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Computationally Efficient Tsunami Modeling on Graphics Processing Units (GPUs)

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Tsunamis generated by earthquakes commonly propagate as long waves in the deep ocean and develop into sharp-fronted surges moving rapidly toward the coast in shallow water, which may be effectively simulated by hydrodynamic models solving the nonlinear shallow water equations (SWEs). However, most of the existing tsunami models suffer from long simulation time for large-scale real-world applications. In this work, a graphics processing unit (GPU)-accelerated finite volume shock-capturing hydrodynamic model is presented for computationally efficient tsunami simulations. The improved performance of the GPU-accelerated tsunami model is demonstrated through a laboratory benchmark test and a field-scale simulation.

INTRODUCTION

Tsunamis are among the most dangerous natural disasters and are reported to potentially pose medium to high risk to most coastlines worldwide. Numerical modeling of tsunami propagation and run-up is essential for evacuation planning, risk assessment, and sometimes real-time forecasting. Numerical models based on the shallow water equations (SWEs) are commonly accepted for simulation of tsunami wave propagation from deep ocean to near shore including inundation.

To solve the SWEs for tsunami modeling, different approaches have been used, including the finite difference method, finite volume method, finite element method, and smoothed particle hydrodynamics (SPH). Most of the conventional tsunami models are based on finite difference leapfrog schemes, e.g., TUNAMI by Goto et al. (1997), MOST by Titov and Synolakis (1995), and COMCOT by Wang and Liu (2006). In recent years, finite volume Godunov-type schemes have also been implemented to solve the SWEs for tsunami modeling and have gradually gained popularity (Popinet, 2011; Leveque et al., 2011). These models boast automatic shock-capturing capability, superior conservation property, and flexibility for implementation on different types of computational grids for better boundary fitting. Because of these advantages, a second-order finite volume Godunov-type hydrodynamic model incorporated with an HLLC Riemann solver for interface flux calculation is used in this work for tsunami simulations. However, these sophisticated fully 2-D hydrodynamic models are normally computationally demanding for high-resolution simulations over large domains, restricting their wider applications.

Different approaches have been explored to improve the computational efficiency for the hydrodynamic tsunami models to enable multiscale tsunami simulations. For example, Leveque et al. (2011) employed adaptive block meshes to accelerate their finite volume Godunov-type tsunami model. Popinet (2011) reported a finite volume tsunami model on dynamically adaptive quadtree grids. Liang et al. (2015) presented another finite volume shock-capturing tsunami model developed on a simplified adaptive grid system that is free of data structure. Depending on applications, these adaptive mesh refinement (AMR) techniques may speed up a model several times (Liang et al., 2015) but have difficulty in ensuring full conservation of both mass and surface gradient during grid adaptation.

Adopting a different approach, Pophet et al. (2011) explored the use of multicore parallel computing to improve computational efficiency for their tsunami model solving the Boussinesq equations. A similar parallel algorithm was also used by Delis and Mathioudakis (2009) to develop their shock-capturing tsunami model, which solves the SWEs.

Accessible even on general desktop PCs, a more promising high-performance computing technique involving the use of graphics processing units (GPUs) has started to gain rapid popularity in the last few years. GPUs have been commonly used in the game industry but are only recently available for scientific computing (Brodtkorb, 2010). There are hundreds of processing elements on a single GPU to provide powerful parallel computing capability, in contrast to a central processing unit (CPU). The benefit of using GPUs to provide high-performance computing is evident. In less than one decade, numerous GPU-accelerated models have been developed and used in many areas of scientific computing, e.g., computational fluid dynamics (CFD), magnetohydrodynamics, and gas dynamics (Wang et al., 2010; Kuo et al., 2011; Rossinelli et al., 2011; Schive et al., 2012).

In computational hydraulics that focuses on SWE models, Brodtkorb (2010) implemented Kurganov–Levy and Kurganov–Petrova numerical schemes to solve the SWEs on a GPU and test the Compute Unified Device Architecture (CUDA)-based heterogeneous architectures for improved computational performance. More recently, Smith and Liang (2013) presented a second-order accurate finite volume Godunov-type SWE model on GPUs. Because of the use of the OpenCL programming framework, their model can be run on any modern GPUs and CPUs and therefore

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KEY WORDS: Tsunami modeling, shallow water equations, finite volume Godunov-type scheme, graphics processing units (GPUs), heterogeneous computing, CUDA.