

Data-Driven Boundary Correction and Optimization of a Nearshore Wave and Hydrodynamic Model to Enable Rapid Environmental Assessment

James M. Kaihatu
Zachry Department of Civil Engineering
Texas A&M University
3136 TAMU
College Station, TX 77843-3136
phone: (979) 862-3511 fax: (979) 862-8162 email: jkaihatu@civil.tamu.edu

Award Number: N00014 N00014-09-1-0503
<http://ceprofs.civil.tamu.edu/jkaihatu/research/proj.html>

LONG-TERM GOALS

The present project is part of a comprehensive effort by the PI, his students, and collaborators at the Naval Research Laboratory to increase the robustness and viability of the Delft3D model suite as an operational forecasting tool, and aid its continued transition to Navy forecasting centers. Prior projects have focused on determining the model's response to characteristics and sample sizes of bathymetric information. The present project focuses on determining the effect of boundary errors on model response, and the development of methods to ameliorate these issues. These boundary errors arise when the numerical grid for the forcing condition (wave model) is insufficiently extended in the lateral (longshore) direction relative to the numerical grid for the current (flow model).

OBJECTIVES

The primary objective of this work is to investigate the effect of boundary forcing errors on the model response. This has a direct impact on the use of Neumann lateral boundary conditions, since these errors arise from insufficient extension of the WAVE (SWAN) grid beyond the lateral boundaries of the FLOW grid. There is a balance between accuracy and computational efficiency that must be struck; the computational bottleneck in the Delft3D system is SWAN, the wave model, and the run time increases with lateral extent of the WAVE grid. While point-by-point comparisons between model and data for various WAVE grid extensions can offer a view of the dependence of accuracy on grid extension, it does not yield any information on the spatial characteristics of the solution; poor data-model comparison could be the result of slight spatial mismatches of highly variable solution fields, or oversmoothed solutions which have little relevance to the physics at hand.

APPROACH

Among the recent enhancements to the utility of the Delft3D model for nearshore process simulation include the implementation of Neumann lateral boundary conditions (Roelvink and Walstra 2004), which allow for flow to enter and leave the lateral boundaries with no artificial circulation. This

boundary condition is formulated by reducing the flow equations in the hydrodynamic model to a single dimension, which has the effect of setting conditions on the *gradient* of the velocities rather than on the velocities themselves. For wave-induced flow, however, one consequence is the need to have a wave-model grid that is significantly wider than the hydrodynamic model grid; this is done in order to keep irregularities in the forcing away from the boundaries of the hydrodynamic model. However, SWAN, the wave model for Delft3D, requires significant iterative steps, and as such is a computational chokepoint for forecast turnaround. One of our primary goals in this project is to evaluate the errors as a function of the lateral grid extent.

One aspect of the error analysis we are investigating is the effect of reducing the lateral extent of the wave model domain. We first analyze the effect that small deviations from complete satisfaction of the Neumann boundary condition have on the hydrodynamic predictions. This is done first by perturbing the equations describing the lateral boundary condition by a small error, and examining the growth or decay of that error, analogous to Chen and Svendsen (2003) for the case of errors in the flow velocity at the boundary. We then indirectly impose a deviation from the satisfaction of the zero Neumann boundary condition by incrementally shortening the lateral extent of the wave model grid, and determining the effect on the model results. The analysis of the error will require some method of looking at the multi-dimensional tendencies of the error and some estimation of the scales most vulnerable to error, rather than just the deviation between model and data. To this extent, we use spatio-temporal analysis methods such as Empirical Orthogonal Function (EOF) analysis to determine the overall scales of motion in the flow field and the extent of the variation of their response to the errors.

Statistical information on the errors along the boundaries will be useful for another aspect of the project, which involves the development of methods to correct these forcing errors using data taken within. A Kalman-filter-style (Van Dongeren 2008) assimilation and correction system will be investigated for use herein to perform this boundary correction; later implementation of simplified versions of this model will likely lead to the use of adjoint methods for this.

Mr. Boyang Jiang (B.S. Hydropower Engineering, Hohai University, Nanjing, PRC) is the graduate assistant in primary charge of this work. He is the second in an envisioned line of students working on various aspects of the Delft3D model while pursuing graduate degrees at Texas A&M University, and is performing the majority of the evaluative work. We anticipate that Mr. Jiang will defend his M.S. thesis in October 2010; he is planning to stay for his Ph.D.

WORK COMPLETED

We have fully implemented the Empirical Orthogonal Function (EOF) analysis into the evaluation of the lateral boundary error and the effect on the hydrodynamic prediction. We have also applied this evaluative methodology to Delft3D applications at Duck, NC (Duck94) and at Scripps Institution of Oceanography, in La Jolla, CA (NCEX). The former application was useful due to the available nearshore data and relatively simply-configured bathymetry, while the latter experiment tested the methodology in a very challenging, complex environment. In order to establish a baseline for the error, we selected a case where the WAVE grid extended 50% beyond the FLOW grid on either side, and referred to that as our “golden standard” by which we compare lesser grid configurations. To clarify: if we call the width of the FLOW grid B and one extension of the WAVE grid beyond the FLOW grid A , then the “golden standard” has $A/B=50\%$. In contrast, our least accurate grid configuration tested was $A/B=25\%$.

The choice of the EOF method to perform the error analysis was based in the method’s ability to separate orthogonal modes of motion in the most compact form possible. The hypotheses informing this implementation are:

- 1) Errors introduced in the lateral boundaries by insufficient grid extensions reflect themselves in the higher modes (which can be loosely connected to shorter scales).
- 2) As errors increase (the grid setups become less optimal for Neumann boundary conditions), these discrepancies between an ideal setup and an erroneous one begin to infiltrate lower modes.

We also further processed the EOF modes to facilitate comparison between the “golden standard” results and the erroneous results. This was done by using the “swirl strength” (Adrian et al. 2000), which is more reliable than vorticity at identifying eddies in general flows.

RESULTS

Figure 1 shows a small section of the NCEX bathymetry with Delft3D output locations marked. This area comprises the FLOW domain for the model. The output locations were used to perform some comparisons between the results from an $A/B=50\%$ setup and $A/B=25\%$. This location is just to the north of Scripps Canyon. Due to the presence of the canyons, a large degree of waveheight variation in the nearshore is expected.

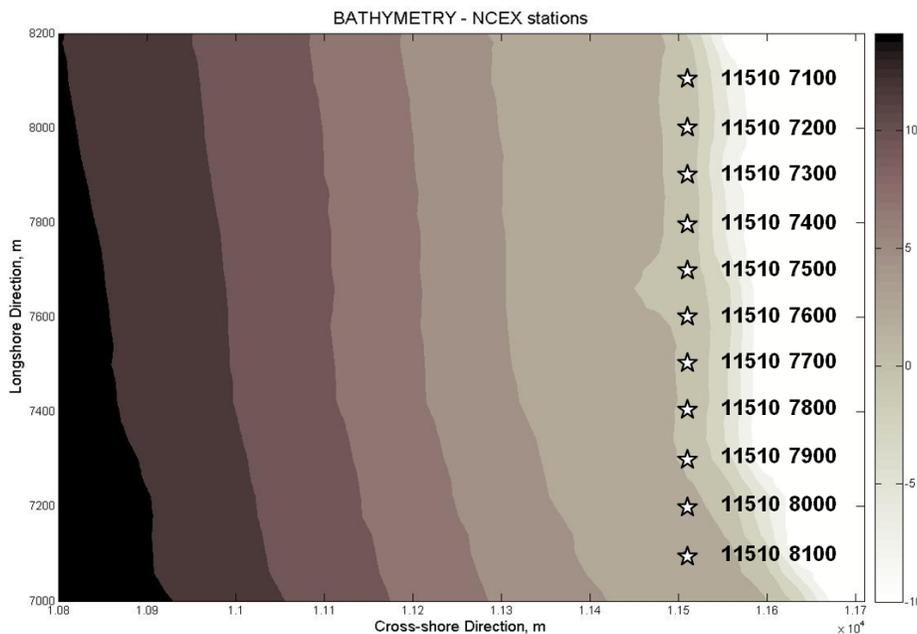


Figure 1. The FLOW domain for Delft3D runs at NCEX. Shoreline is on right.

This smaller domain is a nest within a larger domain; this larger domain was forced by a Coastal Data Information Program (CDIP) buoy (Torrey Pines Inner Shelf). Hourly buoy observations from 9-17 January 2010 were used to force the model; this period was chosen due to a high level of wave energy

present at the buoy relative to other times during January 2010. The results from the hydrodynamic FLOW model were used as data for the EOF. Figure 2 shows a comparison between $A/B=50\%$ and $A/B=25\%$ for Mode 1 of the EOF analysis, while Figure 3 shows the same for Mode 8. While the maps for Mode 1 look very similar between $A/B=50\%$ and 25% , those for Mode 8 exhibit a strong difference between these two grid setups. Inspection of the modes between 1 and 8 bear out the hypothesis that the higher modes are more strongly affected by errors on the lateral boundaries than the lower modes. (We note that the first eight modes contain about 97% of the total variance of the hydrodynamic fields).

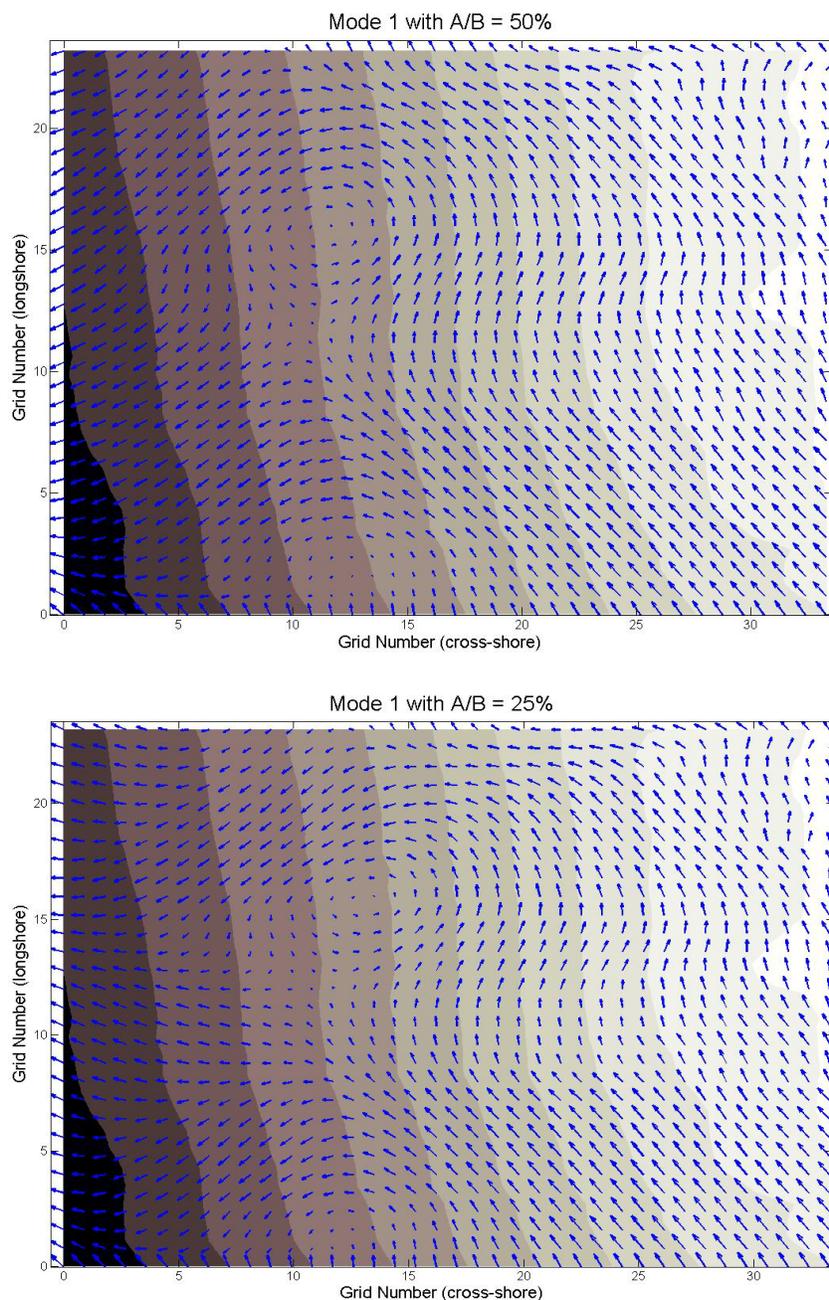


Figure 2. Mode 1 of the EOF analysis performed on Delft3D hydrodynamic results. Top: $A/B=50\%$ (“golden standard”). Bottom: $A/B=25\%$

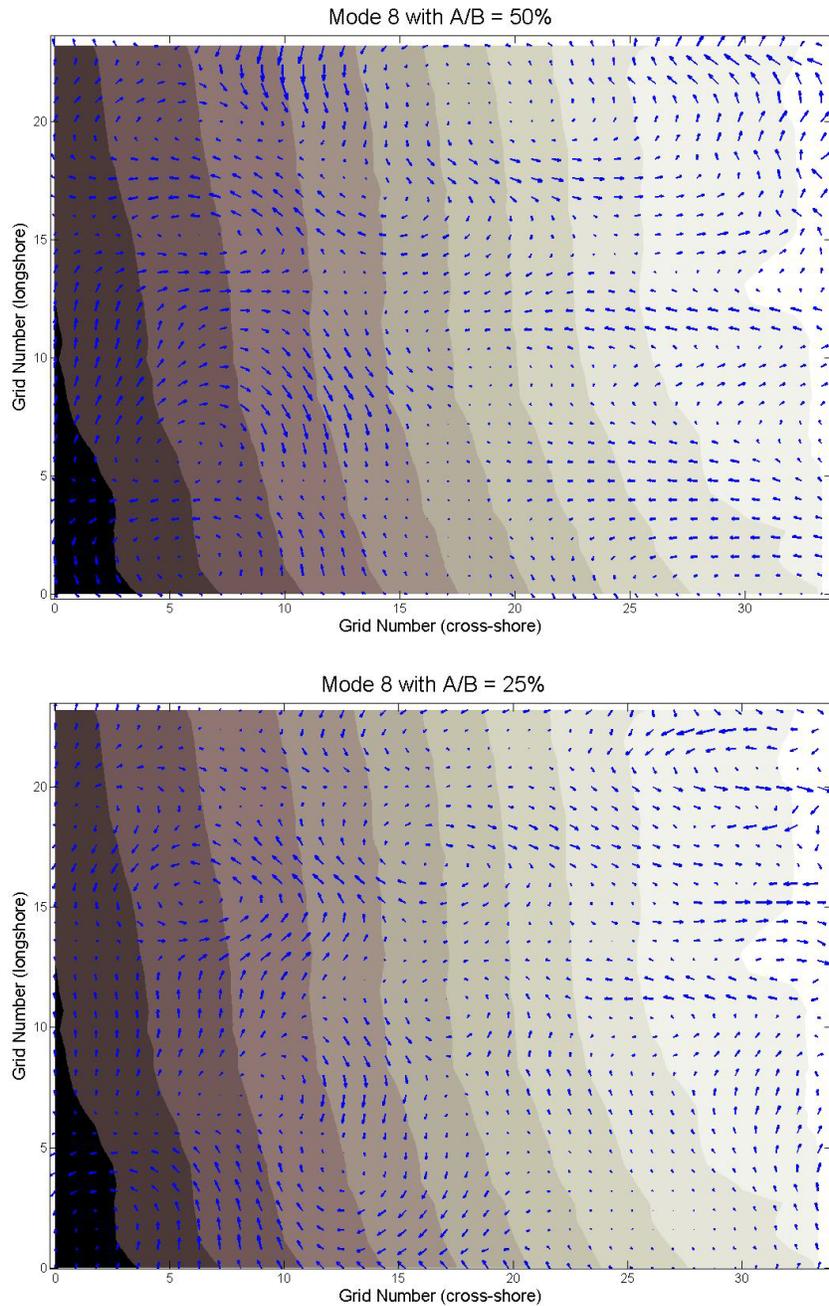


Figure 3. Mode 8 of the EOF analysis of Delft3D hydrodynamic results. Top: $A/B=50\%$ (“golden standard”). Bottom: $A/B=25\%$

Use of the swirl strength helps quantify the curved patterns seen in the EOF analysis in a manner that does not confuse strongly sheared flows with areas of high vorticity. Figure 4 shows contours of swirl strength for Mode 1 of the NCEX case for both $A/B=50\%$ and $A/B=25\%$. There is not significant difference between the swirl strength estimates. However, strong differences can be seen between the Mode 8 swirl strength estimates between both $A/B=50\%$ and $A/B=25\%$; this can be seen in Figure 5. Though Figure 3 showed this as well, it is easier to tell the differences between them in Figure 5.

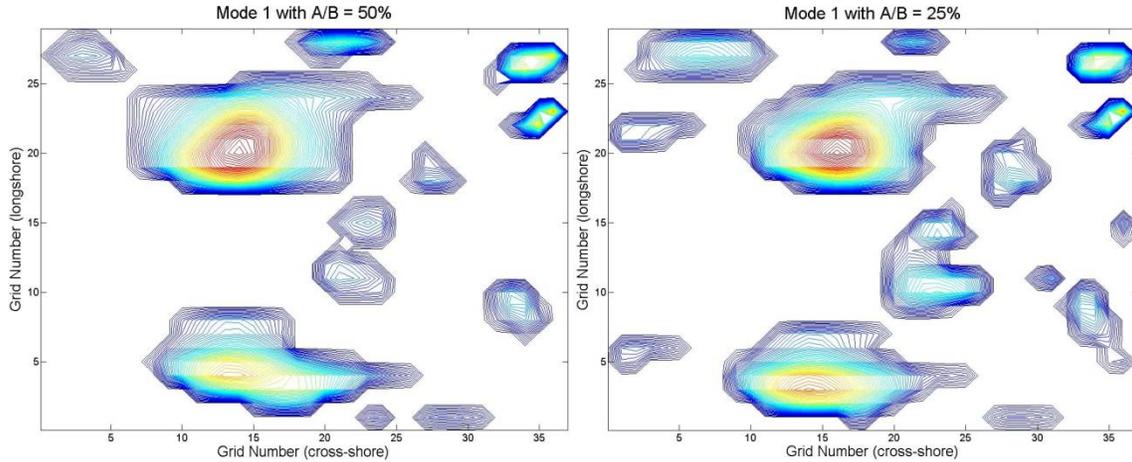


Figure 4. Swirl strength estimates for Mode 1 of the EOF analysis of Delft3D hydrodynamic fields. Left: $A/B=50\%$ (“golden standard”). Right: $A/B=25\%$.

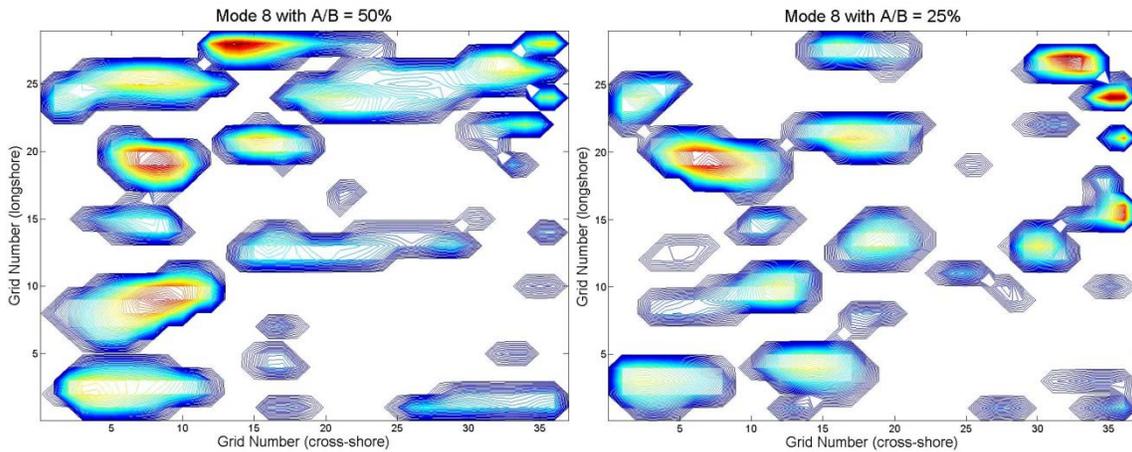


Figure 5. Swirl strength estimates for Mode 8 of the EOF analysis of Delft3D hydrodynamic fields. Left: $A/B=50\%$ (“golden standard”). Right: $A/B=25\%$.

IMPACT/APPLICATIONS

Our analysis methodology can be used to analyze optimum setups for a given area of interest, for which one may anticipate the need for forecasts for a significant span of time. Since the shorter WAVE grids lead to both more error and more expedient calculation, a balance may be sought between accuracy and speed of the forecast. Furthermore, it may be possible to perform EOFs on forcing errors, which can then be used to elucidate process sensitivity to error and, ultimately, to correct boundary information.

RELATED PROJECTS

This project is related to the goals of two other projects:

Estimation of Surf Zone Bathymetry using Small Unmanned Aerial Systems RTP (PI: Dr. K. Todd Holland, Naval Research Laboratory). This project was envisaged as providing tools, findings and methodologies which could potentially support the RTP operations and/or enhance the value of the work completed under the RTP.

Data Assimilation and Sampling Strategies in Nearshore Model Optimization and Validation (PI: Dr. Y. L. Hsu, Naval Research Laboratory). The two projects share many of the same goals, and the PIs have been working closely together to ensure mutual benefit.

REFERENCES

Adrian, R.J., Christensen, K.T., and Liu, Z.-C. (2000). Analysis and interpretation of instantaneous turbulent velocity fields,” *Experiments in Fluids* 29, 275-290.

Chen, Q.J., and Svendsen, I.A. (2003). Effects of cross-shore boundary condition errors in nearshore circulation modeling. *Coastal Engineering* 48, 243-256.

van Dongeren, A.R., Plant, N.G., Cohen, A., Roelvink, J.A., Haller, M.C., and Catalan, P. (2008). Beach Wizard: nearshore bathymetry estimation through assimilation of model computations and remote observations. *Coastal Engineering* 55, 1016-1027

Roelvink, J.A., and Walstra, D.J. (2004). Keeping it simple by using complex models. *Advances in Hydroscience and Engineering*, vol VI, 1-11

PUBLICATIONS

Jiang, B., and Kaihatu, J.M. (2010). Multi-dimensional error analysis of nearshore wave modeling tools, with application toward data-driven boundary correction. *Proceedings of the 32nd International Conference on Coastal Engineering*, Shanghai, China, in press.