Capturing the Dynamics of Compound Flooding in E3SM

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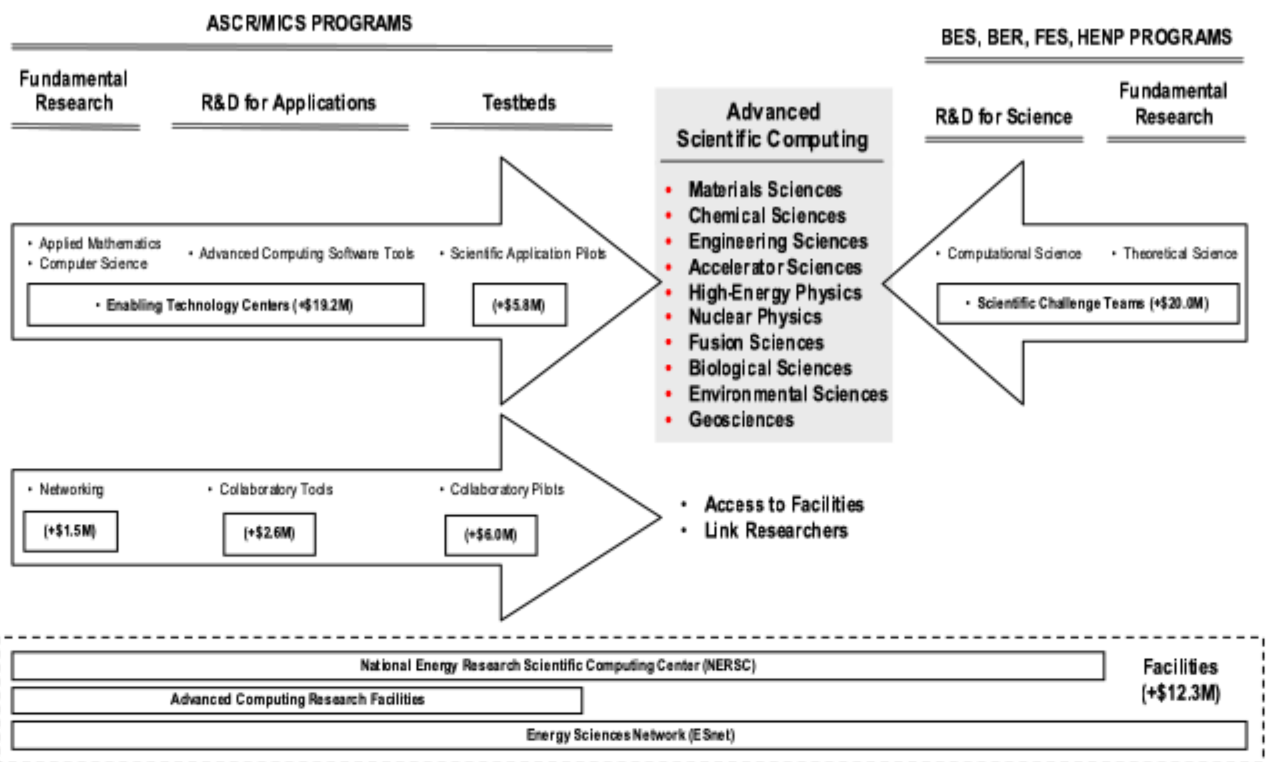
Scientific Discovery through Advanced Computing

Scientific Discovery through Advanced Computing (SciDAC)



Source: SciDAC Report, 2000

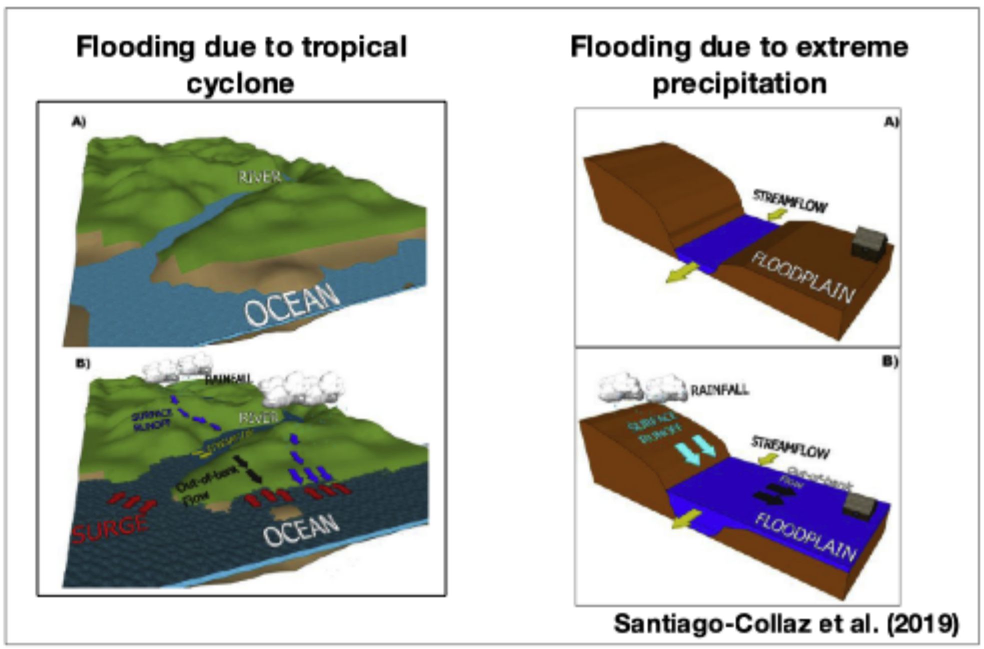
Scientific Discovery through Advanced Computing (SciDAC)

- Started in 2001 (1st)
- Re-competed in 2006 (2nd), 2011 (3rd), 2017 (4th), and 2022 (5th)
- Current SciDAC Institutes include:
  1. FASTMath
  2. RAPIDS
- Current SciDAC BER partnerships include 7 projects

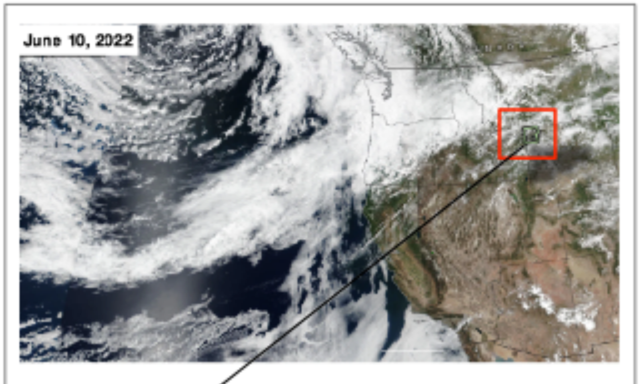
Compound Flooding (CF)

Compound events are described as (IPCC2012)

1. simultaneous or successively occurring (climate-related) events such as simultaneous coastal and fluvial floods,
2. events combined with background conditions that augment their impacts such as rainfall on already saturated soils, or
3. a combination of (several) average values of climatic variables that result in an extreme event

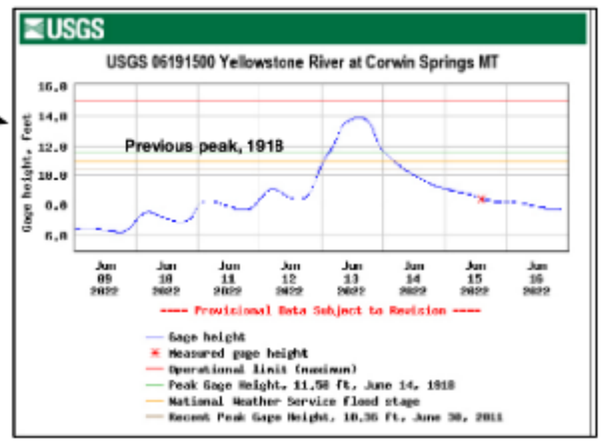


CF and Its Impacts Pose a Significant Threat to Human and Natural Systems



- June 10-13, 2022, an atmospheric river event struck Yellowstone National Park.

- 2-3 inches of rain, combined with warm overnight temperatures, melted large amount of snow, resulting in historic flooding



https://www.usgs.gov/observatories/yvo/news/how-might-devastating-june-2022-floods-and-around-yellowstone-national-park

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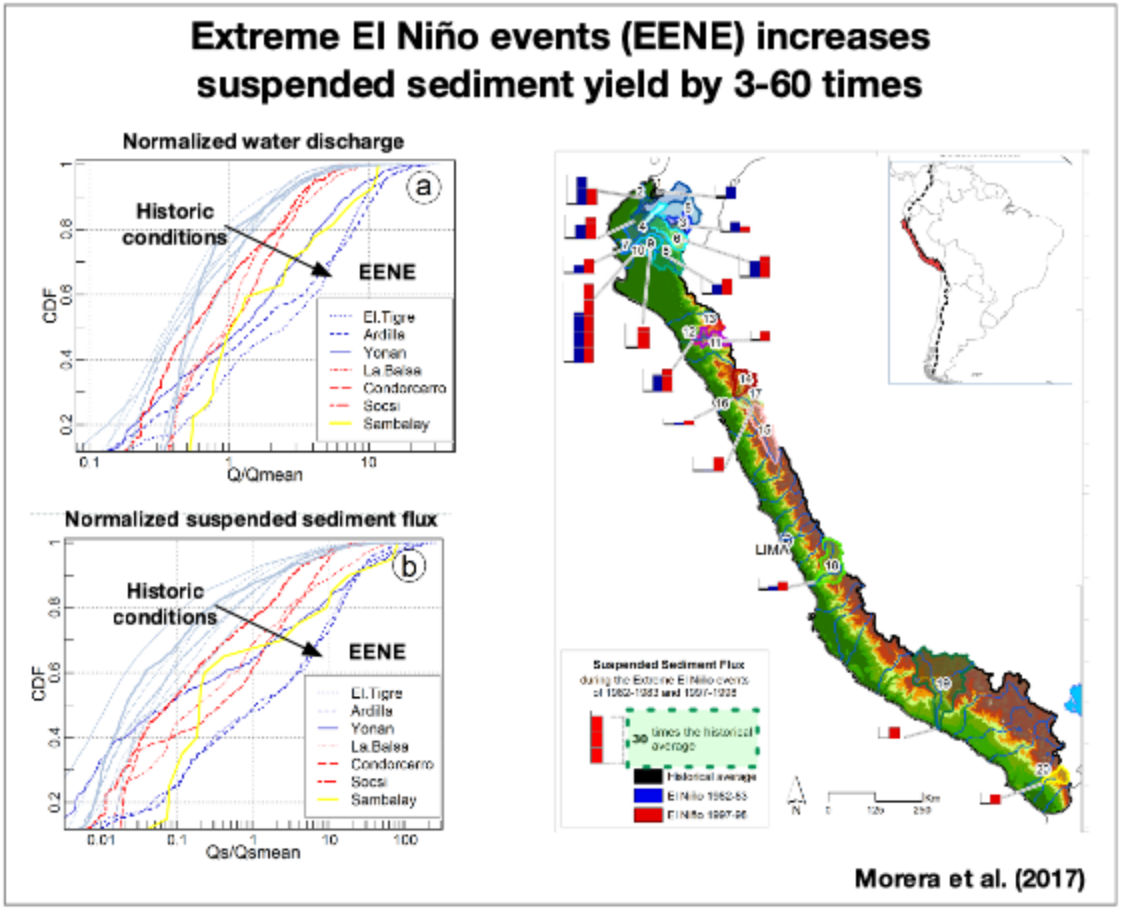
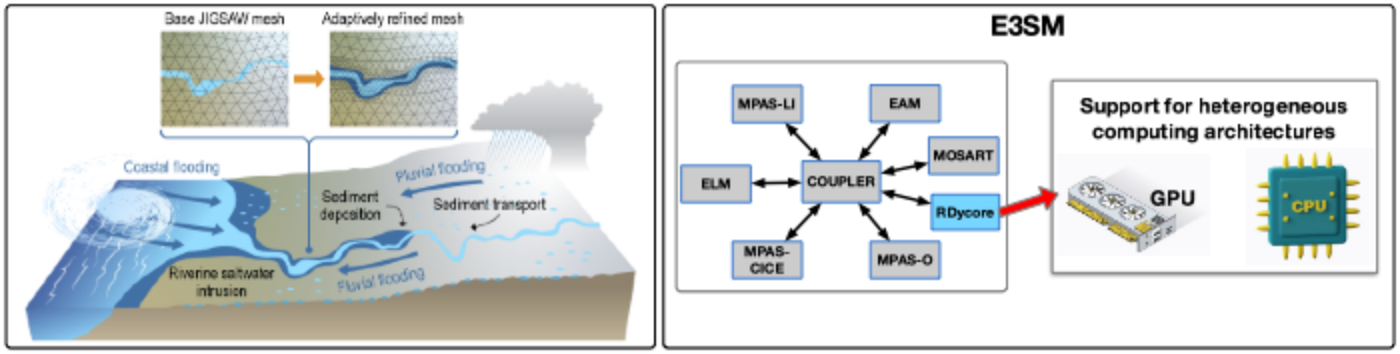


Several **S**cientific and **C**omputational **B**ottlenecks Exists in E3SM for Studying CF and Its Impacts

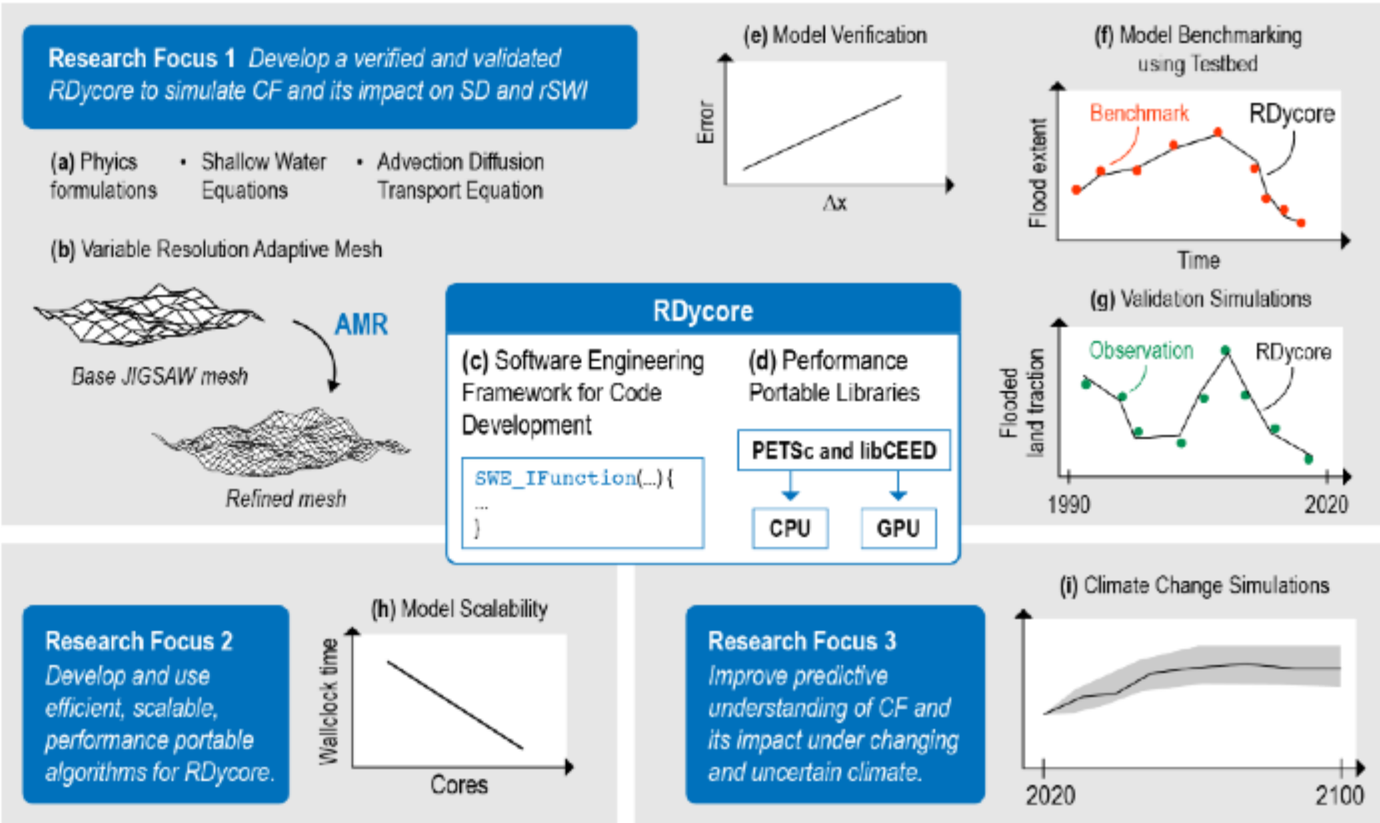
- SB1: MOSART's assumption about subgrid structure limits the finest mesh resolution to be $\approx$ 5km
- SB2: MOSART's existing physics has few limitations in accurately capturing CF events
  - Backwater propagation occurs only along river network
  - Instantaneous exchange of water between river channel and floodplain
  - Lack of density-dependent flow
- CB1: Single discretization implementation does not allow for the evaluation of numerical algorithms for solution accuracy and algorithmic scalability
- CB2: No support for heterogeneous computing architectures

Project Objectives (POs)



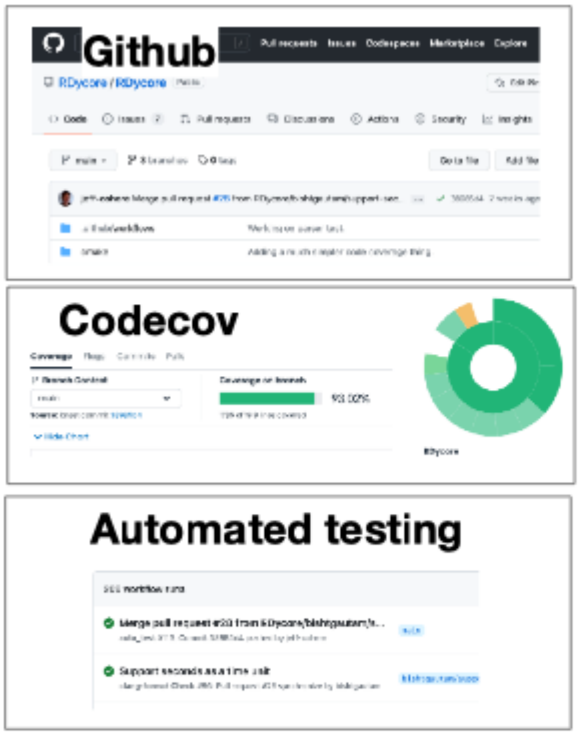
- PO1: Develop a rigorously verified and validated river dynamical core (RDycore) for E3SM to mechanistically model pluvial, fluvial, and coastal compound flooding and their impacts on sediment dynamics and riverine saltwater intrusion.
- PO2: Develop computationally efficient and scalable RDycore and assess its performance on heterogeneous computing architectures.
- PO3: Improve the predictive understanding of CF, SD, and rSWI due to the simultaneous but uncertain occurrence of multiple drivers of floods in a changing climate.

Research Foci

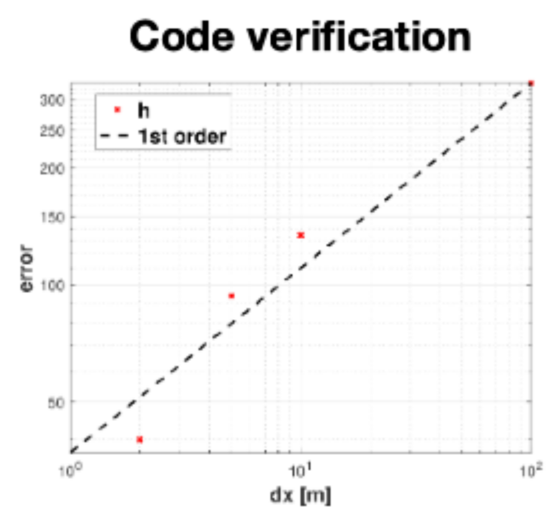


Project Achievements

1. Set up an open source repository for the RDycore library with an initial implementation of the solver for shallow water equation and code verification was performed.



Team member: Jeff Johnson



Team members: Donghui Xu, Gautam Bisht

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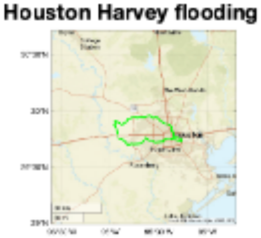
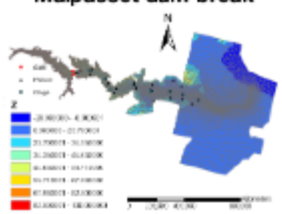
OFM for simulating Houston Harvey flooding



Team member: Donghui Xu

PHIM3D for simulating Malpasset dam break

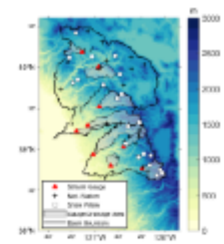


Team members: Mukesh Kumar, Ashwin Raman

TELEMAC-MASCARET for simulating sediment dynamcis in the Amazon

Team members: Zeli Tan, Dongyu Feng

ELM for simulating rain-on-snow in Sierra Nevada



Team member: Dalei Hao

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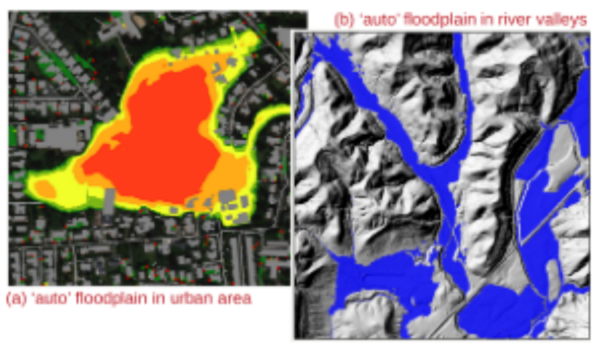
3. Extended E3SM-supported JIGSAW meshing library to new floodplain resolving ultra high-resolution.



Team member: Darren Engwirda

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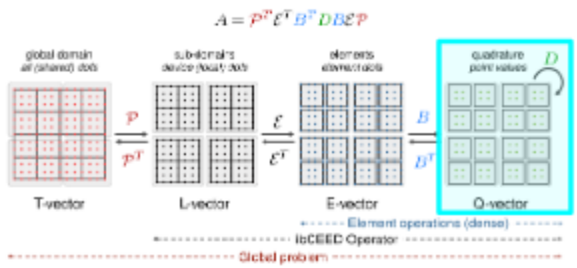
4. Completed an initial development in PETSc and libCEED, a numerical library for higher-order FE methods, to support FV methods in libCEED.



Team member: Jed Brown, Matt Knepley, Antonio Rowie, Mark Adams

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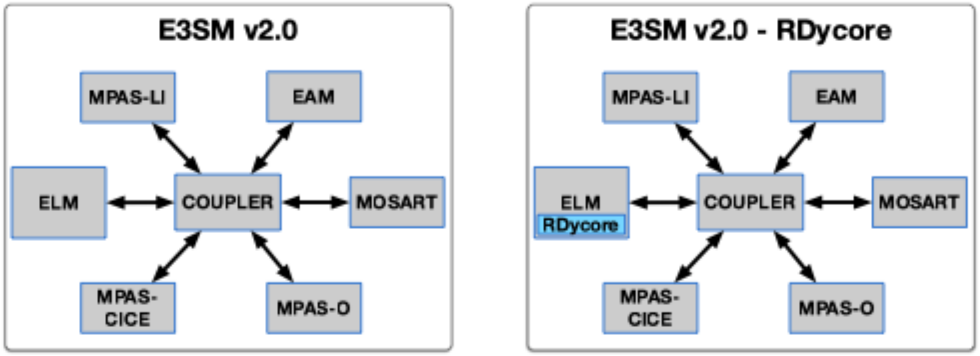
4. Completed an initial development in PETSc and libCEED, a numerical library for higher-order FE methods, to support FV methods in libCEED.
5. Added RDycore within E3SM and performed short simulations on Perlmutter, Summit, Crusher, and Frontier with RDycore using GPUs.

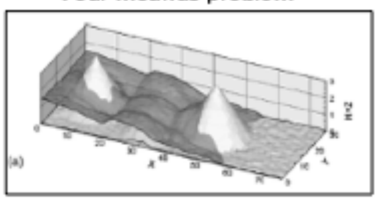


Team member: Gautam Bisht

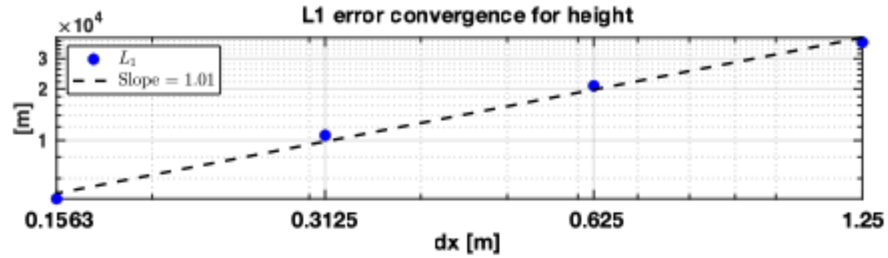
RDycore: Initial Development and Verification

- Implemented first-order accurate space (FV) and time (explicit) discretization methods
- Works on both triangle and quadrilateral mesh
- Performed initial code verification for two previously published problems

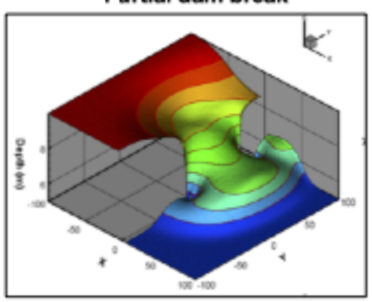
Four mounds problem



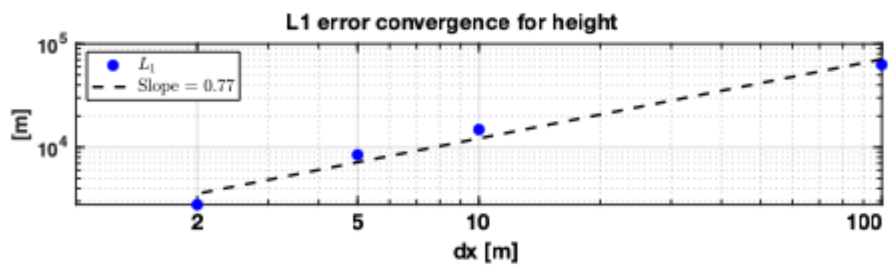
Begnudelli and Sanders (2007)



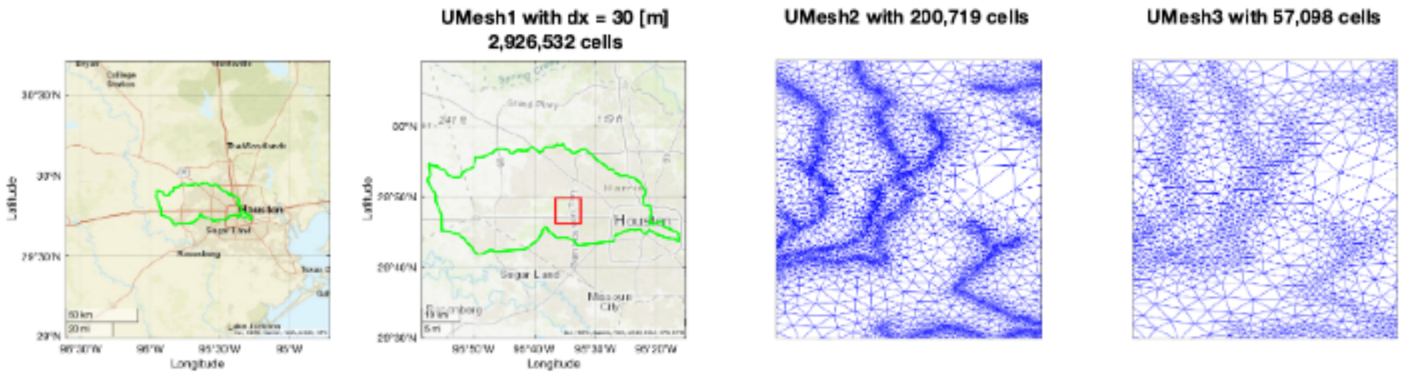
Partial dam break



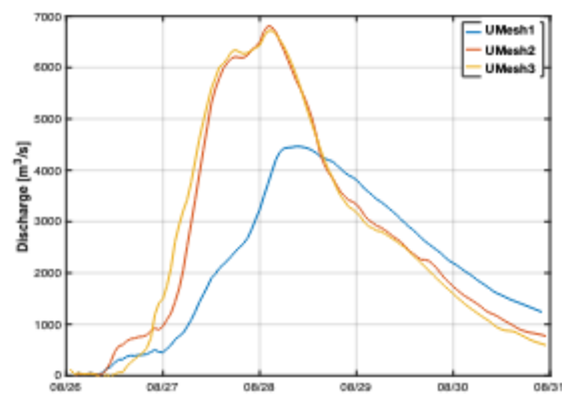
Nikolos and Delis (2009)



Development of Benchmarks: Houston Harvey Flooding

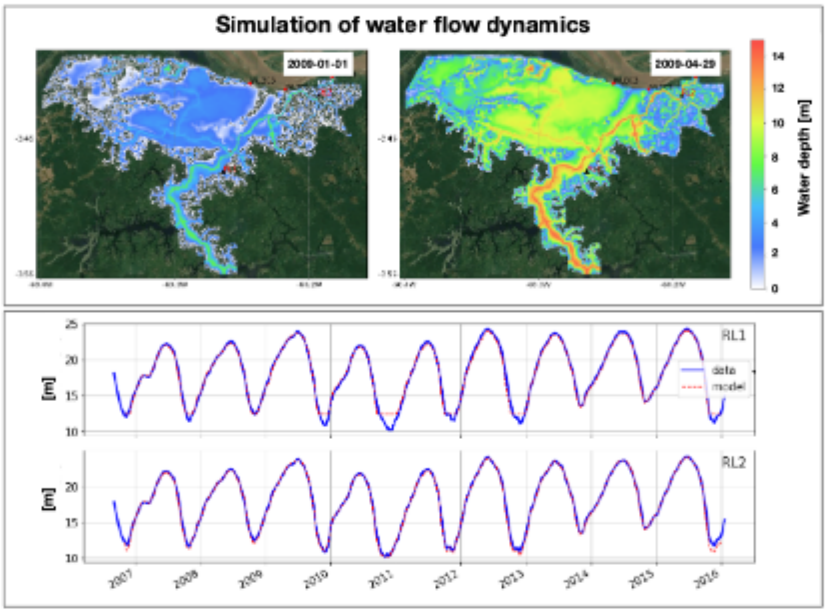


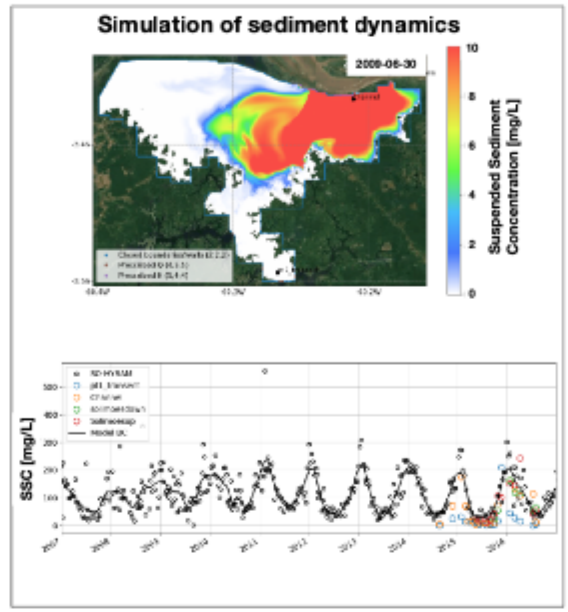
- Selected Overland Flow Model (OFM)
- Selected the Houston Harvey flooding event, August 2017
- Spatially-homogenous, but temporally varying precipitation forcing is applied
- A time-varying tidal stream outflow BC is used
- When coarsening the mesh, the simulation efficiency increases, but accuracy decreases



Development of Benchmarks: Sediment Dynamics

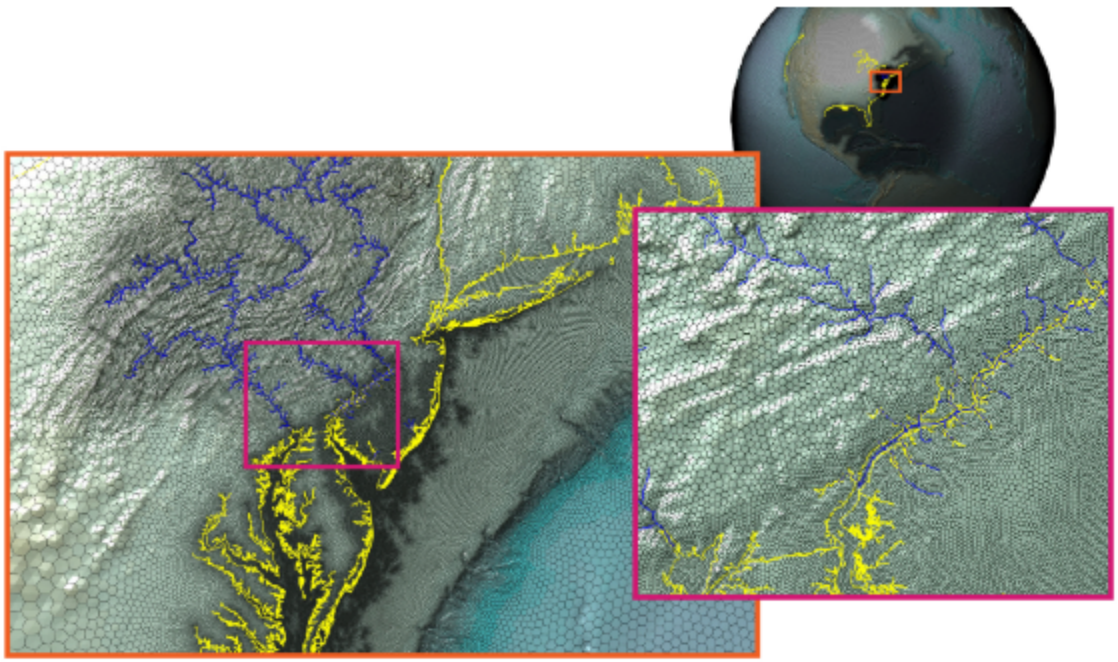
- Selected TELEMAC-MASCARET as the benchmark model
- Selected the Janauaca catchment in the Amazon as the study site
- Completed a 10-yr flow simulation with 8 inflow BCs and 3 open flow BCs
- Performed an initial 1-yr sediment dynamics simulation





Unstructured meshes: global-to-(sub)watershed scales...

Push E3SM unstructured meshing workflow (JIGSAW library) to new 'ultra' high-resolution floodplain resolving levels.



Support additional boundary 'labelling' of geometry as well as XDMF/EXODUS file I/O, for PETSc interoperability.

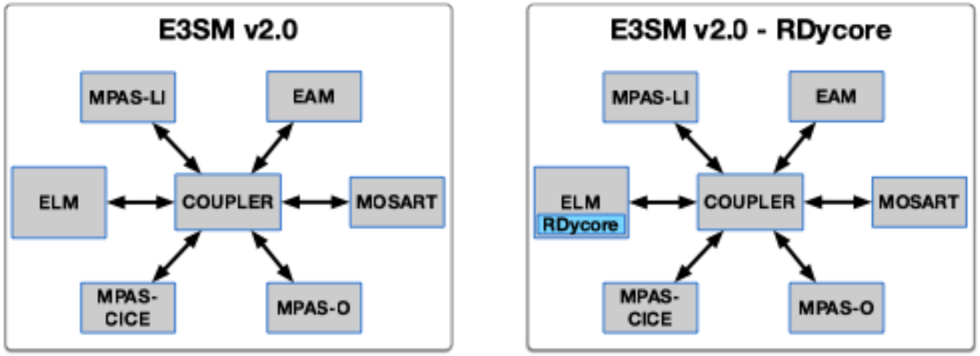
PETSc and libCEED solver GPU/device portability

- Non-linear SWE: $\mathbf{X}_t = F(\mathbf{X})$
- PETSc provides multiple time integration methods
- Portability provided with two options on most architectures:
    - Vendor specific back-ends: CUDA, HIP
    - Kokkos back-end: eg, CUDA, HIP, SYCL, and OpenMP

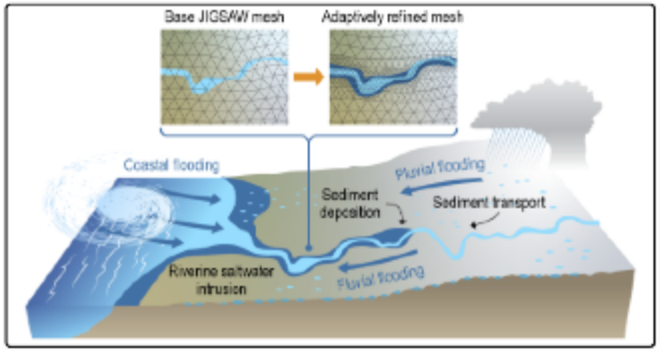
Programming Model	Supporting Package	GPUs (devices)
CUDA	cuBLAS, cuSPARSE, Thrust	NVIDIA
HIP	hipBLAS, hipSparse, hipThrust	AMD
Kokkos	Kokkos, Kokkos-Kernels	NVIDA, AMD, Intel

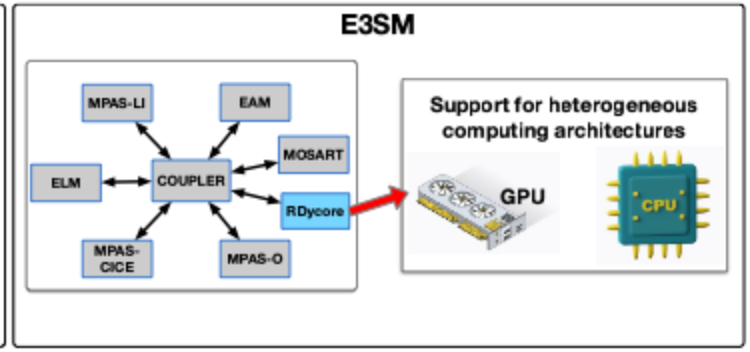
- libCEED has been extended for FV method to compute the $F(\mathbf{X})$ on the device
- PETSc's DMPlex has been extended to support libCEED's FV method

E3SM–RDycore Integration



- A test implementation of E3SM–RDycore has been completed.
- PETSc and RDycore are installed before building an E3SM case.
- RDycore initializes a simulation, runs to completion, and shuts off.
- RDycore tested on GPUs: (a) NVIDIA (Perlmutter and Summit) and (b) AMD (Crusher and Frontier).
- However, presently there is no exchange of information between ELM and RDycore.
- Exploited PETSc's runtime configurability to solve SWE on CPU or GPU via:
  - CPU : `e3sm.exe`
  - GPU via Kokkos: `e3sm.exe -dm_vec_type kokkos`
  - GPU via CUDA : `e3sm.exe -dm_vec_type cuda`
  - GPU via HIP : `e3sm.exe -dm_vec_type hip`


Base JIGSAW mesh
Adaptively refined mesh
Coastal flooding
Pluvial flooding
Sediment deposition
Sediment transport
Riverine saltwater intrusion
Fluvial flooding


E3SM
MPAS-LI
EAM
MOSART
ELM
COUPLER
RDycore
MPAS-CICE
MPAS-O
Support for heterogeneous computing architectures
GPU
CPU

Thank you