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Multiscale modeling of internal waves and turbulence at rough, realistic topography with SOMAR-LES

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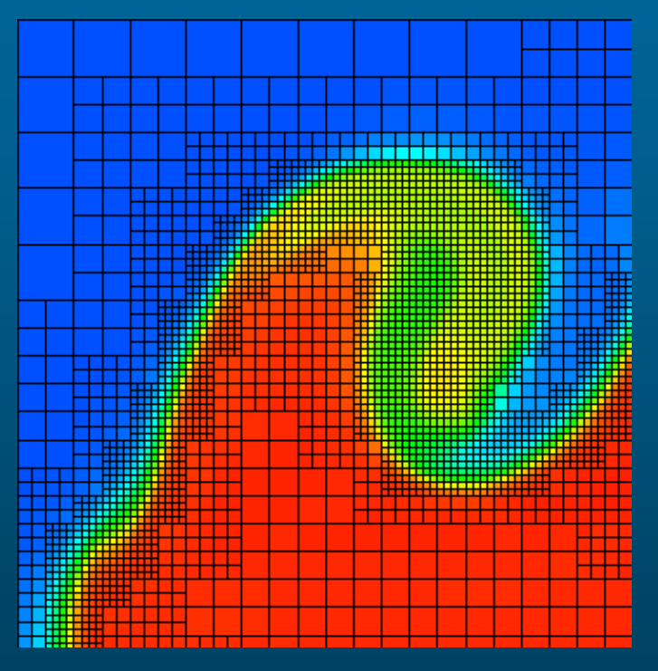


Abstract

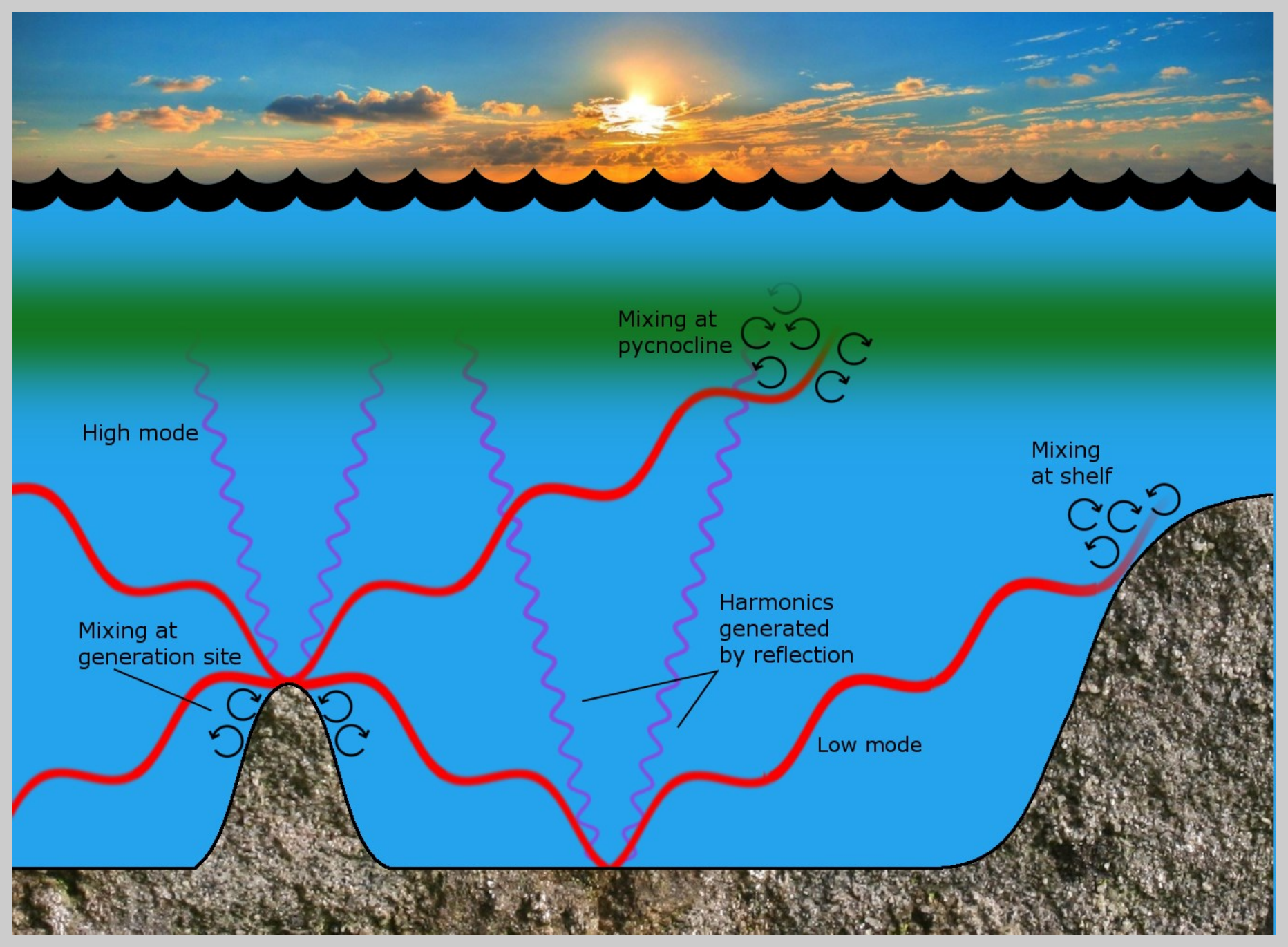
The Stratified Ocean Model with Adaptive Refinement (SOMAR) is a modeling framework with the flexibility of adaptive mesh refinement (AMR) at localized regions with high gradients. Several test cases including the lock-exchange problem, solitary wave propagation, and internal tide generation have been previously considered to validate the method. Local refinement of the grid allows the solver to achieve highly accurate results with substantial reduction in computational cost. Recently, SOMAR-LES has been developed wherein a three-dimensional, body-conforming, Large Eddy Simulation (LES) model that resolves turbulent scales is coupled with SOMAR to accurately represent small scale turbulence as well as its effect on flow evolution at large scales. The coupling is two-way: the LES is driven with large scale forcing, and SOMAR receives feedback in the form of an eddy viscosity, diffusivity, and sub-grid scale fluxes. This novel multi-scale modeling technique is applied to study the near- and far-field baroclinic response when the oscillating barotropic tide interacts with underwater topography. Numerical simulations are currently being performed with SOMAR-LES to examine the flow at Kaena ridge, a steep supercritical generation site, where the topographic length scales are of O(100 km), and the barotropic forcing corresponds to a small outer excursion number (Ex ~ 0.01) and small Froude number (Fr ~ 0.006). The SOMAR-LES results will be used to quantify baroclinic energy conversion and internal wave properties such as the radiated wave flux and modal composition.

The Lifecycle of Internal Tides

"…where does the internal wave energy come from, where does it go, and what happens to it along the way?" -Briscoe, 1966

Generation

The figure to the right illustrates several potential fates of internal tides. It all starts with a submarine feature such as a ridge, canyon, or slope. If the ratio of the tidal drift to feature width (excursion number) is O(1) or larger, lee waves form and locally dissipate. If the excursion number is less than O(1), then internal waves form that transport energy away from the generation site.



Potential fates

As internal waves travel, they bring with them the potential for mixing. This mixing can occur in many areas including continental slopes, sea mounts, or at the pycnocline. When internal waves disrupt the pycnocline, cool, nutrient-rich, deep ocean water is transported to shallow regions and oxygen- and carbon-rich water is sent into the abyss. These poorly understood interactions are crucial ingredients for many marine and atmospheric mechanisms.

The ocean's energy budget

The impact of small-scale processes driven by internal tides on large-scale flows is currently unknown. Our goal is to investigate this very question by realistically driving the small-scale processes that remove energy from the large-scale flow. Hopefully, our coupled model will provide insight into energy conversion processes and help quantify how much energy is dissipated locally at the generation site and how much is dissipated remotely.

Large-Scale Modeling with SOMAR

SOMAR numerically computes the baroclinic response of a stratified fluid of variable depth to barotropic forcing. Since our interest lies in geophysical flows, we make the following assumptions:

- The flow is Boussinesq. (density variations << reference density)
- The flow is incompressible (flow speed << speed of sound).
- The equation of state is linear and temperature determines density.
- The fluid is capped by a rigid lid (to be removed in the future).

The equations of motion are cast into a form that prevents diffusion of the static background stratification. Numerically, we solve these equations in terrain-following coordinates.

$$\frac{\partial \vec{u}}{\partial t} + \overbrace{\nabla \cdot (\vec{u}\vec{u})}^{\text{advection of momentum}} + \overbrace{f\hat{z} \times \vec{u}}^{\text{Coriolis term}} = \overbrace{\nabla \cdot (\nu \nabla \vec{u})}^{\text{diffusion of momentum}} \quad \overbrace{-\nabla p}^{\text{pressure gradient force}} \quad \overbrace{-b\hat{z}}^{\text{buoyant force}}$$

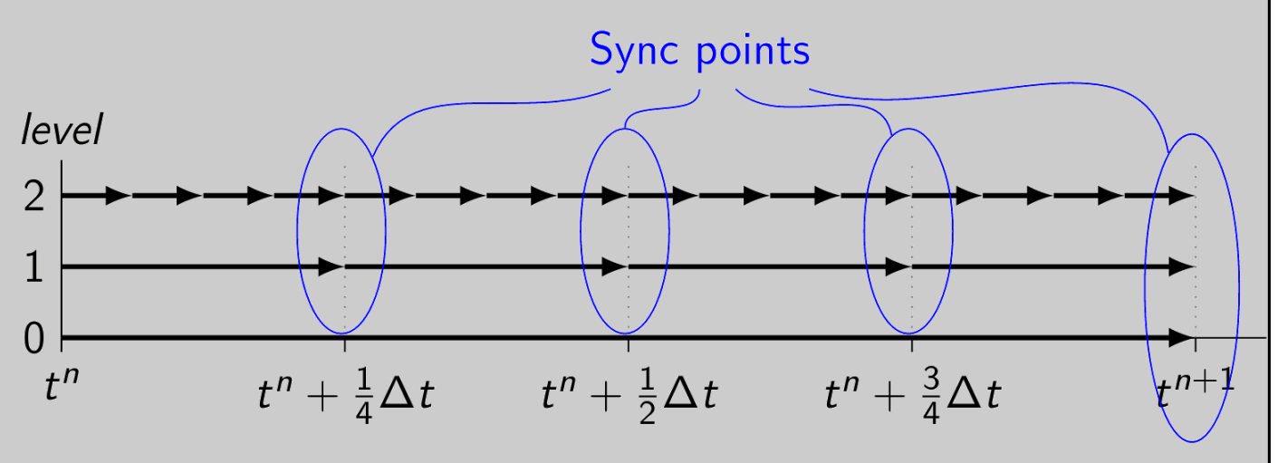
$$\frac{\partial b}{\partial t} + \overbrace{\nabla \cdot (\vec{u}b) - N^2 w}^{\text{advection of buoyancy}} = \overbrace{\nabla \cdot (\kappa \nabla b)}^{\text{diffusion of buoyancy}}$$

$$\overbrace{\nabla \cdot \vec{u}}^{\text{compressibility}} = 0$$

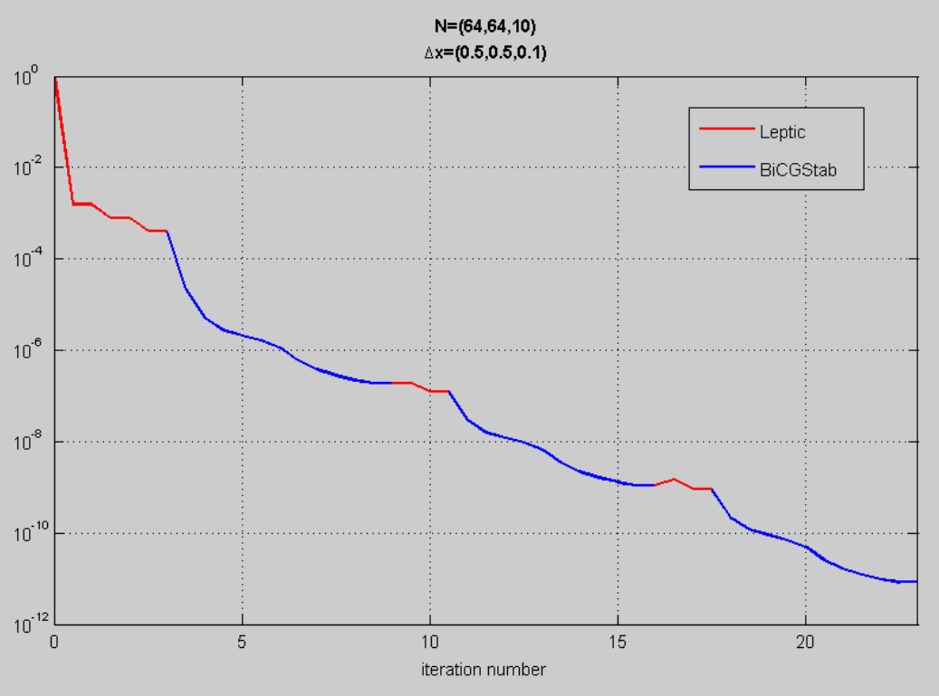
SOMAR provides several features that efficiently produce accurate solutions to the anisotropic, Navier-Stokes equations in three dimensions.

Adaptive mesh refinement (AMR) drastically reduces computational effort by keeping the number of cells at a minimum. Only the key features are finely resolved.

Temporal refinement minimizes numerical diffusion and reduces the number of expensive Poisson solves.



Efficient Poisson solvers enforce the non-hydrostatic incompressibility in 3D. SOMAR uses a combination of semi-coarsening and leptic iteration to reliably and accurately solve Poisson's equation.

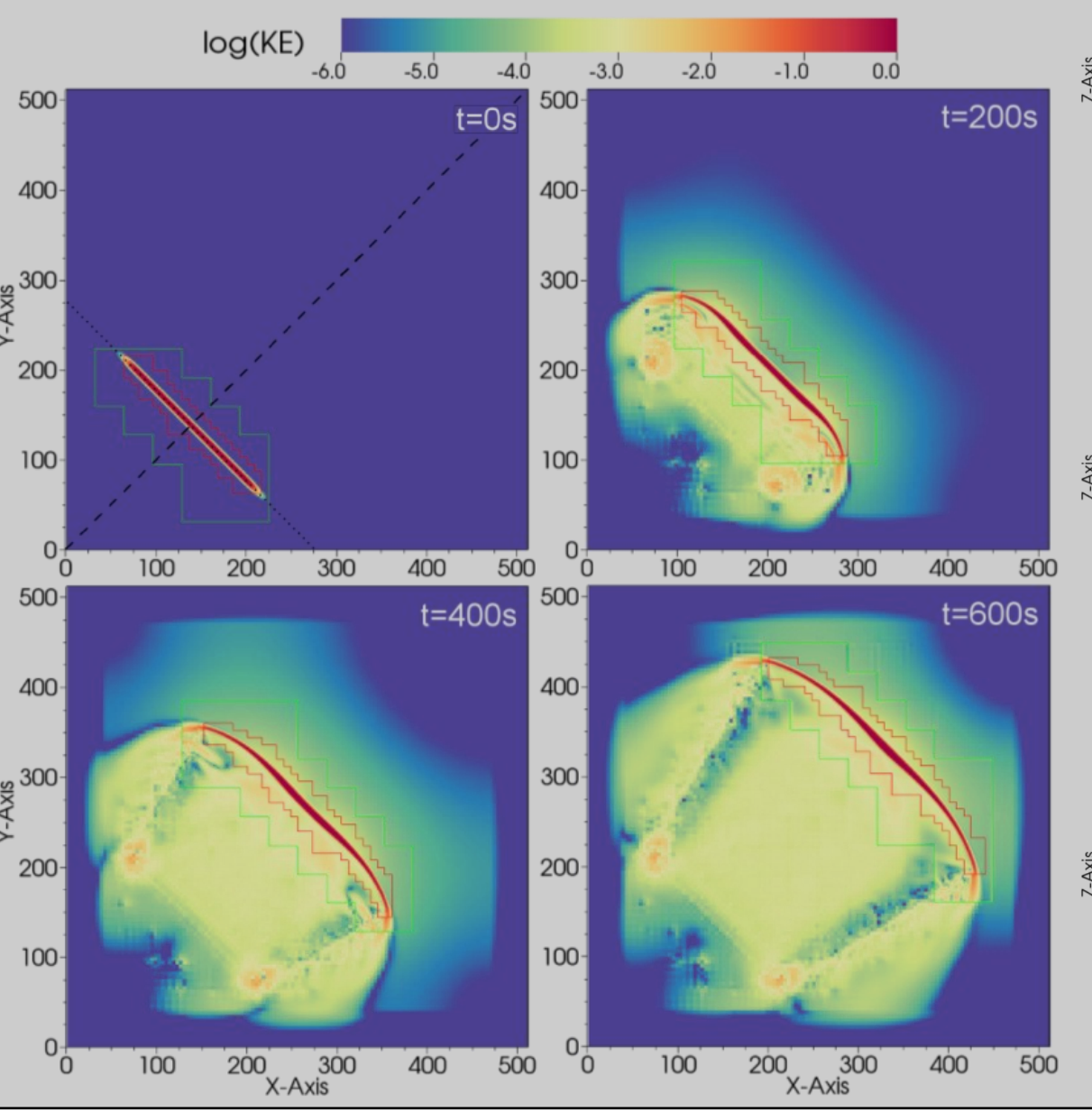


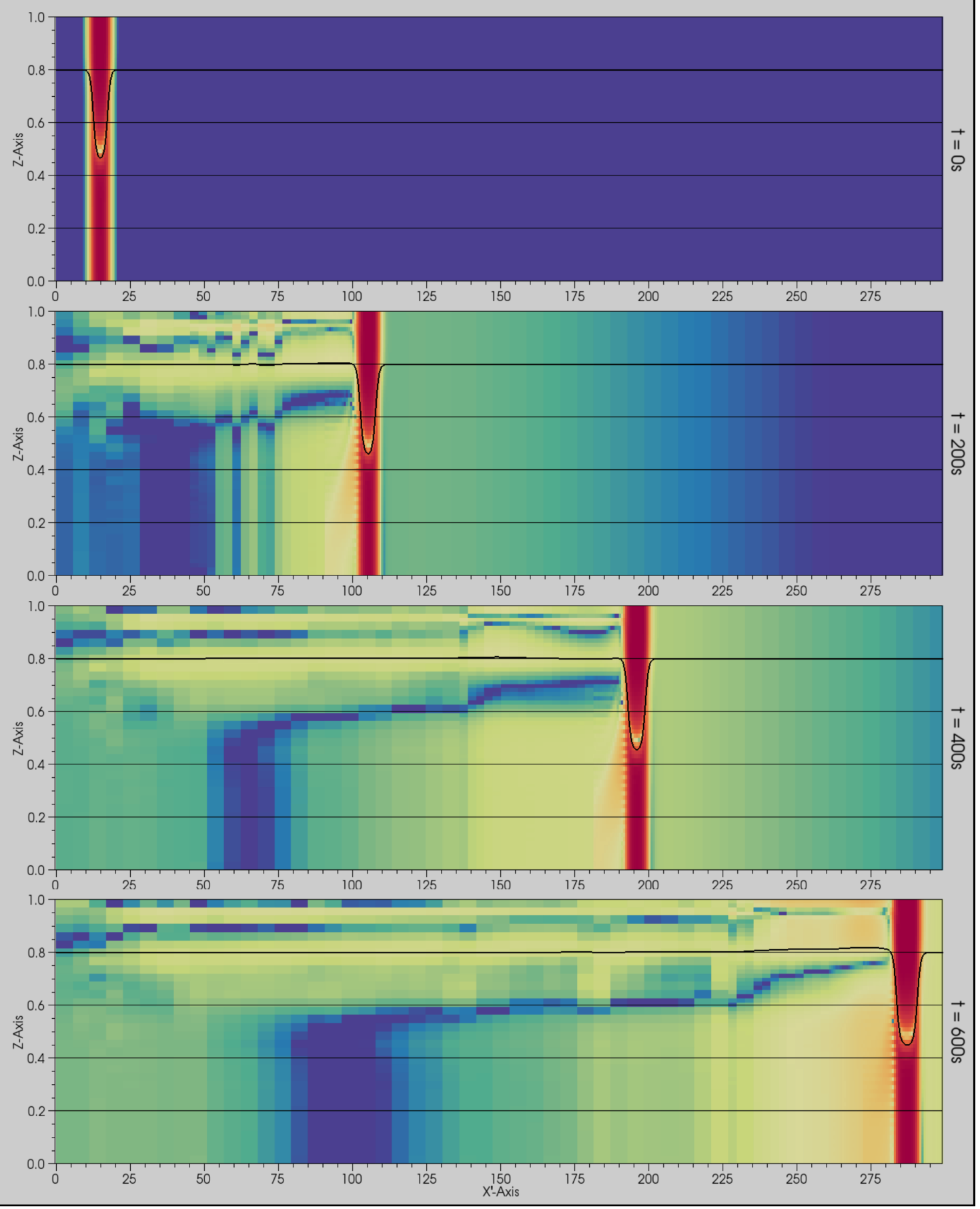
Stable treatment of stratification is accomplished via a new semi-implicit method that piggy-backs on the pressure solver. Coriolis effects are included at little extra cost.

$$\left\{ \nabla_h^2 + \frac{\partial}{\partial z} \left[1 - \frac{(\Delta t \theta N)^2}{1 + (\Delta t \theta N)^2} \right] \frac{\partial}{\partial z} \right\} \varphi = \nabla \cdot \vec{u}^{\star}$$

Accepts subgrid information in the form of an eddy viscosity / diffusivity. This ensures proper mixing and energy dissipation in overturning regions.

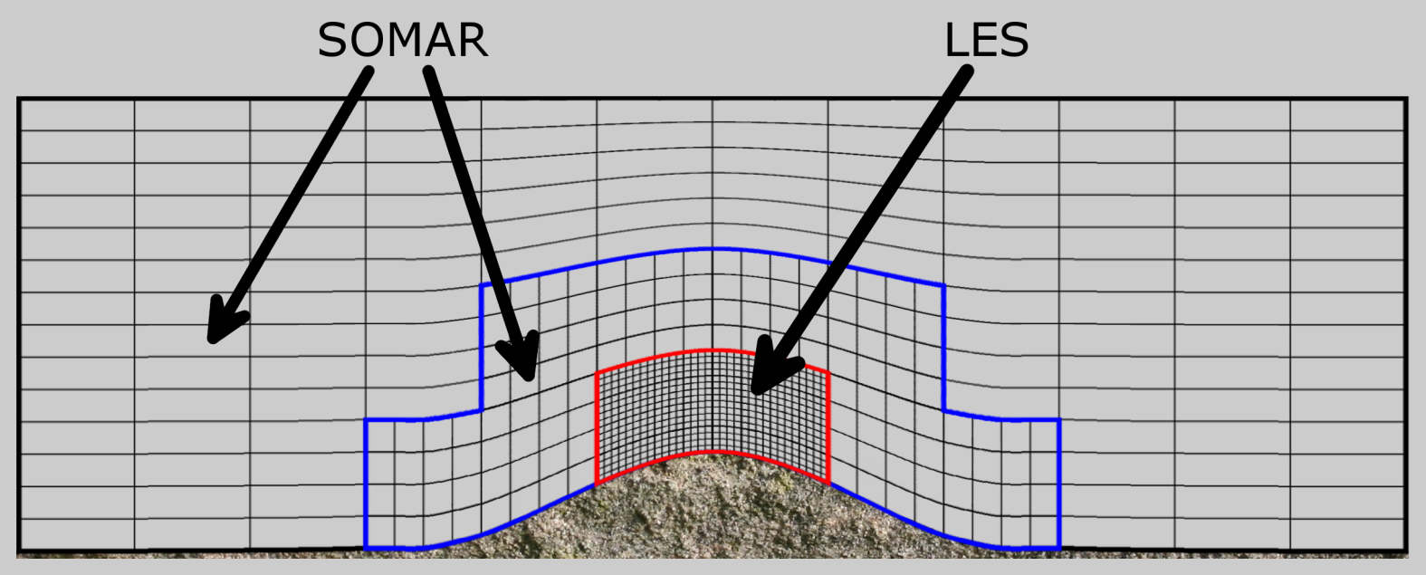
Low dissipation & physically appropriate dispersion has been exhibited in several tests. The figures below show a DJL solitary wave embedded in a 3D domain of non-dimensional length 512x512x1. In an inviscid run, the wave travelled over 270 channel heights while maintaining 92% of its original energy and only a 0.1% error in its propagation speed. This simulation took ~12 hrs on 32 cores and updated only 4.5% of the cells needed in an equivalent single-level run.



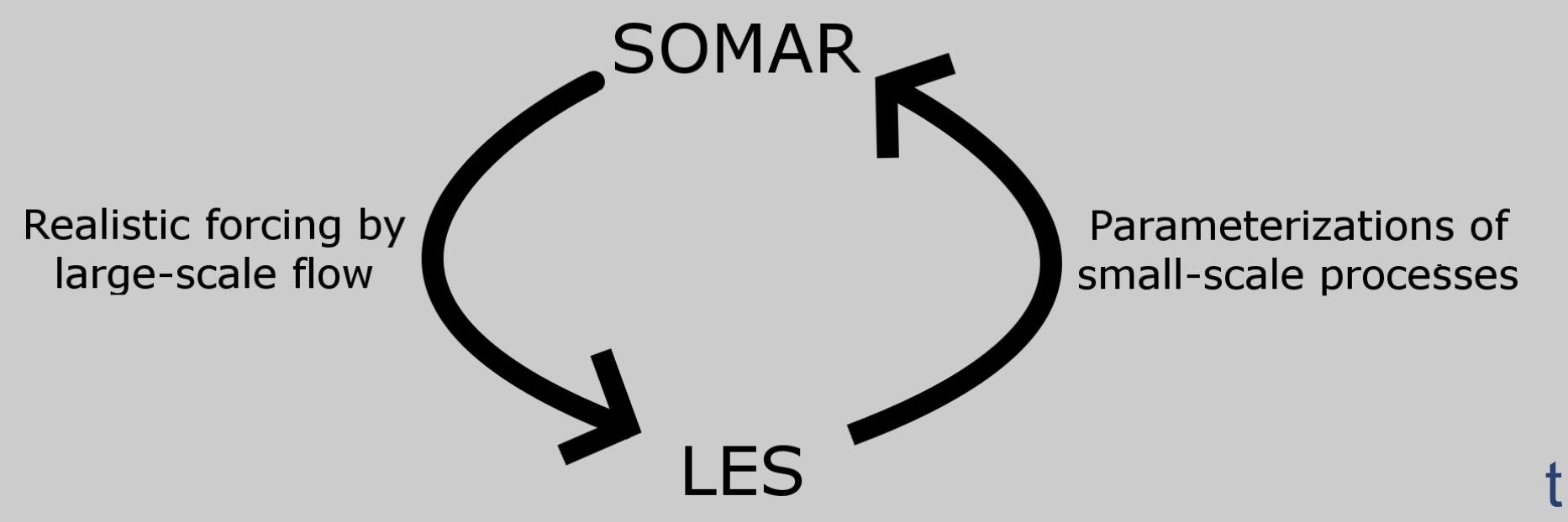


SOMAR-LES

Using the AMR capabilities of SOMAR, we can refine under-resolved regions of the domain. If the region is deemed turbulent, we can send the region's data to an LES.



Once the LES arrives at a sync point, its new data is averaged onto SOMAR's grids. The eddy viscosity and diffusivity that SOMAR receives is used to locally mix the fluid, dissipating energy in the process.

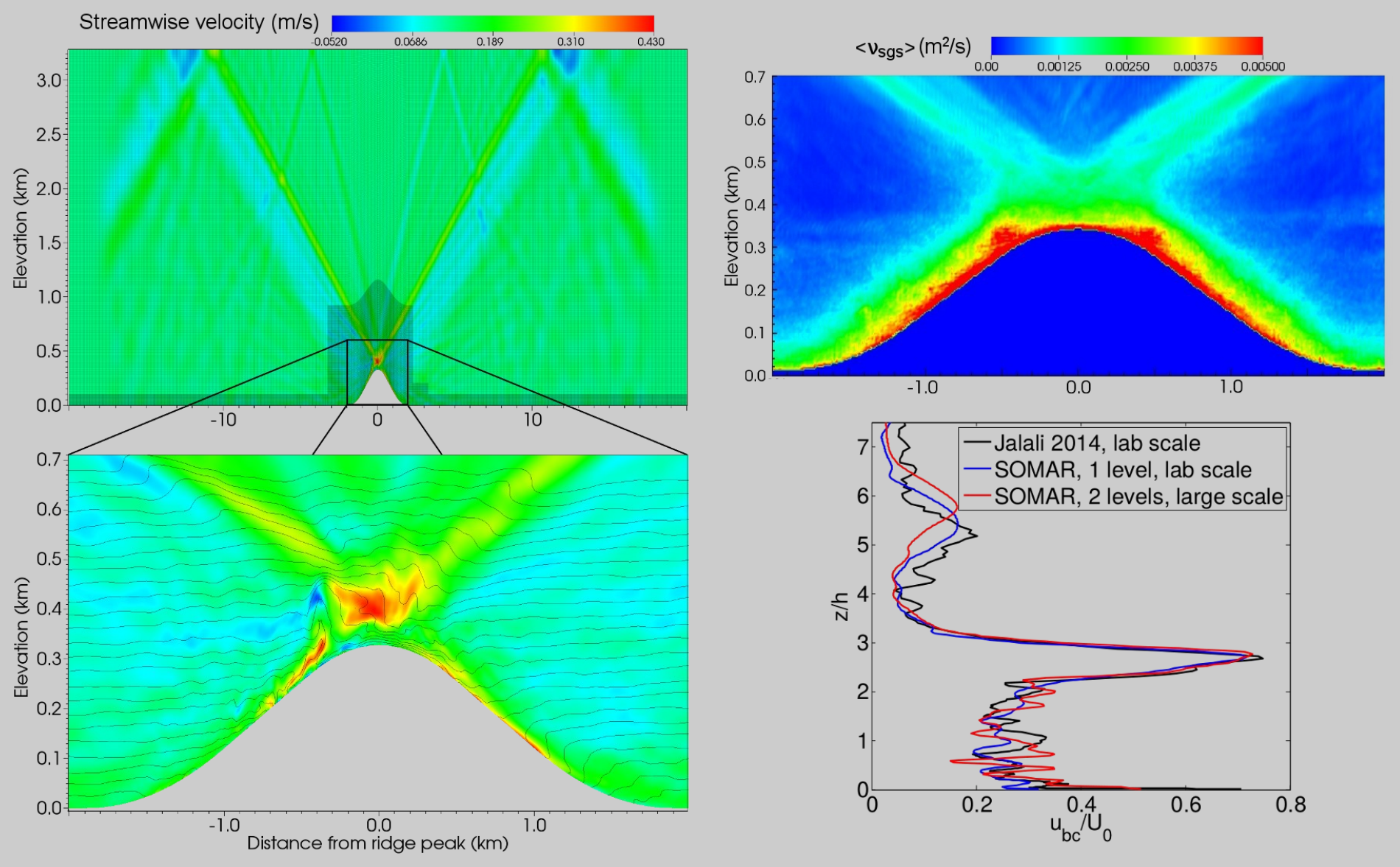

SOMAR

Realistic forcing by large-scale flow

Parameterizations of small-scale processes

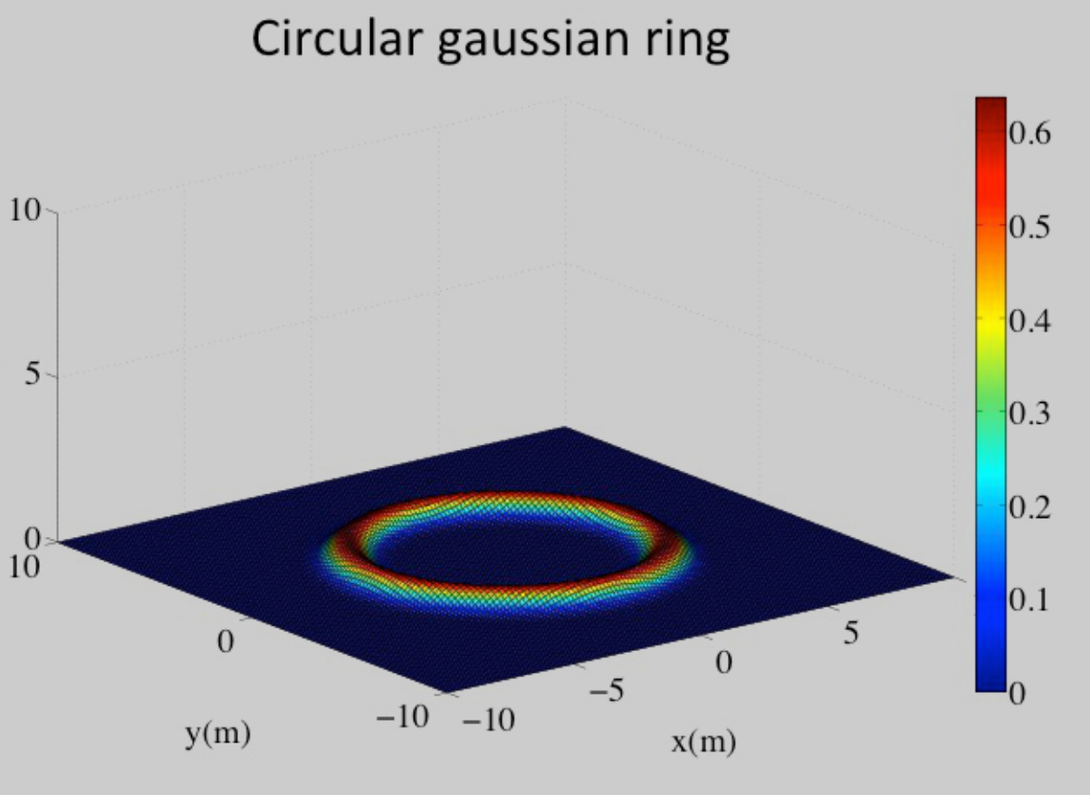
LES

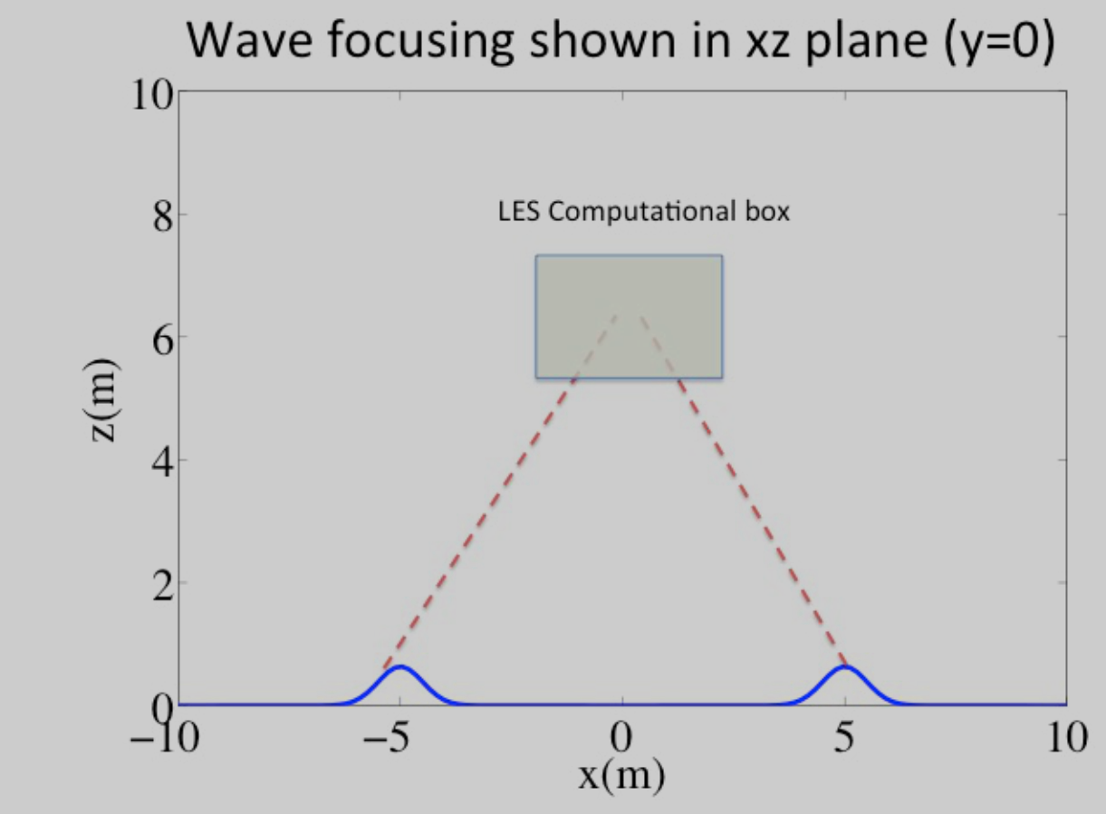
Preliminary tests have shown excellent agreement with scaled-down, pure LES results. One-way communication from LES to SOMAR shows good agreement of the internal wave beam's structure despite a 10x increase in Re.



Ongoing Work

Wave focusing above a ring topography is currently being simulated. The results will be compared to the theoretical models of Bühler and Muller 2007.


Circular gaussian ring


Wave focusing shown in xz plane (y=0)

Kaena Ridge is a site that generates internal waves with large overturns. An idealized topographic map of the site is being used in a SOMAR-LES simulation for comparison with the numerical studies of

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