Highly scalable adaptive mesh refinement for natural hazards modeling

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Natural Hazards Modeling

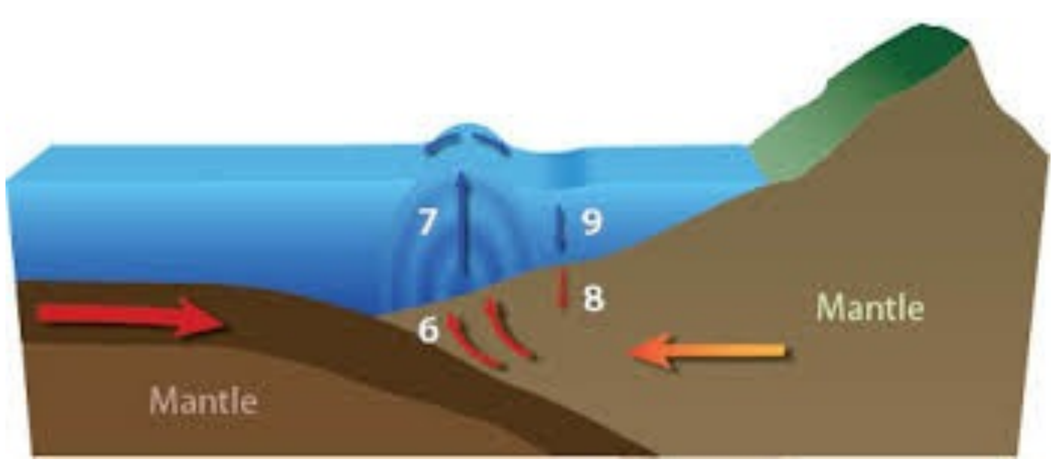
Many natural hazards are well suited to numerical modeling and simulation

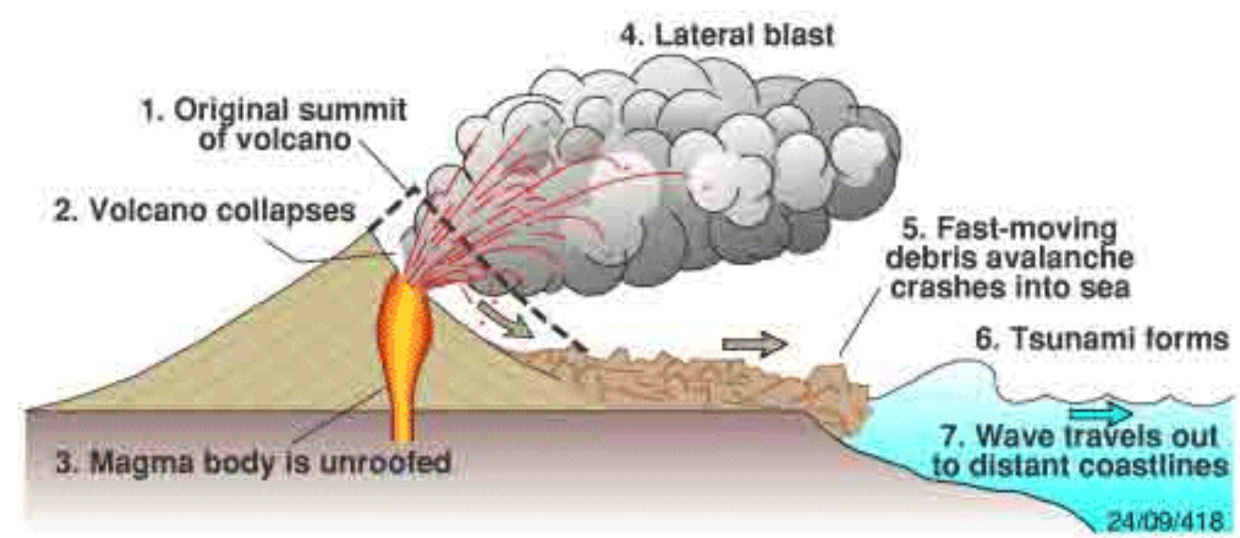
- Tsunamis
- Volcanic ash plumes
- Earthquakes
- Wildfires
- Storm surges
- Debris flows and landslides
- Flooding

Mathematical models are now routinely used to understand these phenomena and predict their behavior

Challenges

- Unknown initial conditions
- Complicated geometry that is not well known or understood.
- Coupled events requiring several different models
- Many temporal and spatial scales are involved
- Simulations should be done in real time to be most useful

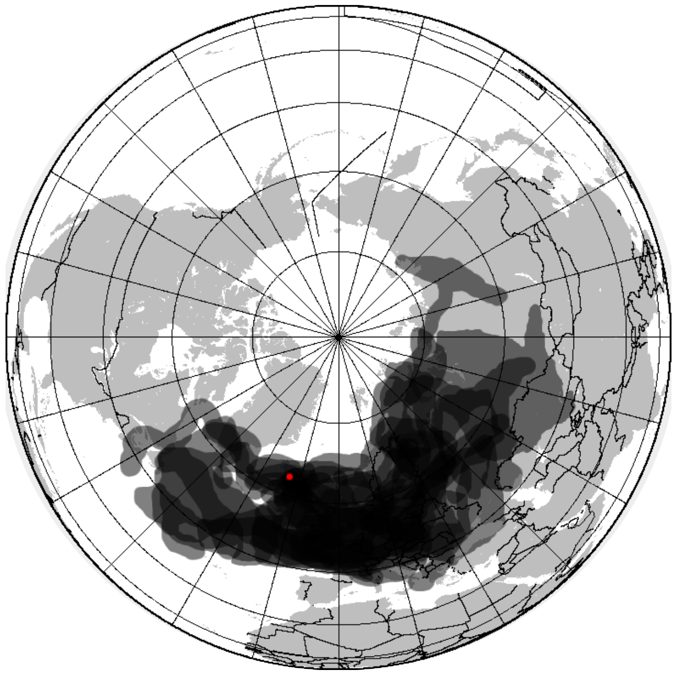




2010 Eyjafjallajökull

The April 15-21, 2010 Ejyafjallajokull eruption in Iceland caused unprecedented disruption to civil European airspace.

- 25 countries and over 4 million passengers were affected
- Cost to the airlines were measured in the billions of Euros (Oxford-Economics, 2010)



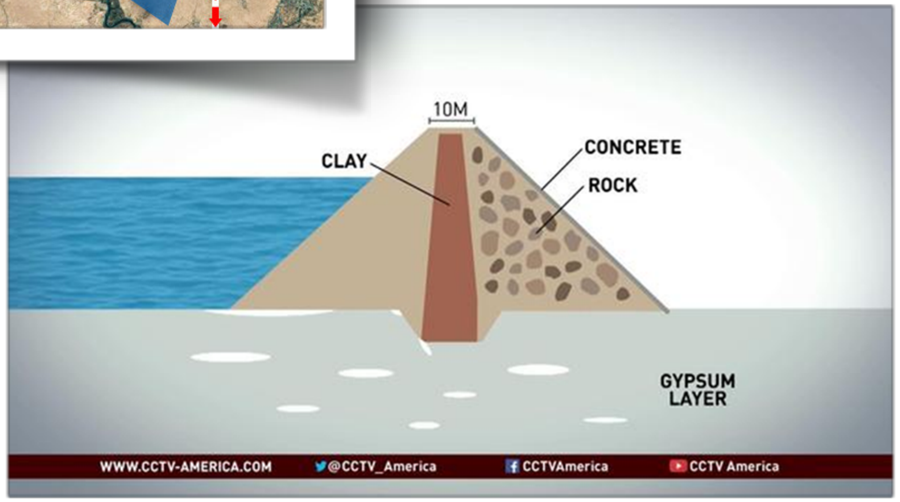
On April 20th, the previous “zero-ash-tolerance” policy were substituted for policies allowing for low level concentrations of ash in commercial airspace.

Numerical models must now be able to report ash concentration levels accurately.

Threats from dam failures

- According to a U.S. Army Corps of Engineers assessment, “Mosul Dam is the most dangerous dam in the world.” (New Yorker, 1/2/2017)
- Failure could results in million and half people losing their lives or becoming homeless.

If the dam ruptured, it would likely cause a catastrophe of Biblical proportions, loosing a wave as high as a hundred feet that would roll down the Tigris, swallowing everything in its path for more than a hundred miles. Large parts of Mosul would be submerged in less than three hours. Along the river banks, towns and cities containing the heart of Iraq’s population would be flooded; in four days, a way as high as sixteen feet would crash into Baghdad, a city of six million people. “If there is a breach in the dam, there will be no warning,” Awash [American-Iraqi civil engineer, advisor on the dam]. “It’s a nuclear bomb with an predictable fuse”. -- New Yorker article.

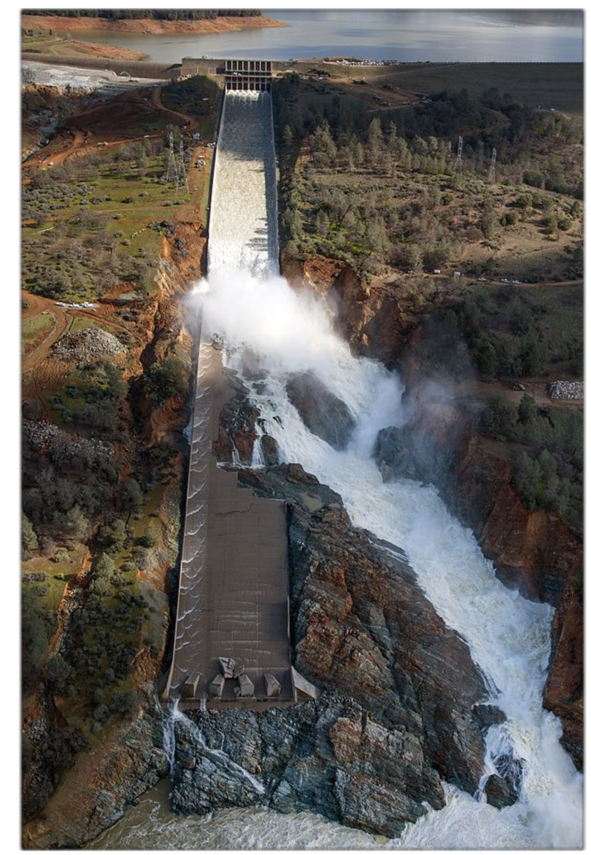


Dam Failures - US

- American Society of Civil Engineers gives the US a grade D for infrastructure -- nearly 20% of US dams have high hazard potential.

Oroville Dam, Oroville, CA. in February 2017, 188,000

Residents were evacuated downstream



Damage in the Oroville Dam Spillway (Dale Kolke / California Department of Water Resources - California Department of Water Resources)

ForestClaw Project

A parallel, adaptive library for logically Cartesian, mapped, multi-block domains

Features of **ForestClaw** include :

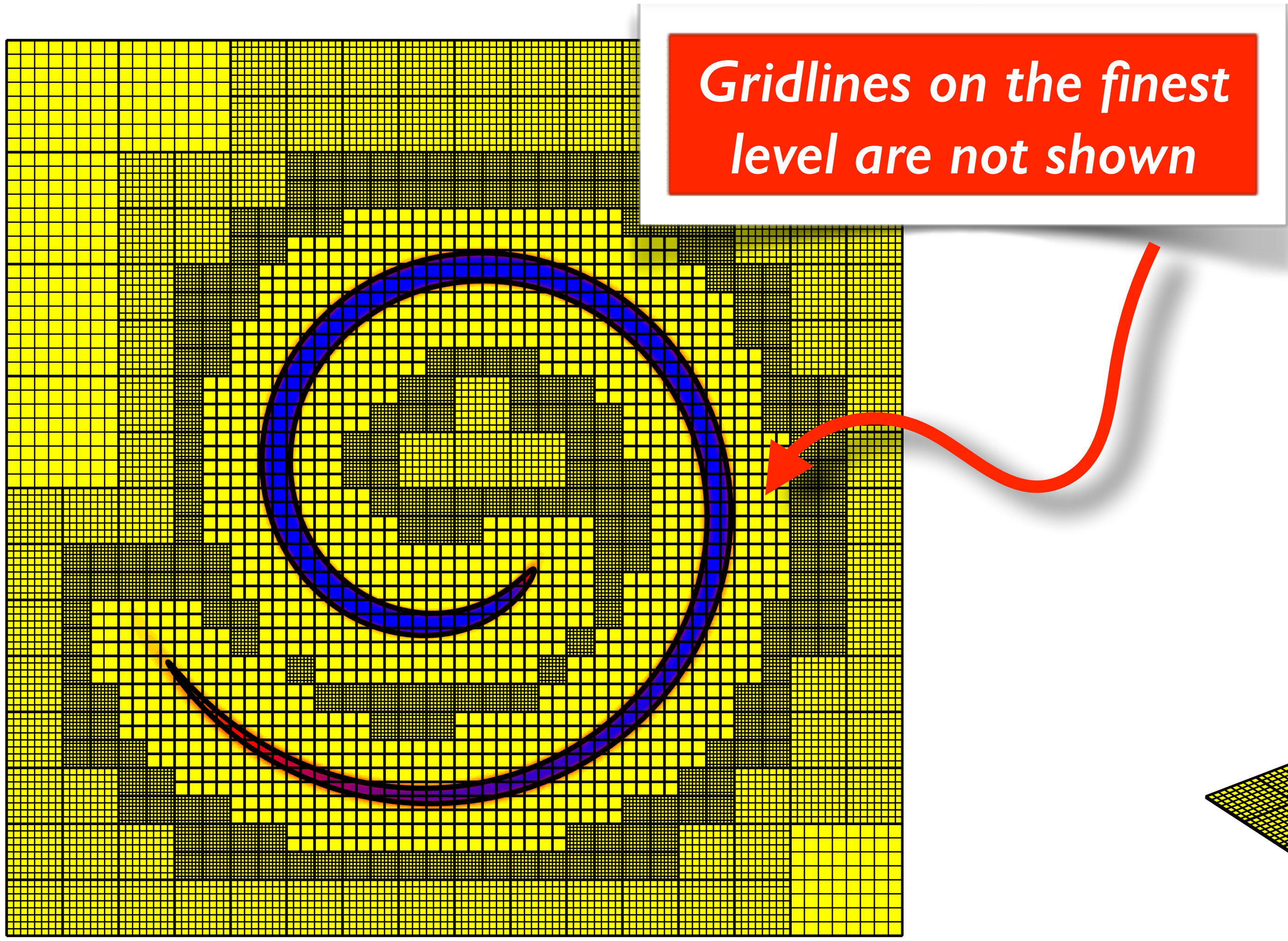
- **Block-based** AMR - Each leaf of the quadtree contains a fixed-size grid,
- Uses the **highly scalable p4est** dynamic grid management library (C. Burstedde, Univ. of Bonn, Germany)
- Has **mapped, multi-block** capabilities, (cubed-sphere, for example) to allow for flexibility in physical domains,
- **Extensible** with custom solvers
- Optional **adaptive** time stepping strategy,
- Uses essentially the same algorithmic components as patch-based AMR

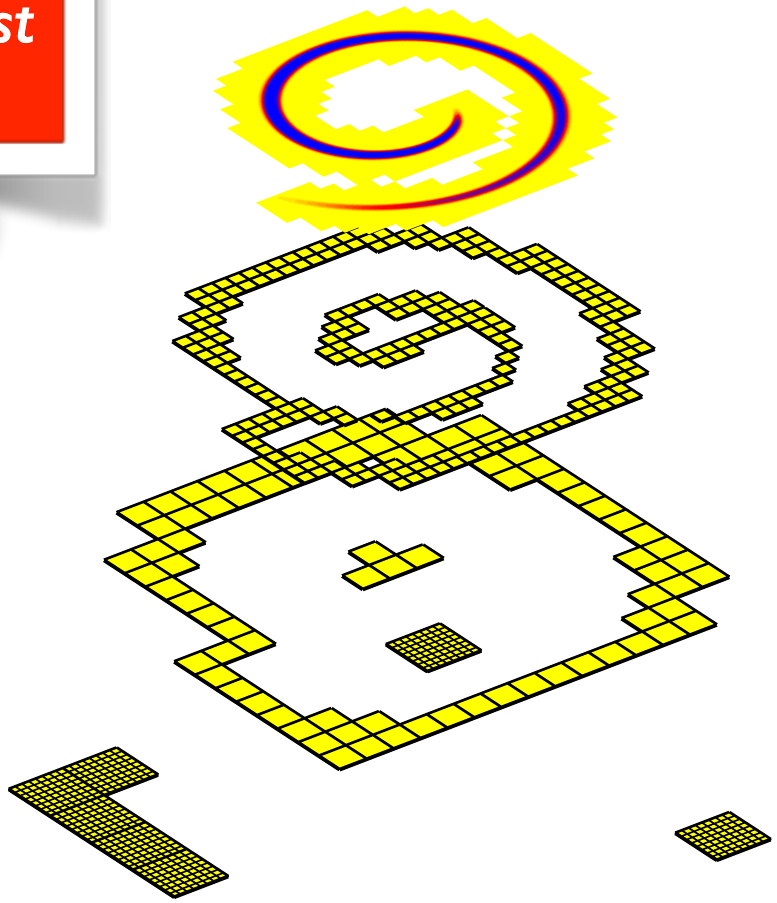
ForestClaw development supported by the National Science Foundation

www.forestclaw.org   **www.github.com/ForestClaw**

Adaptive Mesh Refinement (AMR)

Block-based AMR (regular sized, non-overlapping blocks in a quadtree/octree)





ForestClaw - www.forestclaw.org

Numerical methods

Hyperbolic problems in **conservative form** (gas dynamics, shallow water wave equations, Burgers equation, ...)

$$\mathbf{q}_t + \nabla \cdot \mathbf{f}(\mathbf{q}) = 0$$

and **non-conservative form** ("color" equation, acoustics, seismic, ...)

$$\mathbf{q}_t + \mathbf{A}(\mathbf{q}, \mathbf{x}, \ldots)\nabla \mathbf{q} = \mathbf{0}$$

Spatially varying flux functions (tracer transport, ...)

$$\mathbf{q}_t + \nabla \cdot \mathbf{f}(\mathbf{x}, \mathbf{q}) = 0$$

- All forms handled in a general way using **wave propagation algorithms** (R. J. LeVeque) available in Clawpack
- **Second order finite volume** methods for logically Cartesian meshes; **Riemann problems** used to determine strength and speed of waves moving in and out of finite volume cells; **High resolution limiters** to suppress spurious oscillations

Volcanic ash transport models

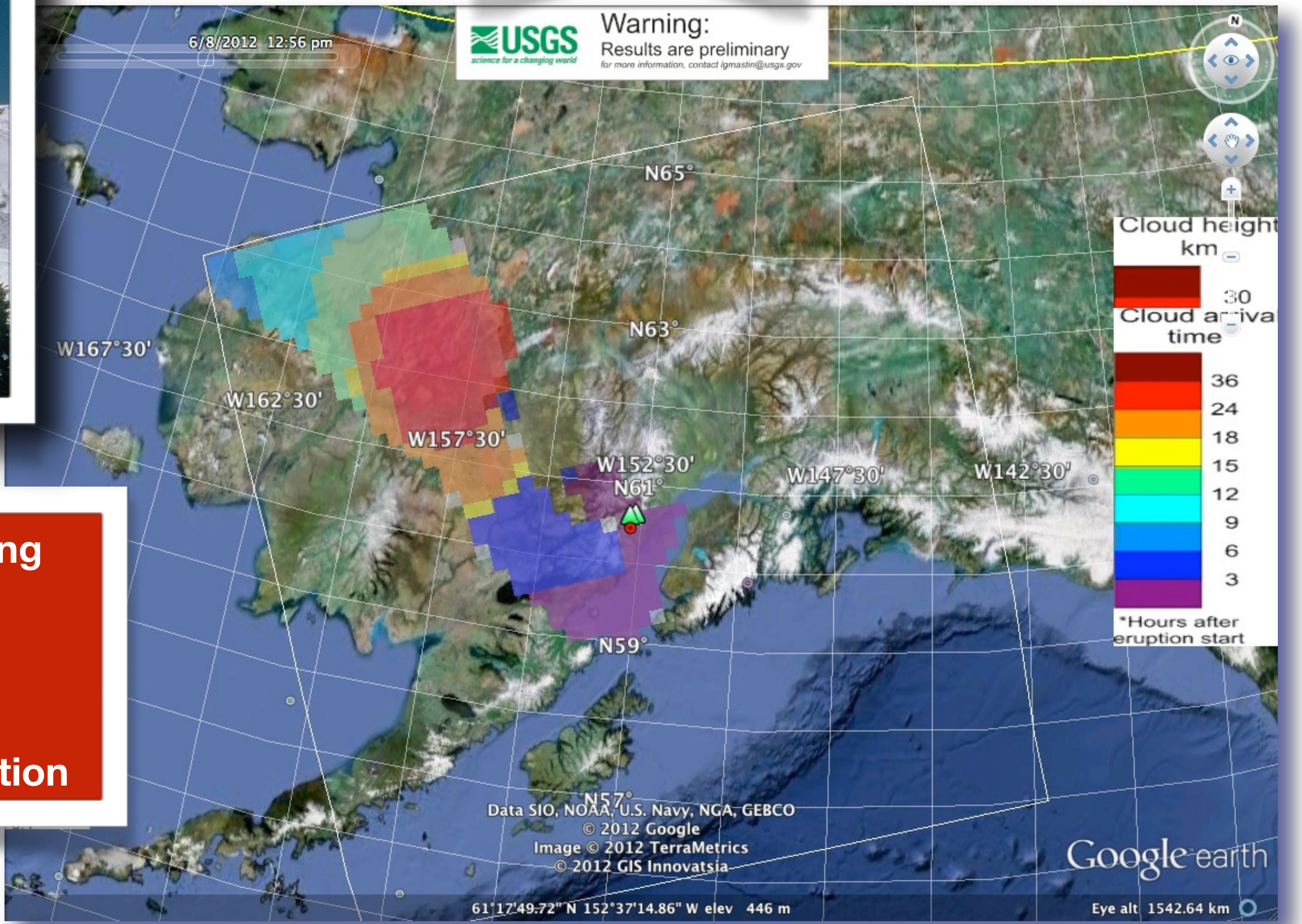
Eruptions lasting several days or weeks can place heavy demands on computational resources.

- Observational evidence supports the idea that there is considerable variation in concentration levels in tracers in the atmosphere, not just large diffuse clouds of ash.
- Important to track small scale structures in smooth, even coarse-resolution wind fields (Behrens, MWR 2000)

Ash plume drifting downwind from Cleveland Volcano, Alaska on May 3, 2006. Public photo taken from the International Space Station.

USGS Ash3d : Volcanic ash transport

Ash3d



- Split horizontal, vertical time stepping
- Fully conservative,
- Eulerian, finite volume
- Algorithms based on wave propagation

Ash3d : A finite-volume, conservative numerical model for ash transport and tephra deposition, Schwaiger, Denlinger, Mastin, JGR (2012)

Ash3d Model

$$\mathbf{q}_t + \nabla \cdot ((\mathbf{u} + v_s)\mathbf{q}) = Q(\mathbf{x}, t)$$

$$\mathbf{f}(\mathbf{x}, \mathbf{q}) \equiv (\mathbf{u}(\mathbf{x}, t) + v_s)\mathbf{q}$$

Spatially varying flux function

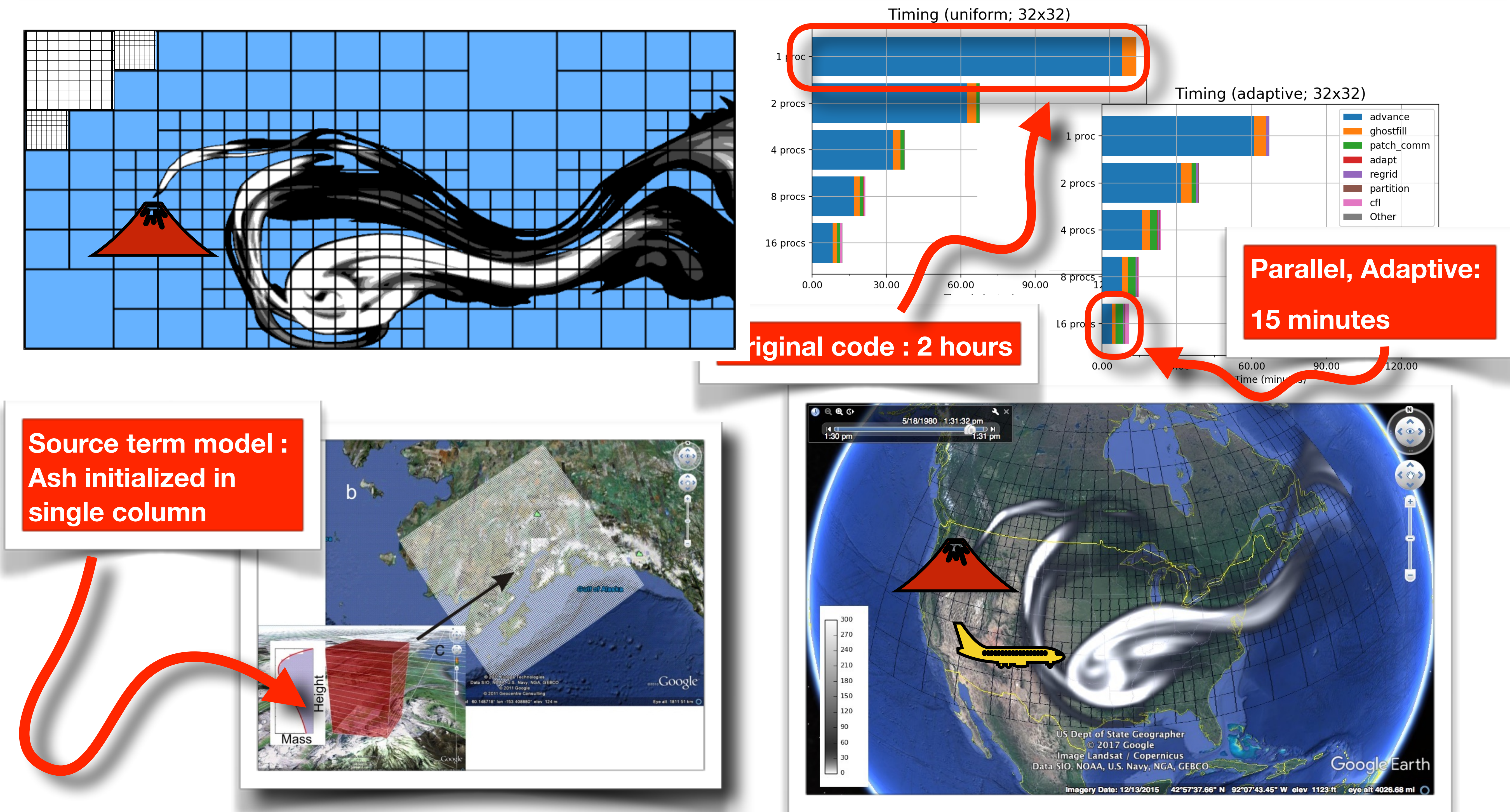
Particle vertical (fall) velocity

Horizontal velocity from wind data

Ash3d Model

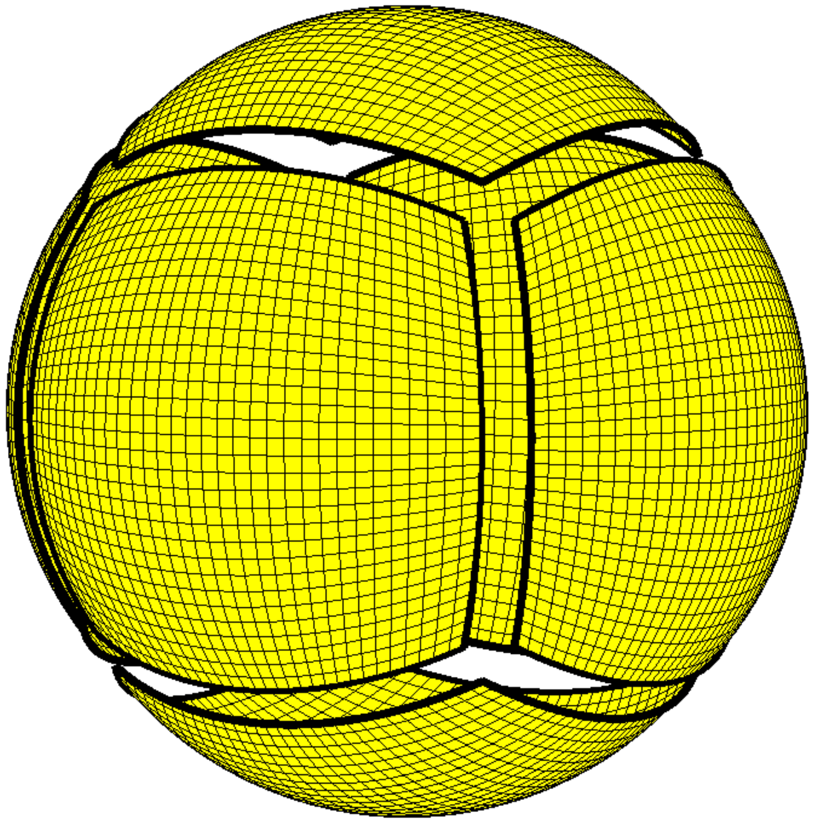
- **Wind fields** interpolated in space and time from re-analysis data available from various weather services.
- **Source term** modeled with a Suzuki distribution (Suzuki, 1983).
- **Multiple grain sizes** tracked
- **Fall velocity** and **deposition** modeled
- Extensive library for reading **meteorological data** in many re-analysis formats

Volcanic ash transport

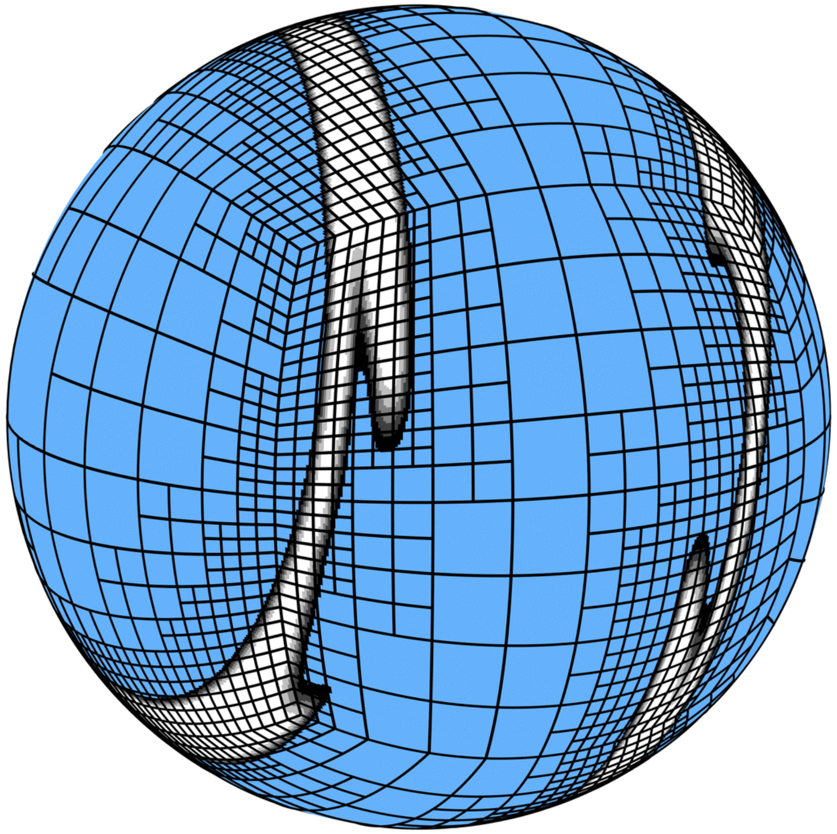


Volcanic ash transport using Ash3d (H. Schwaiger, USGS) extension of ForestClaw

Volcanic ash transport at global scale



Cubed sphere grid

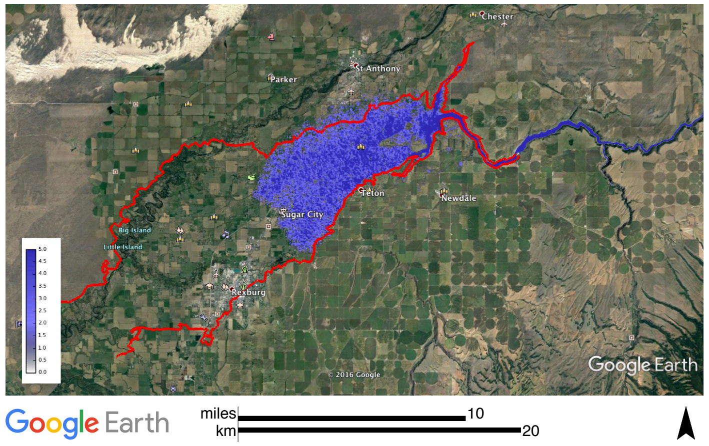


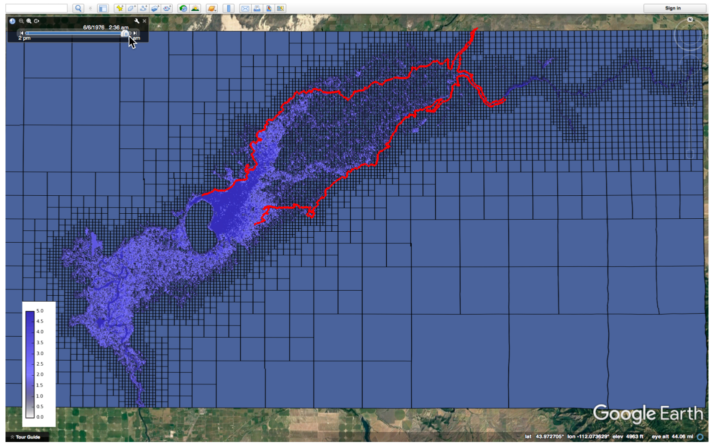
Tracer transport on the cubed sphere

Future plans : Implement Ash3d on full cubed-sphere

Other ForestClaw extensions

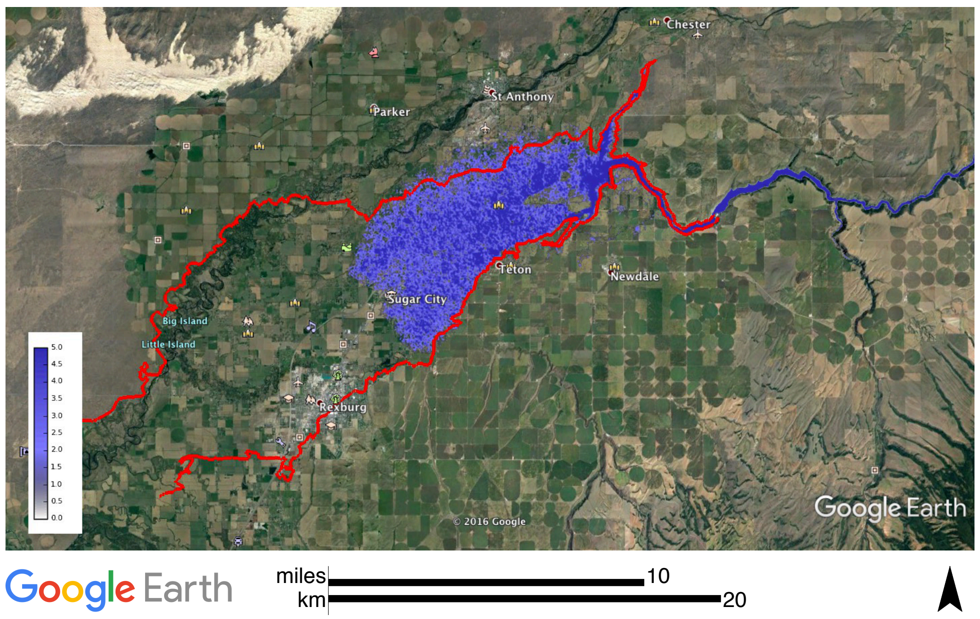
- **Clawpack** (R. J. LeVeque, Univ. Washington) extensions for gas dynamics, acoustics, wave equation, ... *This extension provides Clawpack with distributed, parallel (MPI) capabilities*
- **GeoClaw** for shallow water wave equations (D. George, M. Berger, R. J. LeVeque, K. Mandli, ...). *This provides MPI capabilities to GeoClaw*
- **CUDA implementation** - 5x-10x speed-up in preliminary tests (S. Aiton, M. Shih, X. Qin)

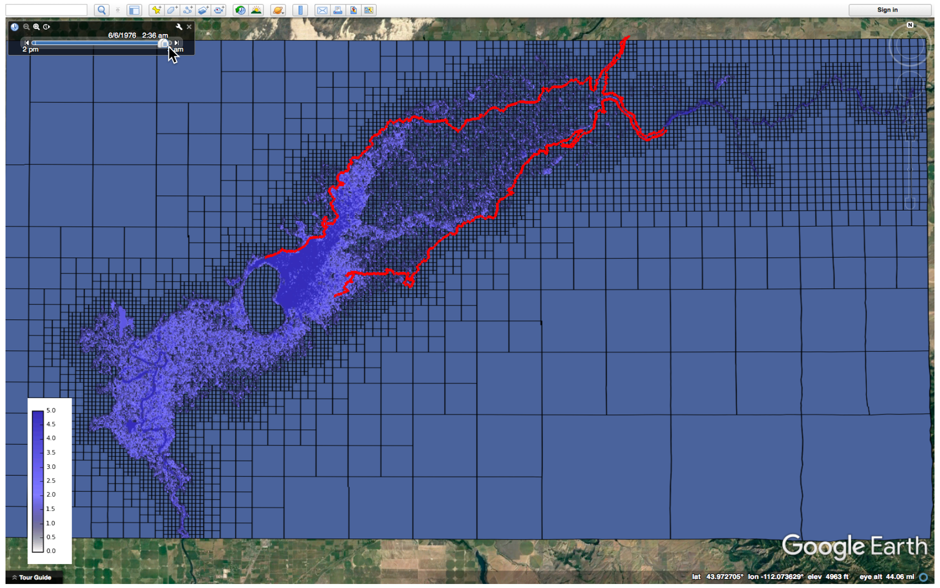




Teton Dam failure (1976, Eastern Idaho) using GeoClaw (D. George, R. J. LeVeque, K. Mandli, M. Berger) extension of ForestClaw

Natural Hazards Modeling





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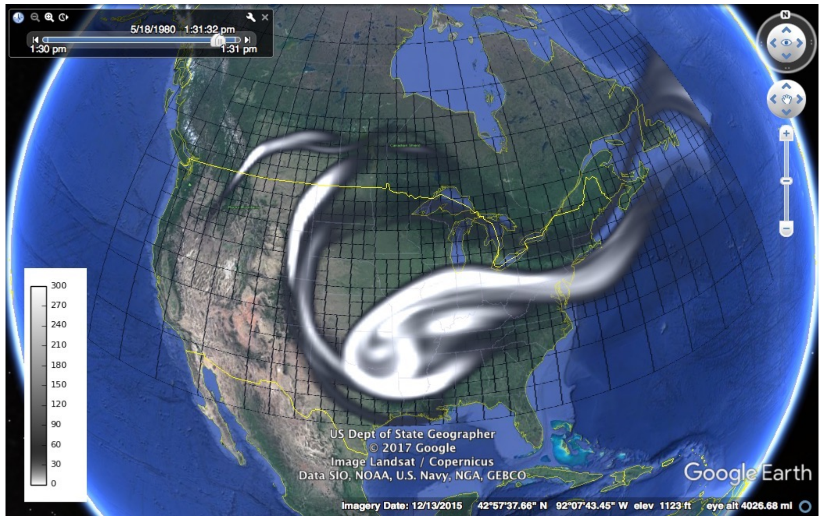

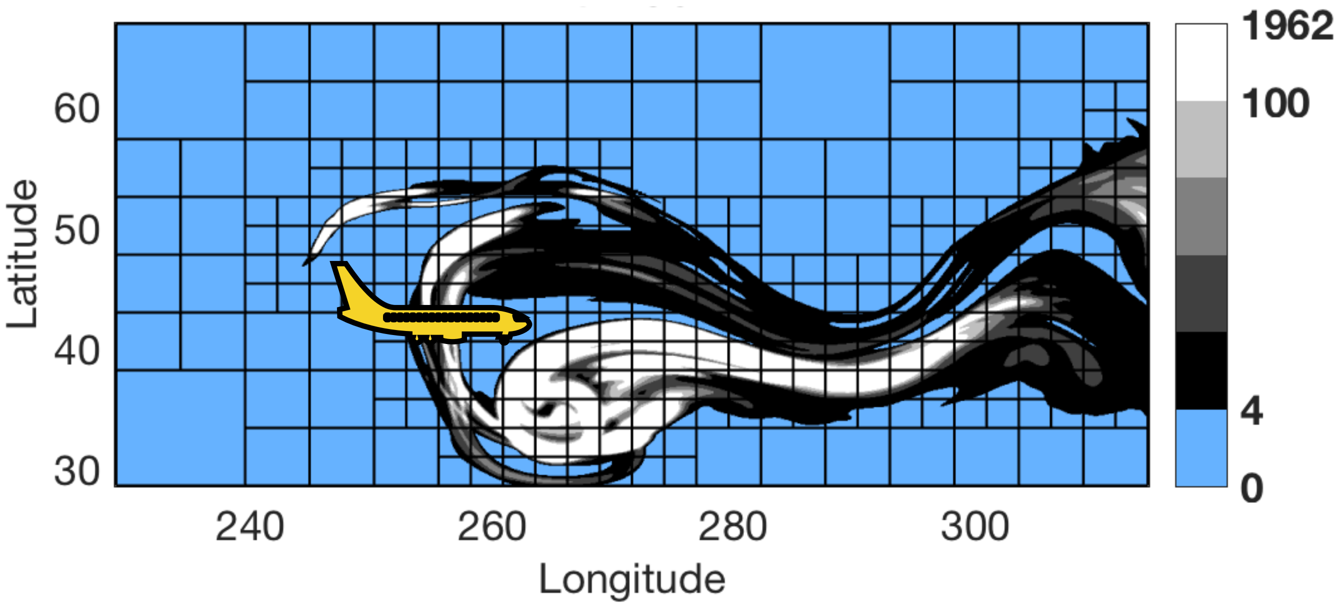

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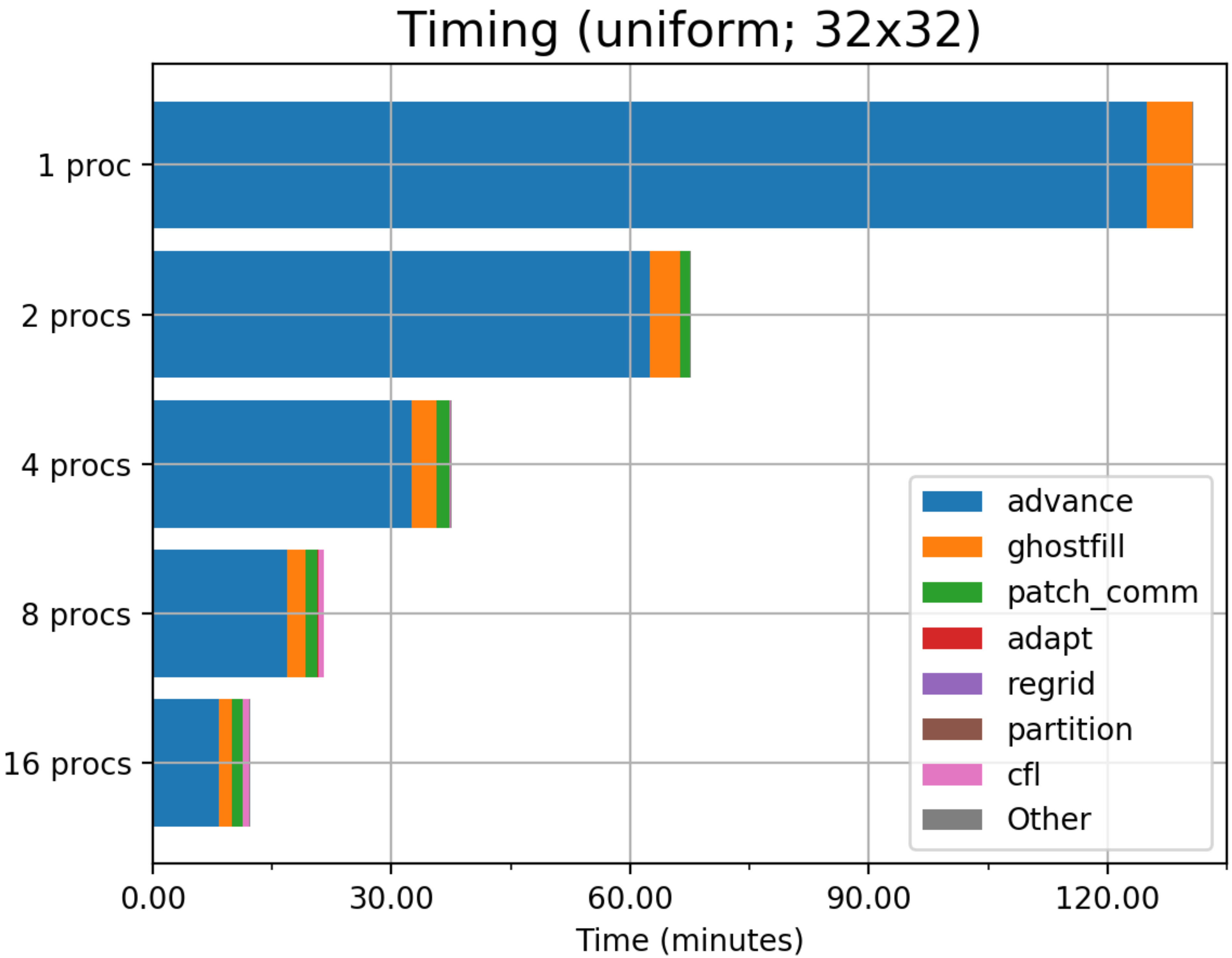
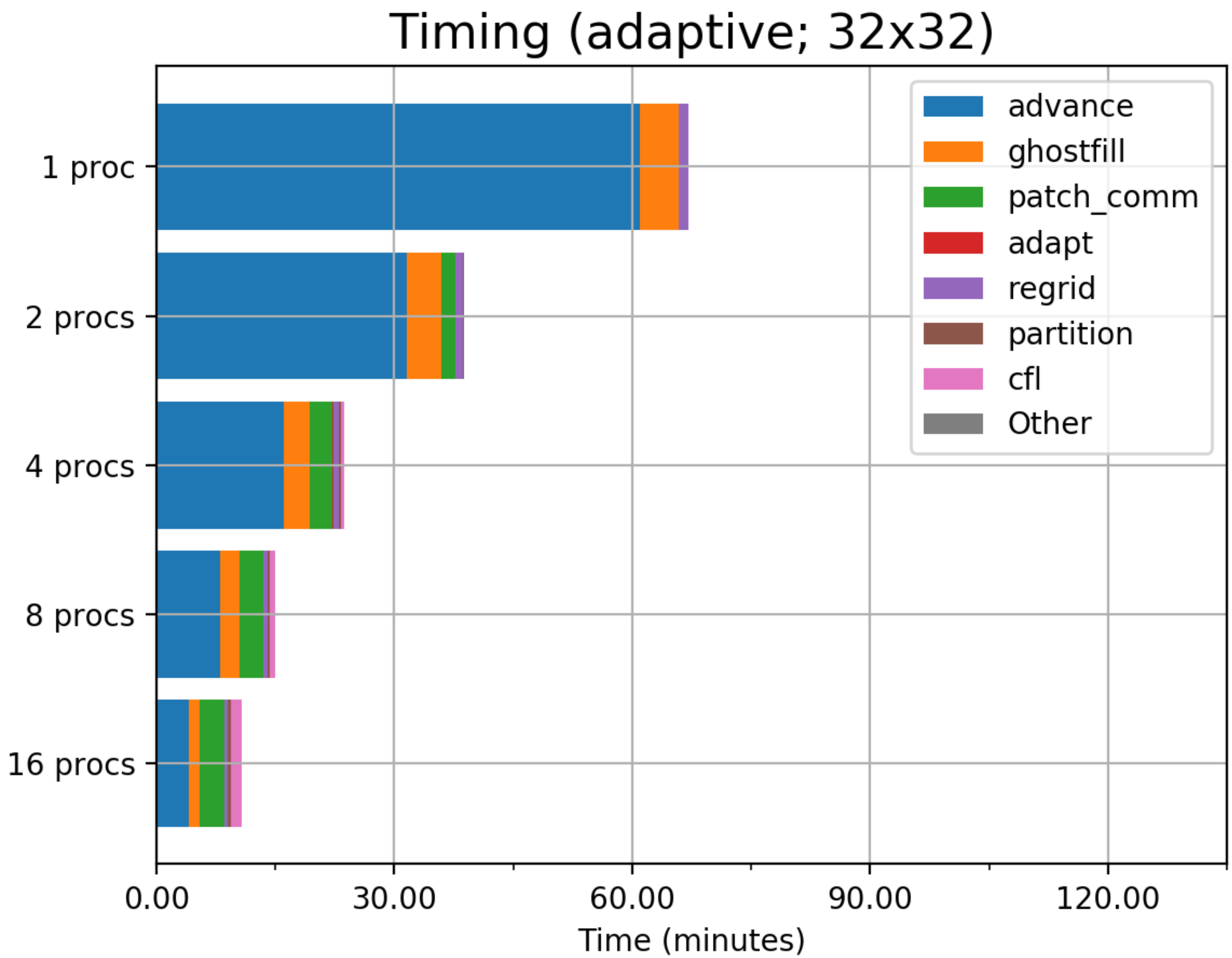
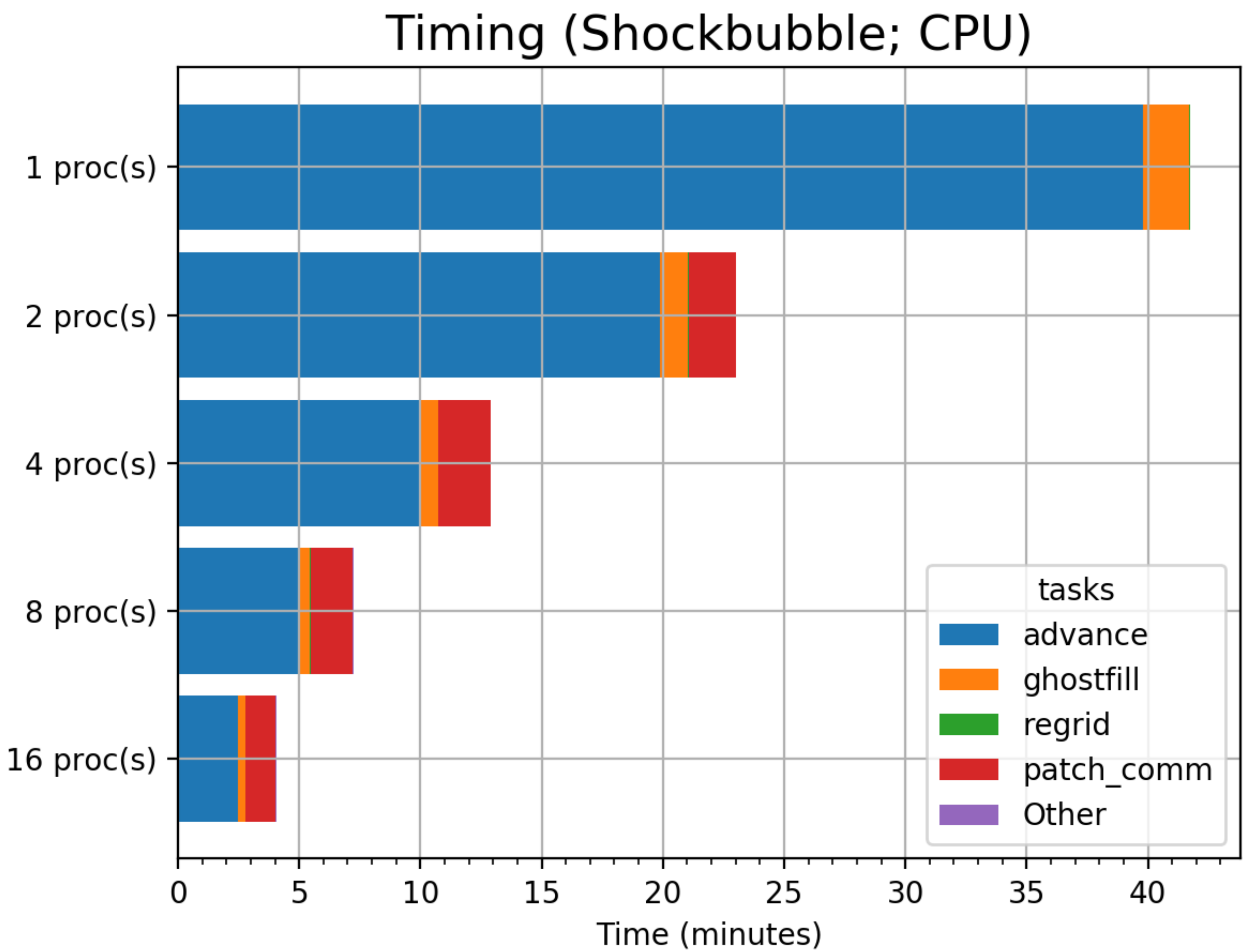
Ash3d efficiency



Ash3d efficiency



ForestClaw + GPUs



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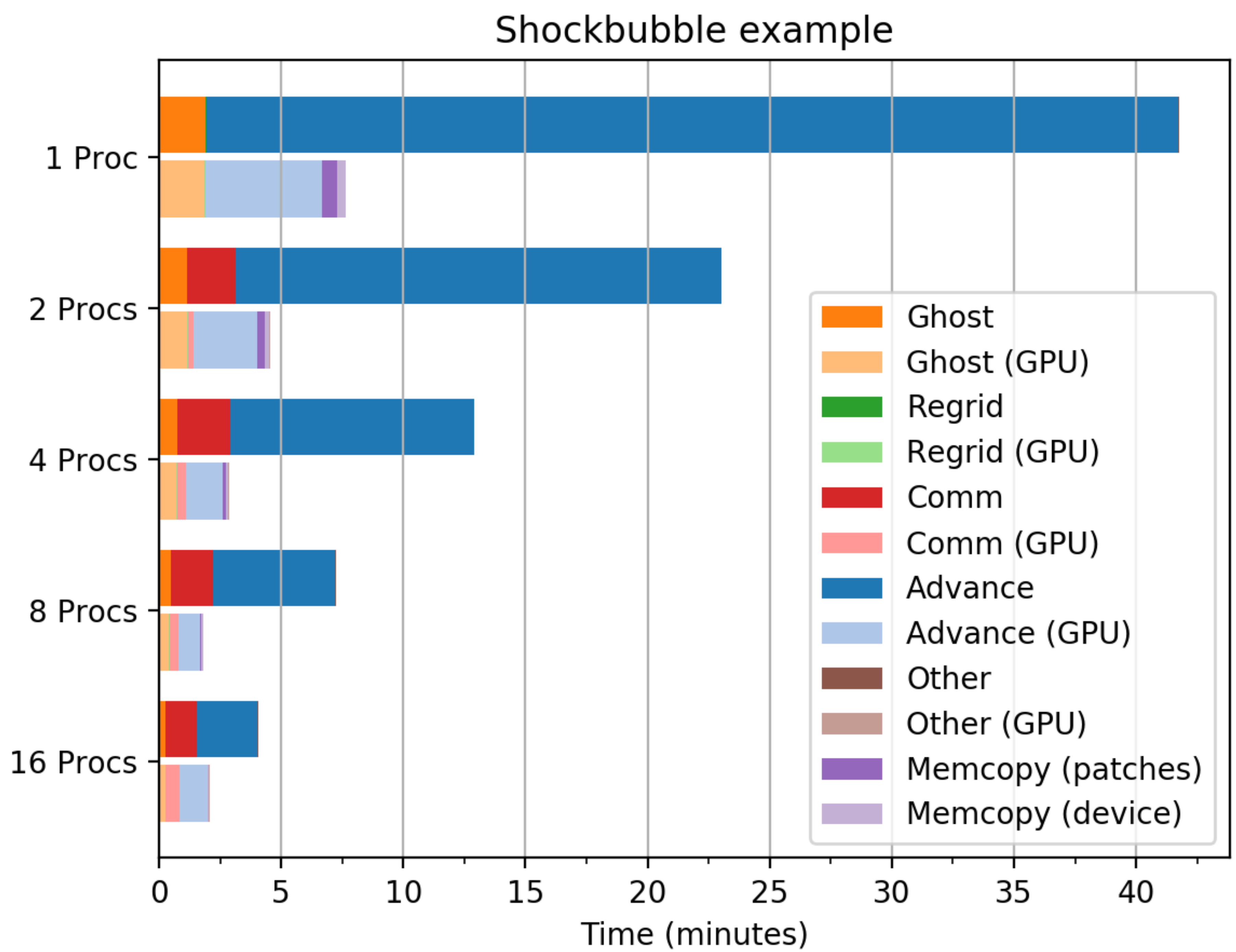
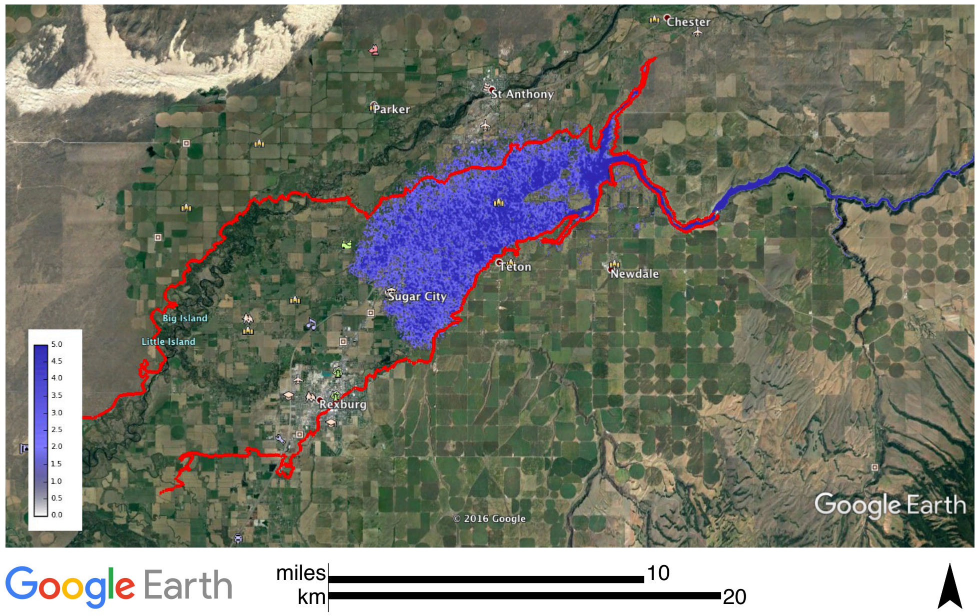
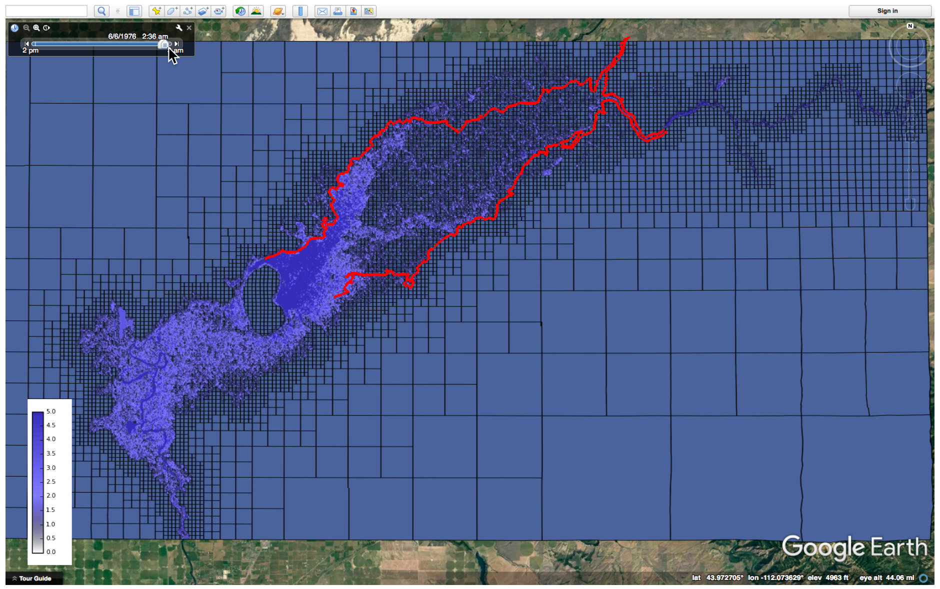


Natural Hazards Modeling





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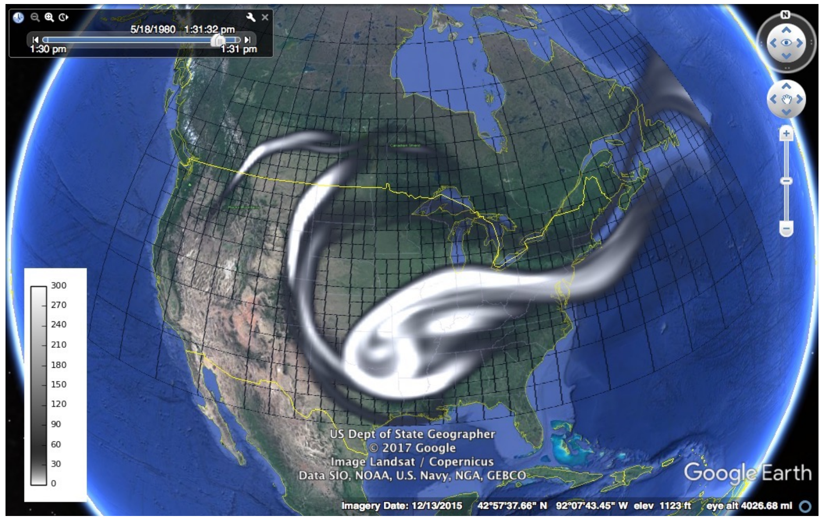

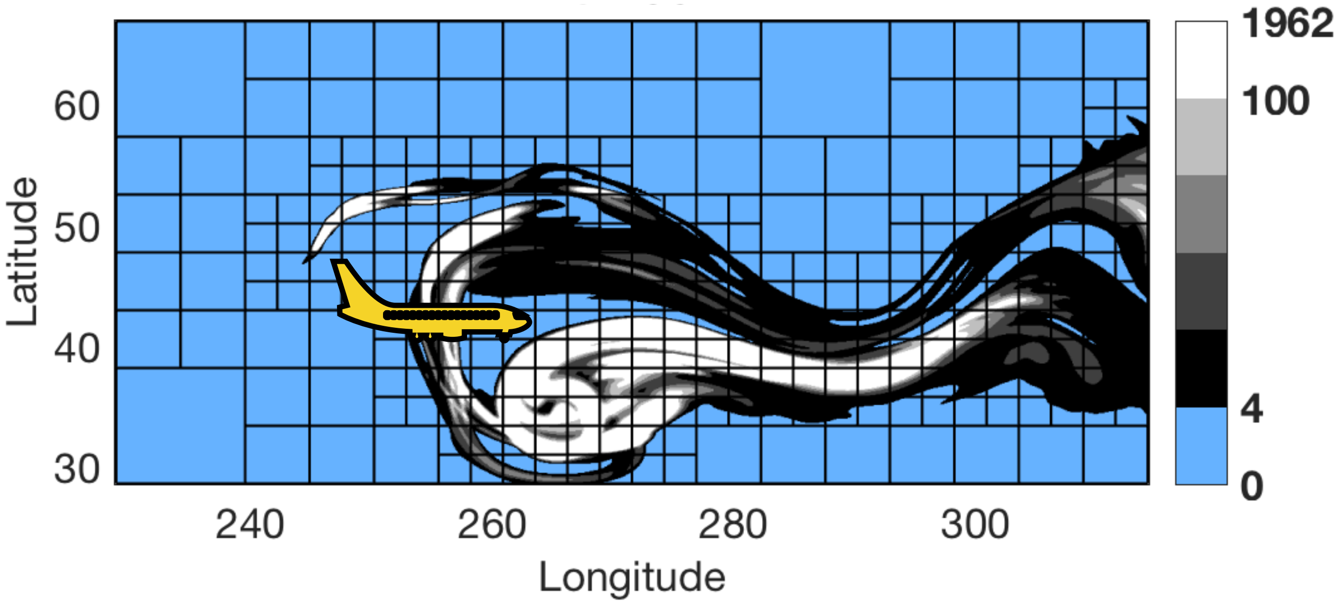

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