Embedding Protective Mechanisms in Coastal Flooding Simulations

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www.github.com/clawpack/geoclaw

Introduction

Flooding in many coastal communities has become a central concern due to the growing threat of climate change, in particular sea level rise. To combat this effective adaptation strategies are needed that are optimized for flood risk reduction but the question remains as to what strategies are the most effective. In this poster we present a methodology for including sea walls, dunes, and other protective adaptation strategies as one piece of a larger adaptation strategy that will aim to provide optimization approaches to the larger problem.

Jocelyn Augustino / FEMA

Goal: Assess Adaptation Strategies for Storm Surge

Climate Change	Forecasting
Sea-level rise Changes in storm frequency and intensity	Uncertainty in hurricane forecasts Critical decision making

Protecting Communities

Placement and size
Regional implications
Optimality

Requirements

Ensemble Computations ~ 10^6
Handling Disparate Scales
Bathymetric Considerations
Represent Protection Strategies

Approach

Adaptive Mesh Refinement
Zero-width barrier representation
H-box methods

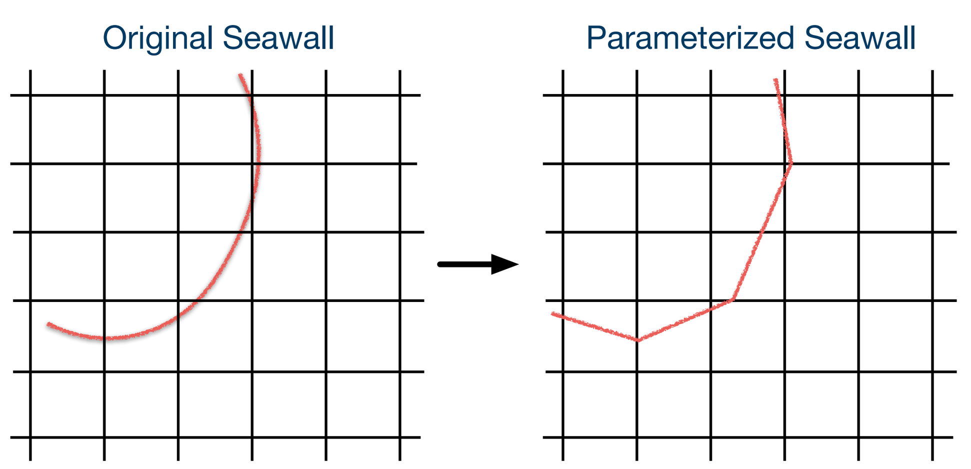
Storm Surge Protection

There are a number of different strategies that can be employed to help protect coastlines from storm surge flooding including adding (or restoring) wet-land and other natural protections, building of dunes, and seawalls. Here we concentrate on sea-walls as they are the most difficult structure to include in a storm surge model.

A seawall can include a number of different types of protection but all are predicated on stopping the flow to a certain height. Critical to this is the accurate representation of the placement and disallowing flow past the barrier unless it is overtopped. We propose a two-pronged approach as illustrated below.

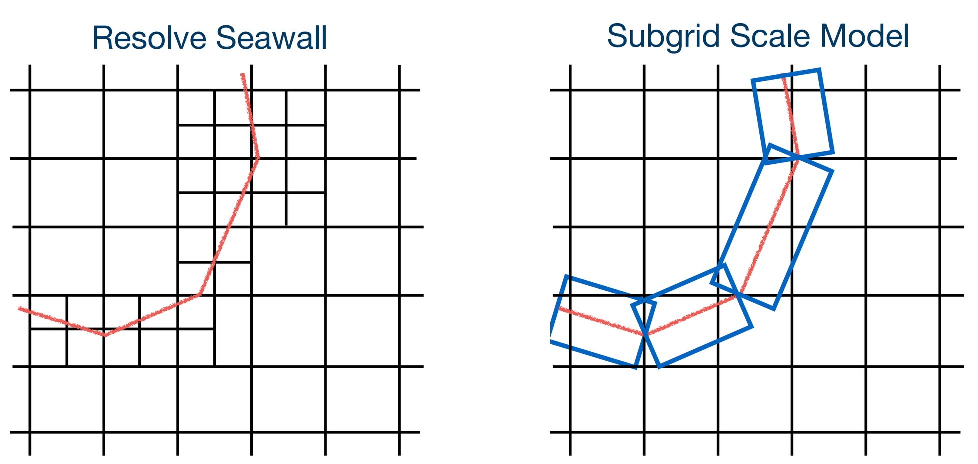
Barrier Parameterization

First we take the seawall design and parameterize it into sections each with their own height. We constrain these sections so that the nodes of the wall are only located at boundaries of grid cells.



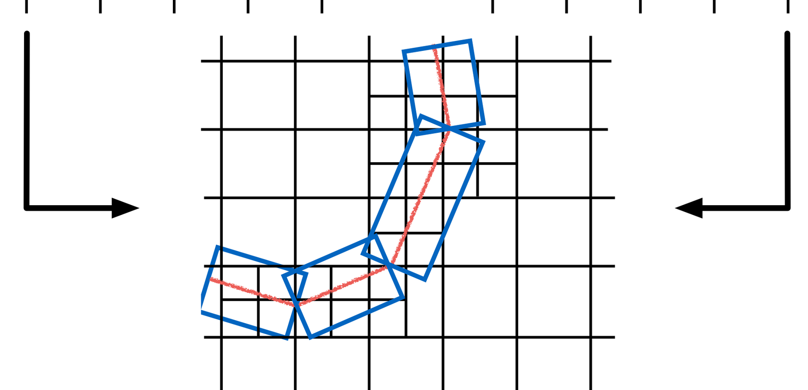
Resolving the Seawall

We will consider two different approaches to representing the wall:
1. Resolve the structure using adaptive mesh refinement.
2. Use subgrid scale models to represent the wall



Approach

We will then combine the parameterized wall with adaptive mesh refinement and the subgrid scale seawall model to represent the seawall.



Resolving the Seawall - Adaptive Mesh Refinement

Adaptive mesh refinement (AMR) uses properly nested refinement patches (see figure 1), respecting the CFL conditions and refinement criteria based on the physics of the problem. This re-gridding occurs at user defined intervals taking into account clustering of flagged cells. Grid boundaries are handled by the code automatically.

As a demonstration of the capabilities of AMR we simulated the storm surge due to Hurricane Ike with the **GeoClaw** [1, 2] package. Comparisons were made to the ADCIRC hind-cast study that was presented in [3]. Table 2 shows the effective resolution at each of the levels of computation.

Even though the ADCIRC simulation utilizes unstructured grids, the AMR **GeoClaw** simulation shows significant computational cost savings with similar performance (see figures to the far left and table 1).

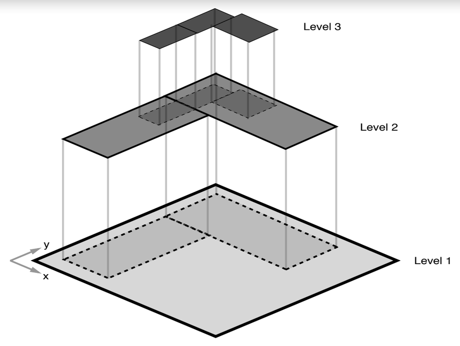


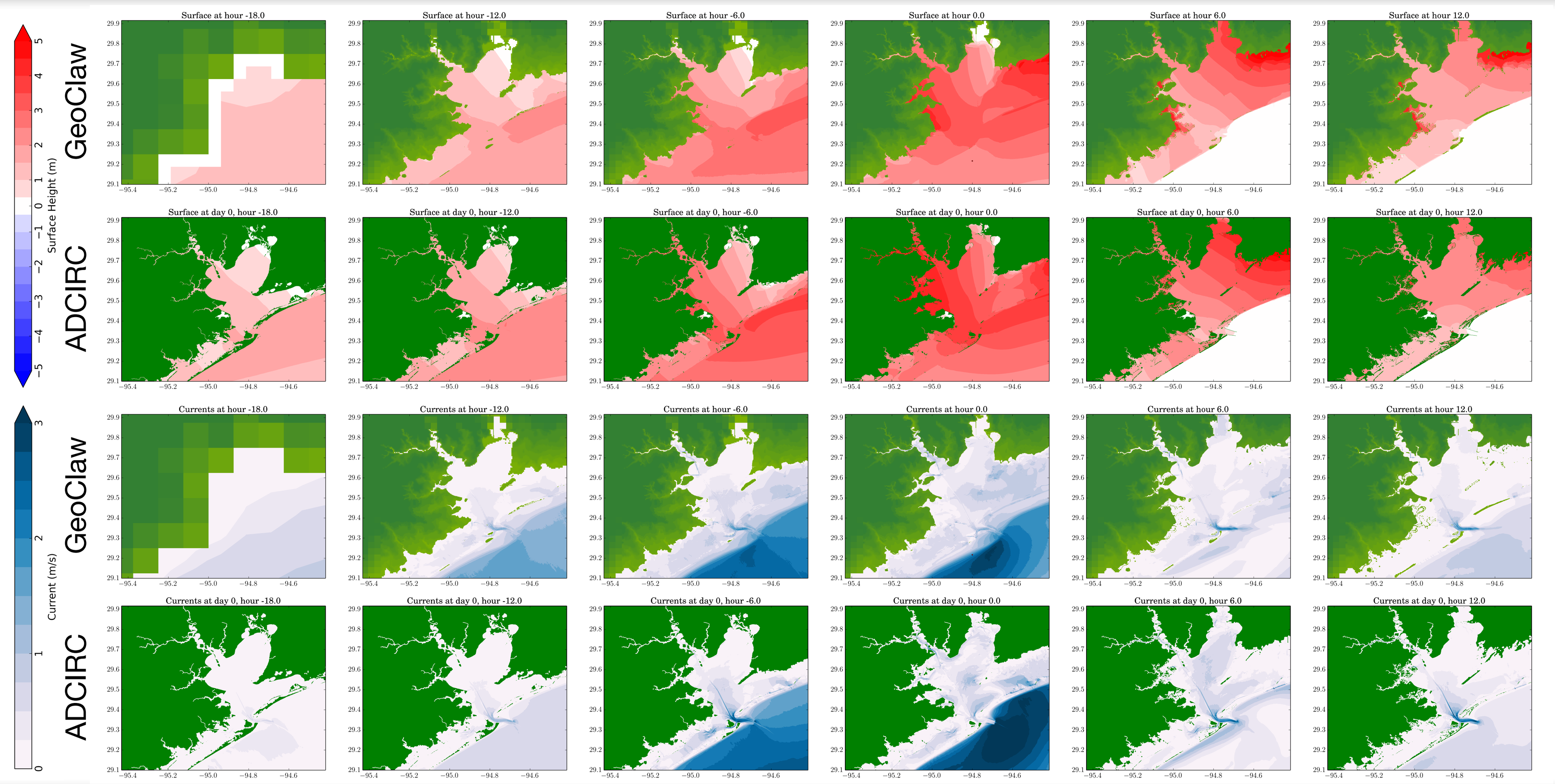
Figure 1: Schematic of the patch layout for patch-based AMR.

Package	Cores Used	Wall Clock Time	Core Hours
ADCIRC	4000	35 minutes	2333 hours
GeoClaw	4	2 hours	8 hours

Table 2: Comparison of computational time taken using two different metrics.

Level	$r^{\ell}_{\Delta x, \Delta y}$	Resolution (m) Latitude	Resolution (m) Longitude
1		25250	27700
2	2	12600	13850
3	2	6300	6925
4	2	3150	3460
5	6	525	575
6	4	130	144
7	4	32.9	36.1

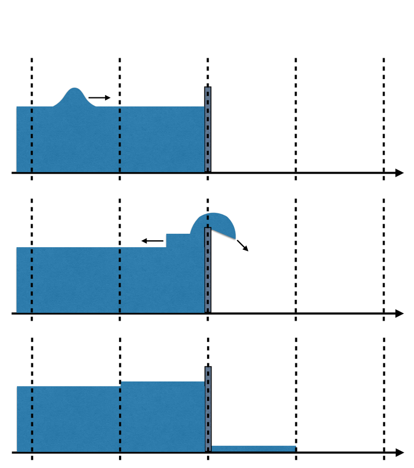
Table 2: Levels and effective resolutions for the GeoClaw simulation.



Subgrid Seawall Model

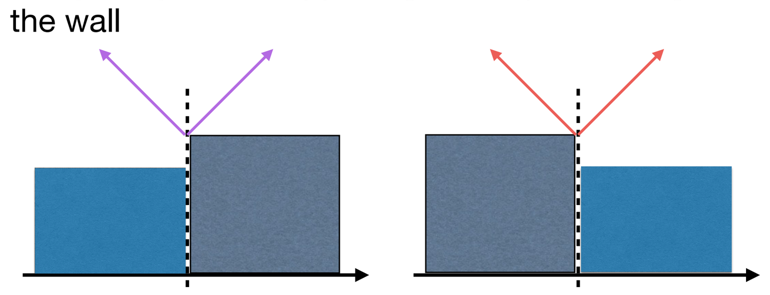
Riemann Problem

The goal in the design of this modified Riemann solver is to include the impact of a jump in bathymetry (a sill for instance) in the limit as its width goes to zero. Importantly water will not be allowed to flow through the boundary if the water is unable to overcome the wall.

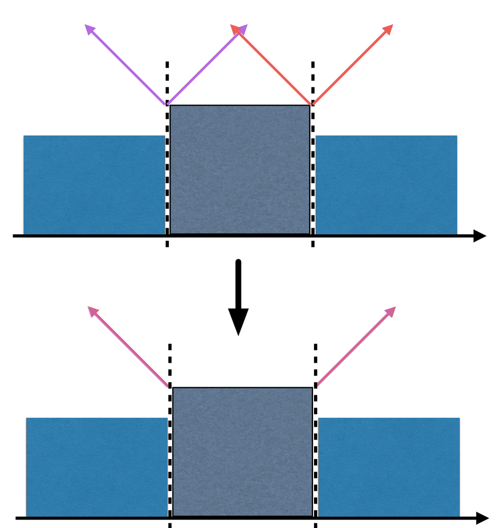


Approach

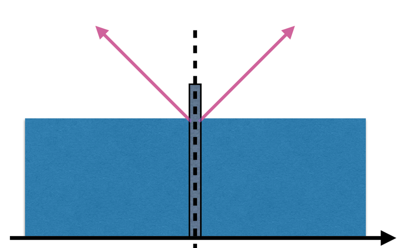
1. Solve two Riemann problems each with bathymetry in the opposing cell equal in height to the wall



2. Take the waves that would be going onto the wall and redistribute them into the waves that are instead going into the wet cells.



3. Finally reincorporate the waves and remove the "ghost" wall cell.



Redistribution

Given the importance of maintaining conservation the redistribution of the waves uses conservation to determine the redistribution.

Given the 4 waves represented by the eigenvectors r^p and scalar wave strengths β^p we can write each wave as

$$\mathcal{Z}^p = r^p \beta^p \quad \text{or} \quad \mathcal{Z} = R\beta$$

The waves that we need to redistribute correspond to the second and third eigenvectors leading to the new expression

$$\hat{\mathcal{Z}} = R\hat{\beta} \quad \text{with} \quad \hat{\beta} = [\beta_1 + \gamma^1, 0, 0, \beta^4 + \gamma^2]^T$$

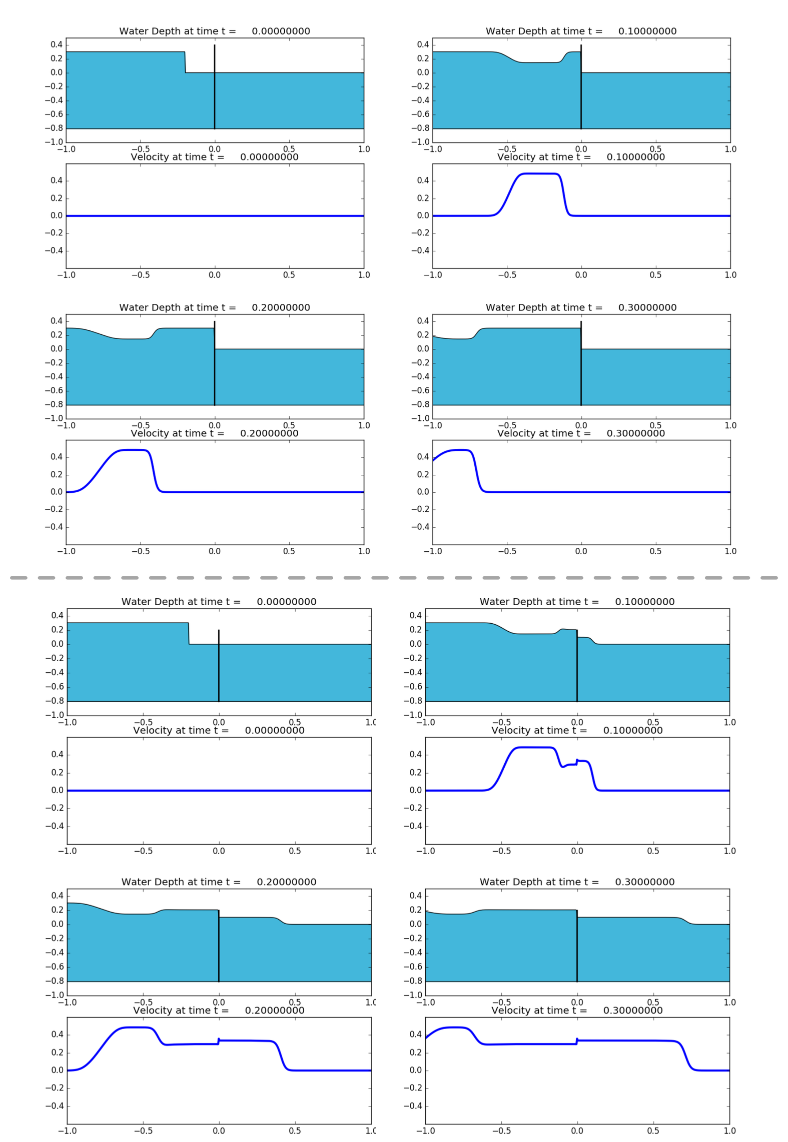
Maintaining conservation then requires the solution of the system

$$R\beta = R\hat{\beta} \quad \text{for} \quad \gamma^1 \quad \text{and} \quad \gamma^2 \quad \text{leading to}$$

$$\gamma^1 = \frac{(s^4 - s^2)\beta^2 + (s^4 - s^3)\beta^3}{s^4 - s^1}$$

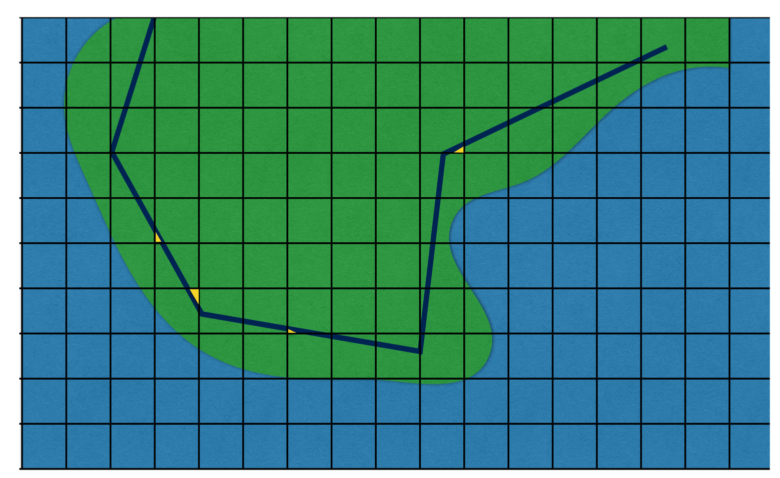
$$\gamma^2 = \frac{(s^2 - s^1)\beta^2 + (s^3 - s^1)\beta^3}{s^4 - s^1}$$

As a demonstration of the proposed method below are two test cases. The first contains a wave that does not overtop the wall where as the second does. Well-balancing is maintained in the long term as well. As the construction of the method leverages a well-balanced solver when calculating the auxiliary Riemann problems at the wall.



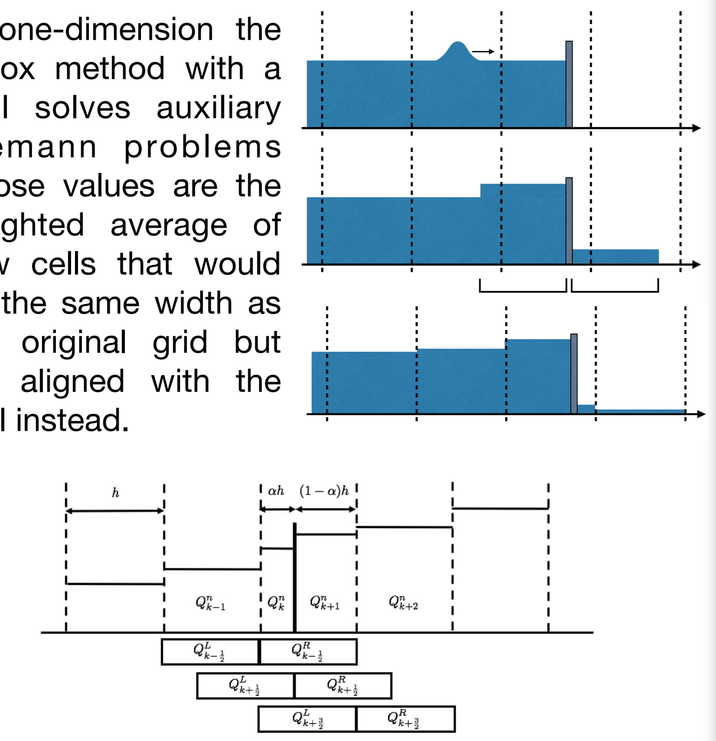
Addressing CFL Constraints

Unfortunately the new Riemann solver has a significant drawback in that it assumes that the wall is aligned perfectly with the grid. Although this may work with sufficient resolution the accuracy of the placement of the wall would be suspect. Instead we utilize an idea from the literature called h-box methods [5,6] that uses modified cells that solve auxiliary Riemann problems.



One-Dimension

In one-dimension the h-box method with a wall solves auxiliary Riemann problems whose values are the weighted average of new cells that would be the same width as the original grid but are aligned with the wall instead.

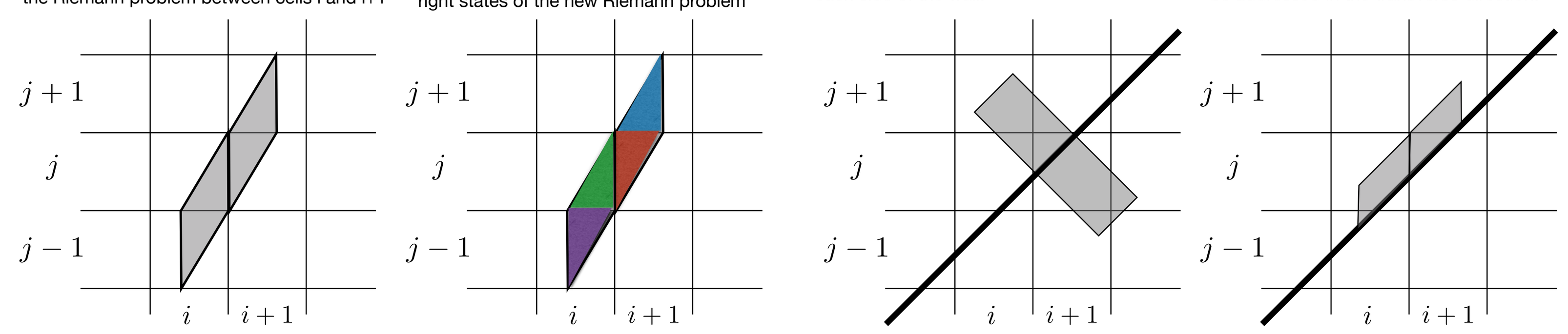


The full method uses a number of overlapping cells, redistributing the resulting waves based on the associated wave speeds.

Two-Dimensions

In 2D h-box methods are partially informed by addressing the problem of advection that is not grid aligned. Instead of forming Riemann problems the usual way the h-boxes are chosen to align with the flow and then weighted averages are used to construct the new Riemann problem.

For the wall problem h-boxes will be used to address the cut-cells that would otherwise lead to severe CFL restrictions. In these cases a set of Riemann problems need to be formulated in each direction both orthogonal and parallel to the wall



Conclusions

- AMR has proven invaluable but does not provide the "total" solution
- Riemann solver matches vanishing limit of single grid cell wide wall
- Preliminary work using h-box method removes the CFL restriction but increases complexity significantly

Future Directions

- Finish implementation of two-dimensional h-box methods
- Combine the subgrid wall model with AMR
- Enhance Riemann solver to better handle true fluid dynamics at the wall

References

[1] Mandli, K. T. A Numerical Method for the Two Layer Shallow Water Equations with Dry States. *Ocean Modelling* **72,** 80–91 (2013).
[2] Mandli, K. T. & Dawson, C. N. Adaptive Mesh Refinement for Storm Surge. *Ocean Modelling* **75,** 36–50 (2014).
[3] Berger, M. J., George, D. L., LeVeque, R. J. & Mandli, K. T. The GeoClaw software for depth-averaged flows with adaptive refinement. *Advances in Water Resources* **34,** 1195–1206 (2011).
[4] Hope, M. E. et al. Hindcast and validation of Hurricane Ike (2008) waves, forerunner, and storm surge. J. Geophys. Res. Oceans 118, 1–37 (2013).
[5] Helzel, C., Berger, M. J. & LeVeque, R. J. A High-Resolution Rotated Grid Method for Conservation Laws with Embedded Geometries. Siam Journal On Scientific Computing 26, 785–809 (2006).
[6] Berger, M. & Helzel, C. A Simplified h-box Method for Embedded Boundary Grids. Siam Journal On Scientific Computing 34, A861–A888 (2012).