LARGE EDDY SIMULATION OF SEDIMENT TRANSPORT AND HYDRODYNAMICS AT RIVER BIFURCATIONS

Allocation: Illinois/250 Knh
PI: Marcelo H. Garcia[1]
Co-PI: Paul Fischer[1]
Collaborator: Som Dutta[1]

[1]University of Illinois at Urbana-Champaign

EXECUTIVE SUMMARY

Bifurcations are fundamental features of all river systems. Our current study focuses on a specific class of bifurcations called diversions. Experiments have shown that the distribution of near-bed sediment between the downstream channels at a diversion is not proportional to the water flow distribution, with a disproportionately higher amount of sediment going into the lateral channel. A better understanding of this phenomenon will help in efficient design of river diversions, which are used for navigation and flood-mitigation and have been proposed as a solution for reclaiming deltas that are slipping under the sea due to rising sea levels. The current study employs large eddy simulations (LES) and direct numerical simulations (DNS) of the flow in idealized diversions of different configurations, with the sediment modeled as Lagrangian particles. The simulations have been conducted using a highly scalable spectral element based incompressible Navier-Stokes solver, Nek5000. The simulation conditions are comparable to laboratory experiments, which make these simulations some of the **largest** and **most complex** to date in the area of river mechanics. Blue Waters provides the computing resources to undertake these highly-resolved simulations. Currently, simulations have been conducted for up to 243.648 million computational points, with strong scaling being shown up to 32,768 MPI ranks.

INTRODUCTION

Bifurcations are fundamental features of all river systems. The current study focuses on a specific class of bifurcations called diversions, where one source channel splits into a main channel and a lateral branch. Laboratory experiments conducted by Bulle in 1926 [1] and later by other investigators have shown that the distribution of near-bed sediment between the downstream channels is not proportional to the flow distribution, with a disproportionately higher amount of sediment going into the lateral channel. This non-linear phenomenon is often referred to as the Bulle Effect. The current study investigates the mechanisms behind this phenomenon through high-resolution numerical simulations of the flow and sediment transport simulations at the scale of, and for configurations similar to, Bulle's experiments.

A better understanding of this phenomenon will help in efficient design of river diversions, which are used for navigation and flood-mitigation. Diversions have been proposed as a way to reclaim deltas that are sinking under the sea due to sea levels that are rising as a consequence of climate change [2]. A prime example is the Mississippi Delta; different diversion designs currently are being explored for diverting water and sediment from the Mississippi River [3]. Our study will also help more accurately predict the short and long-term geomorphological evolution of river bifurcations, thus furthering the state of the art in the field of river mechanics. Our research will also provide insights that will help improve the numerical models used for simulating field-scale bifurcations. A better understanding of the fundamental mechanism behind the Bulle Effect will also help shed light on the related phenomenon of vorticity-driven sediment transport, which affects both natural and manmade systems [4]. Finally, bifurcations are not only found in rivers but also in other places, such as the carotid bifurcation in the human body [5]. Thus, the current study will contribute to our general understanding of dynamics and transport at bifurcations.

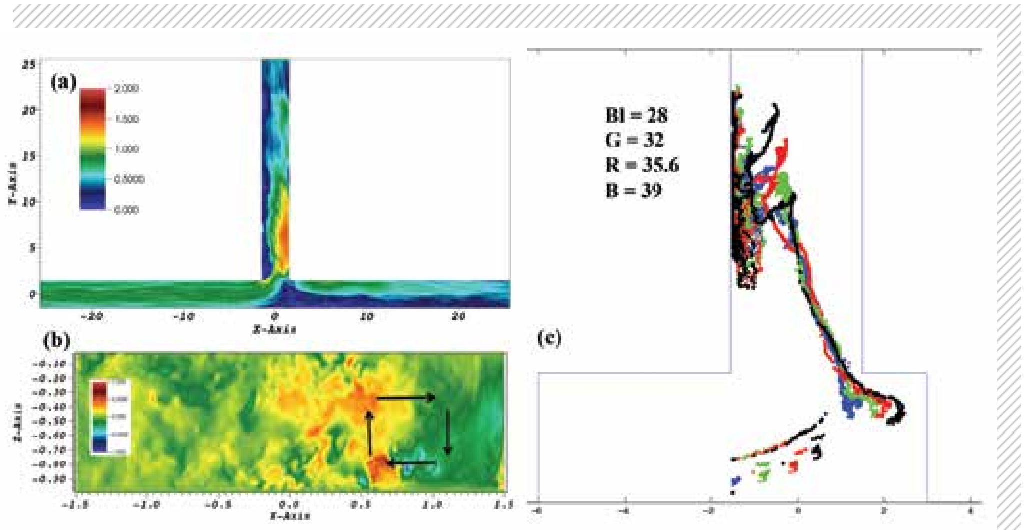

FIGURE 1: (a) Time-averaged velocity magnitude at 5 percent of the height of the channel. (b) Instantaneous velocity in the vertical direction, showing a clear signal of clockwise rotating vortex. (c) Evolution of horizontal positions of the sand particles in time, with Bl being Blue and B black. (c) Clearly shows that most of the sediment enters the lateral channel, which can be attributed to the majority of the flow near the bottom entering the lateral channel [see (a)] even when the total flow split is 50:50.

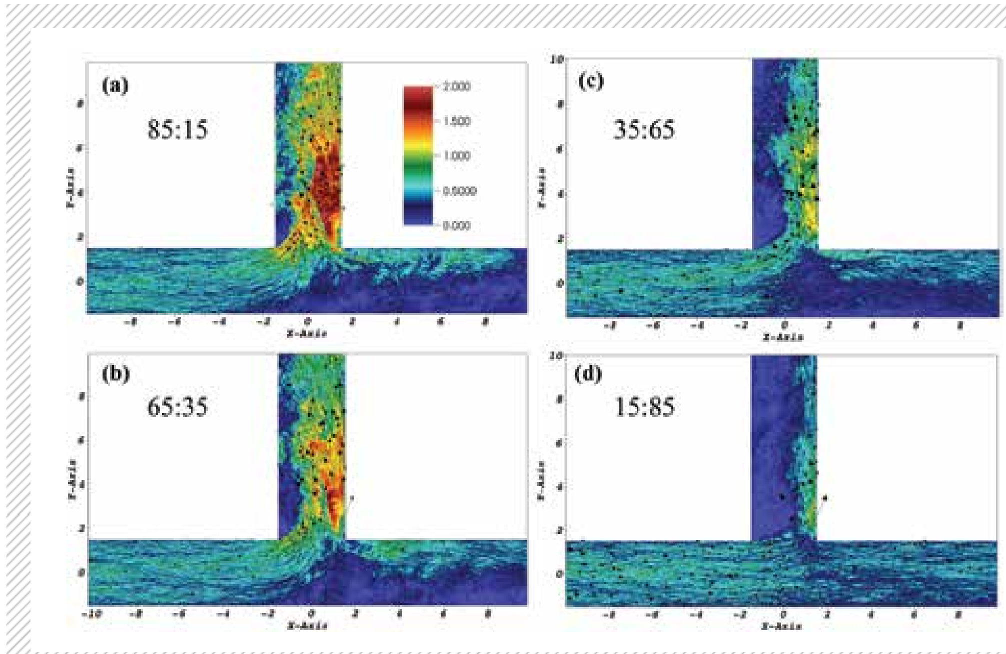

FIGURE 2: The figure shows the instantaneous velocity magnitude of the flow near the bottom of the channel, for a flow of bulk Reynolds number = 25000. Four cases with different % of the total flow going into the lateral channel have been presented; e.g. in case (a) 85 % of the flow is going into the lateral channel. The figures show that even for cases in which, a smaller % of the total flow moves into the lateral channel [case (c)], majority of the flow near the bottom continues to move into the lateral channel.

METHODS & RESULTS

High-resolution large eddy simulations (LES) and direct numerical simulations (DNS) have been conducted of the flow in idealized diversions of different configurations, with sediment being modeled as Lagrangian particles. Use of LES or DNS depends on the Reynolds number of the flow, with simulations conducted for Reynolds number values from 10 to 25,000. For the cases with Reynolds number of 25,000, the conditions are comparable to the laboratory experiments, which make these some of the **largest** and **most complex** simulations in the area of river mechanics. The simulations have been conducted using the open-source, spectral element based higher-order incompressible Navier-Stokes solver Nek5000 [6]. The spectral element method (SEM) combines the accuracy of spectral methods and the flexibility of numerical methods based on local approaches, like the finite elements method [7]. Sediment transport in the flow has been modeled using Lagrangian particle tracking. For simulating transport of poly-disperse sediment particles efficiently, a semi-implicit Lagrangian particle algorithm has been developed for the current study [1].

The first case presented here is of a 90-degree diversion at Reynolds number 20,000, with 50% of the total flow going into the lateral channel [2]. The time-averaged velocity magnitude of the flow near the bottom has been plotted (Fig. 1a) along with the position of the sediment particles (Fig. 1c). The majority of the sediment moves into the lateral channel, which is in agreement with the laboratory experiments. This highly non-linear behavior can be attributed to the fact that most of the flow near the bottom moves into the lateral channel, even though only 50% of the total flow moves into the lateral channel. Another important flow feature that influences the dynamics of the sediment at the diversion is the clockwise rotating vortex near the right-wall of the lateral channel (Fig. 1c). Instantaneous velocity magnitude near the bottom of the channel for different flow splits has also been presented for the 90-degree diversion at Reynolds number of 25,000 (Fig. 2). It shows that even when only 35% of the total flow moves into the lateral channel, most of the flow near the bottom moves into the lateral-channel (Fig. 2c). These results hint toward the underlying mechanism behind the non-linear Bulle Effect.

We are conducting more simulations with poly-disperse sediment for different flow-splits, Reynolds numbers and diversion-angles. The completed study will not only help to fully understand the underlying mechanism behind the Bulle Effect, it will also help in developing a reduced-order model for the phenomenon. This study provides new insights into the hydrodynamics and sediment transport at bifurcations, and it also shows that high-resolution LES can be used to study complex river-mechanics problems.

WHY BLUE WATERS

The current study **pushes the limit** of the scale at which high-resolution large-eddy simulations have been used to study complex multi-phase river mechanics problems, warranting the use of Blue Waters, which can provide sustained computing power at an **unprecedented scale**. For the current study, simulations have been conducted for up to 243.648 million computational points, with the code scaling strongly up to 32,768 MPI ranks. Without access to a petascale high-performance computing system like Blue Waters, completing the study in any realistic time-frame would be impossible. One of the most useful ways to understand a phenomenon is through visualization, thus we are working with Blue Waters staff to create an animation of the flow and sediment transport for one of the simulated cases.

NEXT GENERATION WORK

Access to the next generation of Track-1 HPC system will allow us to step up the scale at which we work, thus allowing us to conduct high-resolution LES of environmental flows at scales and with complexity similar to that of nature. This will allow us to fathom the underlying mechanisms of different environmental phenomena, thus aiding in improved predictions of different natural processes.

HIGH-RESOLUTION EARTH SYSTEM MODELING FOR INTERNATIONAL CLIMATE ASSESSMENT

Allocation: NSF PRAC/31.5 mnh
PI: Robert Rauber[1]
Co-PIs: Warren Washington[2], Gerald Meehl[2], Joe Tribbia[2], and Justin Small[2]
Collaborators: Donald Wuebbles[1], Zachary Zobel[1], Xin-Zhong Liang[3] and Chao Sun[3]

[1]University of Illinois at Urbana-Champaign
[2]National Center for Atmospheric Research
[3]University of Maryland

EXECUTIVE SUMMARY

This is a collaborative project to investigate climate change and regional climate processes using higher model resolutions that would not be possible without resources such as Blue Waters. These simulations allow us to investigate climate change, specifically regarding extremes; regional model performance through dynamic downscaling; and to examine regional model uncertainties about atmospheric processes. These studies are on the **leading edge** of high resolution global and regional climate modeling and provide the pathway for the next generation climate models and assessments. Our studies also allow better understanding of model uncertainties. No previous global modeling study has provided such high-resolution information at the regional scale to fully analyze the potential impacts of climate change on human society across many different sectors (e.g., health, food, water, energy, transportation) and on ecosystems.

INTRODUCTION

This project has several objectives. One objective is to quantify changes in future climate extremes using two high-resolution versions of the Community Earth System Model (CESM): one with a high-resolution atmosphere (0.25° atmosphere, 1.0° ocean) and the other with high-resolution atmosphere and ocean (0.25° atmosphere, 0.1° ocean) where ocean eddies are derived internally instead of being parameterized. Another objective is to evaluate the effects of dynamical downscaling (DD). DD inputs time varying boundary conditions from a lower-resolution, limited-area, global climate model (GCM) into a regional climate model (RCM) [1,2], which is the Weather Research and Forecast (WRF) model. Finally, work on climate parameterization uncertainty continues via a multiple physics ensemble (MPE) analysis.

METHODS & RESULTS

CESM: The CESM pre-industrial (PI) control simulation with a fully coupled 0.25° atmosphere and 1.0° ocean has completed 100 years of simulation. In extended control simulations, it is desirable to have the radiative balance at the top of the atmosphere below |0.1| W/m^2 so that model drift is small and follow-on simulations, such as twentieth century historical or associated climate sensitivity simulations, can be branched with suitably balanced and realistic initial conditions. The PI control run on Blue Waters reached 0.03 W/m^2.

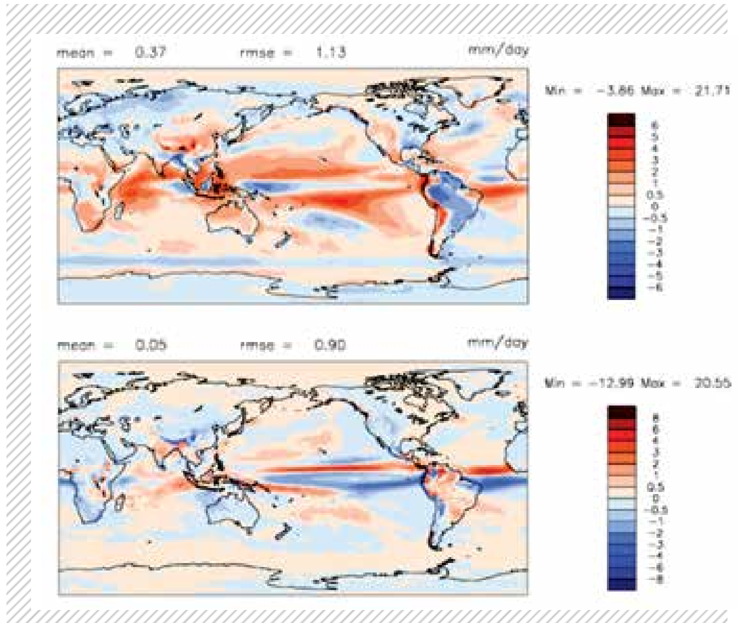

FIGURE 1: Annual mean total precipitation rate difference between a baseline low resolution (1.0°) PI control and GPCP observations (top panel) and between the high resolution (0.25°) PI control conducted on Blue Waters and the baseline low resolution PI control (bottom panel). Wherever the color is opposite in these two panels are regions in which high resolution represents precipitation rate better than low resolution.