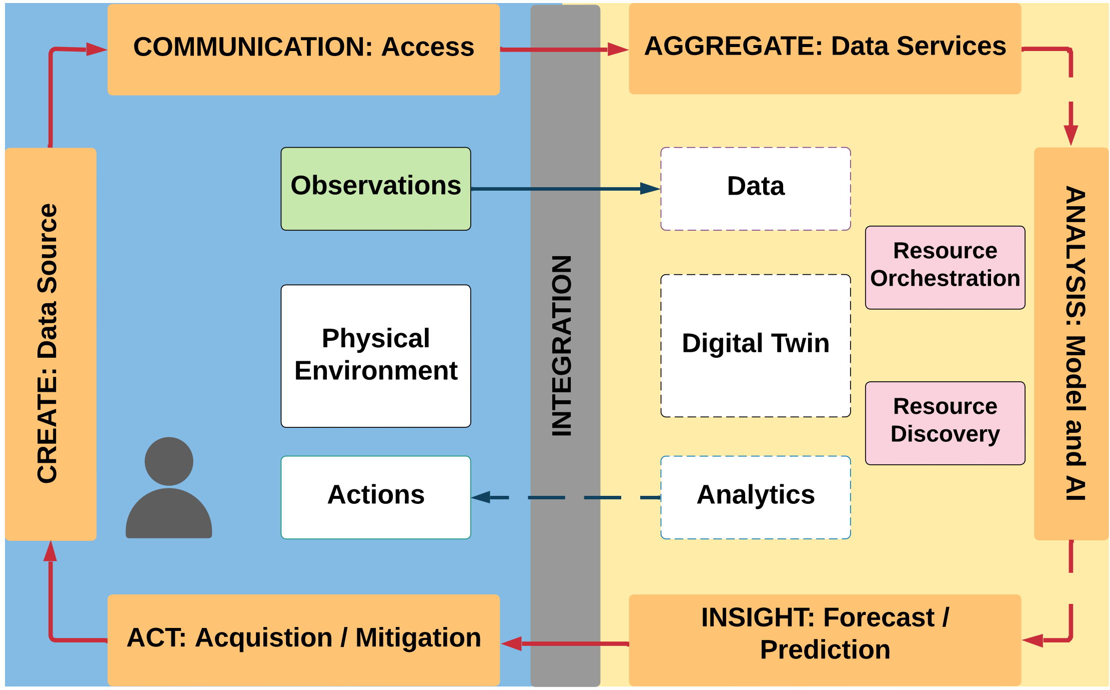
Technology to Bridge the Physical and Digital Environments



- Facilitate access, integration, and understanding of disparate datasets
- Streamline data assimilation for models and analysis
- Enable dynamic integration of new observation and analysis
- Establish interoperable ML models and data services

Earth System Digital Twin: Key Components

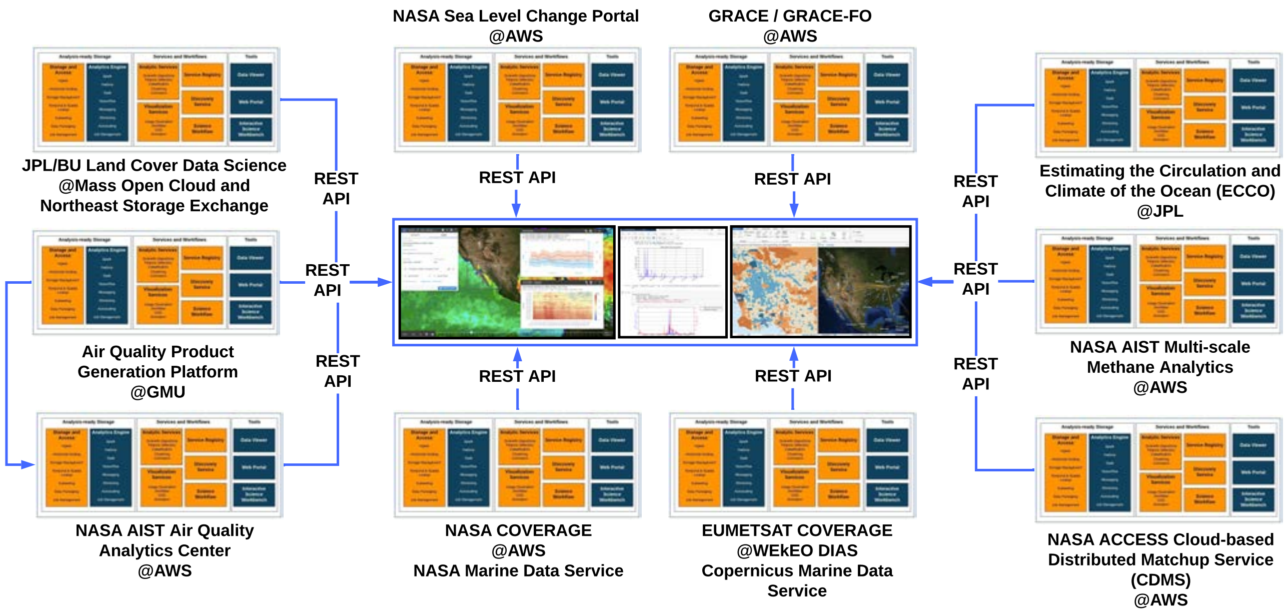
- **Data and Services Assets**: Supports Extract, Transform, and Load (ETL) workflow for metadata harvesting, error detection and correction, re-gridding/reprojecting, Analysis Ready Data (ARD) transformation
- **New Observation and Analysis**: Smarter method to automate onboarding relevant data
- **Integrated Multiphysics, Multi-scale, Probabilistic Models**: Automates inclusion of the latest measurements and supports scenario-based model execution
- **AI and Advanced Analytics**: enables dynamic data acquisition, long-term prediction, data classification, process orchestration and management, etc.

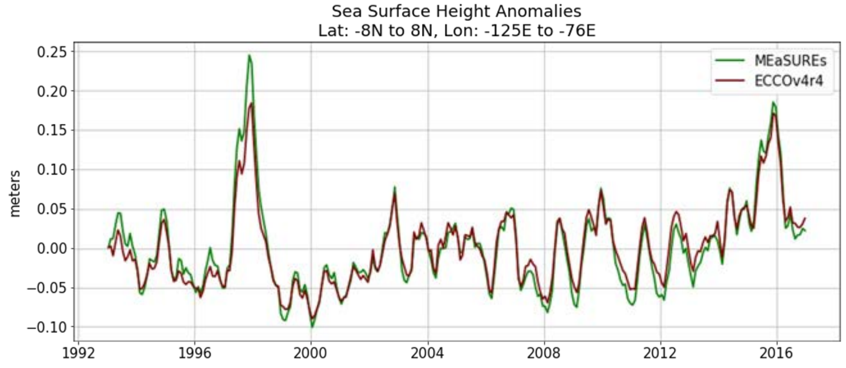


Bridges the Physical Environment and its Virtual Representation

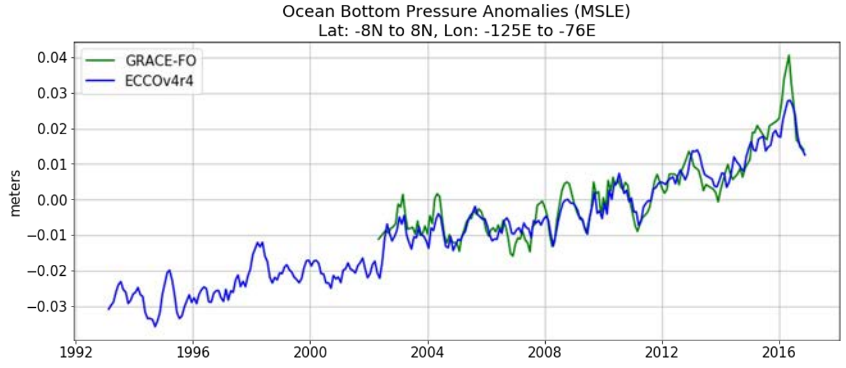
Climate Research – A Community Effort

A community of analytic services that harmonizes data, tools and computational resources to permit the research community to focus on the investigation through common, portable web API





E. Tropical Pacific SSH: ECCO vs. NASA MEaSUREs Satellite Product



Verify ECCO OBP vs. NASA/JPL GRACE-FO Product

IDEAS Teams

Hydrology, Flood Prediction, and Analysis

Partnership between NASA and the CNES-led Space for Climate Observatory (SCO)'s FloodDAM-DT effort

NASA JPL: Thomas Huang, Megan Bull (intern), Cedric David, Gary Doran, Jason Kang, Grace Llewellyn, Kevin Marlis, Stepheny Perez, Wai (William) Phyo, Catalina M. Oaida, and Joe T. Roberts

NASA GSFC: Sujay V. Kumar and Nishan Biswas

NASA LaRC: Paul Stackhouse, David Borges, Madison P. Broddle, and Bradley MacPherson

CNES: Simon Baillarin, Lerre Benjamin, Frederic Bretar Gwendoline Blanchet, Peter Kettig, Raquel Rodriguez Suquet, and Lonjou Vincent

CERFACS: Sophie Ricci, Thanh-Huy Nguyen, and Andrea Piacentini

Collecte Localization Satellites (CLS): Christophe Fatras, Sylvain Brunato, and Eric Guzzonato

QuanCube: Alice Froidevaux, Antoine Guiot, Thanh-Long Huynh, and Romane Raynal

VorteX.io: Guillaume Valladeau and Jean-Christophe Poisson

Wildland Fire, Air Quality, and Health Impact

Partnership with NASA's MAIA Mission, National Institute of Health, and City of Los Angeles

NASA JPL: Thomas Huang, Nga Chung, David Diner, Gary Doran, Sina Hasheminassab, Sarah Hallam (intern), Jason Kang, Olga Kalashnikova, Kyo Lee, Grace Llewellyn, Thomas Loubrieu, Kevin Marlis, Jessica Neu, Joe T. Roberts, and David Schimel

City of Los Angeles: Jeanne Holm, and Dawn Comer

CSU Los Angeles: Mohammad Pourhomayoun, and Pratyush Muthukumar

Howard University: Joseph Wilkins and Jonathan Barnes

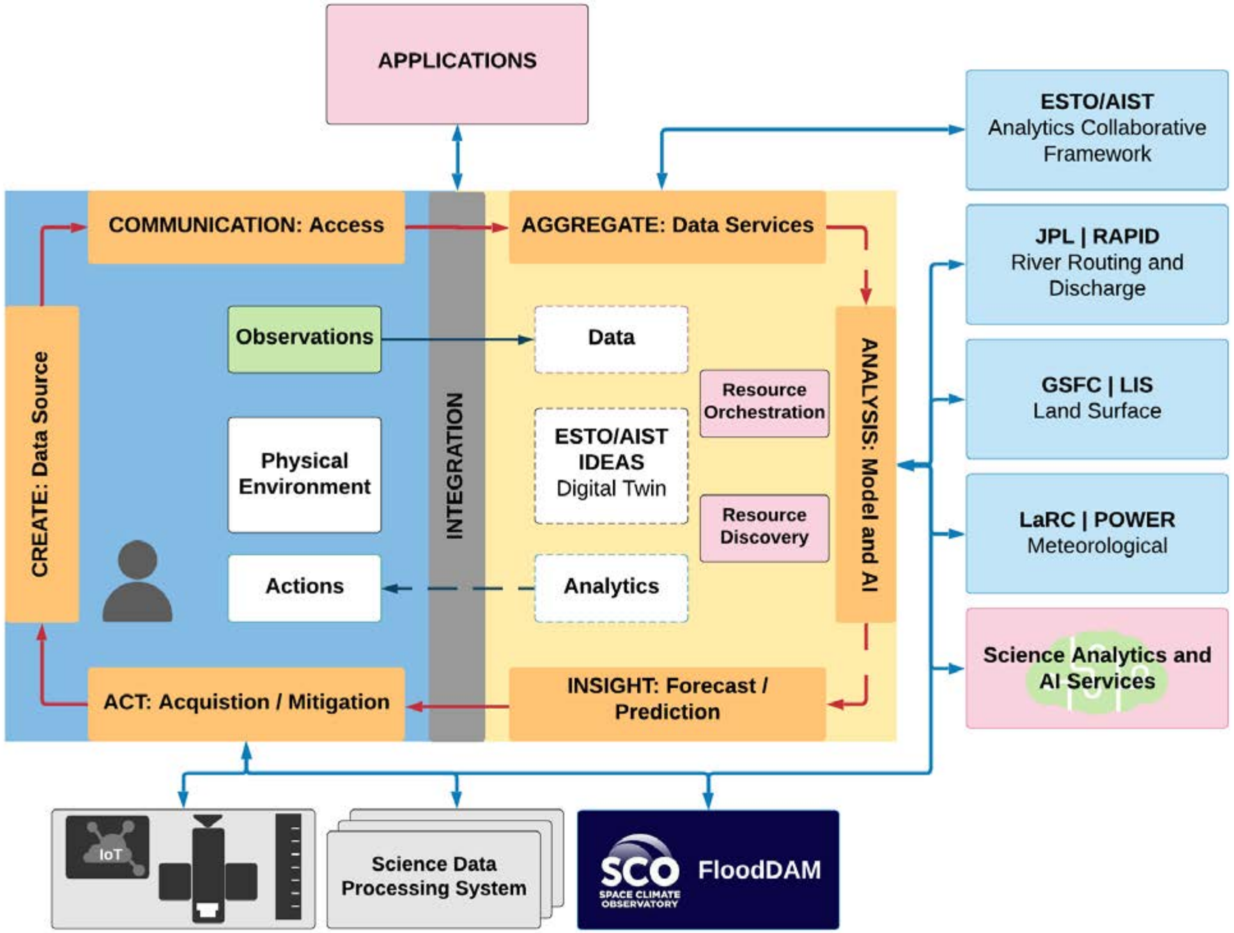
Washington University: Randall Martin

University of Colorado: Daven Henze

Earth System Digital Twins for

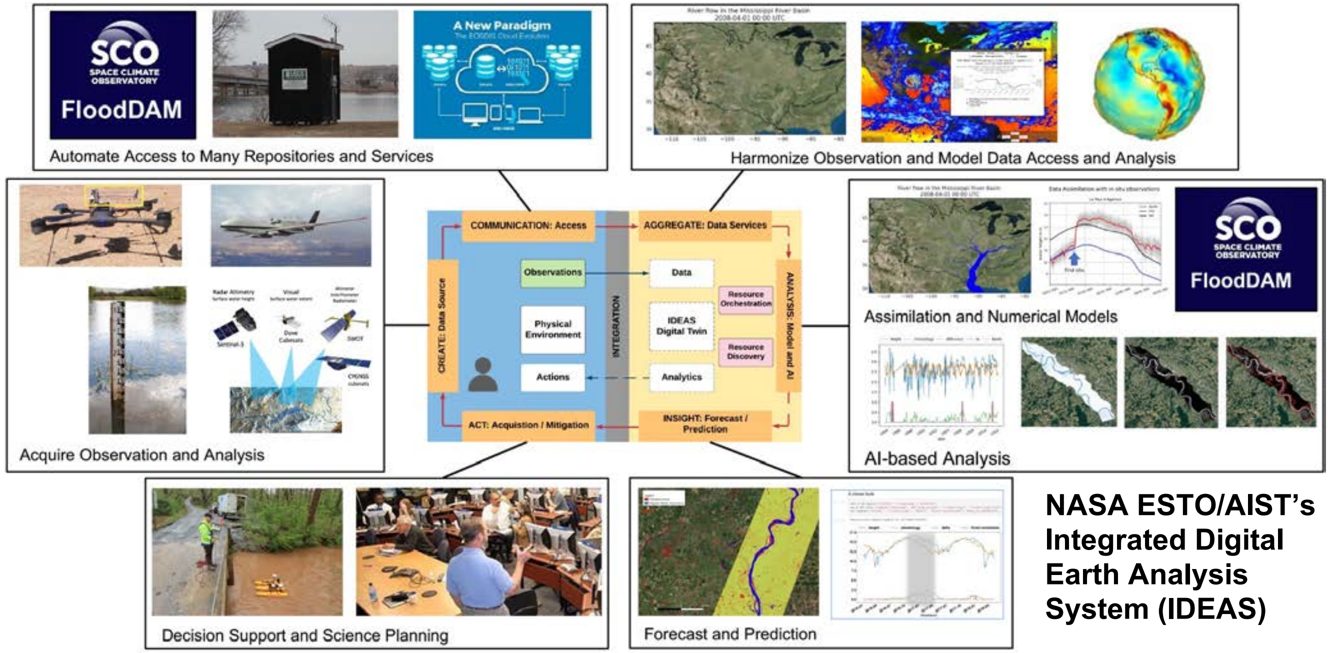
Hydrology, Flood Detection, and Analysis

IDEAS: Water Cycle Application

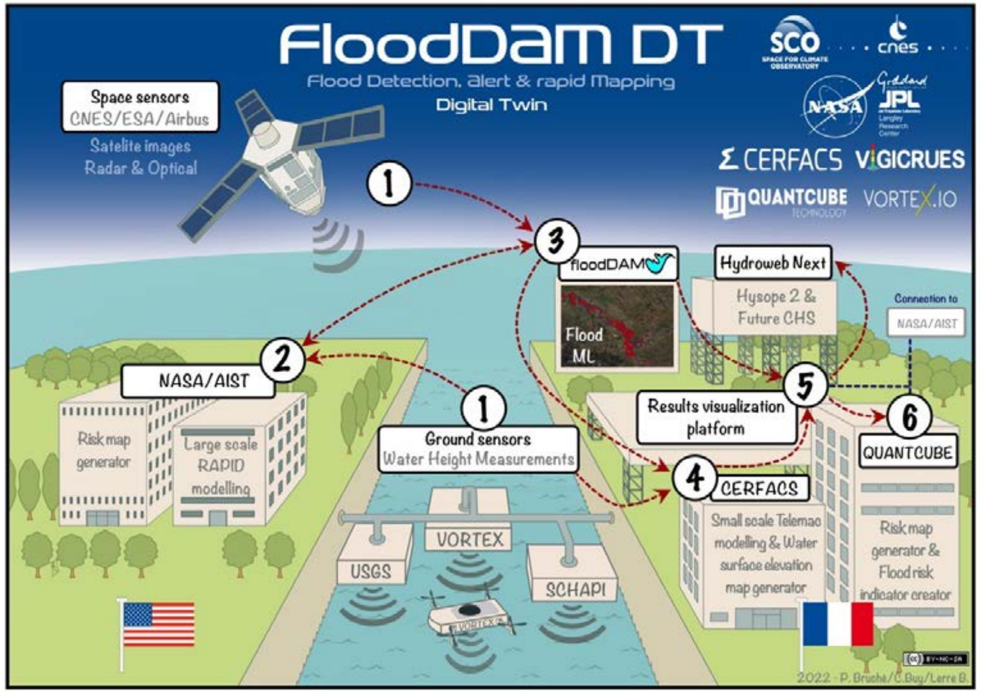


- **Resource Interface** - evaluate/extend emerging DT interface standards
- **Resource Discovery** - central resources registry
- **Resource Orchestration** - provide application-specific resource orchestration
- **Analytics Center** - Apache SDAP for data aggregation, harmonization, and analysis-optimized data services
- **New Observing Strategies** - event-based and ML-driven data acquisition and integration with FloodDAM-DT
- **Multiphysics, Multiscale, and Probabilistic Models** - LIS, RAPID, POWER, and FloodDAM-DT
- **Machine Learning and Deep Learning** - models for flood detection and prediction, data classification, services coordination, etc.

Federated Digital Twins between NASA and CNES



NASA ESTO/AIST's Integrated Digital Earth Analysis System (IDEAS)

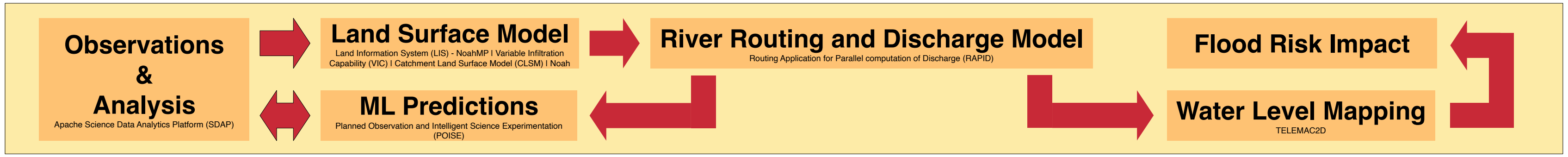


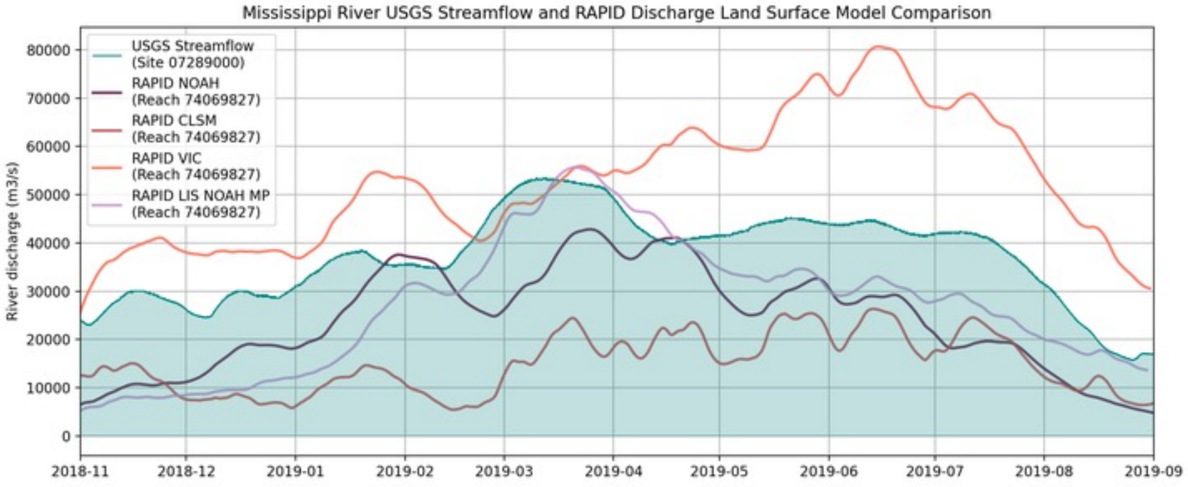
- Establish federated digital twins solution between the **NASA ESTO/AIST's Integrated Digital Earth Analysis System (IDEAS)** (Huang/JPL) and the **Space for Climate Observatory (SCO) FloodDAM-DT** (Rodriguez-Suquel/CNES)
- NASA AIST IDEAS is an open-source Earth System Digital Twins (ESDT) framework
- The collaboration focuses on establishing DT-powered flood alert systems, analysis, and risk maps on local and global scales

PARTNERS:

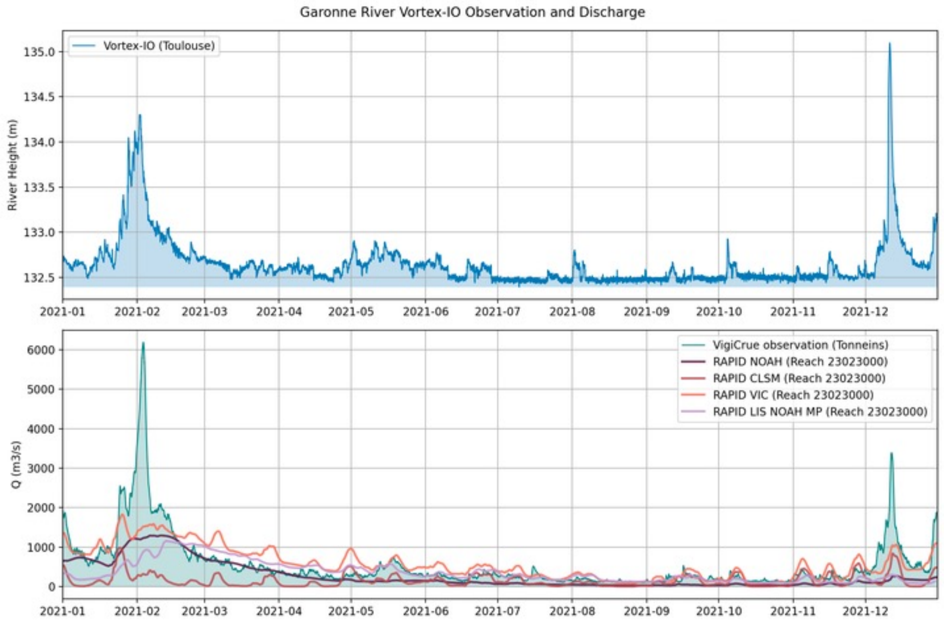
Built for Scenario-based Analysis

- Using the latest observation and analysis to drive model predictions
- Decision support
- On-demand data and analysis acquisition
- Future instrument scheduling and tasking





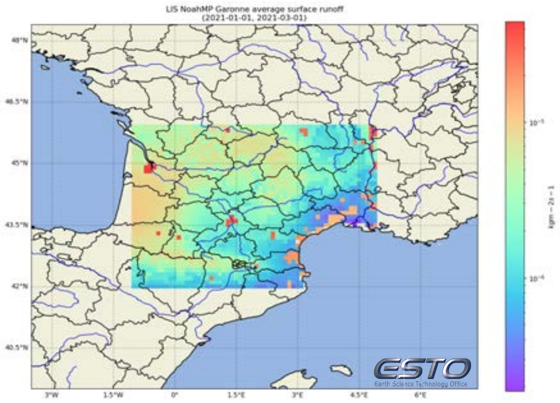
Mississippi Flood Event in 2018 – 2019
Comparing river discharge with USGS stream gauges



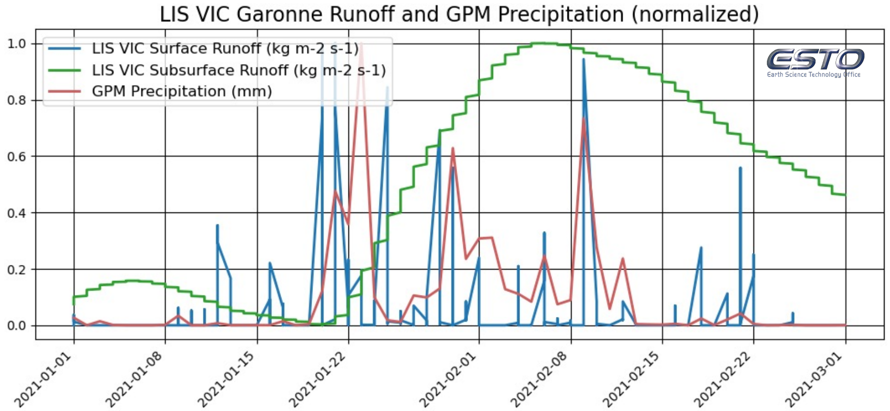
2021-02 Flood Event in Garonne River
Comparing river discharge with micro-station data

Bringing Observations and Models Together

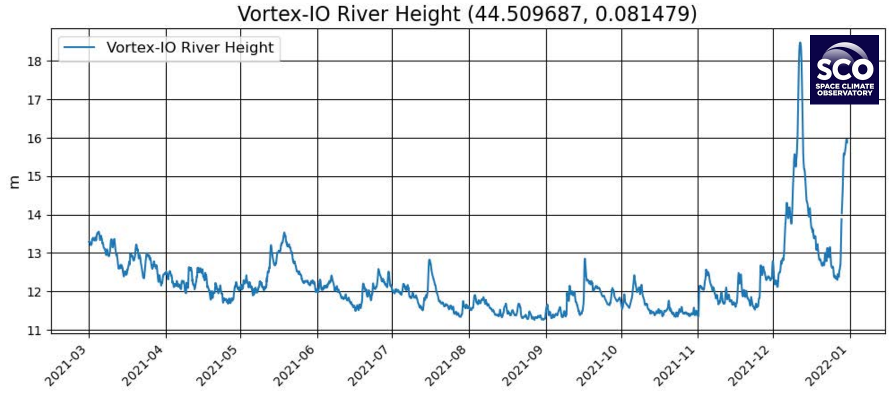
2021-03 through 2021-12 in Garonne



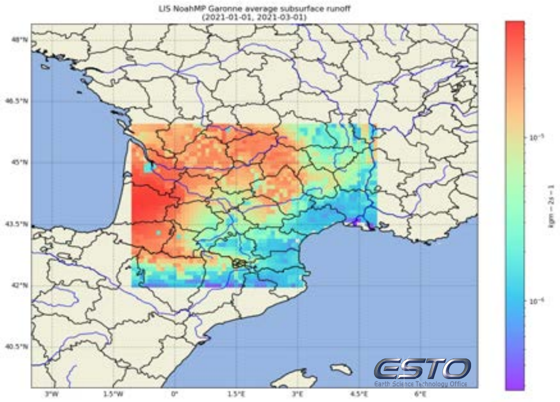
NoahMP Average Surface Runoff



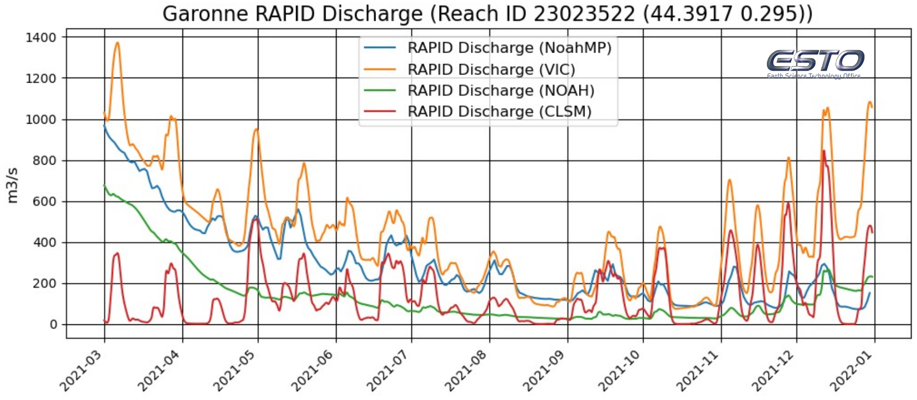
VIC Runoff and GPM Precipitation (normalized)



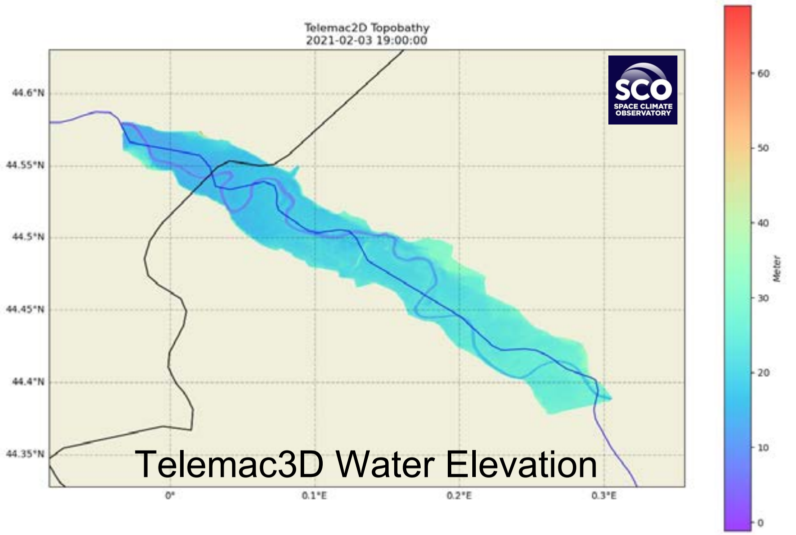
Vortex.Io River Height



NoahMP Average Subsurface Runoff



RAPID Discharge from different Land Surface Models



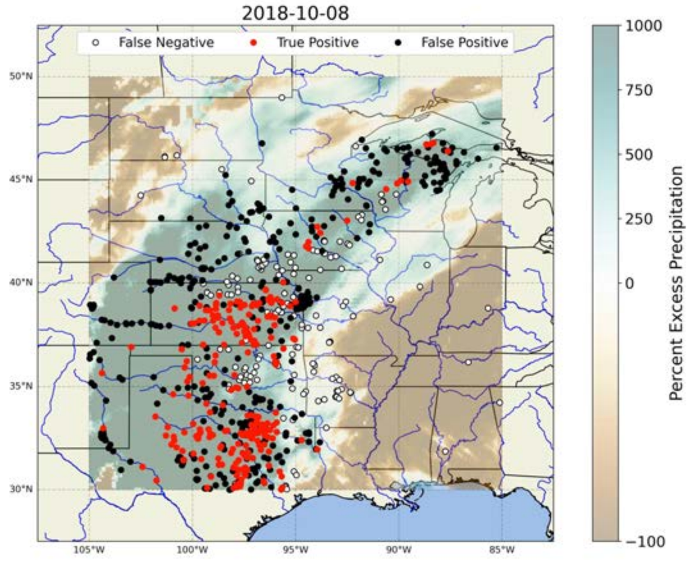
Telemac3D Water Elevation

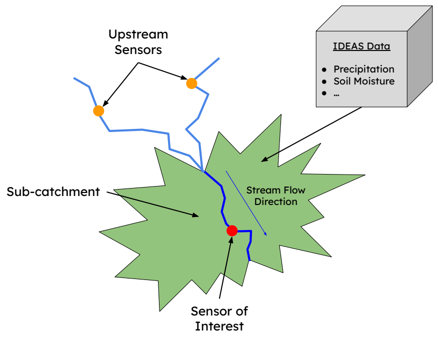
ML-Driven In-Situ Data Acquisition

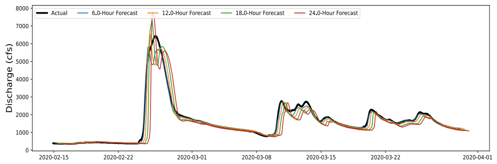
Minimize storage and computation need for pre-staging different in-situ sensor data. Use real-time ML to predict which stream gauges will be most useful for analysis

- **Precipitation-Only Approach**: use GPM data and ML model to predict daily peaks in discharge
- Random Forest model trained on 2,195 gages over 2 years, totaling 2.2 M examples, from midwestern US

- **Incorporating Stream Network**: use MERIT basin/reach database to model propagation of flow during flooding events
- Long Short-Term Memory (LSTM) neural network trained to forecast 6-24 hours into the future for each sensor given upstream readings





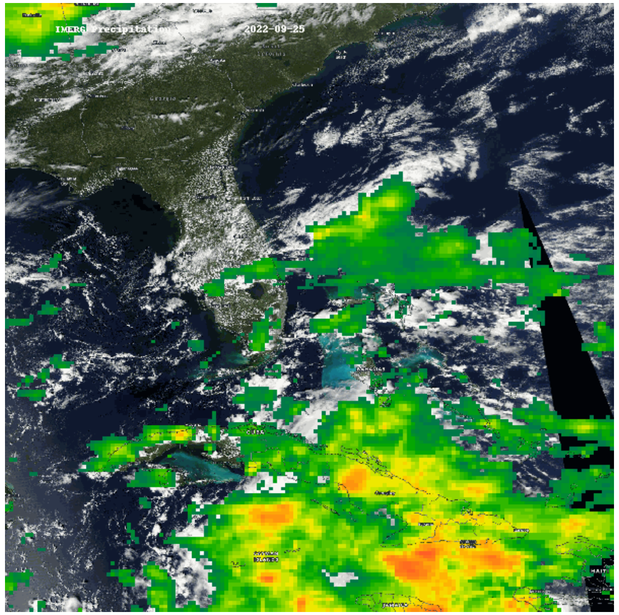


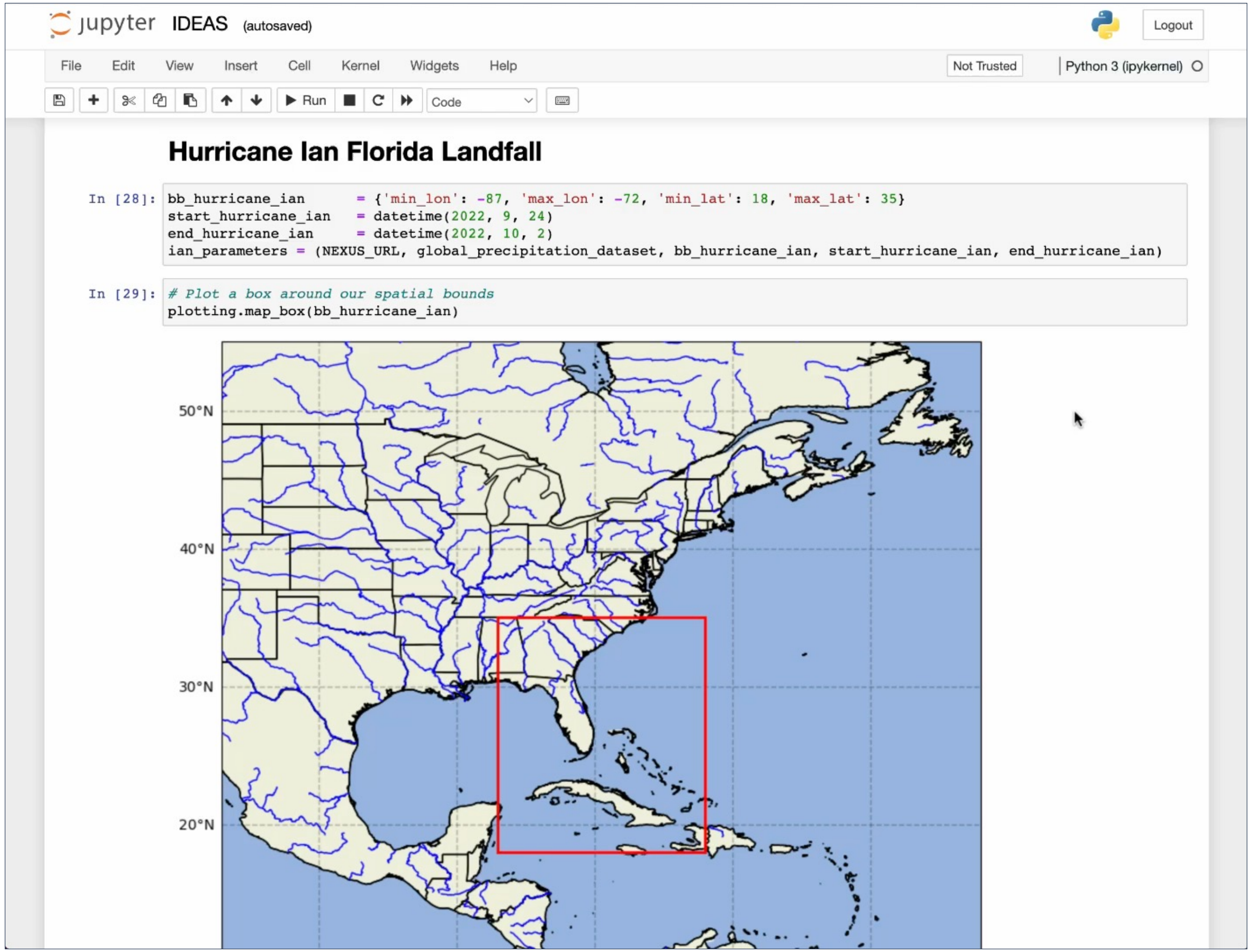
IDEAS-Powered Flood Notebook

https://github.com/EarthDigitalTwin/IDEAS-notebooks/blob/main/Flood_Demo.ipynb

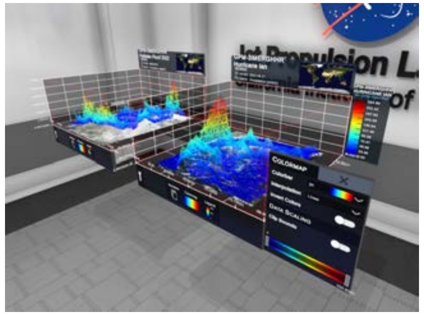
Demonstrates the latest IDEAS API and capabilities

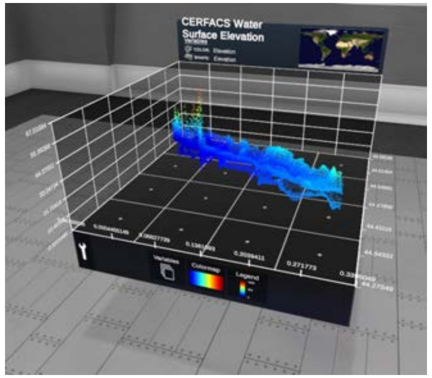
- STAC – Data search and metadata
- Data access – satellite, in-situ, and models
- Interactive, harmonized data analytic capabilities
- Visualizations – Tile WMS and on-demand animation generation

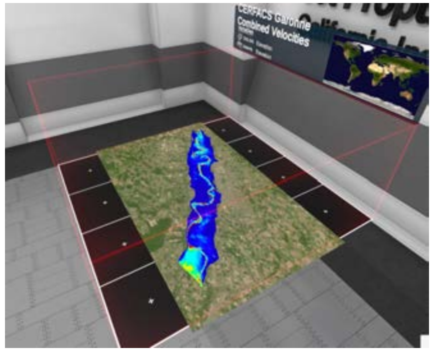


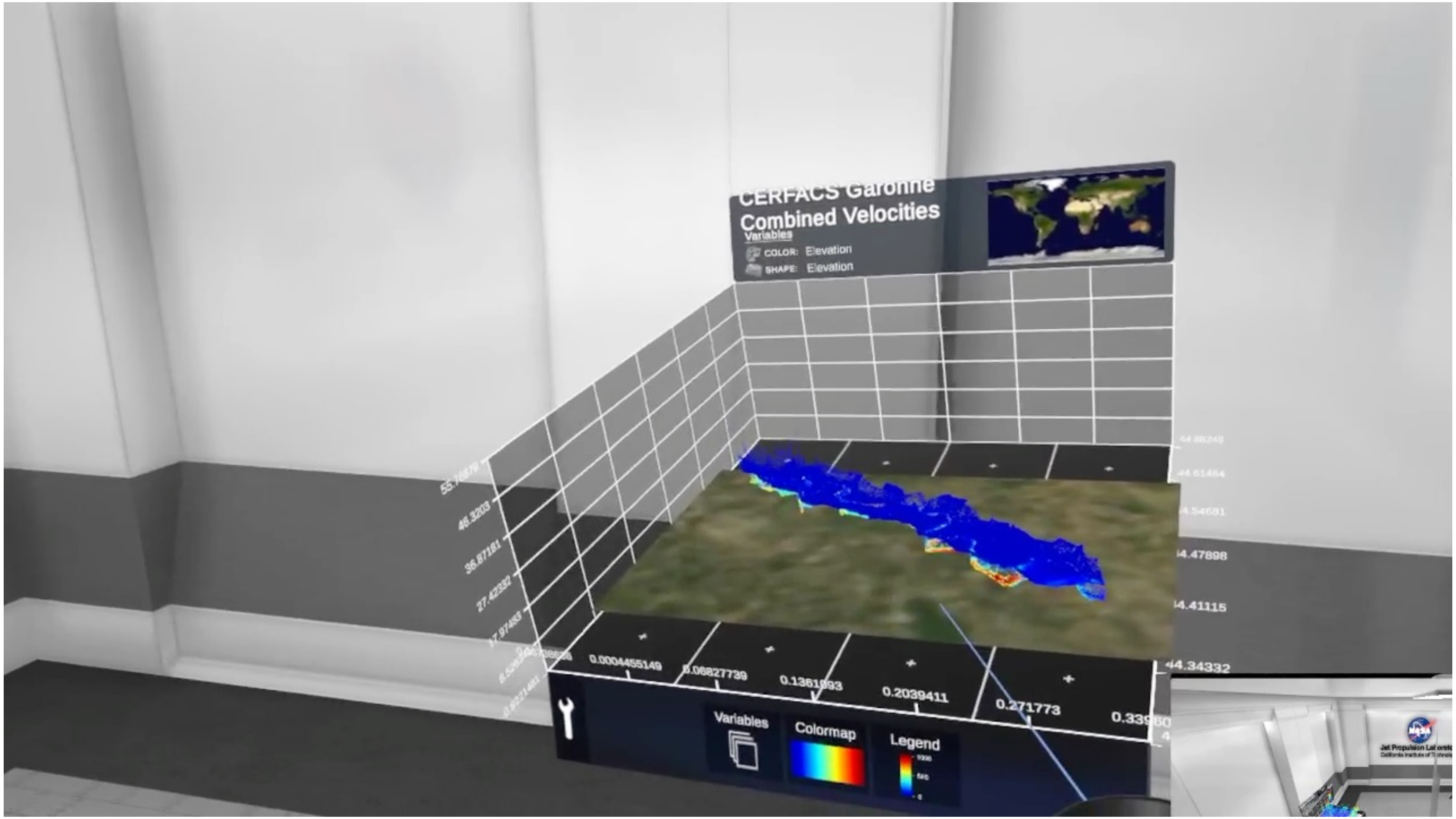


DT Powered VR – Immersive Science

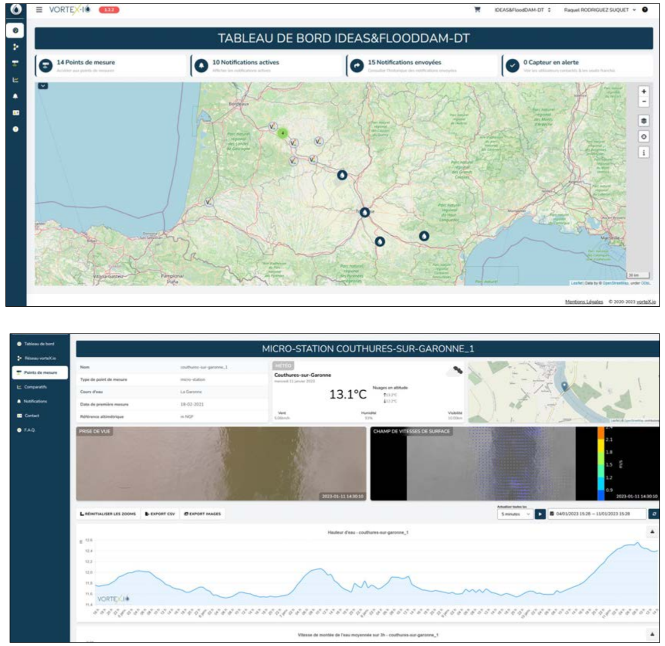




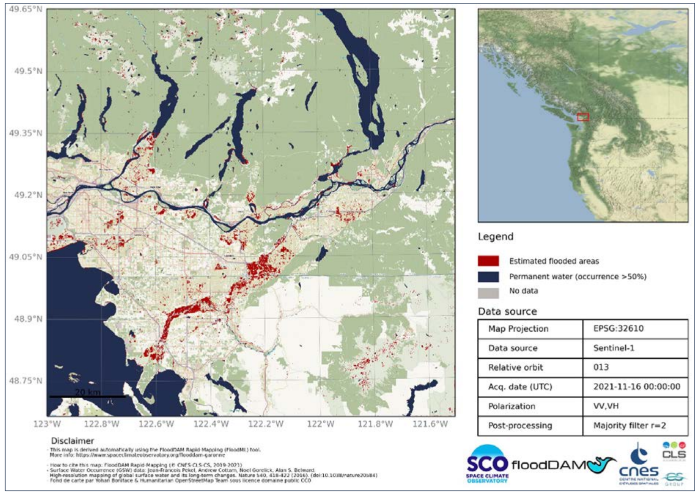




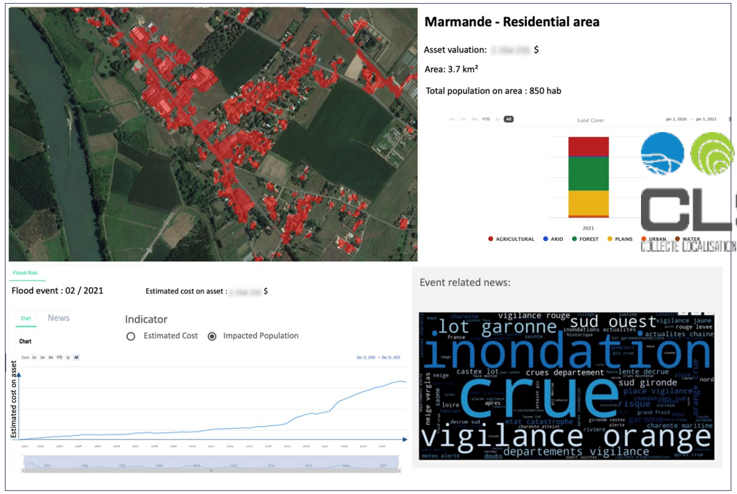
SCO FloodDAM-DT Subsystems



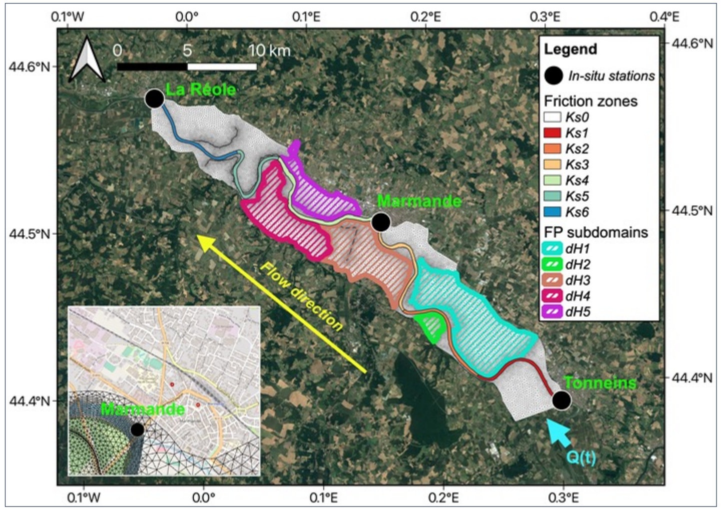
VorteX.io: Micro-stations



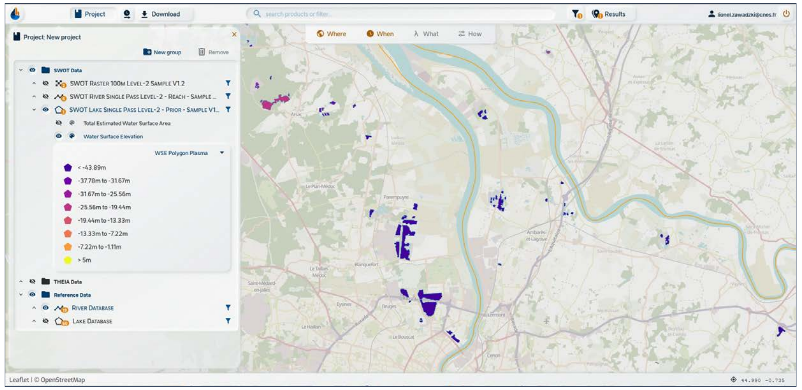
CNES and CLS: Rapid Flood Mapping



QuantCube: Financial Risk Map

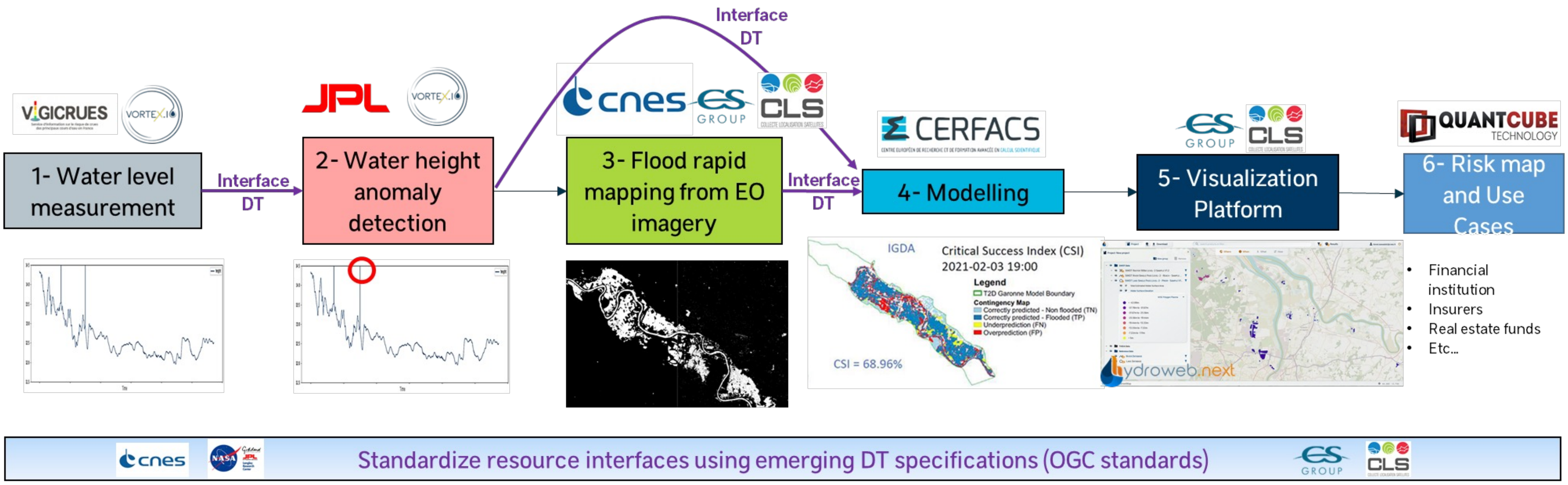


CERFACS: Water Level Map



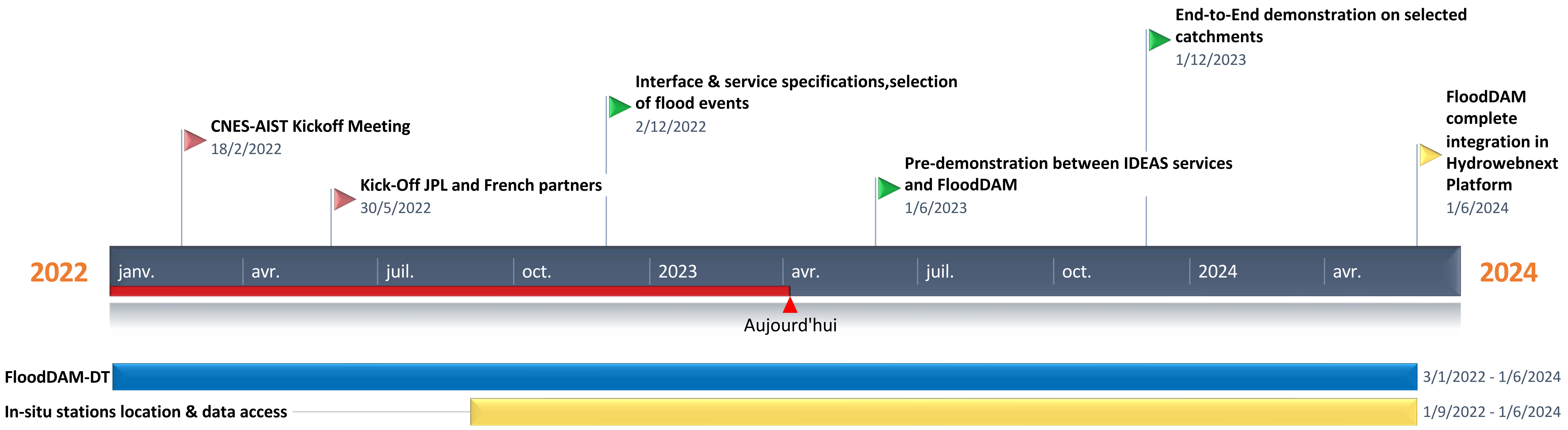
CNES and CS: Hydroweb platform and FloodDAM-DT integration

SCO FloodDAM-DT Pipeline



SCO FloodDAM-DT – Schedule

- **Cooperation IDEAS & SCO FloodDAM-DT**



Earth System Digital Twins for
Wildland Fire, Air Quality, and Health Impact

Jet Propulsion Laboratory
California Institute of Technology

1867
HOWARD UNIVERSITY

GEORGE MASON UNIVERSITY

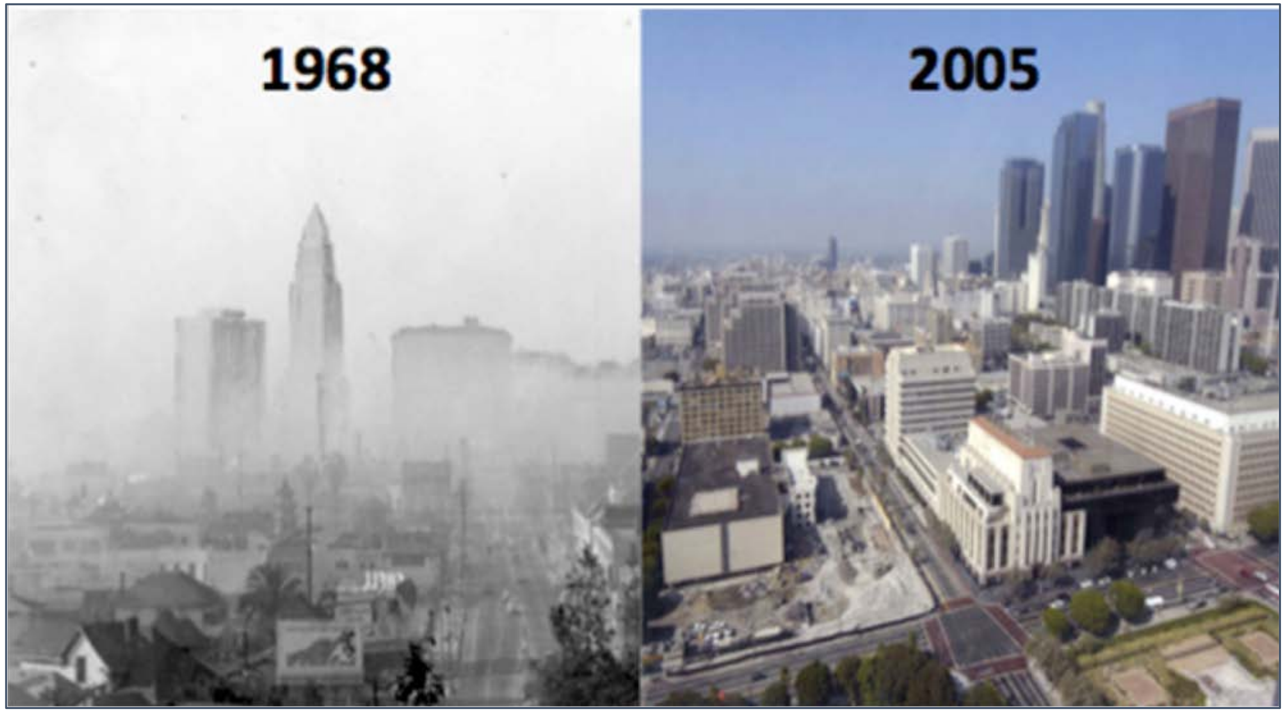
NIH National Institutes of Health
Turning Discovery Into Health

Big Picture Up Front

Improve usability of science data for air quality analysis and prediction

Leverage advanced assimilation of numerical and AI models to Improve Decision Making

Develop sustainable technology solution for sustainable science



"Characterize, understand, and improve the quality of air in urban areas across the planet." – Jeanne Holm, Deputy Mayor for Budget and Innovation at LA

Data Harmonization

2017 – 2018 California Wildfire Season – Interactive Analyze and Visualize ($PM_{2.5}$ O_3, NO, CH_4, TLML, PBL, etc.)

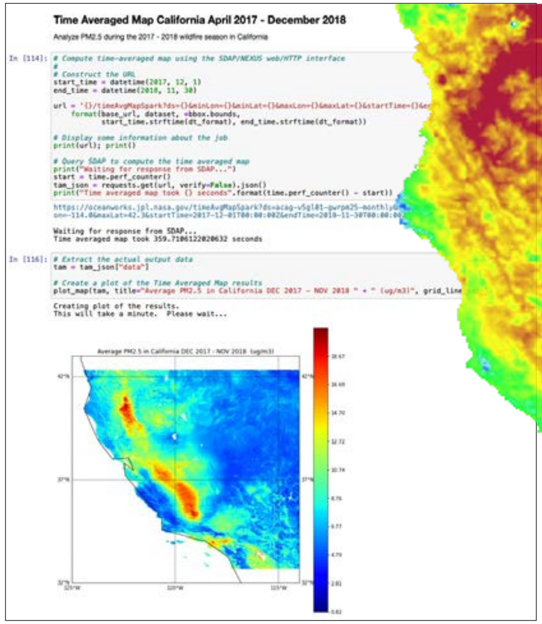
US Crime + Justice Energy + Environment Extreme Weather Space + Science Audio Live TV Log In

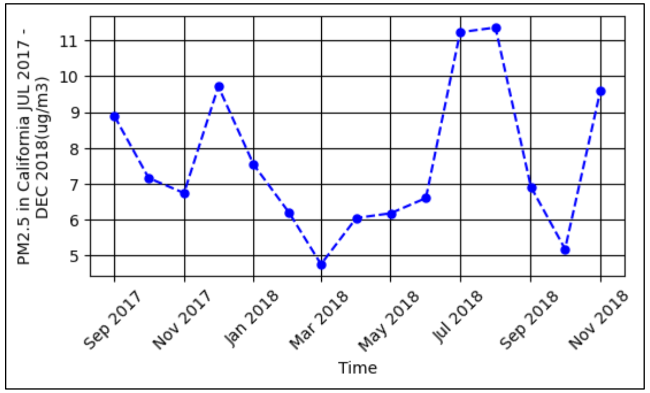
44 dead in California fires as the Camp Fire becomes the deadliest in state history

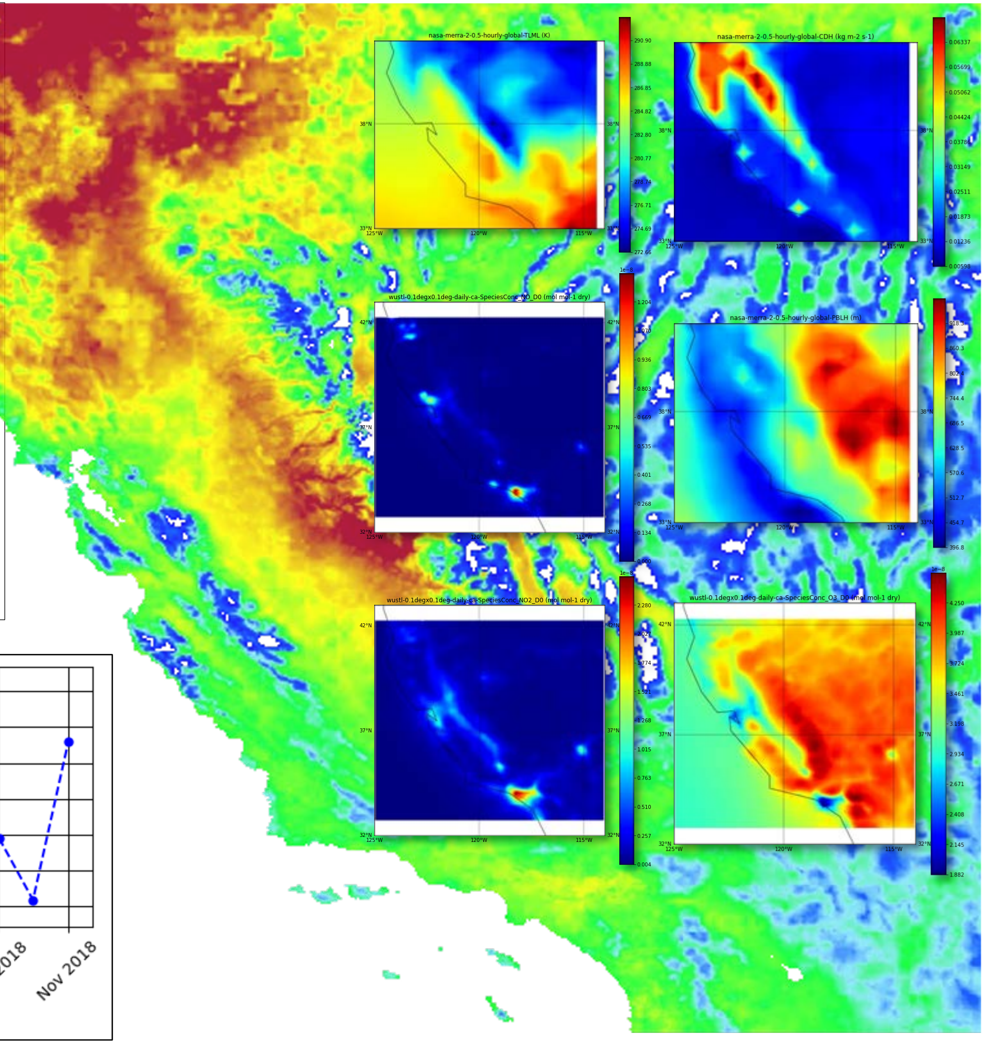
By Emanuela Grinberg and Holly Yan, CNN

Updated 5:35 AM EST, Tue November 13, 2018

Video Ad Feedback

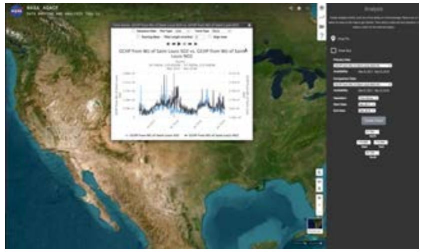


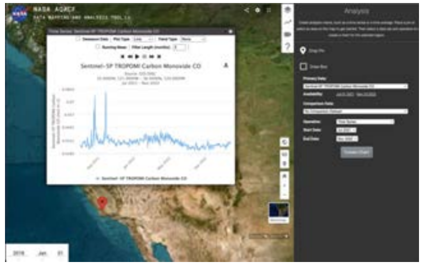


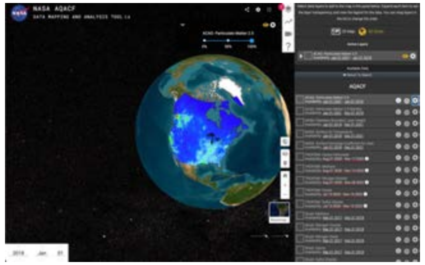


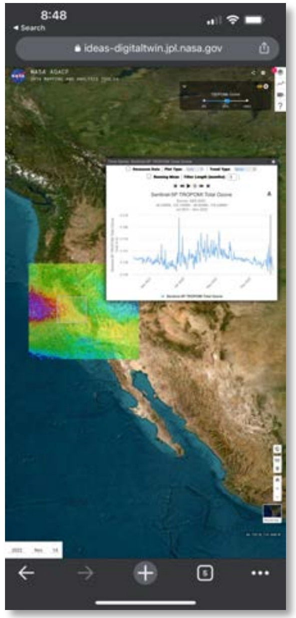
Air Quality Data Analysis Tool

Powered by the AQ ACF Platform









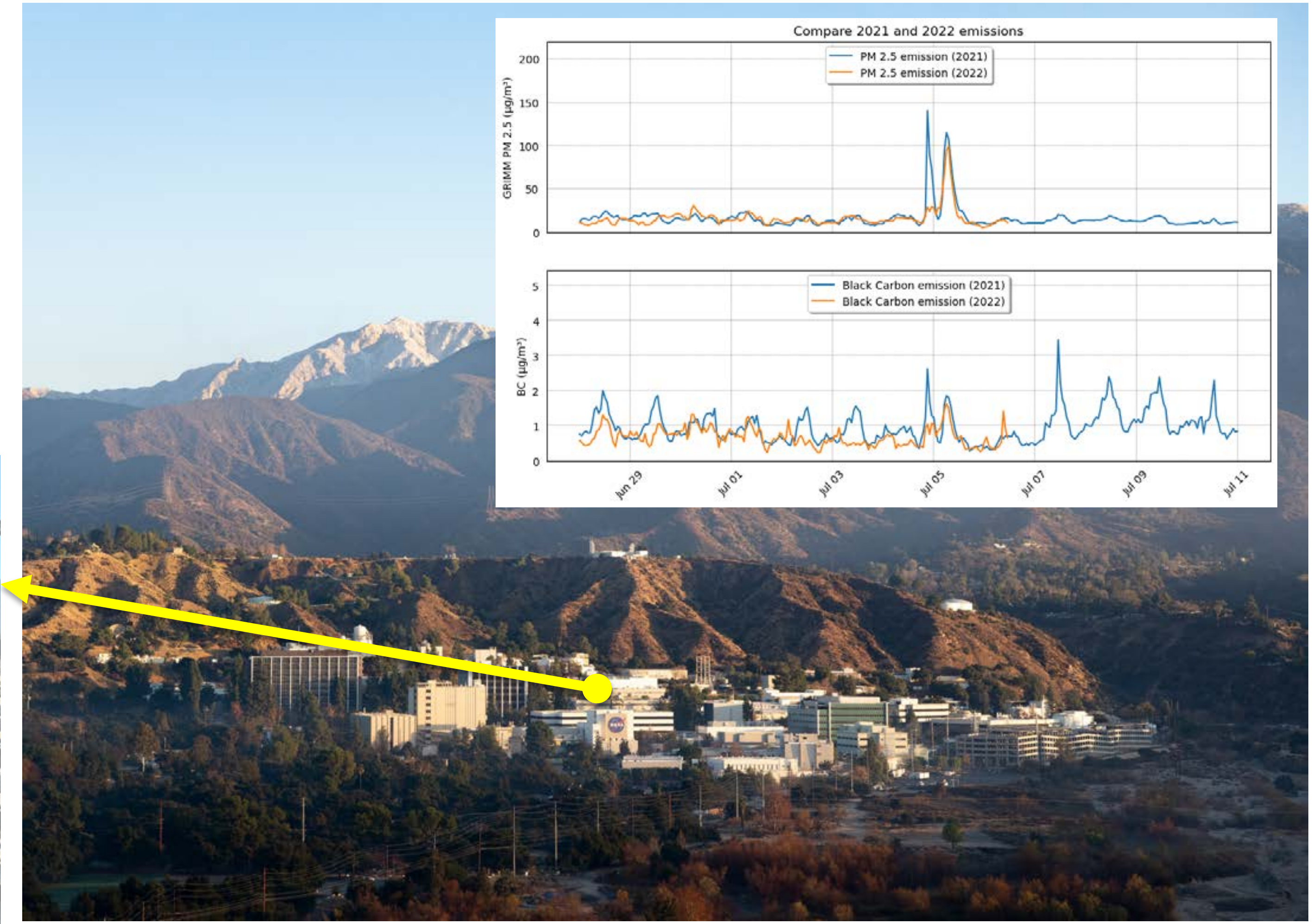
- Interactive analysis and visualization of
  - Satellite Observations
  - Model for atmospheric composition
  - IOT and in-situ sensors

Analyze In-Situ Data

Example: $PM_{2.5}$ and Black Carbon from July 4^{th} Fireworks

Source: San Gabriel Valley Tribute

Dynamic retrieval of in-situ measurements
PM10, PM2.5, BC, CO, NO2, O3, AOD, etc.



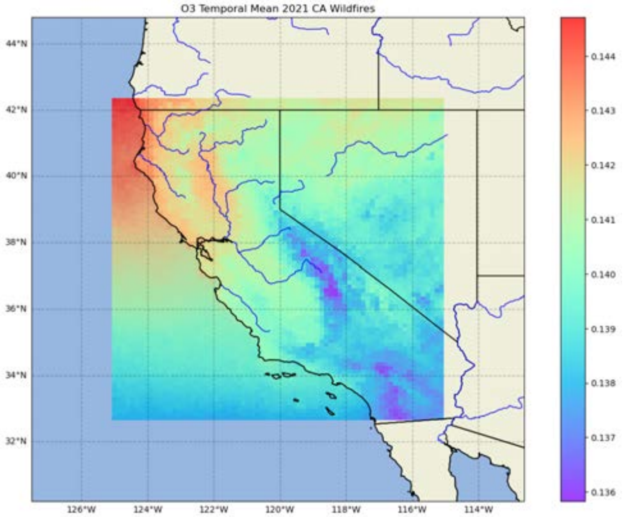
NASA Jet Propulsion Laboratory (JPL), Pasadena, CA

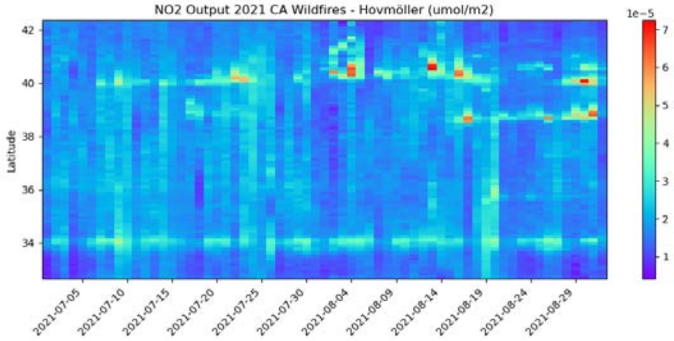
Air Quality Notebook

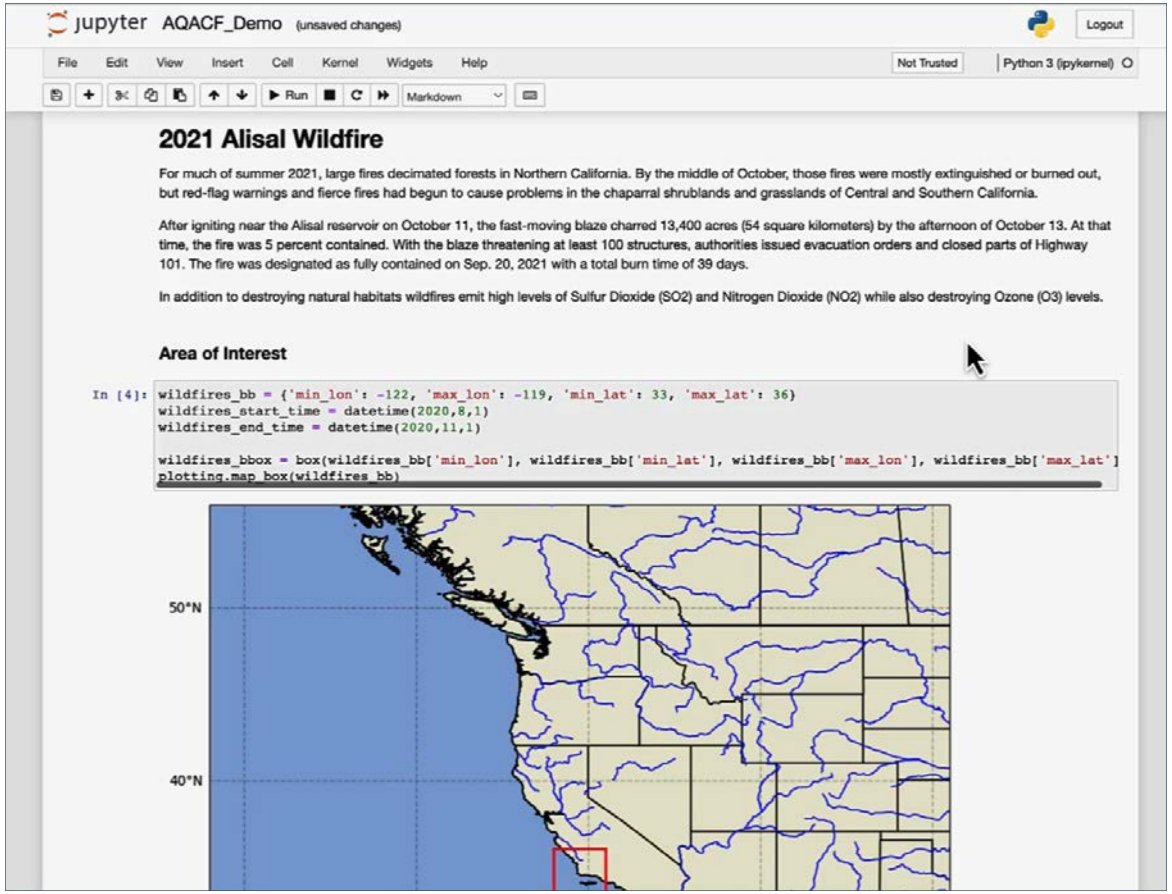
https://github.com/EarthDigitalTwin/IDEAS-notebooks/blob/main/AirQuality_Demo.ipynb

Demonstrates the latest IDEAS API for air quality analysis

- STAC – Data search and metadata
- Data access – satellite, in-situ, and models
- Interactive, harmonized data analytic capabilities
- Visualizations – Tile WMS and on-demand animation generation





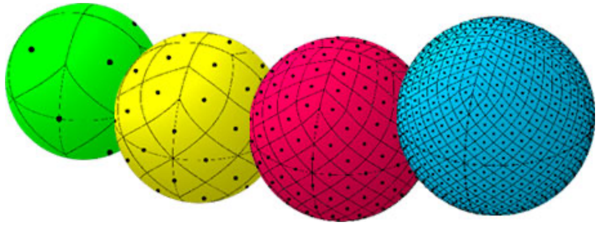


TROPOMI Global Daily Product (O_3, CH_4, NO_2, SO_2, and CO) Generation

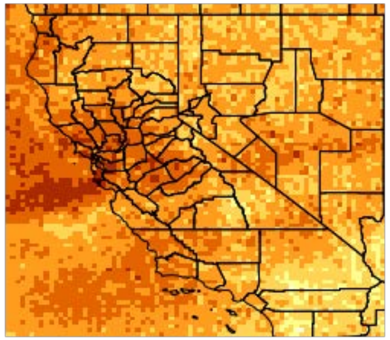
Powers Value-added Product Generation

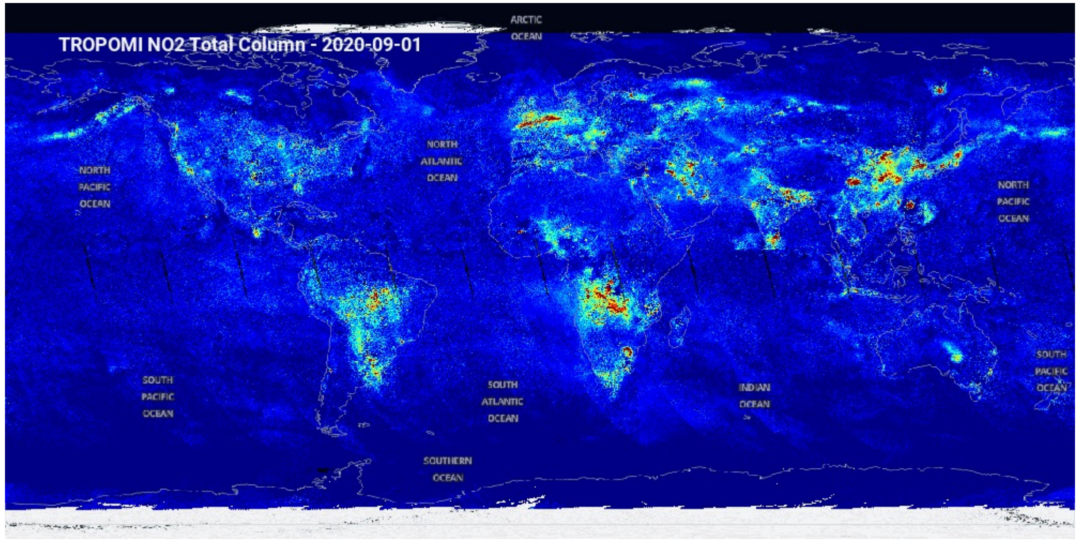
Read individual L2 swath files

Remap the data into HEALPix pixels at various spatial resolutions (6 km, 12 km, 24 km, …)



Global grid and generate a daily mean L3 dataset by averaging valid retrievals

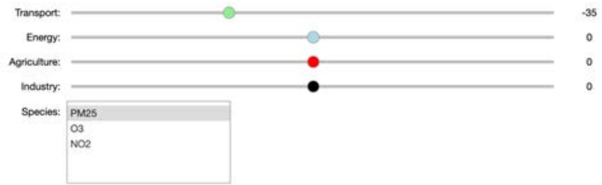


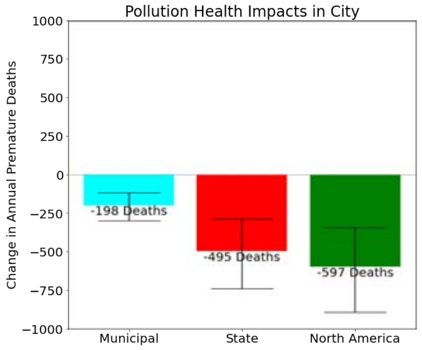


Global NO_2 Total Column
2020-09-01 – 2020-09-03

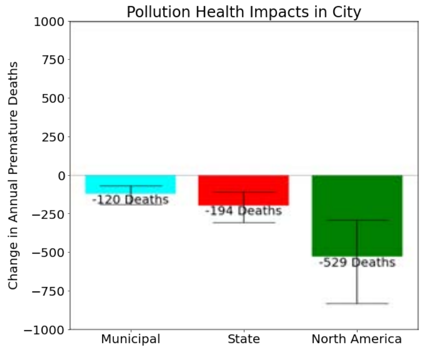
California EV Mandate 2035 (a.k.a. CAL2035)

- The state of California plans to ban the sale of new gasoline-powered cars by 2035
- Requires 35% of new vehicles sold in CA to be electric by 2026.
- Will increase to 68% in 2030 and 100% in 2035
- These actions are estimated to achieve a more than 35% reduction in greenhouse gas emissions and an 80% improvement in NOx emissions from cars.
- Questions
  - **How does air pollution in CA respond to changing vehicle emissions, and what are the impacts on human health and exposure?**
  - **How can air quality modeling data and remote sensing observations be used to present answers to these types of questions?**

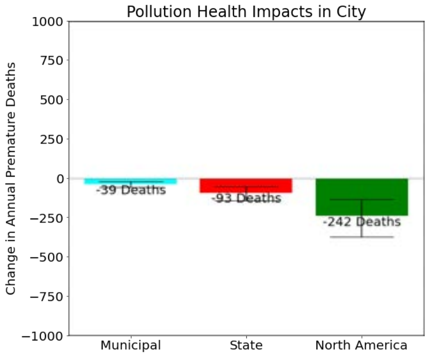




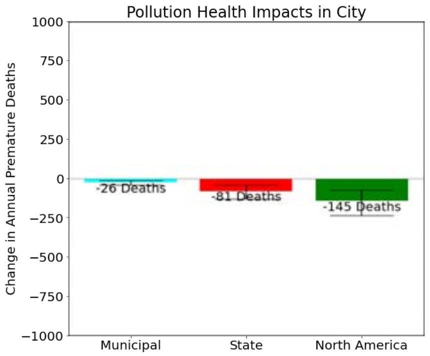
Los Angeles



New York



Chicago



Miami

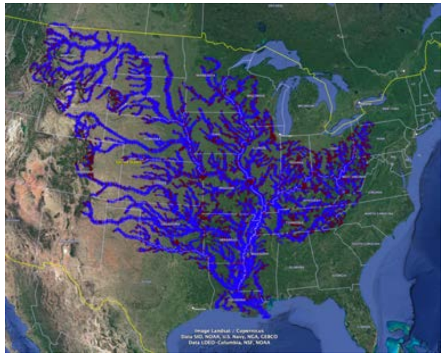
ML-Driven Data Acquisition

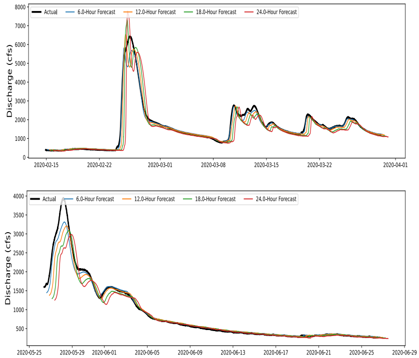
Hydrology, Flood Detection, and Analysis

↔ Shared Conceptual Framework

Inputs:
Precipitation Data, [soil moisture, snow melt, …]

Model:
Predict propagation through river network using MERIT basins/reach database using LSTMs



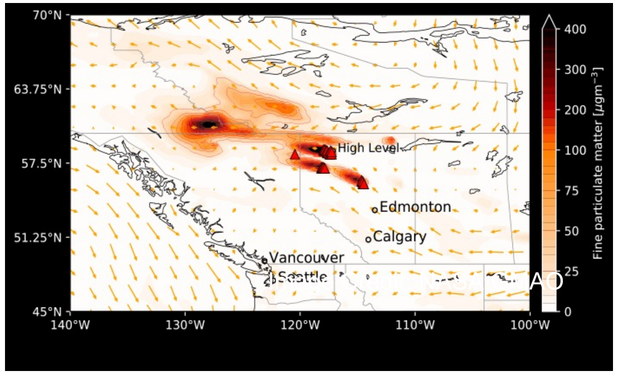


Drives Decision:
Which in-situ stream gauge readings to ingest?

Wildfire, Air Quality, and Health Impact

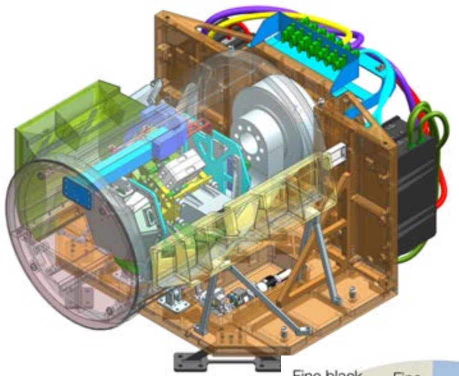
Inputs:
MODIS, VIIRS, Wildfire Risk Index

Model:
Predict wildfire growth and pollutant propagation through atmosphere using (e.g.) GEOS-CF

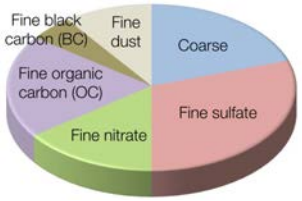


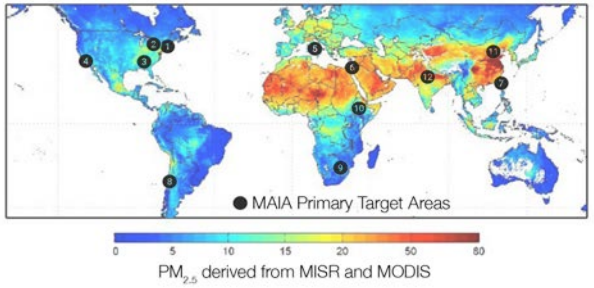
Drives Decision:
Which in-situ air quality readings to ingest?
Future: MAIA Instrument Retargeting

Multi-Angle Imager for Aerosols (MAIA) and Surface Biology and Geology (SBG)

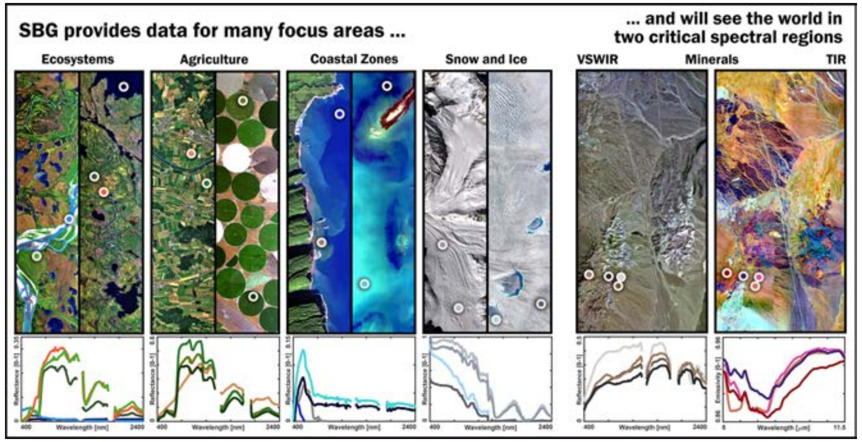


PM type and concentration





Exposure timescale Health outcomes
Acute (days to weeks) Emergency room visits, premature deaths
Subchronic (months) Adverse birth outcomes, pregnancy complications
Chronic (years) Cardiovascular and respiratory diseases

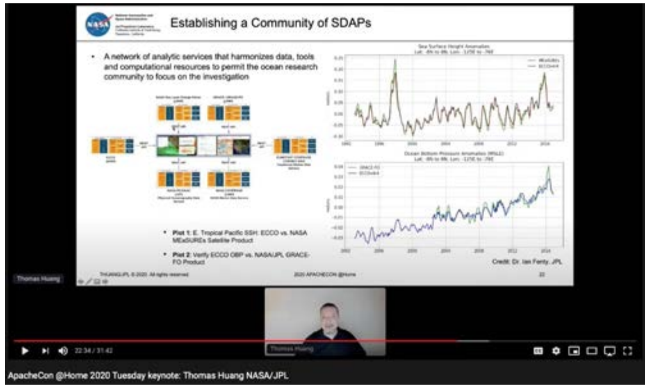


NOS – To simulate retasking of NASA's Multi-Angle Imager for Aerosols (MAIA)

SBG's fire detection and fire radiative power data for fire risk, detection, and analysis

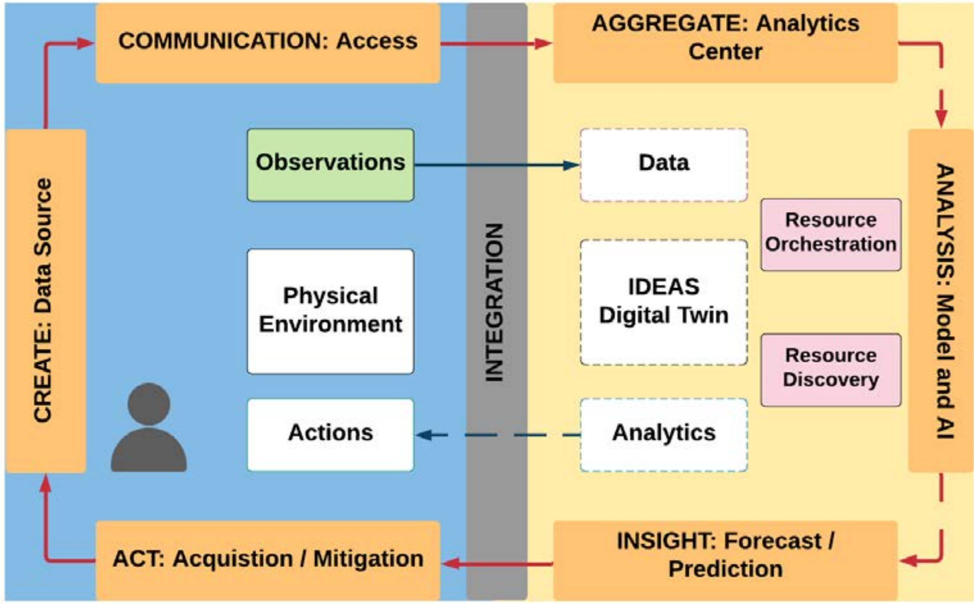
Open-Source Science and Community Collaboration

- Partnership with Apache Software Foundation
- Embrace open-source software
- Evolve the technology through community contributions
- Open-Source Science
  - Share recipes and lessons learned
  - Community validation
  - Technology demonstrations
  - Inclusive and Diverse Project Management Committee (PMC)
- Host webinars, hands-on cloud analytics workshops and hackathons



Conclusion - Big Data is about being Smarter with Data

- Building toward Earth System Digital Twin- opportunity to define and develop reusable, open-source Earth System Digital Twins framework
- Leverage, improve, and define community standards to promote interoperability
- It is about delivering professional quality open-source platform that addresses - Agility | Relevancy | Sustainability
- Enables end-to-end data and computation architecture, and the total cost of ownership
- Start with system architecture aiming for simple interfaces and information model - from generalization to specialization
- MUST team with Science Champions
- Successful big data platform needs to be ready for multi-computing, multi-data-center, and multi-agency



NASA ESTO/AIST's Integrated Digital Earth Analysis System (IDEAS) – an Earth System Digital Twin framework. Framework for pre-fire, during fire, and post fire analysis

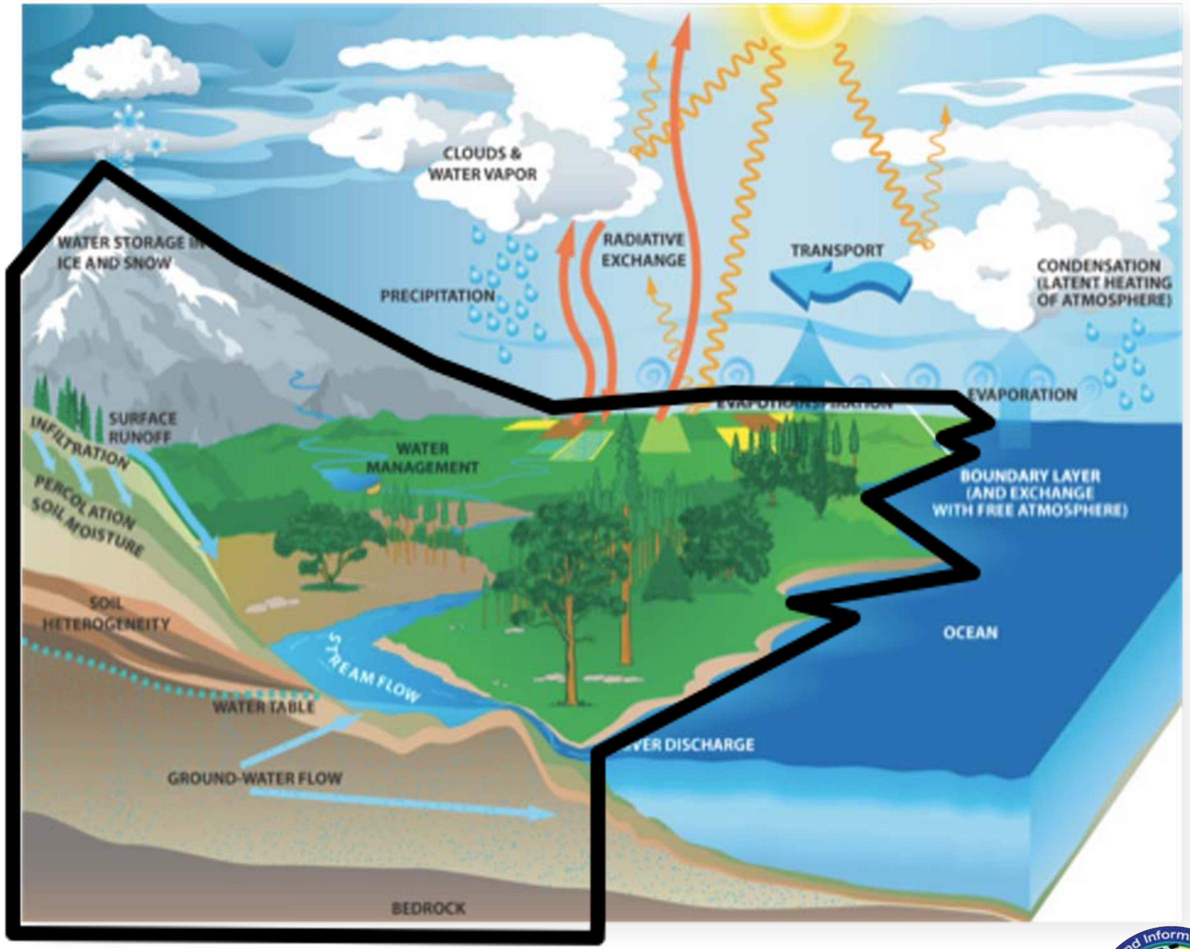
Thomas Huang
thomas.huang@jpl.nasa.gov
NASA Jet Propulsion Laboratory
California Institute of Technology

DARE MIGHTY THINGS
TOGETHER!

BACKUP

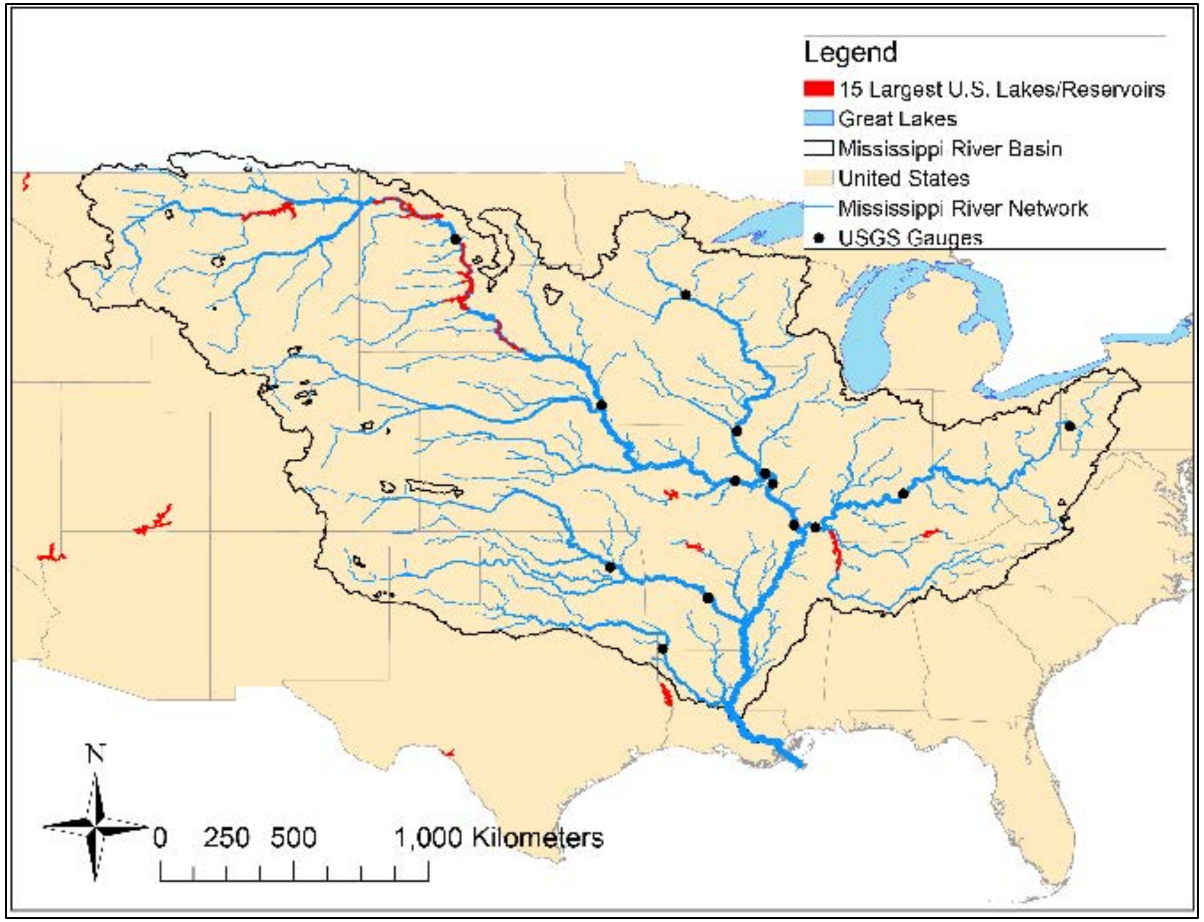
Land Information System (LIS)

- A system to study land surface processes and land-atmosphere interactions
- "Use best available observations" to force and constrain the models
- Applications: Weather and climate model initialization, water resources management, natural hazards management
- Need a system viable at different spatial and temporal scales
- Be able to demonstrate the impact of observations at the scale of observations themselves
- Explicit characterization of the land surface at the same spatial scales as that of cloud and precipitation processes helps in improving the characterization of land-atmosphere interactions
- Need scalable, high performance computing support to deal with computational challenges
- Need advanced land surface models and modeling tools (data assimilation, optimization, uncertainty modeling)



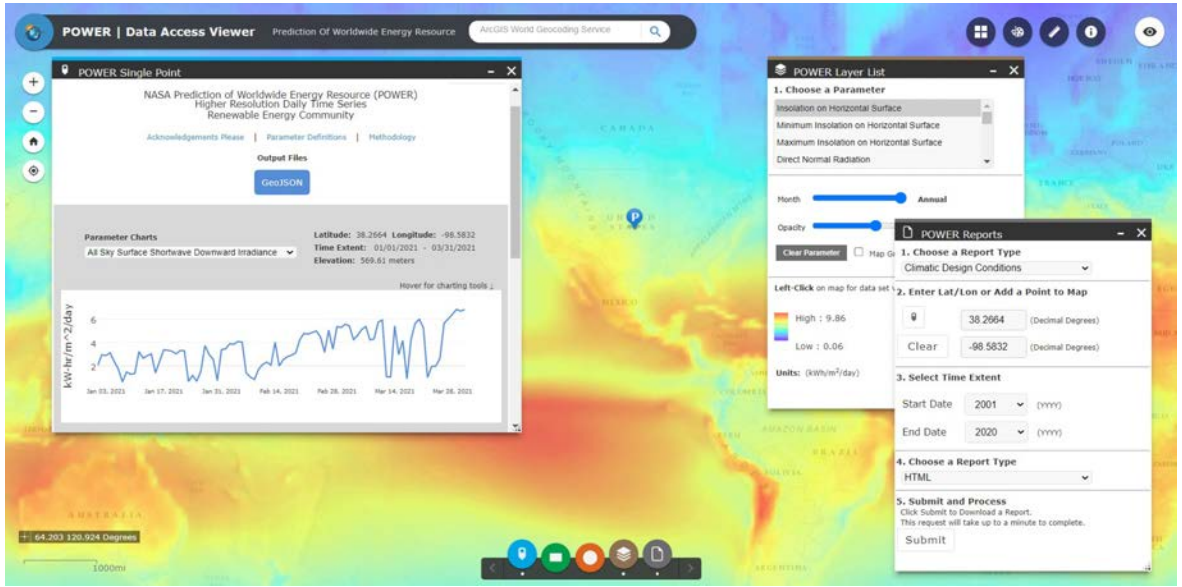
RAPID – River Discharge Model

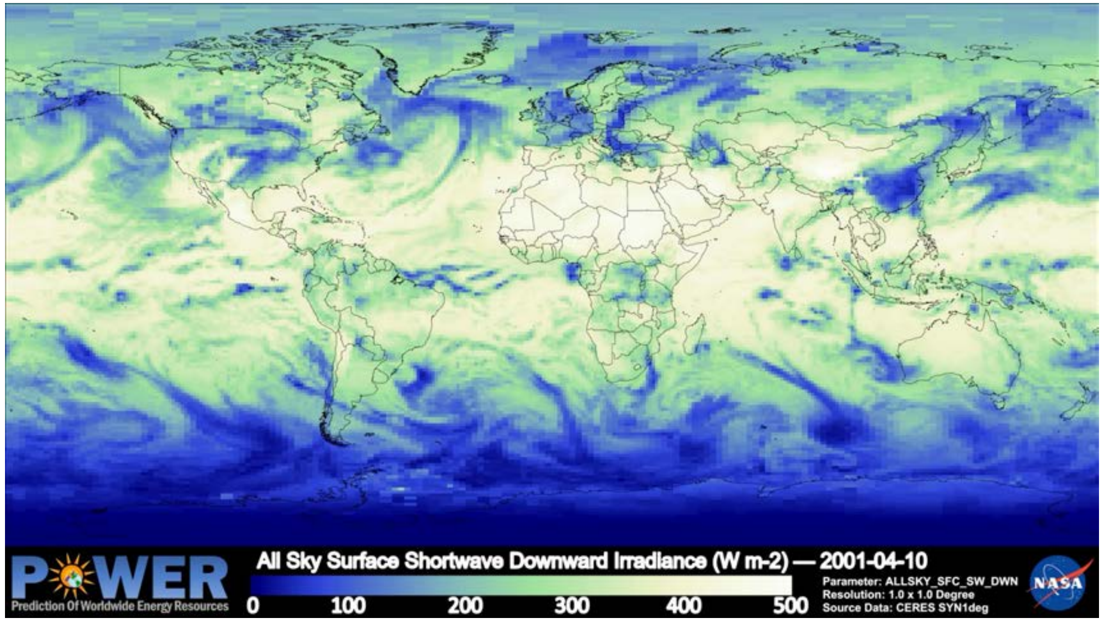
- River Model: Routing Application for Parallel computation of Discharge (RAPID)
  - Written in Fortran90, leverages the PETSc library (high performance computing with MPI)
  - https://github.com/c-h-david/rapid/
- Pre and Post processing: Reproducible Routing Rituals (RRR)
  - Written in Python3, leverages various pip packages
  - https://github.com/c-h-david/rrr
- Sustainable DevOps
  - Continuous Integration with Travis CI
  - Continuous Deployment with Docker Hub
  - Runs on laptop, desktop, cloud, or HPC
  - Inputs and outputs are generally netCDF or CSV. Example inputs/outputs available https://doi.org/10.5281/zenodo.3688690

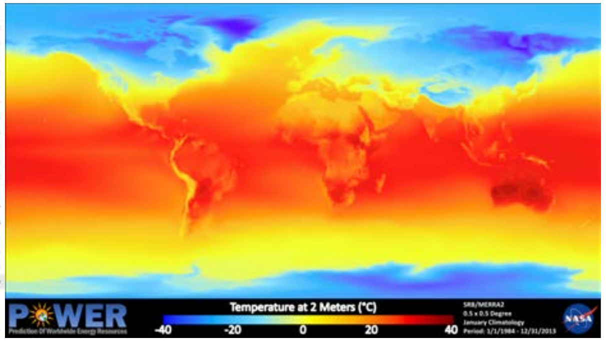


Prediction of Worldwide Energy Resources (POWER)

- Providing key input parameters to the hub in optimized data formats for use in the LIS model.
- Key parameters include
  - Surface meteorological properties
  - Downward surface radiative fluxes (both the solar and thermal infrared wavelengths). The data sources for these latter products is the CERES (Clouds and Earth's Radiant Energy System) mission.

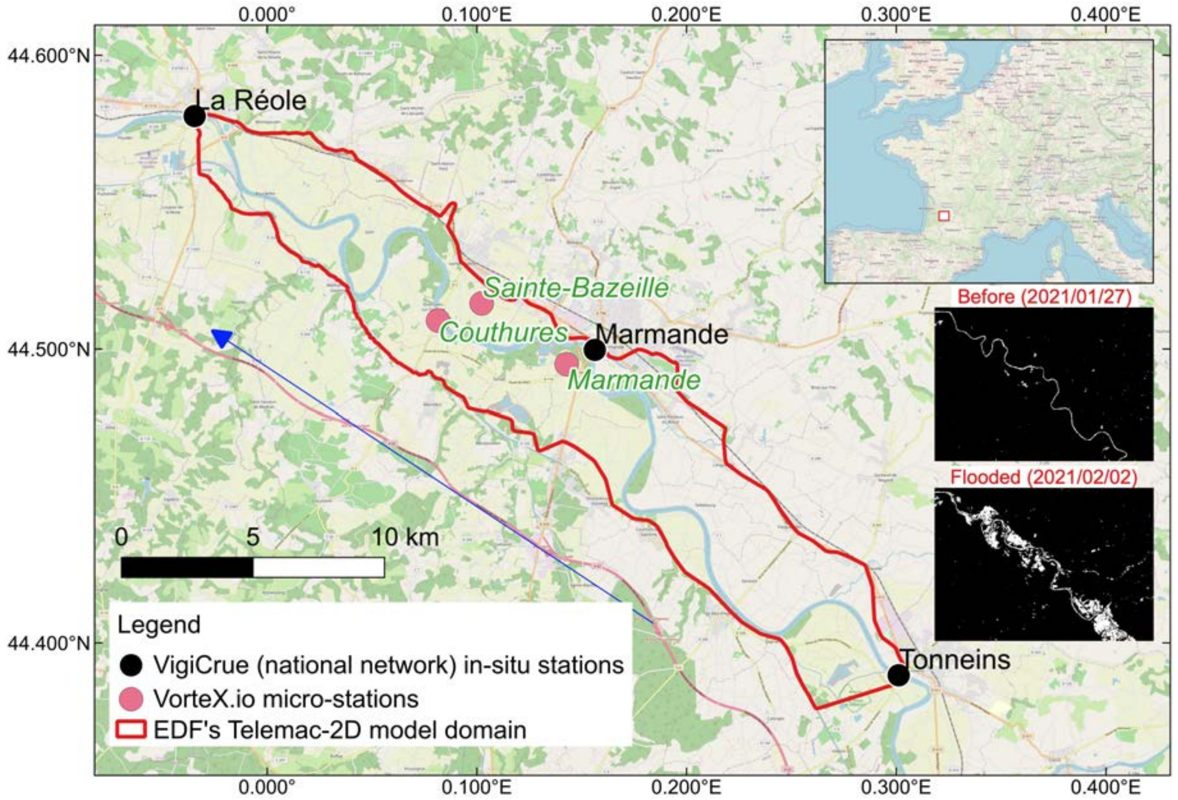




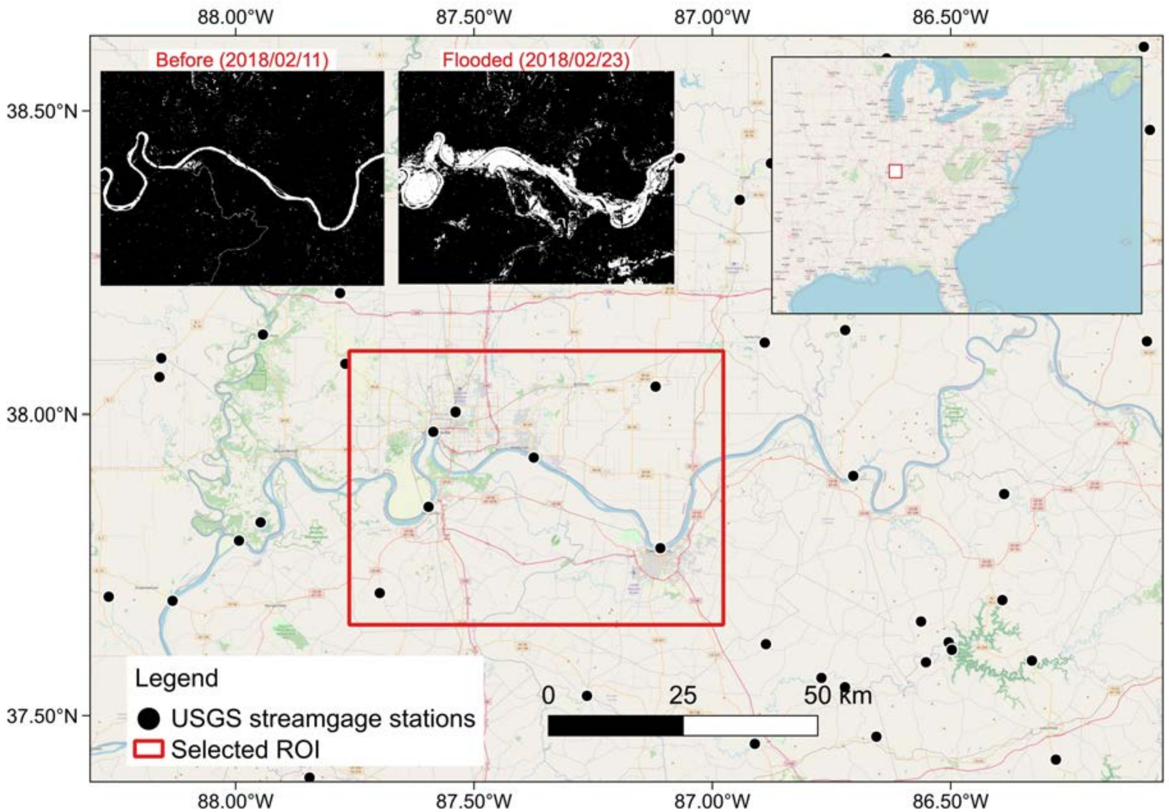


SCO FloodDAM-DT – catchment sites

France Catchment : **Garonne river**

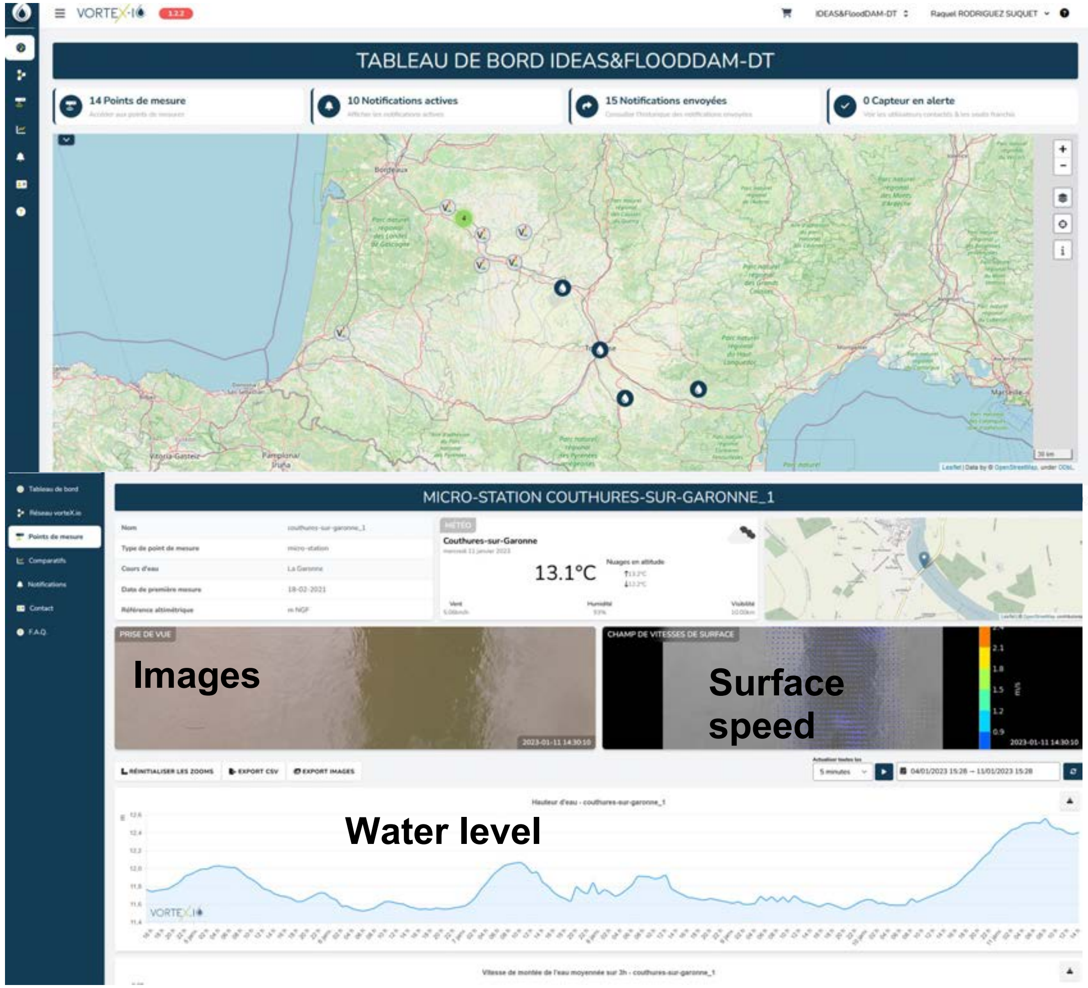


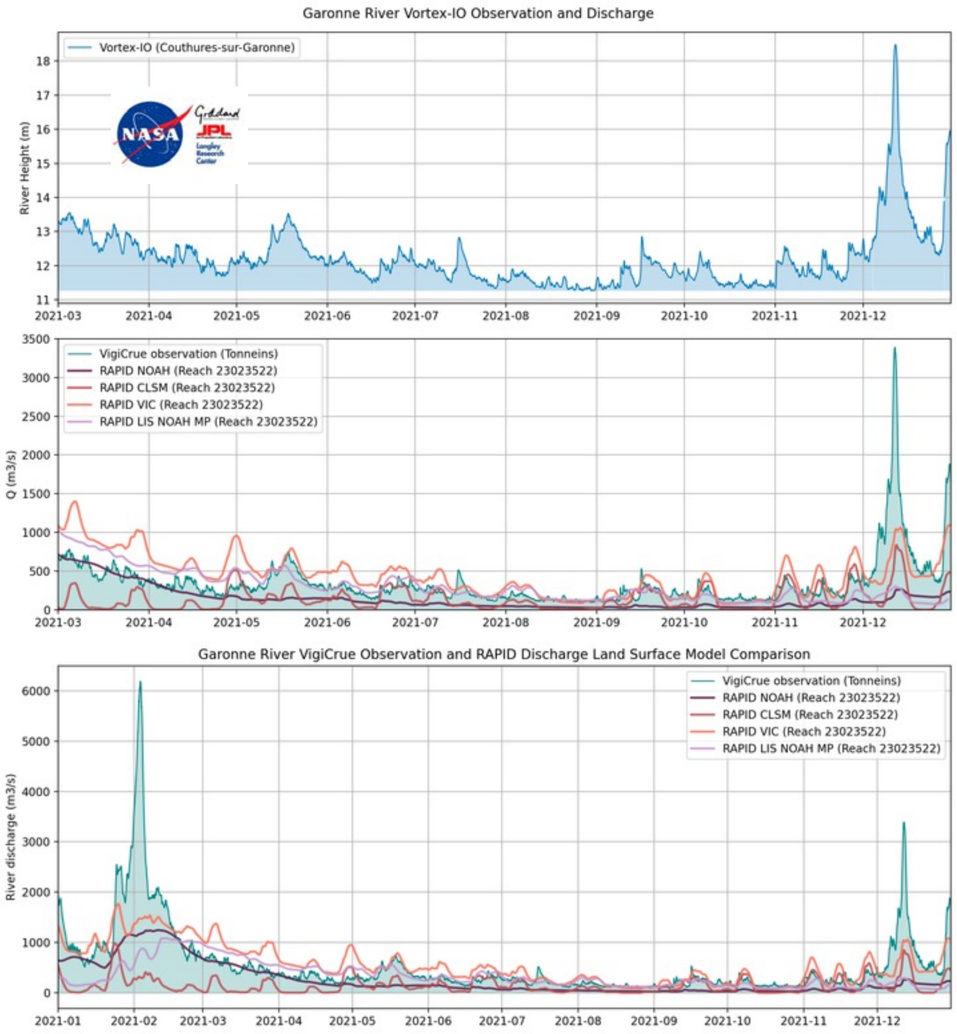
USA Catchment : **Ohio River**



SCO FloodDAM-DT – Micro-stations

- Analyze live micro-stations data collected by VorteX.io

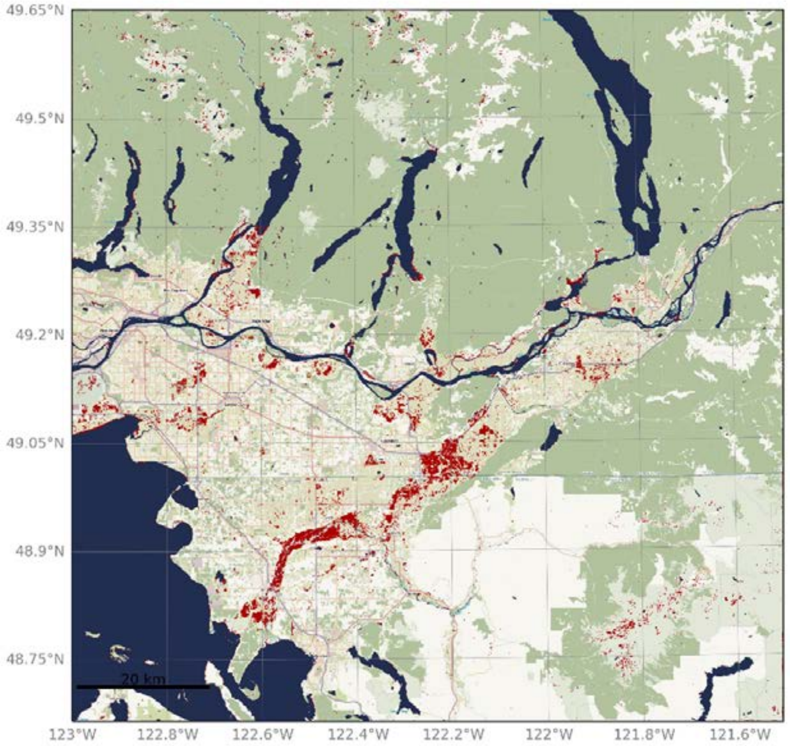




SCO FloodDAM-DT – Flood Mapping

- Rapid Flood mapping generation from SAR and optical data **over the world**
- Developed by CLS (Collecte Localisation Satellite) Group in France

Washington State and Canada flood event 2021-11-16



Legend

- Estimated flooded areas
- Permanent water (occurrence >50%)
- No data

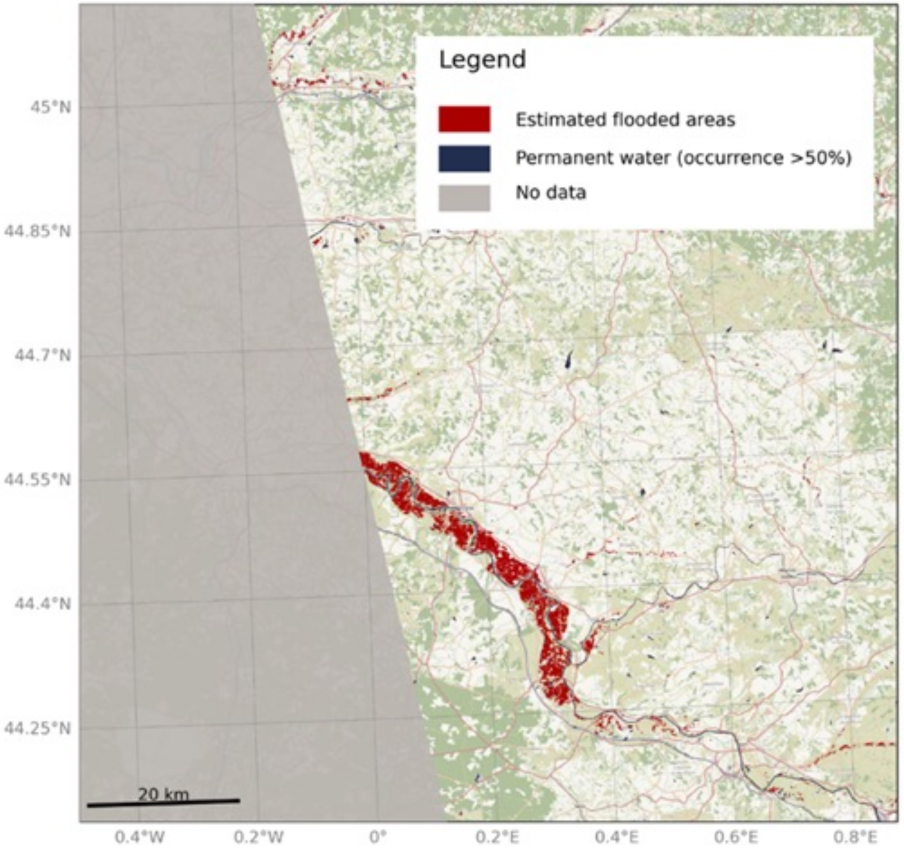
Data source

Map Projection	EPSG:32610
Data source	Sentinel-1
Relative orbit	013
Acq. date (UTC)	2021-11-16 00:00:00
Polarization	VV,VH
Post-processing	Majority filter r=2

Disclaimer

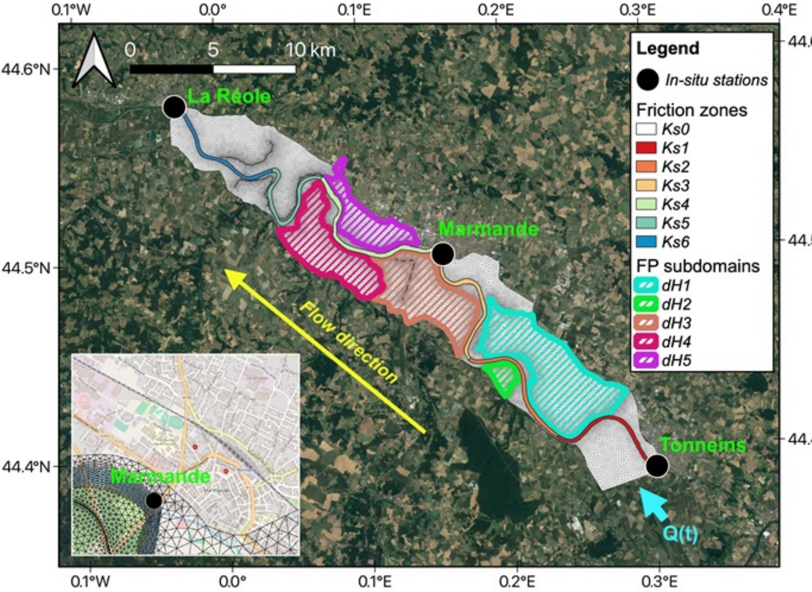
- This map is derived automatically using the FloodDAM Rapid-Mapping (FloodML) tool.
  More info: https://www.spaceclimateobservatory.org/flooddam-garonne
- How to cite this map: FloodDAM Rapid-Mapping (© CNES-CLS-CS, 2019-2021)
- Surface Water Occurrence (GSW) data: Jean-Francois Pekel, Andrew Cottam, Noel Gorelick, Alan S. Belward.
  High-resolution mapping of global surface water and its long-term changes. Nature 540, 418-422 (2016). (doi:10.1038/nature20584)
- Fond de carte par Yohan Boniface & Humanitarian OpenStreetMap Team sous licence domaine public CC0

Garonne Marmandaise flood event 2021-02-03

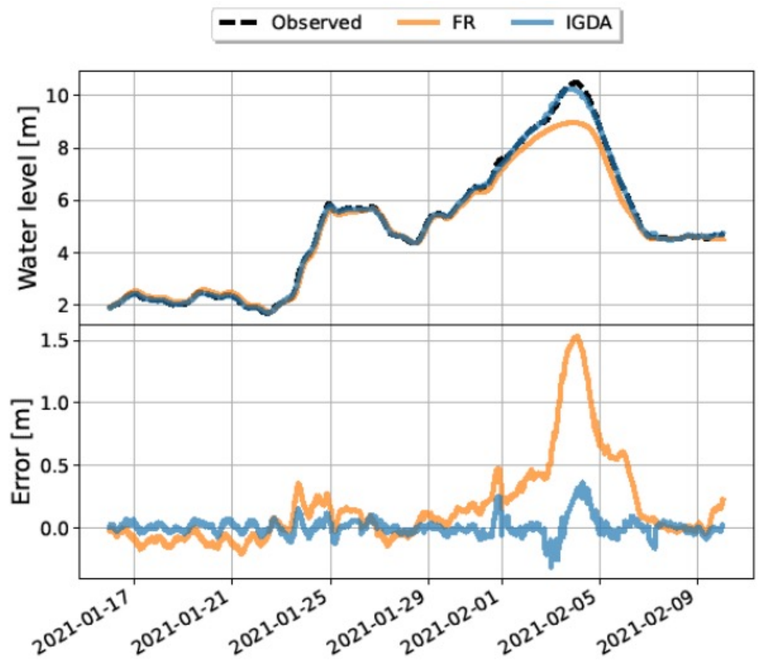


SCO FloodDAM-DT – Water Level Map

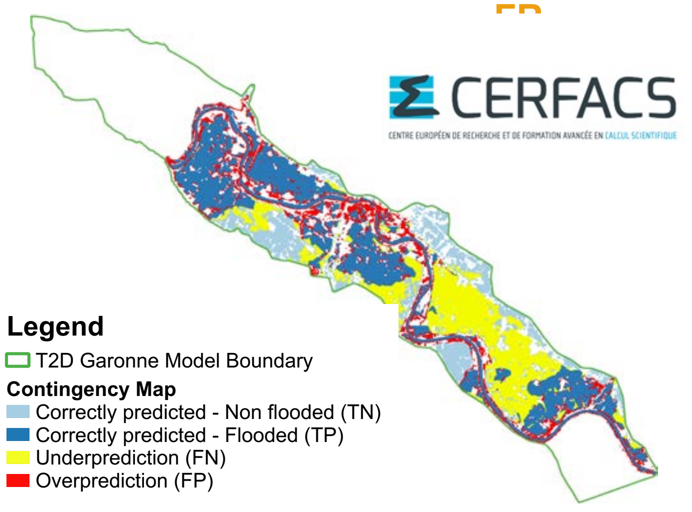
Garonne Marmandaise catchment - flood event 2021-02-03



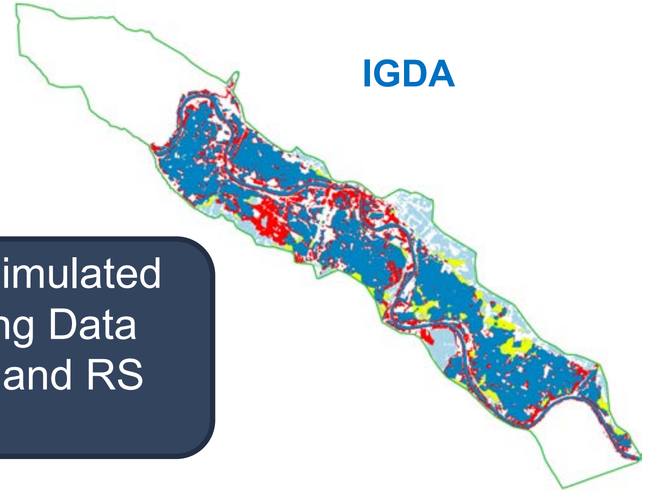
Simulated vs. observed water level



Simulated vs. observed flood extent maps



IGDA



Hydrodynamic model : Telemac 2D

FR : Free run simulation

IGDA : FR simulation with Data assimilation of in-situ and remote sensing observations

Publications:

- *Nguyen et al., (2022) Improvement of Flood Extent Representation with Remote Sensing Data and Data Assimilation, IEEE Transactions on Geoscience and Remote Sensing, 60 (4206022), pp. 1-22, doi:10.1109/TGRS.2022.3147429*
- *Nguyen et al., (2022) Dual State-Parameter Assimilation of SAR-Derived Wet Surface Ratio for Improving Fluvial Flood Reanalysis, Water Resources Research, 58 (11), pp. e2022WR033155, doi:10.1029/2022WR033155*
- *Nguyen et al., Gaussian Anamorphosis for Ensemble Kalman Filter Analysis of SAR-Derived Wet Surface Ratio Observations. IEEE Transactions on Geoscience and Remote Sensing, (Under review)*

Clear improvement of simulated flood extent maps using Data Assimilation of in-situ and RS data

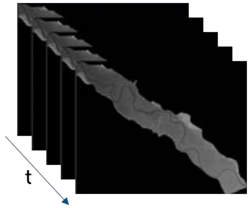
SCO FloodDAM-DT – Financial Risk Map

- **Environmental Intelligence Platform and API**
- **Real time product on financial risk estimation and risk map generation of flooding for different type of assets**

Flood risk map from FloodDAM-DT data combination with :
- Geolocation data of physical assets
- Geolocated Social media data

Pipeline

Input: Flood Map



Hourly flood map + xx hours forecast
- μ average estimated water elevation

Q3 risk modeling

Output

Estimated cost
- Agriculture: XXX $ +/- xx
- Residential: XXX $ +/- xx
- Industrial: XXX $ +/- xx
- Company_1: XXX $ +/- xx

Social/Env metrics
- Impacted population: XX K
- Biodiversity impact: Flood event in a protected area
- ...

Newspaper info
- Le monde: *Flood Event….*
- Le monde: ….

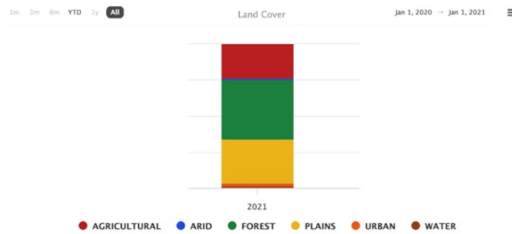
QUANTCUBE TECHNOLOGY

Marmande - Residential area

Asset valuation: $

Area: 3.7 km²

Total population on area : 850 hab



Flood Risk

Flood event : 02 / 2021

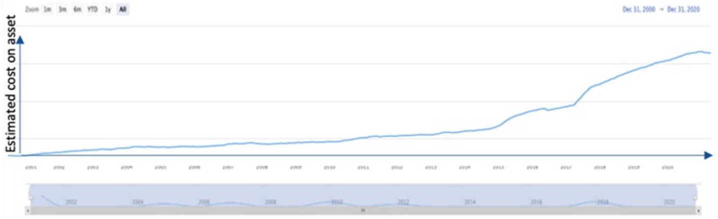
Estimated cost on asset : $

Chart News

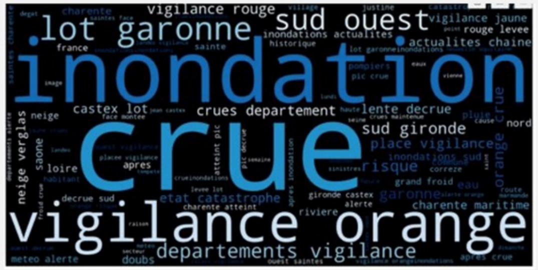
Indicator

Estimated Cost   Impacted Population

Chart

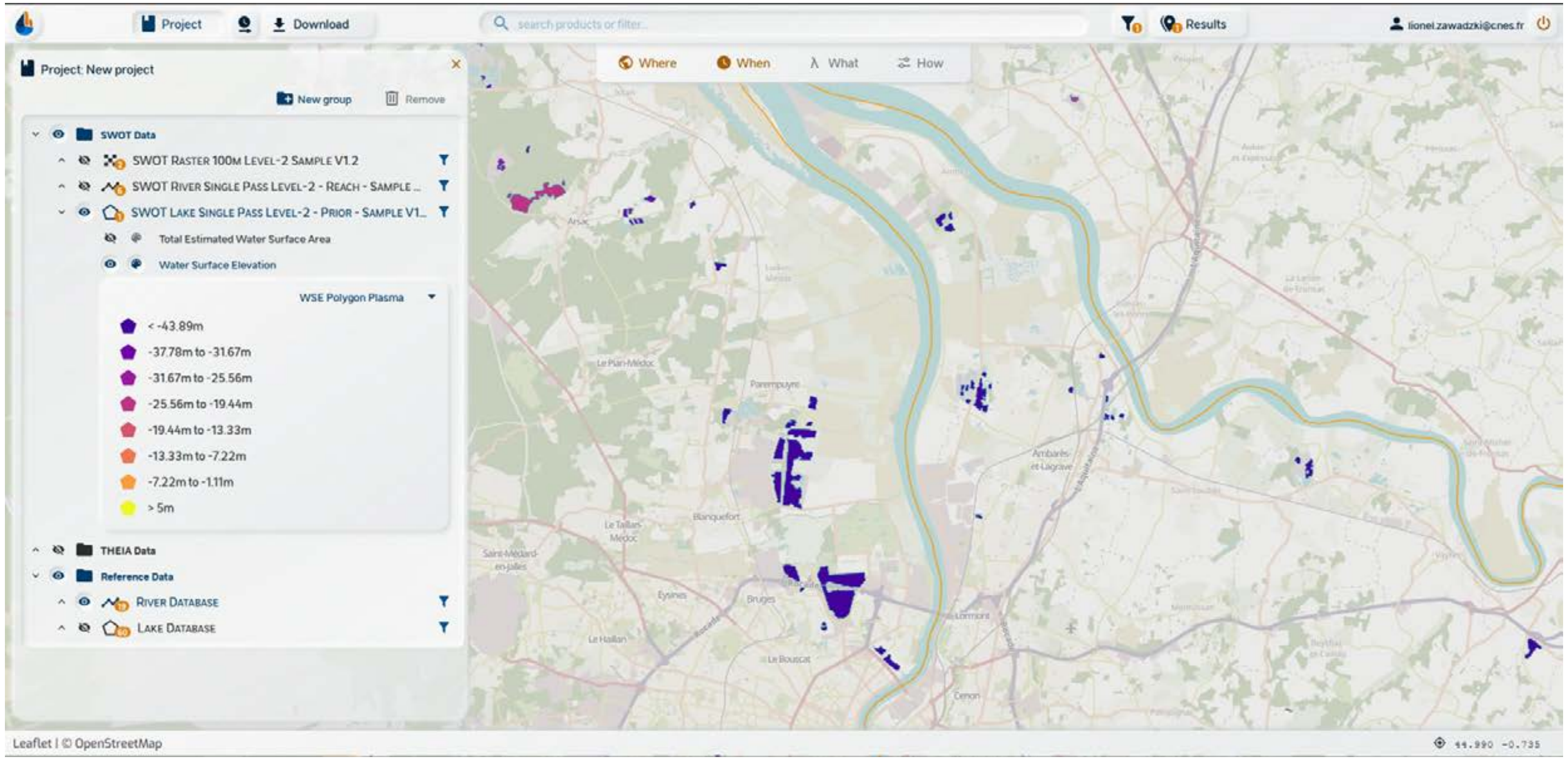


Event related news:



SCO FloodDAM-DT – Hydroweb.next

- FloodDAM-DT processing chain will be integrated in the hydrological platform Hydroweb.next
- CS group responsible of the FloodDAM integration, inter-operability and interfaces



Time series of water levels in the rivers and lakes around the world processed from satellite altimetry

SCO FloodDAM-DT – On going work

- ❖ Improvement of Flood Rapid mapping algorithm from SAR and optical data
- ❖ Working on interfaces and interoperability
- ❖ Chaining RAPID hydrological model with Telemac 2D hydrodynamic model
- ❖ Working on the global financial physical risk model
- ❖ Preparing future micro-station location and installation aux USA