Report for 2001LA2501B: Developement of a Two Dimensional High Spatial Resolution Storm Surge Simulation Model for Single Processors and Distributed Computing Clusters

There are no reported publications resulting from this project.

Report Follows:

1.0 Introduction

Human societies have become increasingly vulnerable to natural disasters like hurricanes. Due to increases in population and urbanization, a hurricane of a similar intensity causes more damage to life and property now than it did fifty years ago. A category four or five hurricane has enormous damage potential and can ruin the economic and social fabric of entire states.

This is especially true in south Louisiana, which due to its geographic proximity to the Gulf of Mexico is extremely vulnerable to hurricanes. Much of this area is low lying and consists of bayous and wetlands, which further increase the threat of storm surge inundation. Major metropolitan areas like New Orleans are especially vulnerable as much of the city is below sea level, and is protected by hurricane levees. Preliminary studies conducted at NSEL indicate that it would only take a category three storm to overtop the levees east of New Orleans submerging the city in over 20 feet of water.

The damage caused by hurricane Andrew has prompted a detailed national re-evaluation of several aspects of hurricane preparedness (National Weather Service, 1992) that has significant relevance to Louisiana. The NWS report pointed out that the problem of hurricane disasters is exacerbated by a continued destruction of natural protective features in the coastal zone, such as beaches, dunes and tidal wetlands. Unfortunately, Louisiana has recently experienced an annual loss of about 25,000 acres of wetlands and expectations are that wetland loss will continue. Thus the hurricane threat in Louisiana will be changing in the future. The NWS report also noted that winds caused most of the damage during Andrew and the emergency preparedness officials must considered the hurricane threat as a "wind/flood/storm surge" event that extends many miles inland from the coast. Therefore assessment of the threat in Louisiana must be comprehensive. Finally, in light of this newly defined hurricane threat, the report states that new approaches and standards must be developed to protect the public. Thus the preparedness and evacuation procedures used in the future in Louisiana need to use the best methods currently available.

Although natural hazards are not preventable, adequate precautions can be taken to minimize losses to both life and property if proper vulnerability assessments can be made before designing large infrastructure projects. These projects include flood control structures like levees, wind resistant buildings, and also in the area of urban planning and management.

2.0 Objectives

The overall goal of the project is to develop a high resolution storm surge simulation model for assessing the impact of hurricanes on coastal communities. To accomplish the project the following specific objectives are defined:

- To develop a coastal hydrodynamic model with sub-grid scale features such as, rivers and barriers, for predicting tidal circulation in the wetlands.
- To implement the NWS 38 hurricane wind model which would characterize the wind field from a particular storm.
- Incorporate the influence of rainfall on spatial flooding patterns.
- Use state of the art parallel and distributed computing paradigms in order to achieve fast and timely execution of all the model components.

- Calibrate the model against historical storms.
- Do a sensitivity analysis of the various model parameters.

3. Methods, Procedures and facilities

This research focuses on the development of a storm surge simulation model with very high spatial resolution of the order of 100 to 200 meters. Due to the high spatial resolutions, the model would enable us to do accurate mapping of the flood threat of urban areas. The high spatial resolutions result in grid sizes, which are of the order of 2000 by 2500, which translates to about five million grid points. Problems of this magnitude requires enormous computational power both in terms of CPU and memory, beyond the capabilities of even the most powerful uni-processor workstation. The only alternative to solving problems of such magnitude is to use parallel/distributed supercomputers. Keeping the above factors in mind, the model has been developed using parallel and distributed computing paradigms and is capable of running on both shared memory systems consisting of a number of processors accessing a global shared memory with processors interconnected by a high speed crossbar bus, and distributed memory multiprocessor architectures which can be clusters of workstations connected by a high speed network. This has been achieved by writing the model code using FORTRAN 90 with High Performance FORTRAN (HPF) extensions. A brief description of the various model components is given below.

3.1 Hydrodynamic Model

The important factors affecting coastal dynamics are tides, and winds. In order to resolve this, water level fluctuations due to both tides and winds must be accurately simulated. This would be accomplished by developing a coastal hydrodynamic model capable of simulating water level fluctuations and currents due to tides and winds. Due to the flat coastal topography and shallow water depths a two-dimensional vertically averaged model would be used.

The governing equations of the model consist of the two horizontal components of momentum and an equation for the conservation of mass. The equations of continuity and momentum are shown in Equations (1), (2) and (3)

Continuity

$$\frac{\partial z}{\partial t} + \frac{\partial (uH)}{\partial X} + \frac{\partial (vH)}{\partial Y} = r \qquad (1)$$

X- Momentum

$$\frac{\partial u}{\partial t} + \frac{\partial (uuH)}{\partial X} + \frac{\partial (uvH)}{\partial Y} + gH\frac{\partial z}{\partial X} = \tau_x^w - \tau_x^b + fv - \frac{gH}{2\rho_0}\frac{\partial \rho}{\partial X} + \frac{ru}{H} \qquad (2)$$

Y-Momentum

$$\frac{\partial v}{\partial t} + \frac{\partial (uvH)}{\partial X} + \frac{\partial (vvH)}{\partial Y} + gH\frac{\partial z}{\partial Y} = \tau_y^w - \tau_y^b - fu - \frac{gH}{2\rho_0}\frac{\partial \rho}{\partial Y} + \frac{rv}{H} \qquad (3)$$

Where:
u and v are the horizontal velocity components in the X and Y directions
r is the rainfall
z is the water level elevation measured from the mean sea level
H is the total water depth
f is the coriolis parameter
ρ is the density of water
ρ_0 is the reference density of water
τ^b_x, and τ^b_y are the bottom friction terms
τ^w_x, and τ^w_y are the wind stress terms

These equations are discretized using a semi-implicit finite difference method developed by Casulli and Cheng (1990). This then results in a set of linear algebraic equations, which is solved using a preconditioned bi-conjugate gradient stabilized (BICGSTAB) method. Due to the semi-implicit finite difference scheme used in this model, the overly restrictive gravity wave stability criterion imposed by most explicit schemes is avoided. The semi-implicit scheme in theory is unconditionally stable and the size of time steps need to be restricted purely from an accuracy standpoint.

Model parallelization is achieved by incorporating HPF extensions into the model code. HPF extensions look like Fortran 90 comments to a sequential program. When the code is run through a HPF compiler a Fortran 90 code with message passing protocols is obtained. Parallelism is mainly achieved by distributing arrays over a number of processors. The parallelism can be described by the following example which describes the parallelisation of the Laplace's equation:

```
Real u(0:imax+1,0:jmax+1)
!HPF$DISTRIBUTE(block,block):: u
!! Setup Gauss Seidel Iterations
tol=1.0e-05
do iter=1,max_iterations
!HPF$ DO INDEPENDENT,  NEW(i)
do j=1,jmax
!HPF$ DO INDEPENDENT, NEW(u1), REDUCTION(duu)
do i=1,imax
u1=u(i,j)
u(i,j)=0.25*(u(i+1,j)+u(i-1,j)+u(i,j+1),u(i,j-1))
duu =  duu + (u(i,j)-u1)**2.0
enddo
enddo
if(duu < tol)
!! Stop iterations
enddo
```

In the above piece of code in line 2 the array u is distributed in rectangular blocks among an abstract rectangular grid of procesors. Line 6 indictaes that the do loop in Line 7 is a parralelisable loop. Line 8 indicates that the Loop in Line 9 is paralleliasable and

that the value duu should be summed across all processors indicating a reduction clause. Similar directives were embedded in the hydrodynamic code to parallelize it.

3.2 Boundary Conditions Formulation

Different types of boundary conditions are needed for the model. Boundary conditions need to be prescribed on all four horizontal boundaries. The boundary condition prescribed on the seaward side includes the water level variation due to tides combined with the prescription of the inverted barometric pressure. At the lateral seaward boundaries a radiation boundary condition is used in order to minimize the reflection of outgoing waves. At the land boundaries a moving boundary condition is used so that that the process of covering and uncovering of tidal flats can be taken into account. An advantage of using this numerical procedure is that the moving boundary aspects can be be taken into account automatically without resorting to specialized procedures.

3.3 Modeling Sub-Grid Scale Features

An important subcomponent of the hydrodynamic model is the resolution of sub-grid scale features. Louisiana has a number of small bayous and big rivers. During periods of low flow tides can propagate upstream along these channels. A one dimensional river model, a component of the hydrologic model, would be embedded in the 2-dimensional hydrodynamic model. Another important feature in the Louisiana landscape is the presence of several natural and artificial levees. These features play an important role in the hydrodynamics in the sense that they block the free movement of sediments and water. A subgrid barrier formulation similar to the one used in the Federal Emergency Management Agency (FEMA) Coastal Hurricane Storm Surge model (Greenhorne and O'Mara, 1985) has been incorporated in the present model.

The different sub grid scale features include, submerged barriers, overtopped barriers, and no flow barriers. Opening through barriers in the forms of culverts, and gates are also incorporated. The barriers also can have weirs at their crest and a weir formulation is also incorporated.

3.4 Hurricane Storm Model

The hurricane storm model describes the distribution and magnitude of the wind velocity and atmospheric pressure within the hurricane and provides the wind stress, pressure gradient, and inverted barometer water elevation forcing to the hydrodynamic model. In the hurricane storm model, a hurricane is considered fully described by its barometric pressure field at sea level and the corresponding 10-meter elevation, 10-minute average wind field over the sea surface. The sea level pressure field is parameterized by, the radius of maximum winds, the central pressure depression, and the far field pressure. The wind field is parameterized by, the radius of maximum winds, the central pressure depression and the storm forward speed. The storm track and its translational velocity are used to describe the complete history of the barometric pressure field and wind field everywhere on the hydrodynamic grid. The wind and pressure distributions are based upon data from a large sample of observed hurricanes. The National Weather Service has provided an updated version of the hurricane description known as NWS-23 (1979) for inclusion into the model. The isobars for hurricanes are

assumed to be circular about the hurricane eye and are therefore defined in a polar coordinate system. The barometric pressure distribution in NWS-23 is described in terms of the central pressure, and the far-field pressure.

3.5 Rainfall Component

During the course of a hurricane event the areas affected by flooding is much larger than the storm surge impact areas, due to the high rainfall intensities experienced by these areas. Interior areas far away from the coast, experience flooding due to high rainfall intensities. This situation is made worse in Louisiana where large areas are impounded by levees. These levees although afford a measure of protection from storm surge flooding, but are vulnerable to rainfall induced flooding. This is especially true in the City of New Orleans, where a large part of the city is below sea level and is surrounded by hurricane levees river levees. High rainfall intensities have caused significant flooding in the city in the past. An important component of the current model is the inclusion of rainfall as a source. This is accomplished by adding a source term to the continuity equation. Once a cell receives the rainfall, as a source the momentum equation would calculate the appropriate velocities associated with the runoff accompanying the rainfall event.

3.6 Data Requirements

- The data requirements for the model include, topography/bathymetry, storm parameters, rainfall amounts, surface roughness characteristics, levee and roadway heights etc. Sources for this data include the USGS, US Army Corps of Engineers, and Louisiana State Department of Natural Resources, Louisiana State University Southern Regional Climate Center, and the National Weather Service. An attempt was made to include accurate topography information from the LIDAR surveys. Due to the delay in the release of data for the entire state this was not undertaken. Due to the dynamic nature of Louisiana's coast LANDSAT-TM satellite images are used to accurately delineate land-water features.
- The data required for running the model at a 100 m resolution is not available. This is especially true regarding bathymetry data. An attempt was made to use the data released by NOAA which integrates USGS DEM and bathymetry data at a resolution of 30 m. It was found that this data set was of poor quality with a lot of missing data.
- It was finally decided to run the and test the model at a resolution of 1 km for which all data were available.

3.7 Computational Design

Although field data were not available at 100m resolution the model has been developed to run simulations at very high resolutions when data does become available. In order to model the entire Louisiana Coast at a grid resolution of 100m typical grid sizes of 2500 X 2000 have to be used. This translates to several Gigabytes of core memory. The time steps range from about 1 minute to 5 minutes. For a one-week simulation, with a time step of one minute the number of time steps is about 10080. This large number calculation indicates the extremely computation-intensive nature of the model. Typically models of this nature are run on shared memory vector supercomputers like the Cray

C90. These supercomputers are extremely expensive costing several million dollars, financially well beyond the reach of university departments.

In order to take advantages offered by a workstation cluster the model algorithm is parallelized using HPF directives. The problem is distributed across the workstation cluster with each node performing a subset of the total computation. The subsets communicate with each other by exchanging messages which travel across the network. An inherent drawback of such a system is the slow speed of the network increasing the communication costs. The challenge lies in minimizing the communication costs by keeping the message passing overhead at a minimum. Conceptually, the program is executed on all processors simultaneously. Since each processor only has access to a subset of the distributed data, there will be times when a processor needs to access data stored in the memory of another processor. The actual details of the inter-processor communication needed to support this access are determined by the compiler rather than being specified explicitly, they are implicit in the program. A great advantage of writing code using HPF directives is that the code is portable across both uni-processor, shared memory multiprocessor, and distributed memory workstation clusters.

3.8 Visualization of model Results

All model outputs are compatible with GIS based visualization systems. ARC/INFO a commercial GIS system is used for visualizing the model results. Vector features like roads, railway lines, parish and state boundaries, levees, etc. would be overlaid. Point features like shelter locations would also used as overlays.

3.9 Facilities used for the project.

The facilities required to complete this work are available at LWRRI. These include a distributed computing cluster, graphics workstations for display and related equipment like scanners, color printers etc. A brief description of the distributed computing cluster is given below.

3.9.1 Distributed Computing Cluster

The distributed computing cluster consists of 32 Pentium II 350 MHz workstations with 256 MB of RAM and 4.5 GB of disk space. The workstations are interconnected using a 100 Mbit fast ethernet network connected through two 24 port 3 Com Superstack II 3300 switch. This provides an aggregate backplane bandwidth of one Gigabit/sec. The switches are interconnected by a matrix cable so that there is no loss of bandwidth when two switches are stacked. The cluster is monitored through a front-end workstation which consists of a Pentium II 350 MHz motherboard with two 100 Mbit fast ethernet cards, a 8 MB Matrox Millenium G200 video card, two 9 GB IDE hard drives, a 24 X CDROM and a floppy drive. The front end also has a Portland Group optimizing C, C++, F77, F90 and HPF compilers. Various GNU compilers like GCC, G77 etc. are also available. Message passing libraries like MPII, PVM, BSP etc. also available. All the nodes in the cluster run LINUX a public domain UNIX like operating system.

4.0 Results:

The storm surge simulation was paralleized and a summary of its performance on a cluster of workstations is shown in Table 1. In order to evalaute the performance a fine grid channel model was used to gauge the performance metrics. The channel consists of a channel 20 km wide and 100km long. The grid resolution was 100 m in both the X and Y directions for 200 grid cells in the X direction and 1000 grid cells in the Y direction. A sinusoidal wave of 24 hr period was prescribed at the southern boundary. A no flow condition was prescribed at the northern, eastern and western boundaries. The model was run period of 7 days with a time step of one minute. The results are summarized in table 1. The first column indicates the number of processors, the second column indicates the total execution time, the third column indicates the Millions of floating point operations per second (Mflop/s), the fourth column indicates the Mlop/second/processor, and the fifth column indiactes the speedup with respect to a single processor run.

Table 1. Performance of a high resolution hydrodynamic model

#of procs	Time (Secs)	Mflop/s	Mflop/s/proc	Speedup
1	3406.67	47.8	47.8	1
9	426.9	394.2	43.8	7.98
16	257.1	654.4	40.9	13.25
25	149.3	1127.0	45.0	22.81

From Table 1. It is apparent that the model scales well from one to 25 processors, with speedup of 22.81 for a 25 processor run. Due to the unavailability of all data at 100m resolution it was decided to run the model at a one km resolution.

A 1km grid resolution run was made on a historical hurricane (hurricane Camille). The model was run for the eastern part of the state with boundary forcings obtained from a coarse grid FEMA model run. The maximum envelope of flooding which indicates the maximum water level obtained at a grid point during the course of the simulation is shown in Figure 1. The model results compared well with observed maximum elevation data.

5.0 Conclusions

The following conclusions can be regarding the study.

- A high resolution storm surge simulation model was developed.
- The model code was parallelized using High Performance Fortran directives.
- The model implemented sub grid scale features such as barrier, levees, inlets through barriers.
- A hurricane wind model based on NWS 23 was developed.
- The model also includes rainfall as a source term so that high intensity rainfall can be incorporated.
- The parallel model scaled well over 25 processors.

- Calibrations against hurricane Camille indicated good agreements.

6.0 Future Enhancements Planned

The model is still evolving. Some of the work underway include:

- Collect high resolution topography and bathymetry data. Currently such data is being gathered by NOAA and the state of Louisiana using LIDAR surveys. Once these data are obtained and quality checked they would be included into the model.
- Use updated Levee information. This information is being collected by the U.S. Army Corps of Engineers. We have obtained a preliminary data set which is currently undergoing testing.
- Although the model includes rainfall as an input this modules has not been thoroughly tested. This would be tested in a future release of the model.
- Incorporate a pollutant transport model. This is important because often times during a hurricane a lot of toxic chemicals may be released, especially if the hurricane hits certain regions of Louisiana where there is a large concentration of chemical industries.
- Update the model by incorporating MPI (Mwssage Passing Interface) as a parallelization protocol instead of HPF. This is important as for a large number of processors MPI is more scalable than HPF.

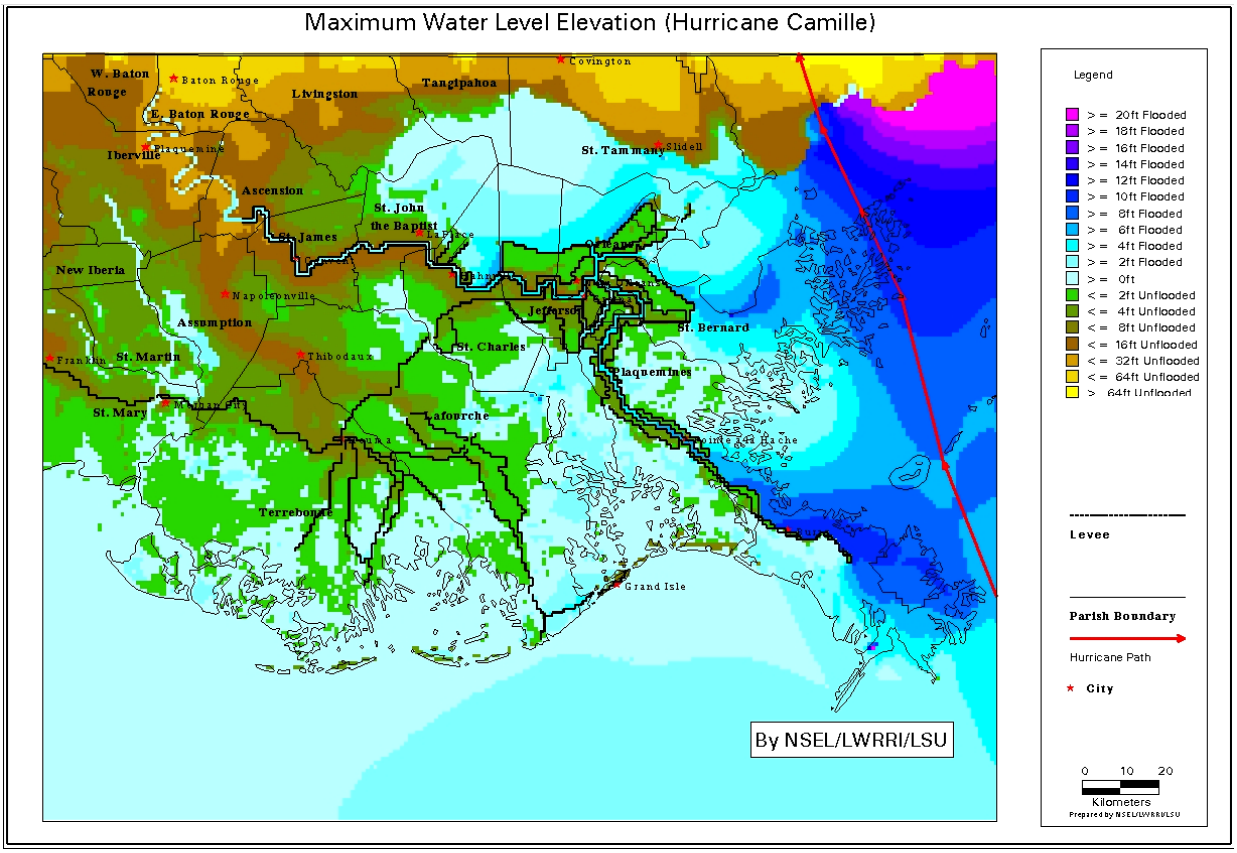

Figure 1. Maximum Water Level Elevation (Hurricane Camille)

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