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Delft Dashboard: a MATLAB-based rapid tool for setting up coastal and estuarine models

Tool description and model verification

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Kees Nederhoff
Ap van Dongeren
Maarten van Ormondt

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Title
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Summary
Delft Dashboard (DDB) is a tool for rapid setup of coastal and estuarine hydrodynamic and basic morphological numerical models. The quality of numerical models created with Delft Dashboard in comparison to observations and/or other well-calibrated models in reproducing water levels is assessed in this report. It is concluded that numerical models created with Delft Dashboard have a good skill in the reproduction of the tidal propagation in the ocean and on the continental shelf. Reproduction of in-situ observations, which are usually obtained near the coast, is, however, more difficult.

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		Ap van Dongeren					
		Maarten van Ormondt					

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final

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Appendices

1 Introduction

1.1 Motivation

Process-based modeling has been a useful and widely-applied tool for researchers and engineers in designing, predicting and analyzing wave and water motions. The performance of a model is determined by how well the physics are represented, by the quality of the numerical approximations and by the quality of the initial and boundary conditions with which the model is driven. Thus an important step in using these models is good pre-processing (e.g. grid generation, bathymetric and topographic input data interpolation, tidal boundary conditions). These activities are, however, typically time-consuming and repetitive. On top of that, there are often problems related to the incompleteness of or inconsistencies in survey data and publicly available datasets (e.g. General Bathymetric Charts of the Oceans, GEBCO). The result may be an inefficient beginning of the numerical study which comes at the expense of the time in which a researcher or engineer can show his or her added value, namely the interpretation of results and the recommendations for design which are based on these results.

1.2 Rapid model set-up

Deltares has developed Delft Dashboard (DDB) as a tool for the rapid setup of coastal and estuarine hydrodynamic and basic morphological numerical models. DDB has the capability to define a computational domain and grid on a world map, define the numerical parameters and processes, and import relevant initial (e.g. bathymetry and topography) and boundary conditions (tides, winds, waves) from publicly-available internet or dedicated sources. The user can have a model running within minutes. However, it is not a priori known which settings to use in DDB and what the quality of a 'quick-and-dirty' model is.

1.3 Question

The U.S. Naval Research Laboratory (NRL) has asked Deltares to extend the capabilities of the DDB model for their purposes and perform a study in order to gain a better understanding of the quality of a numerical model created with DDB. The latter is addressed in this study. The central question of this study is:

What is the quality of a numerical model created with Delft Dashboard (DDB) in comparison to observations and/or other well-calibrated models in reproducing water levels and which settings in DDB should be applied to maximize the performance of the model created by DDB?

1.4 Report outline

In this report DDB as a tool will first be described (Chapter 2) Then, the report contains three different model validations. First of all a model for the Gulf of Mexico is set up and verified (Chapter 3). The focus is on the quality of the predicted water levels compared to measurements and practicalities related to grid and settings. Next, a Mississippi coastal model previously developed by NRL (Chapter 4) and an existing North Sea model developed by Deltares (Chapter 5) are reconstructed using DDB. The focus will be on the quality of water levels compared to measurements and also compared to the already existing model. Finally, conclusions are presented in Chapter 6. For a description of the methods used to assess the model performance see Appendix A.

2 Tool description

Delft Dashboard (DDB) is a software program that has been developed for setting up of new and modifying of existing numerical (Delft3D and XBeach) models. DDB is an open source standalone Matlab-based graphical user interface (i.e. GUI) and part of the OpenEarth suite (van Koningsveld et al., 2010). DDB is developed in Matlab version 2013B and has been tested for Matlab version 2013B to version R2016a. Furthermore, the tool can be launched from the Matlab command line or as a standalone executable. There is no license needed and the software can be downloaded from the Deltares Wiki (https://publicwiki.deltares.nl/display/DDB).

In this section we will first explain how the tool is structured and which data sources it uses. After that we will focus more on the functionality DDB offers for modelers contained in the so-called *Toolboxes*.

2.1 Software structure

When DDB is launched, a world map is shown in a Map View window (Figure 2.1). This window is used to define the geographical extent of the area model. Furthermore different menus (Top Menu and Model Menu) allow the user to select a specific Working space to define the content and settings of the area model.

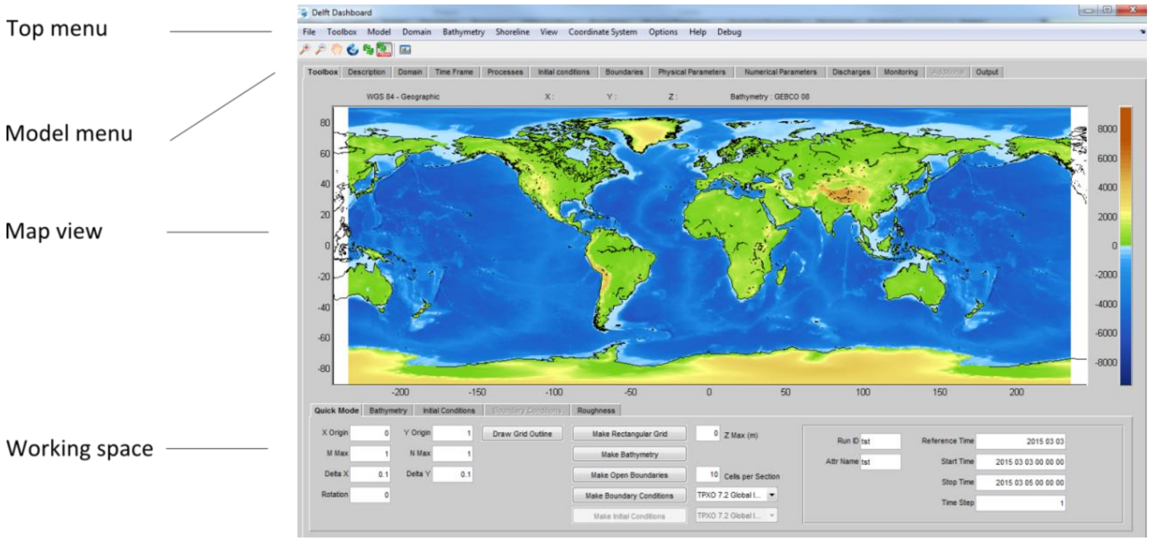


Figure 2.1 The start-up screen of DDB with the different fields

2.2 Data sources

DDB uses online open source data sets as input and most of the data we use are stored as a NetCDF (Network Common Data Form) file on an OPeNDAP (Open-source Project for a Network Data Access Protocol) server of Deltares. The advantage of NetCDF in combination with openDAP is that it allows users to only extract the data he or she is interested in (e.g. a particular time period or location/area), avoiding downloading full information files.

For bathymetric data DDB provides the option to use global (e.g. GEBCO ’08, SRTM 4.1) or regional and local data sets (e.g. Coastal Relief Model). Additionally, there is the possibility to add a user’s bathymetry set. Bathymetric data is saved in tiles as NetCDF on our OPeNDAP server. Tiles are a way to deliver data in small parcels. The advantage of saving bathymetry as tiles is that only data that is needed is cached, making it fast and accurate in areas of interest. Bathymetric information can either be directly applied for the generation of grids and bathymetries in numerical models or exported as an *.xyz or *.asc file. Navigational charts can be a reliable data source for research or consultancy projects where there is a lack of good quality bathymetric data. Currently DDB provides access to charts of the US coast generated by NOAA (National Oceanic and Atmospheric Administration) and charts of the seas near Singapore. Data from these navigational charts will be directly downloaded from the institution that create them and can be used to identify land or as model input by extracting the xyz-locations.

Aerial imagery (Microsoft Bing Maps) offers worldwide orthographic satellite, map and hybrid imagery. Coverage varies by region, with the most detailed coverage in the USA and United Kingdom. Aerial imagery can also be exported for application in post processing, for example in plotting your model results on an aerial image. The data from Bing Maps is cached directly from the Microsoft server.

For shoreline information DDB currently only offers the use of the World Vector Shoreline. Shoreline data can be used to display shoreline boundaries, classifications, and associated features. Shoreline data in DDB can be used solely for viewing purposes in the Map View or can be exported to apply in post processing. World Vector Shoreline is stored as NetCDF tiles on the Deltares OPeNDAP server.

For tidal information we use inverse tide models like TPXO (6.2, 7.2 and 8.0; (http://volkov.oce.orst.edu/tides/global.html) for global forecasting and European Shelf (2008) for local forecasting. TPXO*.* is a global model of tides that best fit, in a least-squares sense, the Laplace Tidal Equations and along track averaged data from TOPEX/Poseidon and Jason. Files are saved as NetCDF on the Deltares OPeNDAP server as amplitudes and phases and can be used via DDB for the generation of boundary conditions. This information can be viewed within DDB on a map or exported as*.mat or *.tek file.

Observation data in the form of tidal predictions based on constituents database (e.g. IHO and XTide), tide gauges (e.g. CO-OPS) and buoys (e.g. NDBC or DART) are also supported in DDB. For all of these locations one can either view or download the observations. These data can be used to validate the computed water level within the domain by creating an observation point in your numerical model.

2.3 Toolboxes

The strength of DDB is the combination of this access to open data along with scripts that can perform standard pre-processing tasks like the generation of a numerical grid and associated input files. The scripting of pre-processing tasks is done in the different Toolboxes Deltares supports. The functionality varies depending on the toolbox.

The most important toolbox is the Model Maker toolbox which is used to generate a new Delft3D (FLOW and WAVE) or XBeach model from scratch. DDB also supports toolboxes for nesting, hurricane modelling and much more. Details of the Model Maker toolbox and Tropical Cyclone toolbox are discussed below, since we are going to use them both for the evaluation of DDB in two case studies. The other toolboxes are briefly mentioned in this report, but a full description can be found on the Deltares Wiki (https://publicwiki.deltares.nl/display/DDB).

2.3.1 Model Maker toolbox

The start of a numerical study often involves standard pre-processing tasks such as the generation of a numerical grid in combination with a bathymetry data set. However, these tasks are very repetitive and have often limited flexibility, for example related to grid resolution. For this purpose the Model Maker toolbox can be used so that area models are quickly generated by loading online available data (e.g. bathymetry: GEBCO '08, tide: TPXO 7.2). The Model Maker toolbox has three functions. The first two functionalities (i.e. grid generation and bathymetry interpolation) are available for all the models supported by DDB. The last functionality (i.e. generating boundaries and forcing it with tides) is only supported for Delft3D-FLOW at this moment. We will discuss these functionalities in more detail below.

2.3.2 Tropical cyclone toolbox

A tropical cyclone is a rotating storm characterized by a low-pressure center, strong winds, and a (anti)cyclic movement. Depending on its location in the world and its strength, a tropical cyclone is referred to as hurricane, typhoon or tropical cyclone. Within Delft3D it is possible to apply space varying wind velocity components and atmospheric pressure on a spider web grid. However, the generation of the required input files can be quite time consuming and not so flexible (e.g. creating a spiderweb with a fixed asymmetric or a radius-varying wind speed component or applying the parametric wind speed profile from Holland, 2010 or Fuitja, 1952).

In addition to that, building an accurate computer model to simulate tropical cyclone events requires high quality meteorological data on past events as the basis of the statistical components of the model and the basis of research. Often the amount of data available is limited, for example the IBTrACS database often only provides the smoothed path of each tropical cyclone including a maximum wind speed (Vmax) or pressure drop (DP). Therefore parametric relationships are needed to construct the full shape of the cyclone.

The Tropical Cyclone toolbox offers the option to create input files for Delft3D. The user can easily switch between the different parametric relationships that form the basis of approach to assess the impact of cyclones. There are relationships between pressure drop and maximum winds (e.g. Holland, 2008) as well as the radius of maximum winds (RMW or Rmax) and the pressure drop and latitude (Vickery and Waldhera (2008). Holland (2010) revised his parametric wind profile by allowing the possibility to apply additional information available from hurricane archives or in hurricane warnings in the hurricane profile. Besides these relationships, the hurricane in a spider web is described with a limited amount of directional bins, radial bins, and a maximum radius. Besides these parametric relations, physical constants and numerical settings can be varied which makes it possible to create a spiderweb file (.spw file) for Delft3D which takes 4 steps.

The cyclone that one can model is either based on a fictional cyclone track defined by you or by a ‘real’ cyclone track provided by different agencies (e.g. Joint Typhoon Warning Center; JTWC or Tropical Cyclone Programme; TCP).

1. All the relevant variables (e.g. environmental background pressure, # radial bins and inflow angle) are loaded from the interface.
2. The track, maximum wind speed, pressure drop and radius of maximum wind based on parametric relationships is determined.
3. The full wind profile will be created. If possible, depending on the relationship and the amount of data, the hurricane profile can be fitted.
   Holland (2010) gives the possibility to fit the exponent of the hurricane vortex with, for example, information about the radius of 35 knots wind (R35). For other relationships (e.g. Holland, 1980 or Fuitia, 1952) this is not possible.
4. The spiderweb created is saved as .spw file and the settings of the active Delft3D are changed in such a way that the simulation can be carried out with the winds and pressures from the spiderweb.

2.3.3 Other toolboxes

Besides the Model Maker Toolbox and the Tropical Cyclone toolbox, 14 other toolboxes and 6 advanced toolboxes are implemented into DDB. A toolbox is advanced if you need to get permission to access the subversion. This can have two reasons. First of all, this is done to support private toolboxes which cannot be shared with the public (e.g. NRL CSISPS toolbox). Secondly, some toolboxes are still under development (beta phase) and are tested in a smaller community (e.g. Curvi Model Maker toolbox). Once the beta toolboxes have extensively tested; they will be released to the full DDB community.

See below for the full list of available toolboxes in DDB:

Toolbox	Functionality
Model Maker	Construct or refine an existing model
Bathymetry	Import, export and merge bathymetry data
Domain Decomposition	Setup a simulation in which a model is divided into several smaller model domains which makes it possible to apply parallel computing (i.e. computations carried out simultaneously which will reduce the computational time)
Dredge Plume	Create a time- and space-varying discharge point of a conservative contaminant such as a dredge soil material from a ship
Geo Image	Download satellite images to be used as model output background
Navigation Charts	Download data from navigation charts
Nesting	Setup a simulation where a coarser large-scale model is used to derive the boundary conditions for a finer small-scale model.
Nourishments	Define the extent and shape of a nearshore nourishment
Observation Stations	View and create observation point based on a number of databases
Shoreline	Download and export of shoreline data
Tide Database	Download and export 2D tidal astronomical constituents on a predefined grid
Tide Stations	Download water level time series derived using astronomical constituents for a selected tidal station
Tropical Cyclone	Define the size, shape and time variation of a wind field and pressure drop generated by a cyclone
Tsunami	Define the initial displacement of the sea surface induced by an earthquake

A list of available advanced toolboxes is given in the table below.

Advanced Toolbox	Functionality
Advanced Nesting	n-level nesting in a tree structure setup
Advanced Tropical Cyclone	Added functionality: ensemble forecasting
Curvilinear Model Maker	Model maker for the generation of curvilinear models
Meteo Data	Download meteorological data and apply it in Delft3D
Ocean Models	Nest Delft3D in ocean models like HYCOM
NRL CSIPS	This is a private toolbox for the NRL in which the amount of options of the Model Maker toolbox has been decreased to decrease the setup time

3 Gulf of Mexico model

3.1 Introduction

The Gulf of Mexico (GoM) is an ocean basin largely surrounded by the North American continent. It is bounded on the northeast, north, and northwest by the Gulf Coast of the United States, on the southwest and south by Mexico, and on the southeast by Cuba, as can been see in Figure 3.1.

In this chapter the performance of Delft3D-FLOW models made by DDB in reproducing the hydrodynamics (water levels due to tide) is assessed. A fundamental question is how the user should choose the model settings in Delft3D-FLOW (e.g. time step) and toolbox settings in DDB (e.g. grid orientation) in order to achieve the best model performance. The model performance is quantified by comparing the model results with water levels from inverse tide models (e.g. TPXO 7.2) and from in-situ observations.

This general question is answered within three different sub questions focused on:

1. **Where to define the model grid?**
2. **How many and what type of boundary sections have the best performance?**
3. **Are there model parameter settings that should be changed in other to improve the performance?**

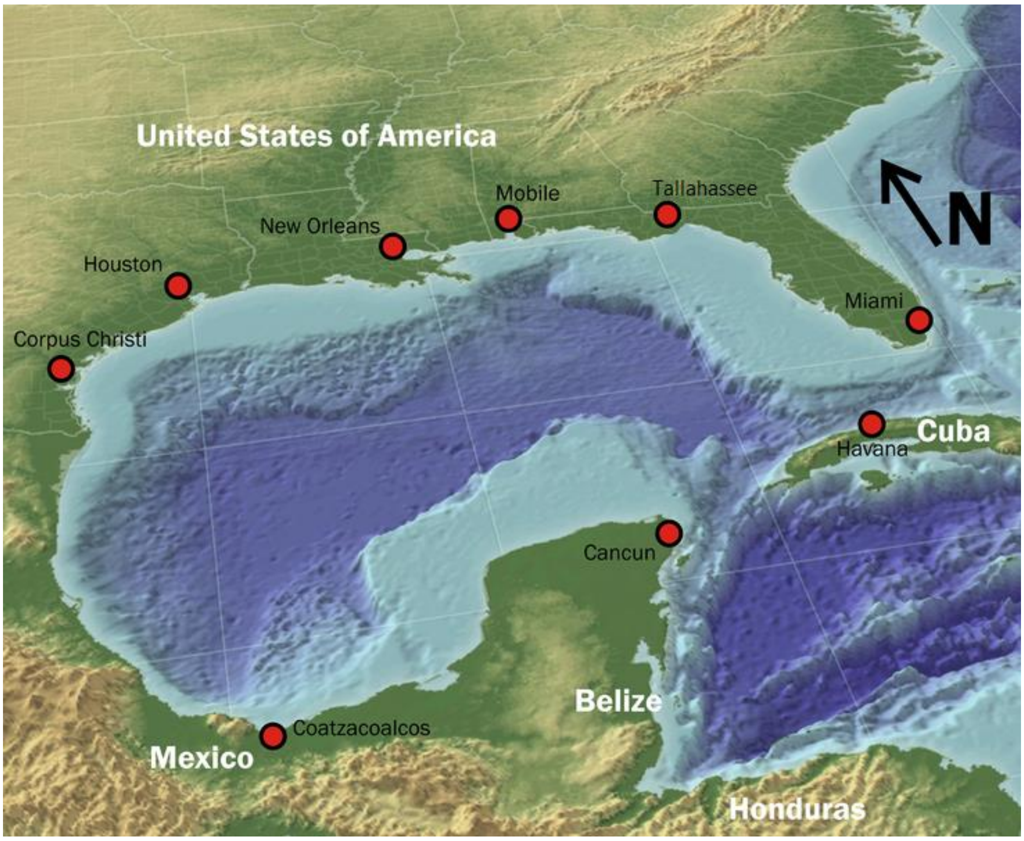


Figure 3.1 The Gulf of Mexico in 3D perspective.
Source: http://oceanexplorer.noaa.gov/technology/tools/mapping/media/GulfofMexico.jpg

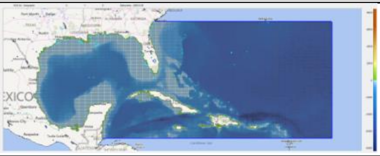
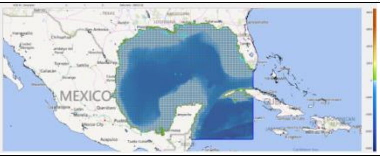
3.2 Model setup

Several Delft3D-FLOW models have been set up with Delft Dashboard (DDB) in order to analyze their performance. In this chapter, there will be no comparison with other well-calibrated models, since the focus of this chapter is an inter-comparison of DDB-models. The different model domains are presented in Section 3.2.1. Other (numerical) settings are described in Section 3.2.2

3.2.1 Model domains

Five different model setups with identical grid resolution have been created. This is done to analyze the impact of where the model grid is defined with DDB. The simulations are listed below (see Table 3.1).There are two medium-size models (Option 1 and Alternative 2), two small-domain models (Alternative 3 and Alternative 4) and one large-domain model (Alternative 5).

Table 3.1 Five different model domains

Alternative [#]	Domain	Relative size	# grid cells	Visual impression
1	GoM including large part of the Caribbean	Medium	433 x 155	
2	GoM including smaller part of the Caribbean	Medium	268 x 140	
3	Only GoM with clear north-south and west-east grid orientation	Small	178 x 137	
4	Rotated grid of only the GoM	Small	171 x 121	
5	Large part of the Atlantic Ocean	Large	526 x 288	

3.2.2 Other settings

All the Delft3D-FLOW models are depth-averaged (2DH) and forced with water levels from the boundaries (Riemann boundaries with 2 grid cells per section). Tidal forces (all components possible) and bed roughness (Manning value of 0.020 $m^{1/3}/s$; default value) are activated. The simulation starts with a constant water level which is set at mean sea level (MSL). Waves, wind and pressure are not taken into account. .

The resolution of every alternative from Table 3.1 is 1/10° x 1/10°. The bathymetry is based on the GEBCO world bathymetry and boundary conditions are derived from the TPXO 7.2 database. The simulation period covers the entire year of 2014 with a computational time step of 1 second.

3.3 Goodness of fit criteria

The performance of the model in reproducing water levels is based on:

1. Tidal propagation over the continental shelf. A harmonic analysis is carried out on 85 altimeter points (TPXO 7.2), see Figure 3.2 (red circles). For this analysis the bias and RMSE of the tidal amplitude and phases are determined. The VD is determined to take into account frequency, since it describes the difference per constituent in modeled and observed amplitude and phase. Note: TPXO*.* is a global model of ocean tides, which best-fits, in a least-squares sense, the Laplace Tidal Equations and along track averaged data from TOPEX/Poseidon and Jason. It is assumed that TPXO provides an accurate prediction of tidal constituents and because there is no other data it is used as benchmark to compare Delft3D.
2. Reproduction of in-situ observations. A water level analysis is carried out on 11 situ stations, see Figure 3.2 (green circles). For this analysis the RMSE is determined. Note: processes likes wind-driven setup and set-down are obtained from the measured signal.

One is referred to Appendix A for all the definitions and formulas for the model skill parameters used in this chapter.

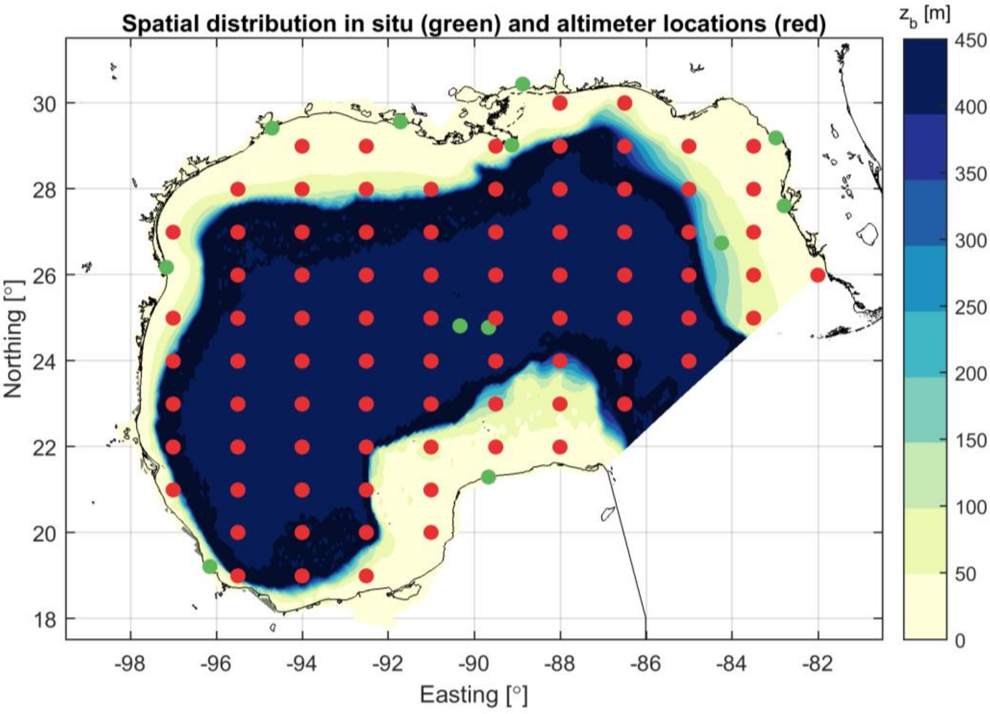


Figure 3.2 Spatial distribution of in-situ (green) and altimeter locations (red)

3.4 Analysis 1: grid orientation and location

3.4.1 Computation time and spin-up time

Spin-up is the time required for a model to reach a state of statistical equilibrium under the applied forcing. In order to check the spin-up time the same model setup is modeled for two years (2013 & 2014) instead of one (2014). It is assumed that the model is sufficiently spun up if the hourly result of all the altimeter observations stations of the one-year model has an R2 is 0.99, bias is lower than 0.001m and the RMSE lower than 0.01m compared to the two-year model which already reached statistical equilibrium under the applied forcing.

In general it is assumed that the spin-up increases when the model domain becomes larger. This is indeed one of the patterns which one can notice in Table 3.2. It is interesting to see that Alternative 4 (small and rotated grid) has a 62% shorter spin-up time than Alternative 3 (almost the same grid size). It is hypothesized that this is related to the number of boundaries. Due to the orientation of Alternative 4 the model has only one (Riemann) boundary in southwest-northeast direction. Alternative 3 has two (Riemann) boundaries: one in north-south and the other in east-west direction. It is hypothesized that the number of boundaries has an (negative) influence on the amount of spin-up. Moreover there is a large difference in spin-up comparing Alternative 1 with 2. The difference between the two model domains is that Alternative 1 covers the entire Caribbean, but does not intersect any islands. Alternative 2 covers only part of the Caribbean and therefore intersects multiple islands. It is hypothesized that a more complex geometry at the boundary has an (negative) influence on the spin-up time.

Table 3.2 Computation and spin-up time for the five Delft3D-FLOW model setups.

Alternative	Computation-time [s]	Spin-up time [h]
1	77000	93 (4 days)
2	41204	1014 (42 days)
3	25516	57 (2.4 days)
4	20434	35 (1.5 days)
5	138547	413 (17 days)

3.4.2 Performance of the altimeter observations

Figure 3.3 to Figure 3.5 show the tidal amplitude (left panel) and phase (right panel) as calculated by the different alternatives (i.e. model domains) created with DDB for four most important tidal constituents (i.e. M2, S2, K1, O1). Only Alternative 1, 4 and 5 are presented here, since this already shows the biggest differences, for a complete overview the reader is referred to Table 3.3. The different constituents are determined via a Fourier analysis of the full time series of water level elevation and the colors (from white to black) indicate the value of respectively the amplitude in centimeters and phase in degrees. The circles indicate the values from the inverse tide model TPXO 7.2. The color difference between the colored field and circles can be used to assess the relative error made (i.e. qualitative evaluation). On top of that, the RMSE of the model for all circles is determined (i.e. quantitative evaluation). It is assumed that TPXO provides an accurate prediction of tidal constituents, see also Section 3.3.

M2 tidal constituent

For the M2 tidal constituent (Figure 3.3) Alternative 4 and 5 have a similar pattern. In both model domains the M2 amplitude in the southwest of the GoM is underestimated. The phase is mainly overestimated (i.e. lagging). Between Alternative 4 and 5 there is only a difference at the TPXO output near Florida. This is related to incorrectly imposed boundary conditions due to the combination of shallow water and a Riemann boundary section in Alternative 4. This can be solved by changing the water depth locally; however it is chosen to show this impact since it illustrates one of the things that can go wrong when applying DDB for creating Riemann boundaries.

For Alternative 1 there is an overestimation of the amplitudes offshore of Louisiana, but the amplitudes are well reproduced in the rest of the model domain. In this same area near Louisiana the amplitudes of Alternative 4 and 5 are well reproduced, but the amplitudes are underestimated in the rest of the model domain. Tidal phases on the Eastside of the GoM are also overestimated in Alternative 1 (i.e. lagging), but become underestimated when going to the West (i.e. leading). This means the tidal M2 wave propagates faster in the model than in reality assuming TPXO 7.2 is reproducing the M2 wave accurately.

For Alternative 4 and 5 the phase is overestimated in the entire model domain, which means the propagation speed is correct but the M2 tidal wave is already lagged when entering the Gulf compared to TPXO results. The propagation speed is related to the location of the amphidromic point in combination with the bathymetry. When changing the grid location and size the amphidromic point and thus the propagation of tidal waves will change too.

S2 tidal constituent

For the S2 component (Figure 3.4) a similar pattern as with the co-tidal charts for M2 can be seen, however the errors (i.e. differences between the model and measurement) are smaller. The tidal amplitudes are well reproduced by all models. TPXO points near the coastline of Florida are underestimated by all alternatives. Moreover, Alternative 4 underestimates the amplitudes in the southwest of the GoM. For the tidal phases Alternative 1 and 5 have a pattern of first overestimation (i.e. lagging) in the east. The presentation improves in the west. Alternative 4 overestimates the phases in the entire model domain. On top of that there is an amphidromic in the northwest of the Gulf visible in Figure 3.4, this point cannot be distinguished based on the TPXO dataset and is neither reported in literature (Gouillon et al, 2010). Creating a 'numerical amphidromic point' is one of the potential threats when placing the boundary conditions too close to the area of interest.

K1 tidal constituent

When focusing on the reproduction of the K1 component (Figure 3.5), which is the second biggest contributor to inaccuracy, all alternatives reproduce the phases are accurately. This is

also related to the lack of variation in space. However, there are large differences for the amplitude. Alternative 4 (smallest model domain) underestimates the amplitude with 1 to 2 cm.
Alternative 5 overestimates the K1 amplitude. Generally speaking: the bigger the model domain becomes, the larger the K1 amplitude gets. It is hypothesized that the tidal forces in Delft3D-FLOW are either too high or that the bed friction is too low (Jones & Davies, 2007). For all the alternatives a default DDB Manning value of 0.020 $m^{1/3}/s$ is applied. Possibly better results can be obtained by applying higher roughness values. There would however no physical reasoning for this higher roughness value, since no vegetation or rocks are known to influence the seabed of the GoM. Moreover, in other studies (Dietrich et al., 2011) lower roughness values (0.1 $m^{1/3}/s$) are applied for the GoM.

O1 tidal constituent
A similar pattern can be observed for the O1 constituent compared to the K1. The phase errors are limited; however there is a relatively large amplitude error. Alternative 3 and 4 underestimate the O1 amplitude with about 1 to 2 cm. Alternative 5 overestimates with 2 to 3 cm.

Vector Difference (VD)
In order to evaluate the model performance in the frequency domain, the VD can be determined. This means that errors in amplitude and phases (modeled compared versus observed) can be taken into account together. It can be concluded from Table 3.3 that the main driver of the RMS RSS VD is the error made in the M2 constituent. On top of that, the VD in the semi-diurnal components (i.e. M2 and S2) are mainly related to phase errors. For diurnal components (i.e. K1 and O1) the VD are mainly related to amplitude errors.

Table 3.3 Overview of the skill scores (RMSE and VD) for different tidal constitutes and all alternatives

Criteria	**Alternative 1**	**Alternative 2**	**Alternative 3**	**Alternative 4**	**Alternative 5**
M2					
RMSE amplitude [cm]	1.15	1.21	3.51	3.31	1.82
RMSE phase [°]	22	25	29	32	26
RMS VD [cm]	2.3	2.5	3.8	3.9	2.7
S2					
RMSE amplitude [cm]	0.91	1.21	1.15	1.15	1.15
RMSE phase [°]	22	22	39	40	27
RMS VD [cm]	1.0	1.1	1.3	1.3	1.4
K1					
RMSE amplitude [cm]	0.88	0.92	1.51	1.47	2.01
RMSE phase [°]	4	4	3	3	4
RMS VD [cm]	1.4	1.5	1.6	1.6	2.3
O1					
RMSE amplitude [cm]	1.43	1.45	1.36	1.35	2.72
RMSE phase [°]	4	4	3	3	2
RMS VD [cm]	1.7	1.8	1.4	1.4	2.9
RMS RSS VD	**3.6**	**4.1**	**4.7**	**4.8**	**5.0**

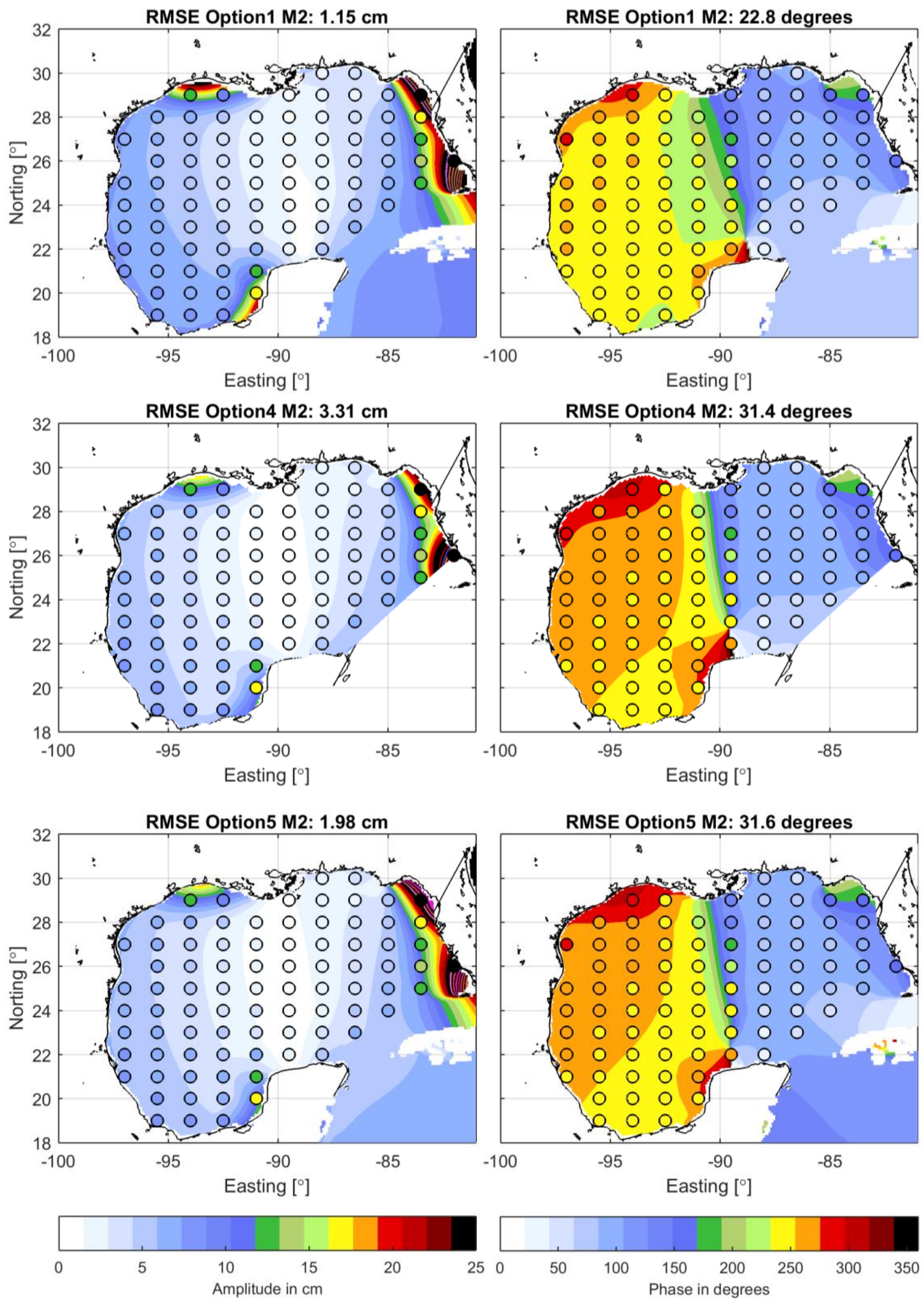


Figure 3.3 Reproduction of the M2 amplitude (left) and phase (right) by Alternative1 (upper panel) and Alternative 4 (middle panel) and Alternative 5 (lower panel). Circles are TPXO results.

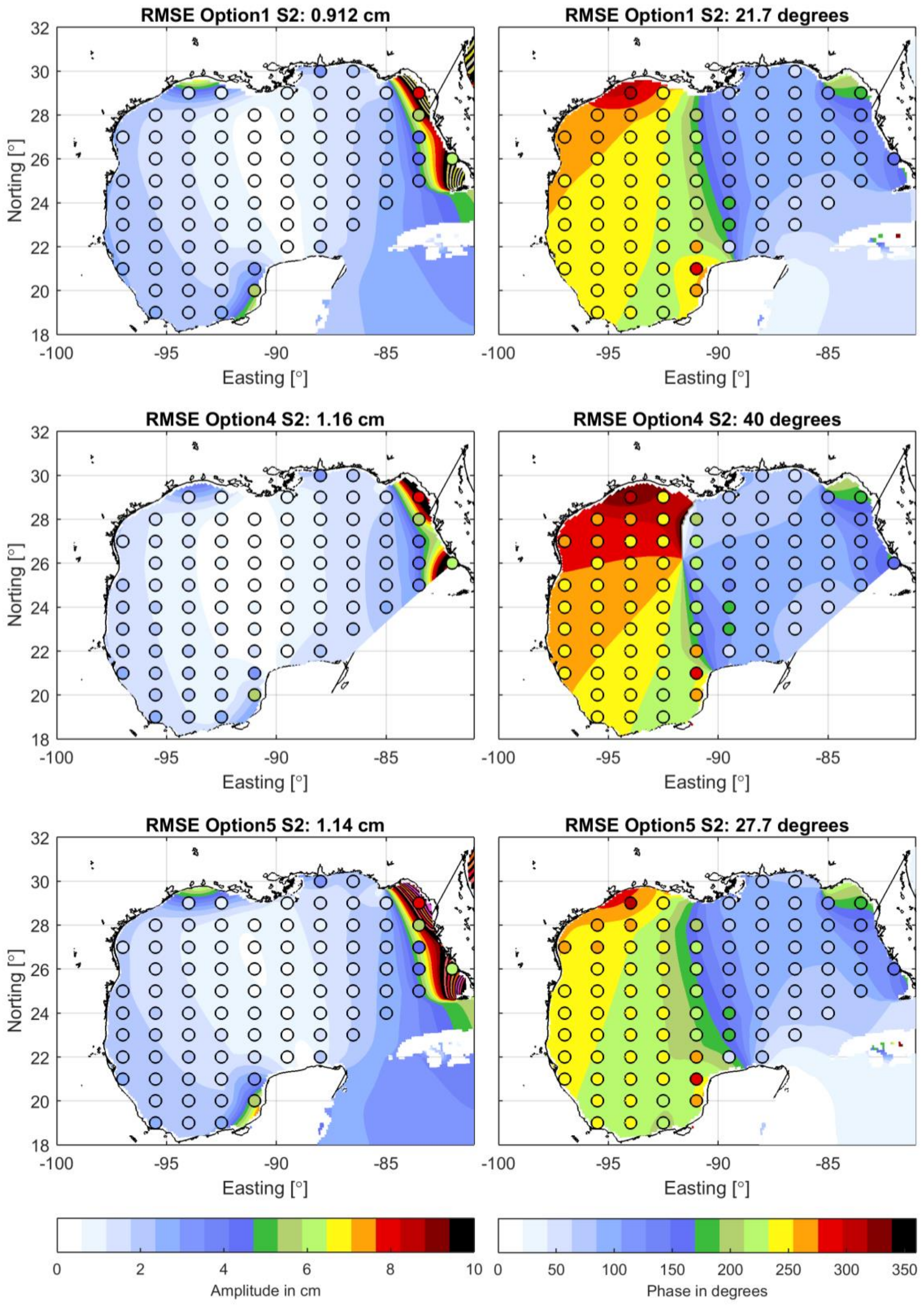


Figure 3.4 Reproduction of the S2 amplitude (left) and phase (right) by Alternative1 (upper panel) and Alternative 4 (middle panel) and Alternative 5 (lower panel). Circles are TPXO results.

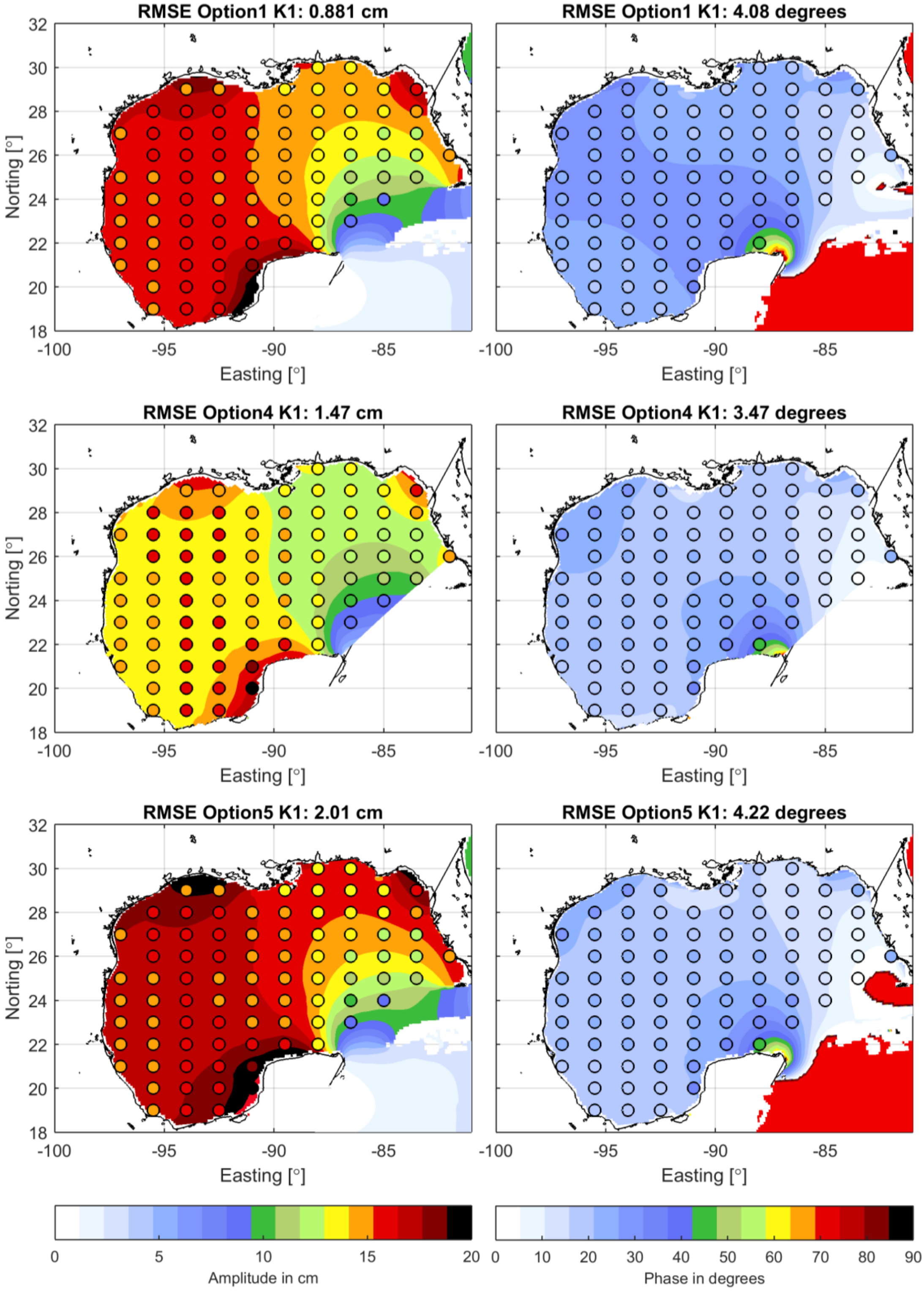


Figure 3.5 Reproduction of the K1 amplitude (left) and phase (right) by Alternative1 (upper panel) and Alternative 4 (middle panel) and Alternative 5 (lower panel). Circles are TPXO results.

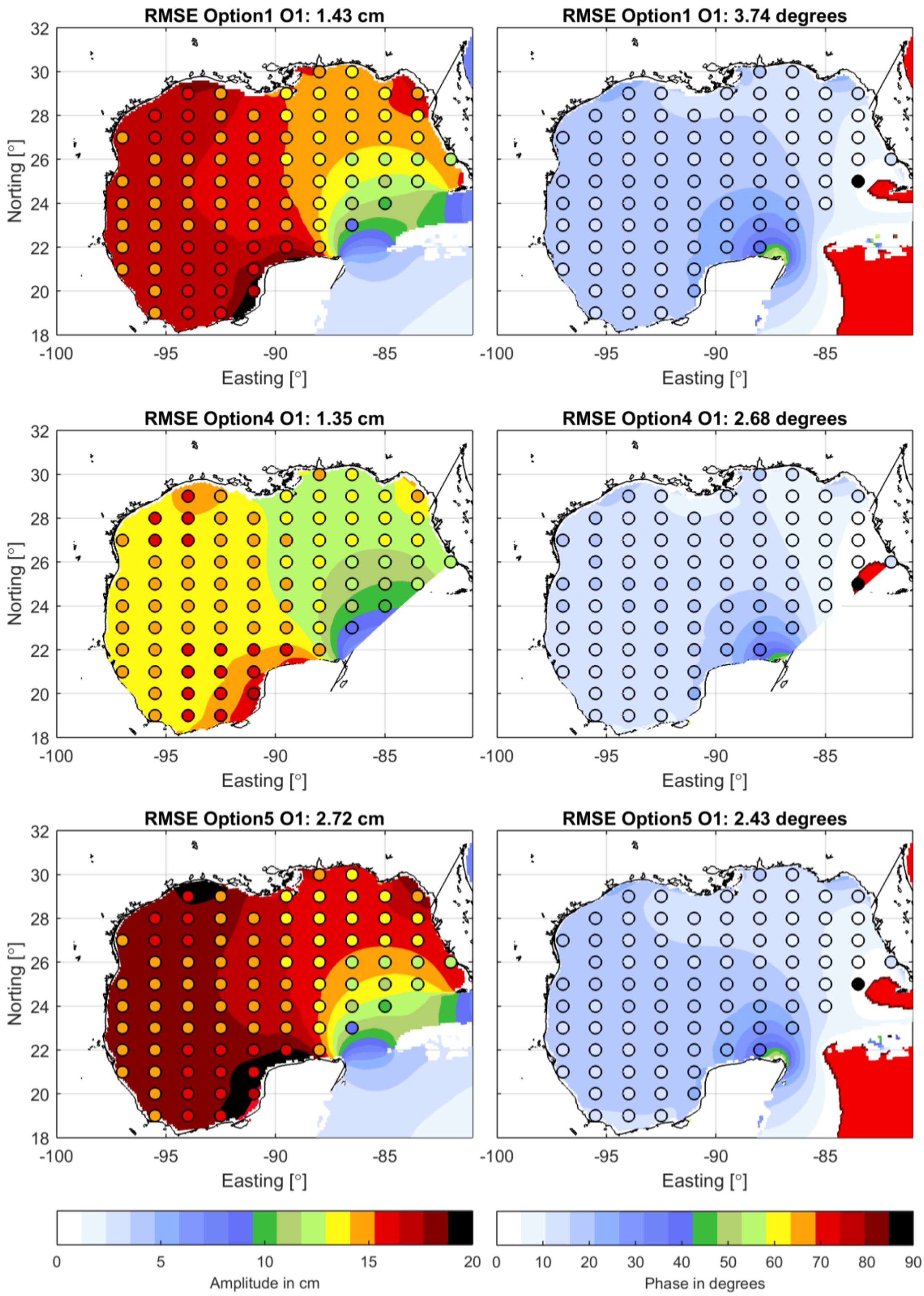


Figure 3.6 Reproduction of the O1 amplitude (left) and phase (right) by Alternative1 (upper panel) and Alternative 4 (middle panel) and Alternative 5 (lower panel). Circles are TPXO results

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3.4.3 Model performance at the in-situ observations

Eventually one would like to be able to reproduce the tidal movement at several locations. The error in the water level reproduction is determined by calculating the RMSE from the model compared to measurements from the full calendar year of 2014. Processes like wind-driven setup and set-down are taken out of the measured signal, since this is not modeled either. This is done by determining the tidal constituents with a harmonic analysis and recreating the time series based on the found phases and amplitudes. The performance of the model is assessed for the following in-situ locations, see Figure 3.7.

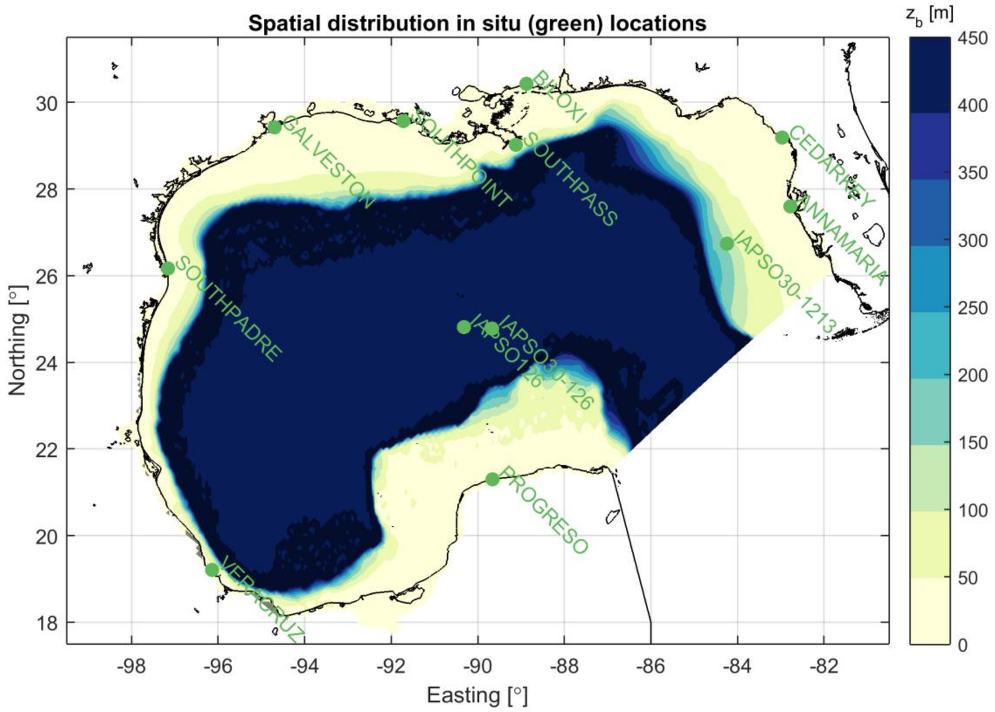


Figure 3.7 Selected in-situ (green) locations for the analysis

Overall one can see in Table 3.4 that the medium-scale models (Alternative 1 and Alternative 2) perform the best. The small scale models (Alternative 3 and 4) have a marginally larger RMSE than the medium-scale models and this is most likely a result of the limited reproduction of tide-generated forces within the model domain. It is better to let the model resolve these patterns within the model domain. The largest model (Alternative 5) has the largest error because the tides constituents are mainly generated within the model domain and therefore errors due to an inaccurate bathymetry start to dominate. In this study GEBCO is used as bathymetric data source, which has as advantage everywhere there is data available. The downside is however that locally the accuracy can vary, see also Chapter 2.2.

By looking in more detail at the different stations it can be concluded that the error made at tidal stations in shallower areas with larger tidal amplitude (e.g. Cedar Key, Figure 3.9) is larger than that of tidal stations in deeper water with limited tidal amplitude (e.g. IAPSO30-126IHO, Figure 3.10). This pattern of better reproduction in deeper water is found regardless of the alternative, see Figure 3.8. For example not taking into account Cedar Key, FL. will result in a lower mean RMSE for all alternatives. It depends per model domain how large the difference is (Table 3.4).

Stations in shallower areas (for example Cedar Key) can be reproduced with coarser Delft3D-FLOW models used in this study; however a good/bad reproduction per station in shallow water is a direct result of the generated grid and bathymetry with DDB. Since Delft3D-FLOW uses a staggered grid there is a possibility for a mismatch between the water level (depth calculated by the maximum of the four corner cells) and the velocities in x and y (calculated by the mean of the two adjacent corner cells). The user does not have a possibility to steer this performance directly (without redefining the grid) and therefore one should keep into mind that sufficient wet cells are surrounding an observation station when generating a grid in order to reproduce the water levels. The best approach in such a case would be to increase the model resolution. A work around could be by placing the observation point in a (nearby) grid cell which does not have this problem which means replace the observation point in more open water.

Table 3.4 RMSE in centimeters for the selected in-situ observations

Alternative	RMSE with all 12 stations	RMSE 11 stations (without Cedar Key)
1	7.1	6.0
2	10.9	5.6
3	7.0	6.5
4	10.3	6.2
5	7.1	6.5

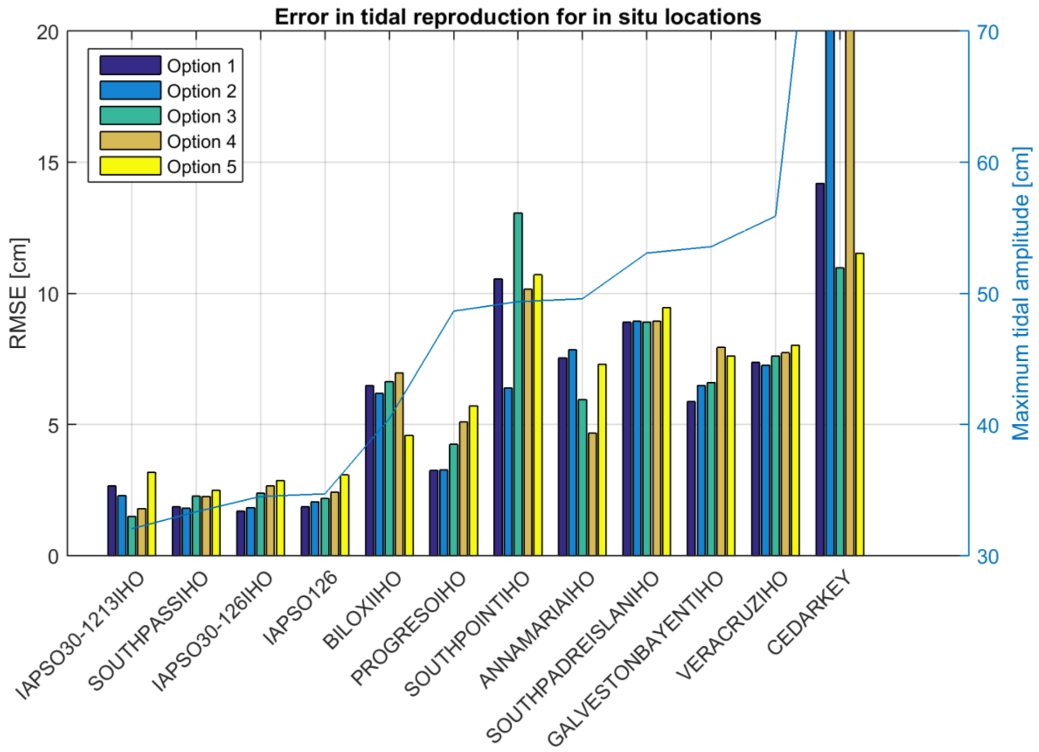


Figure 3.8 Pattern in error in tidal reproduction versus tidal amplitude

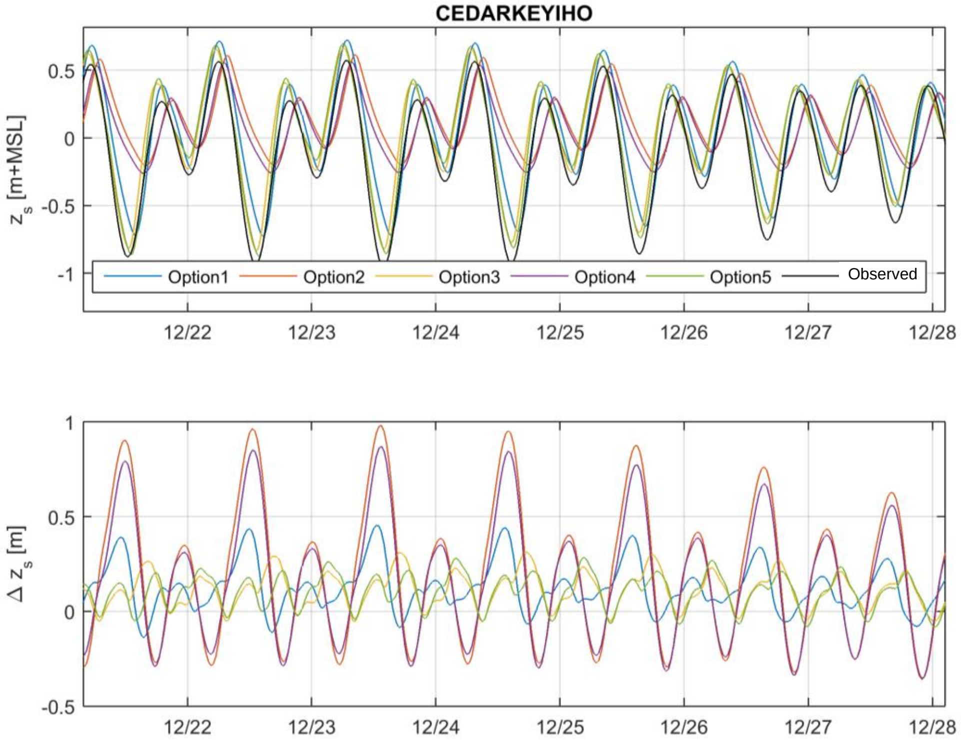


Figure 3.9 Time series of Cedar Key, FL, for the end of December, 2014 for several model setups (upper panel). Lower panel is the difference plot between the different model Alternatives and the observed water level

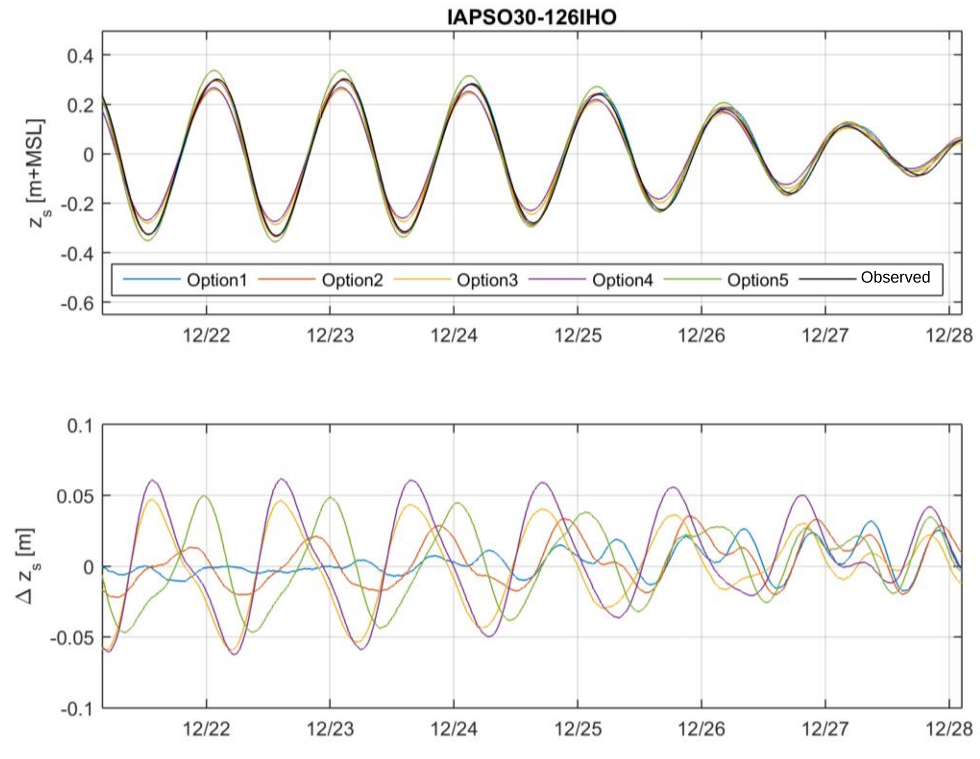


Figure 3.10 Time series of IAPSO30-126, for the end of December, 2014 for several model setups (upper panel). Lower panel is the difference plot between the different model Alternatives and the observed water level

RMSE of water levels are often the end goal of the assessment of model performance, but are however subjective (as shown in Figure 3.8). This is because of the influence of the tidal amplitude in the error (e.g. small phase error results in large RMSE error). Therefore the RSS VD per station is presented in Figure 3.11. On top of that the combined RMS RSS VD is presented in Table 3.5. This makes it possible to focus on the combined effect of the error made in amplitude and phases of the tidal constituents.

Table 3.5 shows the RMS RSS VD for all the alternatives and for both 12 stations (middle panel) and for 11 stations (without the improperly defined observation point of Cedar Key (dry point); right panel). Similar conclusions can be drawn based on this table as already done based on the RMSE. The different model domains (Alternative 1 t/m Alternative 5) result in a RMS RSS VD of 6.0 cm (Alternative2) till 7.5 cm (Alternative 3), Overall one can see in Table 3.5 that the medium-scale models (Alternative 1 and Alternative 2) perform the best (i.e. the RMS RSS VD is the lowest). The small scale models (Alternative 3 and 4) and large-scale (Alternative 5) have a marginally larger RMS RSS VD than the medium-scale models.

Table 3.5 RMS RSS vector difference in centimeters

Alternative	RMS RSS VD All 12 stations	RMS RSS VD 11 stations (without Cedar Key)
1	7.4	6.3
2	13.4	6.0
3	7.6	7.5
4	12.6	6.7
5	7.6	7.4

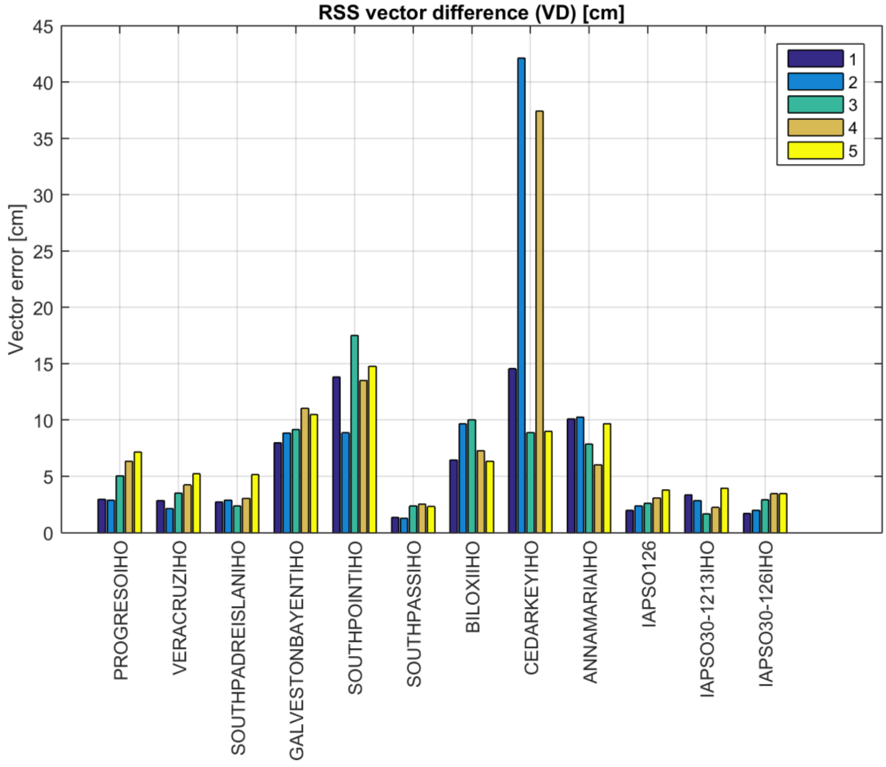


Figure 3.11 Cumulative vector difference in cm (for the six most important tidal constituents)

3.5 Analysis 2: boundary type and number

Thus far the DDB models ran with Riemann boundaries determined per section of 2 grid cells. Every Riemann section is based on its Riemann invariant and is depth-dependent, as can be seen in Equation (3.0) (Deltares, 2011). This makes it important to have sufficient detail and thus relatively small boundary sections in order to calculate the Riemann invariant correctly. How many Riemann sections are needed is analyzed in this paragraph.

$$U = 2\sqrt{gH} \approx U + \sqrt{gd} + \zeta\sqrt{gd} \tag{3.0}$$

An important property of the Riemann boundary is its weakly reflective properties. This makes it possible to reduce the spin-up time. In this paragraph the reduction in spin-up time for the Riemann boundaries compared to water level boundaries is also determined.

3.5.1 Number of boundary sections

When varying the number of sections the computational time does not change, see Table 3.6 Also the spin-up time does not change. This was expected on beforehand, since the calculations in Delft3D-FLOW are principally identical. However for the performance there is a decreasing skill when less boundary sections (more # grid cells per boundary) are used. As can be concluded from the RMS RSS VD of the water level, reproduction decreases with 16% when 2 boundary sections were applied compared to 25. Going from 2 to 10 boundary sections has hardly any impact.

Table 3.6 Run and spin-up time for several Delft3D-FLOW model setups all for Alternative 4

# sections	Run-time [s]	Spin-up time [h]	RMS RSS VD [cm]
25	77000	96 (4 days)	6.4
10	76856	95 (4 days)	6.4
2	77027	96 (4 days)	7.4

3.5.2 Different boundary types

In Table 3.7 the impact of different boundary types is presented. When varying the type of boundary conditions (i.e. Riemann versus water level) the run-time does not change. The spin-up time, however, does change with a factor 8 to 10. For the accuracy (i.e. RMS RSS VD) there are some variations between the simulations with the Riemann and water level boundaries, however the variations are relatively small (<2%).

Table 3.7 Run and spin-up time for several Delft3D-FLOW model setups.

Alternative	Run-time [s]	Spin-up time [h]	RMS RSS VD [cm]
1: Riemann	77000	96 (4 days)	6.4
1: WL	77188	786 (33 days)	6.5
4: Riemann	20434	35 (1.5 days)	7.6
4: WL	20578	370 (15.5 days)	7.5

3.6 Analysis 3: parameters in Delft3D-FLOW

3.6.1 Coriolis effect

The Coriolis effect is the apparent deflection of moving particles when the motion is described relative to a rotating reference frame. This applies to water particles as well due to the Earth's rotation, and in Delft3D-FLOW this effect is also taken into account. In order to calculate the Coriolis terms the tangential velocities should be interpolated. In the case of Delft3D the tangential velocities have to be reconstructed from the cell normal velocities. According to Kleptsova et al. (2009) this has to be handled with care otherwise the calculated Coriolis terms can be inaccurate which can lead to instabilities. By default Delft3D uses the 'old' numerical implementation which does not ensure this stability. To use the more stable expression the keyword OCorio= #N# can be used in Delft3D-FLOW. This can also be done in DDB. In this paragraph the impact of a different numerical scheme to calculate Coriolis force on water level forecasting is analyzed.

There is no clear difference in skill scores (R2, bias and RMSE) between the two numerical schemes of implementing the Coriolis force. When looking in more detail at the six most important tidal constituents, it can be concluded that applying the 'old' Coriolis in Delft3D-FLOW results in smaller errors, however the differences are very small (in this case negligible). Based on Table 3.5 it is concluded that error in water level reproduction increased with 3% when applying the new numerical scheme.

Table 3.8 RMS RSS VD of 11 stations in the Gulf (without Cedar Key, FL) in centimeters for two numerical schemes to calculate the Coriolis force. Skill scores are both based on Alternative 4.

Alternative	RMSE [cm]	RMS RSS VD
Old Coriolis	6.2	6.4
New Coriolis	6.4	6.5

3.6.2 Grid resolution

So far the DDB models ran with a grid resolution of 1/10° x 1/10°. In order to analyze the influence of different resolutions, multiple DDB models have been created with a varying resolution of 1/5° x 1/5° to 1/40° x 1/40°. When increasing the resolution with about a factor 10, the VD decreased with 40-50%. This is driven by a better reproduction of both the phases and amplitude. Adding more resolution is, however, computationally expensive (due to the number of grid cells). Adding more resolution than 1/20° x 1/20° is in this situation undesired as the input errors are found dominant in that case (e.g. accuracy in GEBCO, TPXO). The results of this exercise are presented in Table 3.9

Table 3.9 RMS RSS VD of 11 stations in the Gulf (without Cedar Key, FL) in centimeters for various resolutions for Alternative 4 and 5. Run time is based on the computational time of a single core i7 note on UNIX.

Resolution	RMS RSS VD Alternative 4 [cm]	Run time Alternative 4 [hours]	RMS RSS VD Alternative 5 [cm])	Run time Alternative 5 [hours]
1/5° x 1/5°	10,8	1,1	9,1	7,6
1/6.6° x 1/6.6°	9,3	1,9	8,5	13,0
1/10° x 1/10°	6,7	4,4	7,4	31,6
1/13.3° x 1/13.3°	7,2	7,9	6,6	55,1
1/20° x 1/20°	5,4	18,0	6,3	122,7
1/40° x 1/40°	5,2	77,4	6,0	522,8

3.6.3 Time step

In Delft3D-FLOW a stable combination of second-order-central and third-order-upwind spatial discretization is used, plus a so-called ADI-type time stepping scheme to solve the discretized equations in time. This offers a combination of accuracy, stability and acceptable computation times. In theory the ADI method is an unconditionally stable integration method. However, in real world applications with irregular coastlines, this is not the case. In this subsection, the numerical time step has been varied between 0.5 and 100 minutes. Based on depth-dependency in the stability criteria, a time step of 2 minutes should be stable for all alternatives. The DDB models from previous sections have been ran with a time step of 1 minute, which is the default of DDB.

As can be concluded from Table 3.10, when varying the time step between 0.5 to 10 minutes the error made stays more or less the same. However, when increasing the time step even more (i.e. to 50 or 100 minutes) the errors start to increase substantially. This is the case for both Alternative 4 and 5. Moreover, the decrease of the run time stops. This is most likely related to the communication time between the CPU and the (network) hard disk drive.

Table 3.10 RMS RSS VD of 11 stations in the Gulf (without Cedar Key, FL) in centimeters for various time steps for Alternative 4 and 5.

Time step [minutes]	RMS RSS VD Alternative 4 [cm]	Run time Alternative 4 [hours]	RMS RSS VD Alternative 5 [cm])	Run time Alternative 5 [hours]
0.5	6.7	11,5	7.3	56
1	6.7	6,2	7.3	32
2	6.7	3,2	7.4	17
5	6.7	1,3	7.5	6,6
10	6.7	0,67	8.0	3,3
50	8.3	0,67	15.8	3,3
100	12.6	0,67	35.5	3,3

3.6.4 Roughness

Thus far the DDB models ran with Manning's roughness coefficient of 0.02 [$m^{1/3}$/s]. There are several friction descriptions (e.g. Chezy, White-Colebrook), but often roughness values are used to calibrate the hydrodynamic results. A typical Manning value for sandy coasts would be in the order of 0.02 $m^{1/3}$/s, however values between 0.012 and 0.3 are typically used in coastal areas to take into account vegetation on the sea bed or presence of relatively smooth mud beds. In this paragraph the roughness coefficient has been varied for Alternative 4 and 5. As can be concluded from Table 3.11, reducing the roughness can result in a decrease of the error made (i.e. RMS RSS VD), however this was not observed for both alternatives. From literature (e.g. Dietrich et al., 2011) can be concluded that model skill increases when a lower friction coefficient is used, especially off the coast of Louisiana and Mississippi where there is more fine material (see Alternative 4 in Table 3.11). However, for the large-domain the amplitude of the diurnal constituents where already overestimated by the model (see Section 3.4.2) with a roughness of 0.02 $m^{1/3}$/s. A too high roughness with a too high tidal amplitude cancels each other out (i.e. two wrongs makes it right).

Table 3.11 RMS RSS VD of 11 stations in the Gulf (without Cedar Key, FL) in centimeters for various resolutions for Alternative 4 and 5.

Roughness value [$m^{1/3}$/s]	RMS RSS VD Alternative 4 [cm]	RMS RSS VD Alternative 5 [cm])
0.012	6.4	8.4
0.020	6.7	7.4
0.030	7.4	7.4

3.6.5 Bathymetric sets

All the simulations so far have been simulated with a bathymetry based on GEBCO (more information in Chapter 2.2. However, for the area modeled there are also other data sources available like the Coastal Relief Model (CRM) or the Gulf of Mexico bathymetric set of SURA. For more information about these datasets one is referred to https://data.noaa.gov/dataset/u-s-coastal-relief-model-northeast-atlantic for CRM and http://gcoos.tamu.edu/products/index.php/bathymetry/ for SURA. Since both bathymetric dataset have higher resolution in the area of interest, it is expected on forehand that this will improve the model skill. In this subsection the impact of applying different bathymetric datasets is analyzed.

We observe, before running the Delft3D-FLOW simulations, large differences in bed levels between the different datasets, see Figure 3.12 and Figure 3.13. For grid cells with a depth between 0 and 20 meters the difference is on average 1.77 meters. This means that SURA and CRM are always deeper than GEBCO, however this not related to a standard datum issue. It is expected that this will have an impact on the phase of the tidal constituents since the tidal wave propagates faster.

From Table 3.12 it is concluded that changing the input bathymetry results in a lower skill in the tidal reproduction than a Delft3D setup with only the GEBCO bathymetry. The RMS RSS VD increases for Alternative 4 with 2 to 14% for respectively CRM and SURA. For Alternative 5 the increase in error is lower with 0 and 2%.

Table 3.12 Station-averaged RSS VD of 11 stations in the Gulf (without Cedar Key, FL) in centimeters for various resolution for Alternative 4 and 5.

Bathymetric dataset	RMS RSS VD Alternative 4 [cm]	RMS RSS VD Alternative 5 [cm])
GEBCO	6.7	7.4
SURA+GEBCO	7.5	7.5
CRM+GEBCO	6.8	7.4

These results can be surprising, since one would expect that the CRM and SURA bathymetry would be more accurate due to the fact it is a local dataset. The reason for the decrease in model skill is found in the semi-diurnal components, since for the diurnal components the variation in bathymetry does not have any influence.

In general the amplitudes of the semi-diurnal constituents stay about the same. Variations do occur. For example near Florida there is an increase and near Texas a decrease. However, the phases do vary significantly, Figure 3.14. This is mainly the case near the amphidromic point and the relatively slow middle part of the Gulf of Mexico. Tidal waves will travel faster in the deeper bathymetry. However, the tidal wave was already leading. This means that in the model setup with GEBCO the difference in phase start to decrease due to the too slow propagation of the tidal wave. This is a classic example of two wrongs makes it right. The suggestion here would be improving the accuracy of the boundary condition in combination with applying higher quality bathymetry data. In the situation with SURA or CRM the tidal wave travels faster, however the wave was already leading, meaning the accuracy will start to decrease.

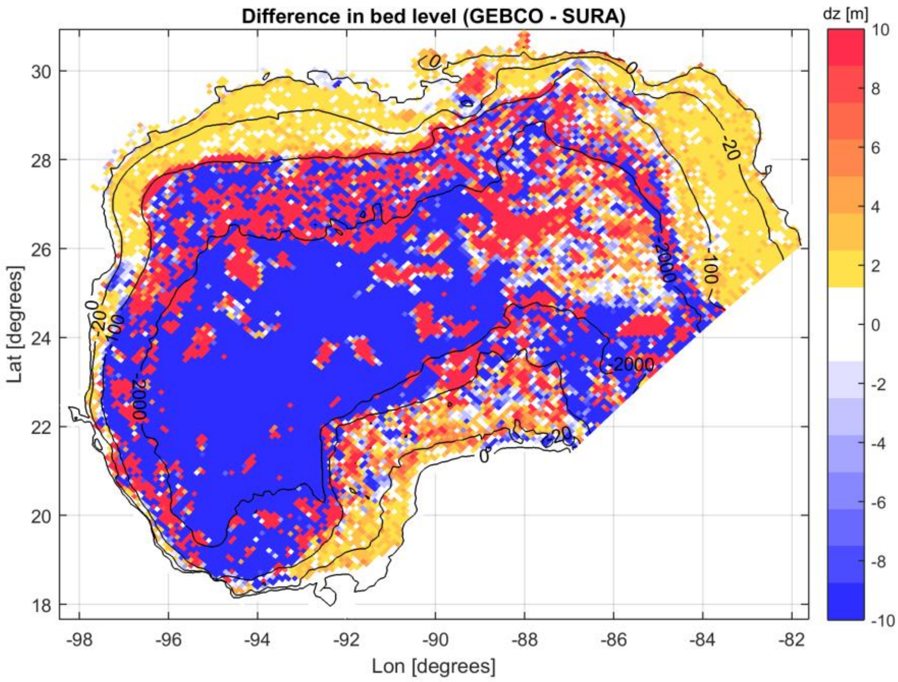


Figure 3.12 Difference in bed level between GEBCO and SURA+GEBCO

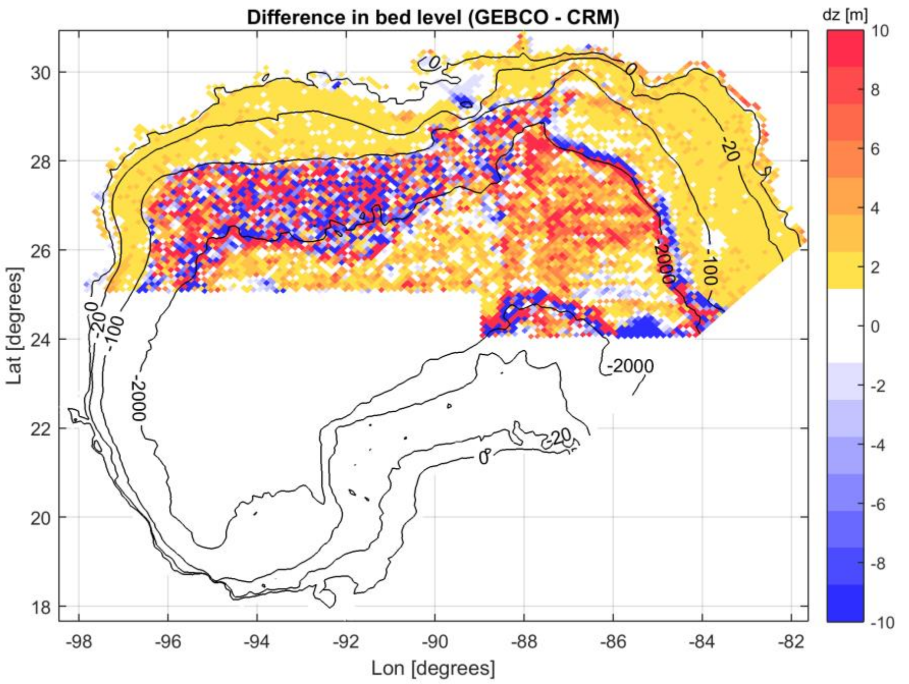


Figure 3.13 Difference in bed level between GEBCO and CRM+GEBCO

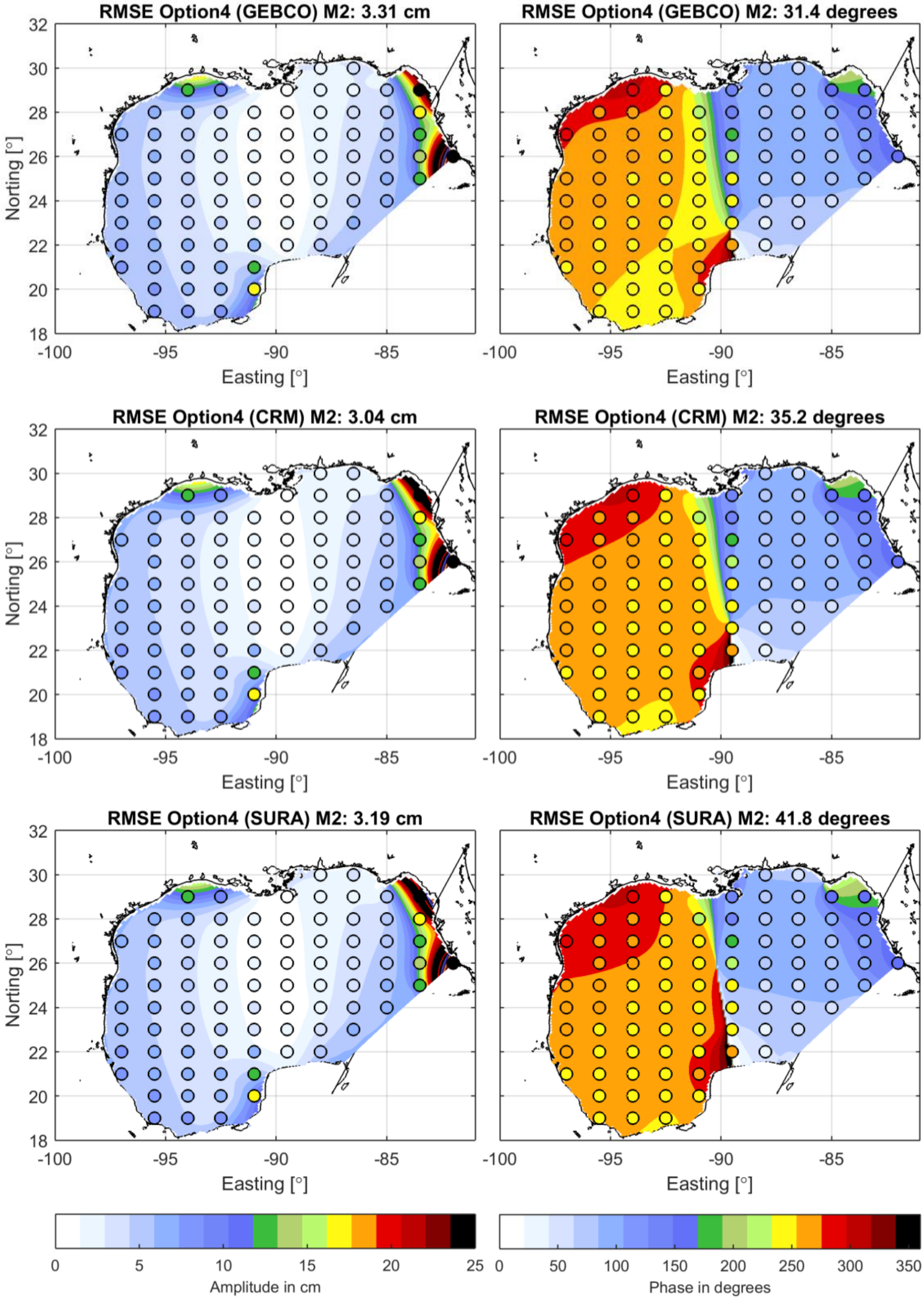


Figure 3.14 Reproduction of the M2 amplitude (left) and phase (right) by GEBCO (upper panel), CRM (middle panel) and SURA (lower panel). Circles are TPXO 7.2 measurements.

3.7 Conclusion

In this Chapter the performance of Delft3D-FLOW models made by DDB in reproducing the hydrodynamics (water levels) in the Gulf of Mexico have been analyzed. The fundamental question is how to choose the model settings in Delft3D-FLOW (e.g. time step) and toolbox settings in DDB in order to get the best performance.

1 Where to define the model grid?

Based on the case study of the GoM, it is recommended to define a model grid which is marginally larger (factor 1.5) than area of interest. When making the grid smaller the semi-diurnal constituents are not completely reproduced. When making your grid larger the diurnal constituents will be overestimated. It is not recommended to intersect islands, since this will increase the spin-up time. An intersection of islands does not affect the performance.

2 How many and what type of boundary section has the best performance?

Riemann boundaries will result in 8-10 times shorter spin-up time compared to water levels. In the field case of the Gulf of Mexico there were no differences performance-wise between Riemann and water levels boundaries.

3 Are there other parameters which should be varied in other to improve the performance?

1. Applying the 'new' numerical implementation of Coriolis in Delft3D-FLOW does not result in an improvement of the water level reproduction. In the field case of the Gulf of Mexico the error increased with 4%.
2. Increasing the resolution of the model will result in a better reproduction of the tides. Going from 1/5°x1/5° to 1/10°x1/10° to 1/20°x1/20° resulted in a decrease of 2,5 and 12% in error respectively.
3. In theory the ADI method is unconditionally stable, however, for the case study of the GoM a stable accuracy was achieved for time steps (in combination with a resolution of 0.1 x 0.1 degrees) of 5 to 10 minutes.
4. Varying the roughness value applied can result in an increase in skill scores, however there were no patterns found which will question the default Manning coefficient of DDB of 0.02 [$m^{1/3}/s$].

Different sources in bathymetry can result in relatively large variations in bed levels per grid cell. However, in this situation the performance of the models was more or less similar. Applying the bathymetry of SURA resulted in an increase of the error with 2 to 15%. For CRM there was an increase of the error of 0 to 2%.

4 Mississippi Sound model

4.1 Introduction

The Mississippi Sound model is a Delft3D numerical model that has been developed for the area around the Chandeleur Islands, a chain of uninhabited barrier islands located in the Gulf of Mexico (GoM). They form the easternmost point of the state of Louisiana. Around the Chandeleur Islands the Mississippi River Delta, New Orleans and the coasts of Mississippi (Gulfport) and Alabama (Mobile) are located (
Figure 5.1).

In this chapter a well-calibrated Delft3D model ('msound'; Gilligan, NAVO-Stennis, personal communication, 2015)) will be compared with a quickly-generated model within Delft Dashboard (DDB). The focus is the reproduction of the in-situ measurements of water levels for stations within the area of interest.

This chapter answers the following two questions:

1. **What are the differences between the well-calibrated (msound) model and the Delft Dashboard (DDB) model in reproducing the water levels (both in skill and spatial patterns)?**
2. **What is the added value of each step per complexity (e.g. nesting, physical processes) in reproducing the water levels both for the msound model and for the DDB model?**

First the msound model is compared with measuremens. Then, the study is divided into two analyses. In the first analysis more complexity (i.e. physical processes) is added gradually to both models and compared with the original msound model. The second analysis focuses on the added value (i.e. model skill) per complexity step per model setup. The four complexity levels are shown in Table 4.1.

Table 4.1 The five levels of complexity

#	Level	msound	DDB
1	Astronomic	TPXO 7.2	TPXO 7.2
2	Nesting	Apply original files	Nested in large model
3	Discharges	Apply original files	Include discharge with new toolbox
4	Meteo	Apply original files	Apply the meteo toolbox

Figure 4.1 Overview of the area of interest in this study. Source: Google Earth

4.2 Model setup

4.2.1 Mississippi Sound (msound)

The Mississippi Sound model is a Delft3D model which includes the following processes: hydrodynamics (water levels and tidal currents), waves, river discharges and wind. The flow model consists of 285x326x9 grid cells, is non-equidistant curvi-linear and has a minimum resolution of 1200x1200 meter and a maximum resolution of 500x200 meter (respectively in the direction: southwest-northeast and southeast-northwest). For the waves the grid is marginally coarser (i.e. grid cells: 63x68, resolution: 4 to 5 times lower resolution compared to the flow grid). The model domain is shown in Figure 4.2. The simulation period covers the entire month of December, 2014.

The msound is created by the Naval Oceanographic Office (NAVOCEANO) and is, in this comparison, used as a well-calibrated benchmark model. The grid is created with the use of RGFGRID and the result is a curvi-linear grid which refines closer to the shore (and thus near the measurements locations). However other pre-processing steps like bathymetric interpolation and boundary generation have been carried out with DDB. The model is nested in a larger scale hydrodynamic model. Both models are forced with wind and pressure fields. Moreover, no additional calibration of the bed level or bed roughness has been carried out. It is estimated that the total setup time is about 10 hours which is mainly spent at grid generation. Therefore it is expected on forehand that the differences in water level reproduction between msound and the DDB model will be limited.

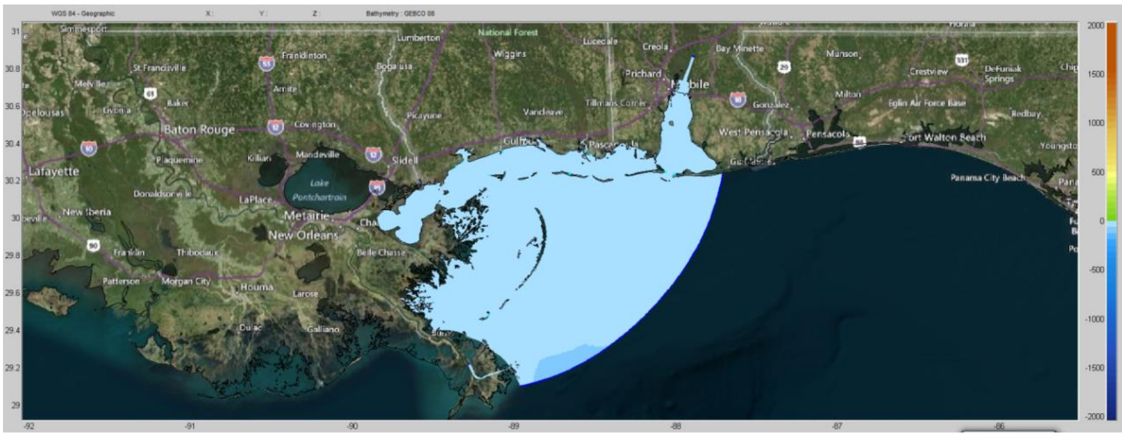


Figure 4.2 Delft3D model setup of the Mississippi Sound (msound)

4.2.2 Delft Dashboard (DDB)

The DDB model is also a Delft3D model (only FLOW) but is depth-averaged. Waves have not been included, since the focus of this study is to reproduce surge water levels. The model is depth-averaged since the influence of a three-dimensional (3D) versus depth-averaged (2DH) model on the reproduction of water levels is expected to be negligible. Besides these differences, the DDB model includes all the processes described by the msound model. The model consists of 231 x 312 cells, is equidistant rectilinear and has a spatially uniform resolution of 1000x1000 meter. The area modeled is comparable with the msound model (marginally larger due to rectilinear grid). The model domain can be seen in Figure 4.3. The simulation period again covers the entire month of December, 2014.

The DDB model is generated within 10 minutes by using Delft Dashboard as a tool for pre-processing. The bathymetry is based on the Coastal Relief Model (CRM) and boundary conditions are derived from the TPXO 7.2 database (i.e. tide boundary conditions). The model is therefore only driven with tides from the boundary.

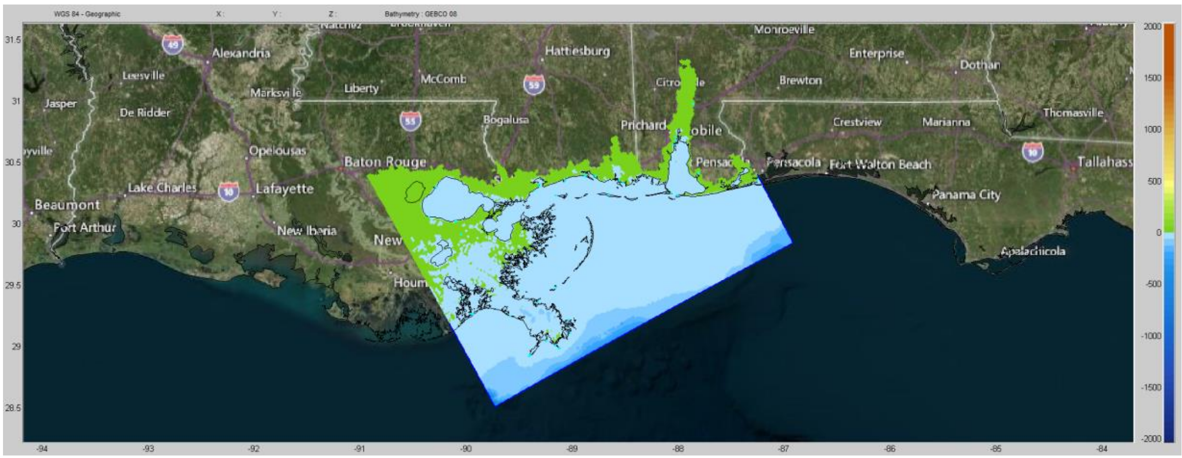


Figure 4.3 Delft3D model setup of the Delft Dashboard model (ddb)

4.3 Goodness of fit criteria

The performance of the model in reproducing water levels at seven in-situ stations is determined based on the water levels at the observations stations (Figure 4.4). The R2, bias and RMSE are determined of the water levels for entire month of December, 2014. One is referred to Appendix A for all the definitions and formulas.

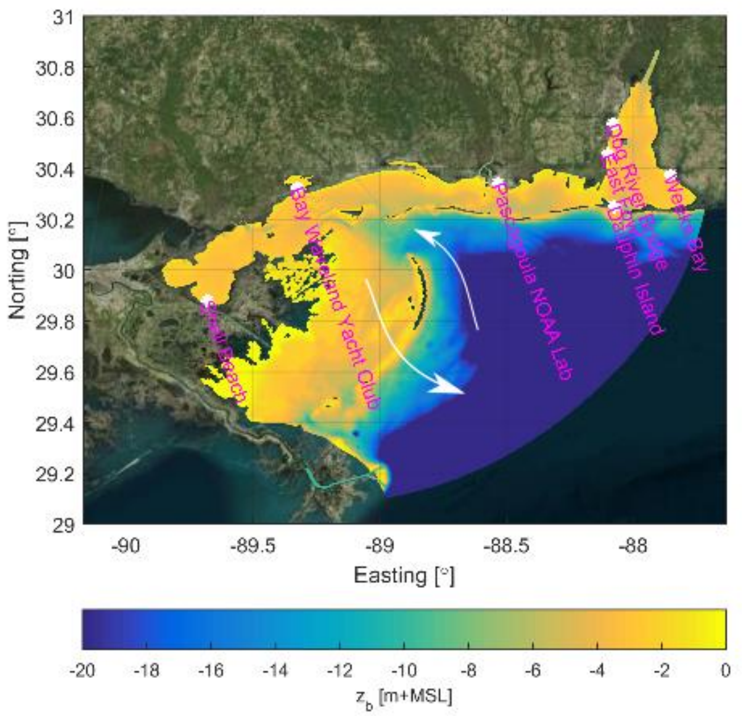


Figure 4.4 Observation points in the area of interest. The white arrows indicate the dominant tidal inflow north and an outflow south (Blumberg et al., 2000)

4.4 Model results: performance of msound-model

Before comparing the msound model with the DDB model, the capability of the existing model setup (i.e. msound model) in reproducing the water levels of several stations in the area of interest is assessed. First, general patterns of the measurements and model results are described. Secondly, the skill scores (R2, bias and RMSE) are determined.

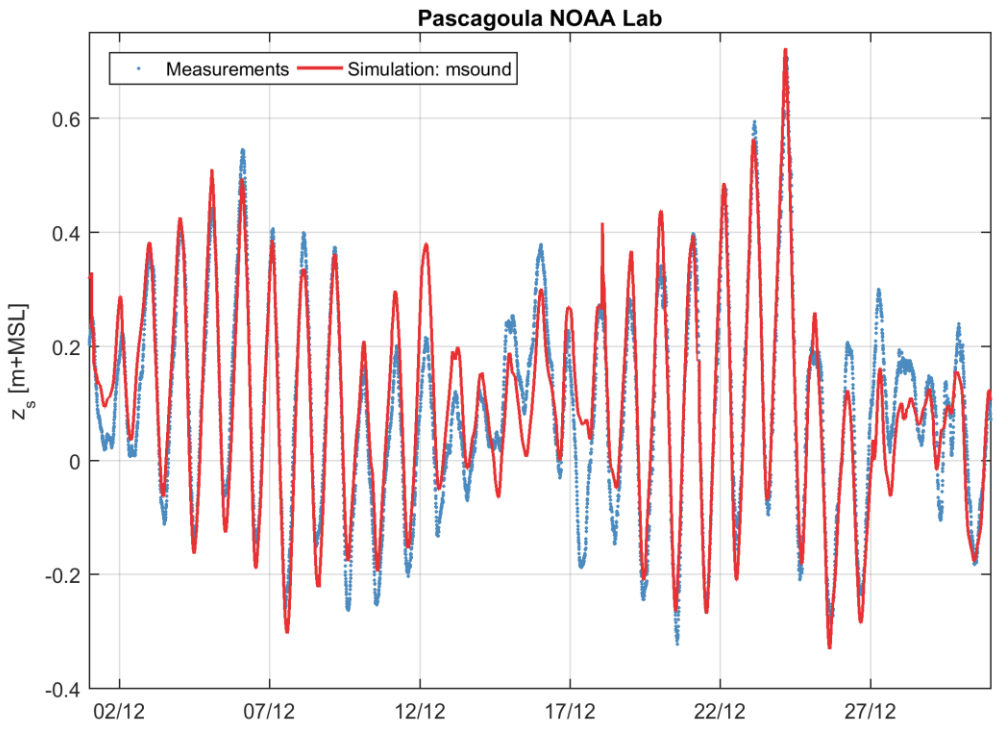
Around the Chandeleur Islands there is a dominant tidal inflow north and an outflow south (Blumberg et al., 2000); see white arrows in Figure 4.4. Based on the TPXO 7.2 database maximum tidal water levels are expected to be around MSL + 0.5 -1.0 m, but higher water levels can be observed due to meteorological effects (e.g. wind setup or atmospheric pressure drop). In the period of December 2014 there is a spring-neap cycle visible in the observations and model results, see Figure 4.5 Figure 4.4, with a neap tide at December 15th and a spring tide at December 6th. On December 24th, fairly high water levels were recorded. This was related to meteorologically induced setup.

The msound model is capable of reproducing the patterns at station Pascagoula, see upper panel of Figure 4.4. Tidal variations like spring and neap cycles can be recognized. On top of that, the surge in combination with high tidal water levels on December 24th is also reproduced. For Shell Beach, see lower panel of Figure 4.4, the reproduction is much less accurate. It seems that the tidal wave is too late and too low. This is related to a combination of errors in the bed roughness and errors in the model bathymetry, and is expected to improve when better quality bathymetry data would be available locally.

The msound model as provided by the NAVOCEANO has an R2 of 0.58 with a bias of 0.05 m and an RMSE of 0.12 m. The model has a higher skill for observation stations near the boundary (i.e. Daulphin Island and Pascagoula) and a lower skill behind the salt marshes of the Mississippi (.e.g Shell Beach), as can be seen in Table 4.2. The most likely reason for this is that no variation in bed roughness is applied. However, in reality there are mud beds.

Table 4.2 Skill score in reproducing the water levels at 7 observation stations

Station	R2 [-]	Bias [m]	RMSE [m]
'Bay Waveland Yacht Club'	0,65	-0,04	0,11
'Dauphin Island'	0,78	-0,02	0,07
'Pascagoula NOAA Lab'	0,85	-0,01	0,07
'Shell Beach'	0,00	-0,05	0,22
'East Fowl'	0,61	-0,07	0,12
'Dog River Bridge'	0,40	-0,11	0,16
'Weeks Bay'	0,75	-0,02	0,10
Mean	**0,58**	**-0,05**	**0,12**



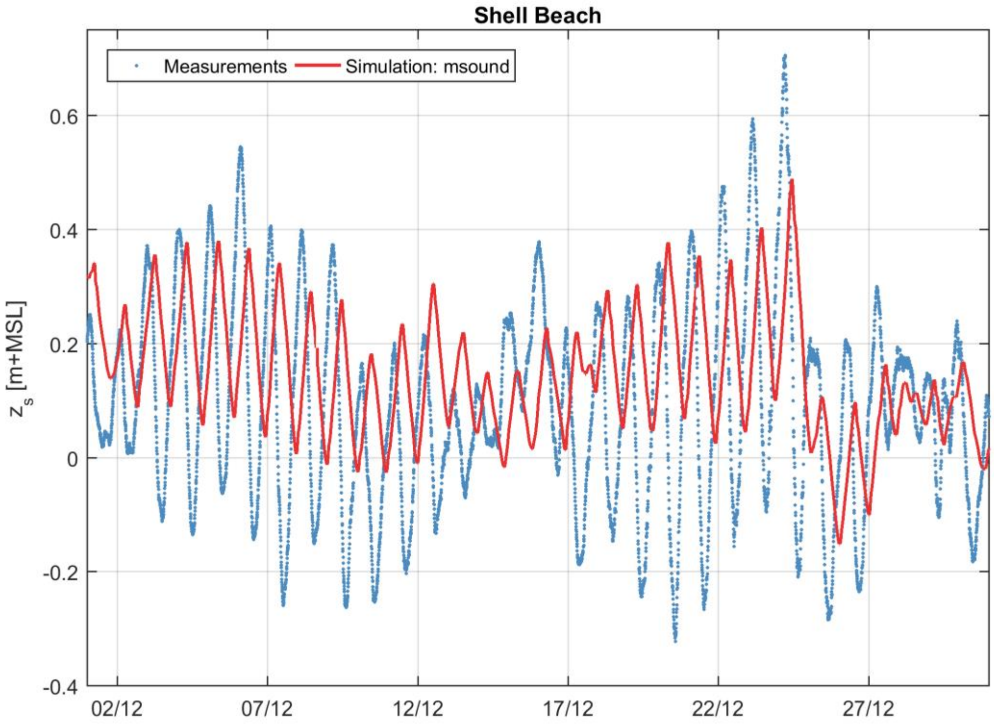


Figure 4.5 Water level observations (blue) and model results with msound (red) for Pascagoula (upper panle) and Shell Beach (lower panel) for the entire month of December, 2014

4.5 Analysis 1: add complexity (more processes)

4.5.1 Astronomic simulations

The simplest model setup is a Delft Dashboard model which is forced with astronomic boundary conditions (.bca file) based on TPXO 7.2. In order to make a fair comparison the complexity of the msound model is reduced. This means the model runs depth-averaged (2DH) and is forced with the same boundary conditions (i.e. TPXO 7.2), and without wind forcing. In the following section, a comparison is made between a DDB model and msound with only (astronomical) tidal boundary forcing versus the original msound model (msound full).

For the individual stations all model setups perform poorly for Shell Beach (R2 < 0). It is hypothesized that this is related to a (local) bed roughness which is too high and therefore the tidal wave is dissipated too much. In both models a similar (high) Manning coefficient of 0.038 m2/s is applied, since this was the value applied in the original msound model. Furthermore, the Delft Dashboard model is not capable in reproducing observations at Pascagoula NOAA Lab. The reason is that the algorithm in DDB responsible for selecting observation points in the model grid chooses the observation point in a dry grid cell. It is stressed here that one should be careful which grid cell to select for the comparison with observations. Therefore, in this comparison Shell Beach and Pascagoula NOAA Lab are not taken in to account in the skill determination of Table 4.3.

For station Bay Waveland Yacht Club, see Figure 4.5, one can see that the general tidal pattern of spring and neap tide are reproduced by all three models. Logically, setup due to meteorological induced effects is not taken into account in both astronomical models.

On average the astronomic msound model has a 6% lower R2 and a 17% higher RMSE than the full three dimensional msound model. The difference between the msound and DDB, both forced with astronomic boundaries, is much lower (1% lower R2 and a 1% higher RMSE), as can be seen in Table 4.3 and Figure 4.6. This means that grid of msound is not performing significantly better in predicting water levels than a grid quickly created by Delft Dashboard.

Table 4.3 Station-averaged skill scores for three models: msound with all processes (blue), msound simplified and forced with astronomic boundaries (green) and DDB forced with astronomical boundaries (yellow)..

Model setup	R2 [-]	Bias [cm]	RMSE [cm]
msound: full	0,865	5,1	11,4
msound: astronomic	0,815	-6,5	13,2
DDB: astronomic	0,807	-6,1	13,3

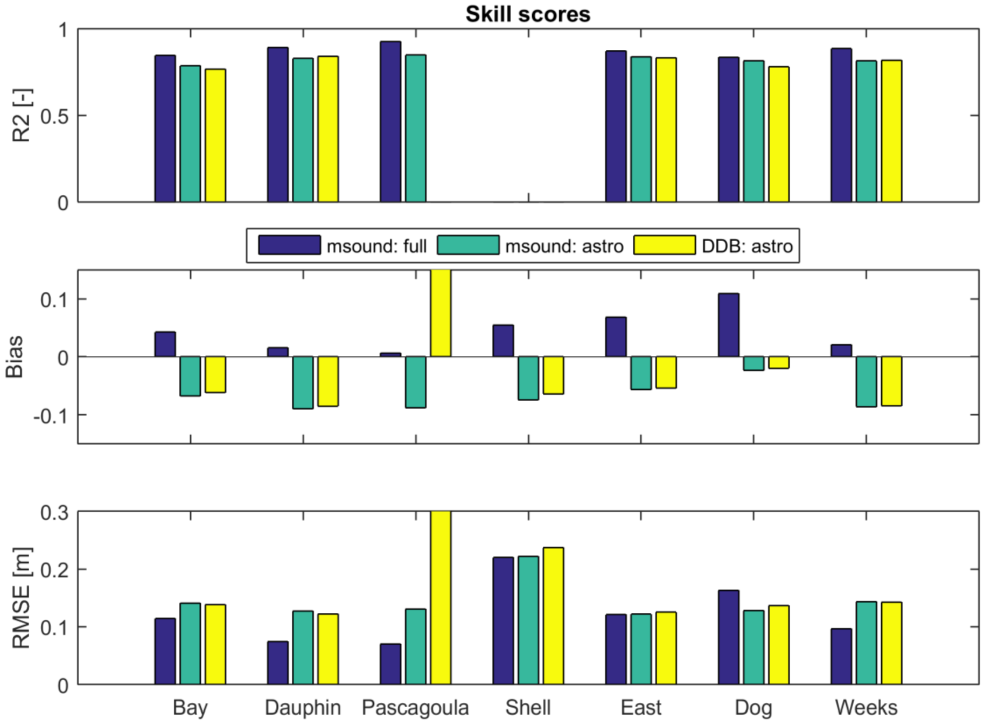


Figure 4.6 Skill scores for seven observations stations for three models: msound with all processes (blue), msound simplified and forced with astronomic boundaries (green) and DDB forced with astronomical boundaries (yellow).

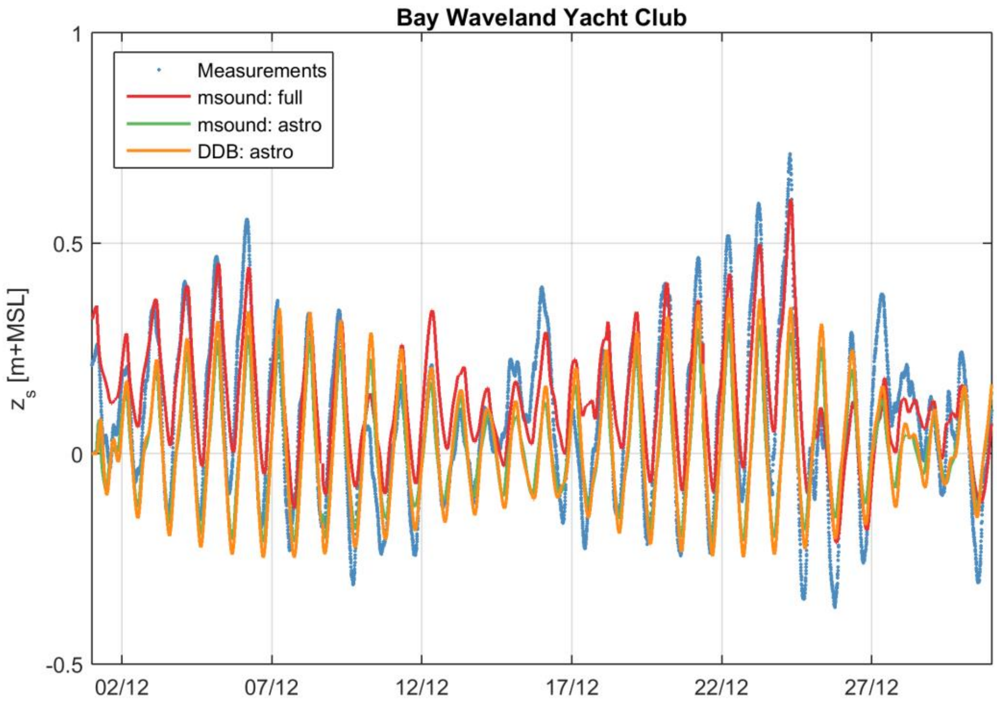


Figure 4.7 Water level observations (blue) and model results with msound full (red), msound astronomic (green) and DDB: astronomic (orange) for Bay Waveland Yacht Club for the entire month of December, 2014

4.5.2 Nesting in larger model

The first step of adding complexity in the Delft3D-FLOW model is nesting the detailed model in a larger hydrodynamic model. Msound is nested in a three-dimensional GoM model from the NAVOCEANO which includes meteorologically induced forcing besides tides. DDB is nested in the model from Section 3. This model is also depth-averaged and only forced with tides (tidal forces within the model domain and TXPO 7.2 from the boundary conditions). Winds and waves are in this model not taken into account, since DDB does not provide an access to a data source. The water level derived at the boundaries will for both models replace the astronomic boundary conditions based on TPXO 7.2. In order to make a fair comparison the complexity of the full msound is again reduced and water level boundaries (through nesting) are applied (i.e. no discharges, meteo and waves).

For station Bay Waveland Yacht Club, see Figure 4.9, the msound model nested in a larger-scale GoM model has almost a similar reproduction as the full sound model. The peak during flood (i.e. high water) in combination with surge is fairly well reproduced and there is almost no difference between the full msound model and the msound model which is ‘only’ nested. The DDB model is not capable of reproducing the high water as a result of flood and surge. It is concluded that this high water peak is mainly related to wind and pressure effects on a larger scale (GoM) versus a smaller scale (msound; Chandeleur Islands), since only the meteorological effects in the larger scale model are taken into account.

The nested msound model has a 5% lower R2 and a 3% higher RMSE than the full msound model. For the DDB model these differences increase substantially to 7% for R2 and 13% for RMSE, see Table 4.4 and Figure 4.8. The added skill for the msound nesting is much higher than that of the nesting done with Delft Dashboard. This is related to the lack of meteorologically forcing within the overall DDB model in comparison to the model msound is nested in. Therefore, the skill scores for DDB are similar with or without nesting.

Table 4.4 Skill scores for msound full, msound nested and ddb nested. Skill scores for msound full, msound astronomic and ddb astronomic. Station-averaged values and do not include stations of Pascagoula NOAA Lab and Shell Beach

Model setup	**R2 [-]**	**Bias [cm]**	**RMSE [cm]**
msound: full	0.865	5.1	11.4
msound: nested	0.823	3.7	11.8
DDB: nested	0.805	-5.0	12.9

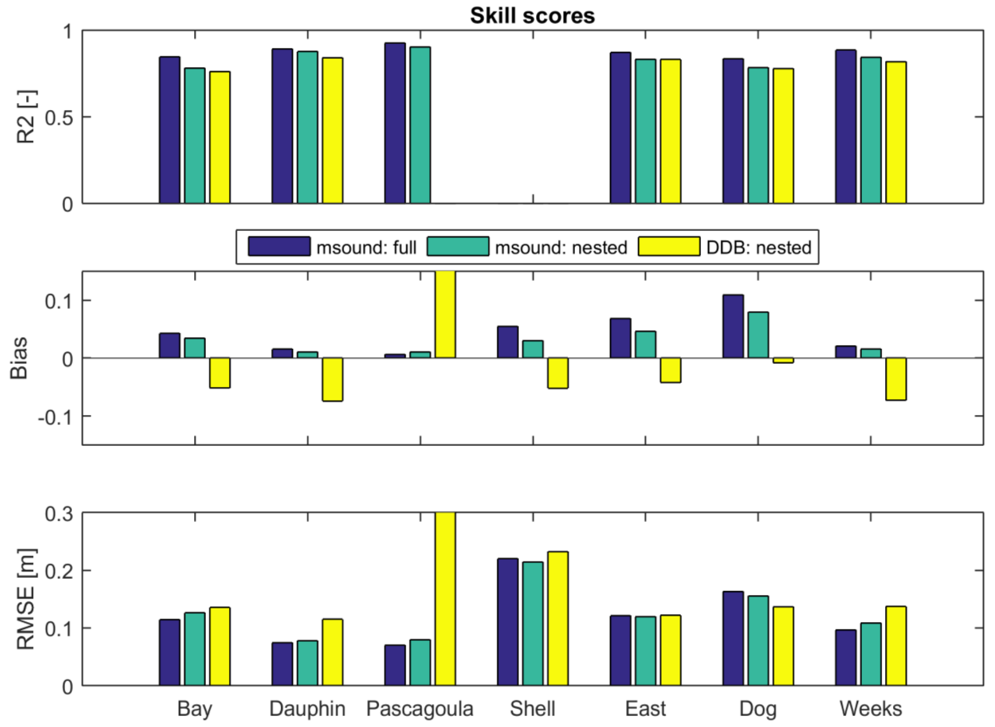


Figure 4.8 Skill scores for seven observations stations for three models: msound with all processes (blue), msound simplified with only nested boundary conditions (green) and DDB forced with nested boundary conditions (yellow)

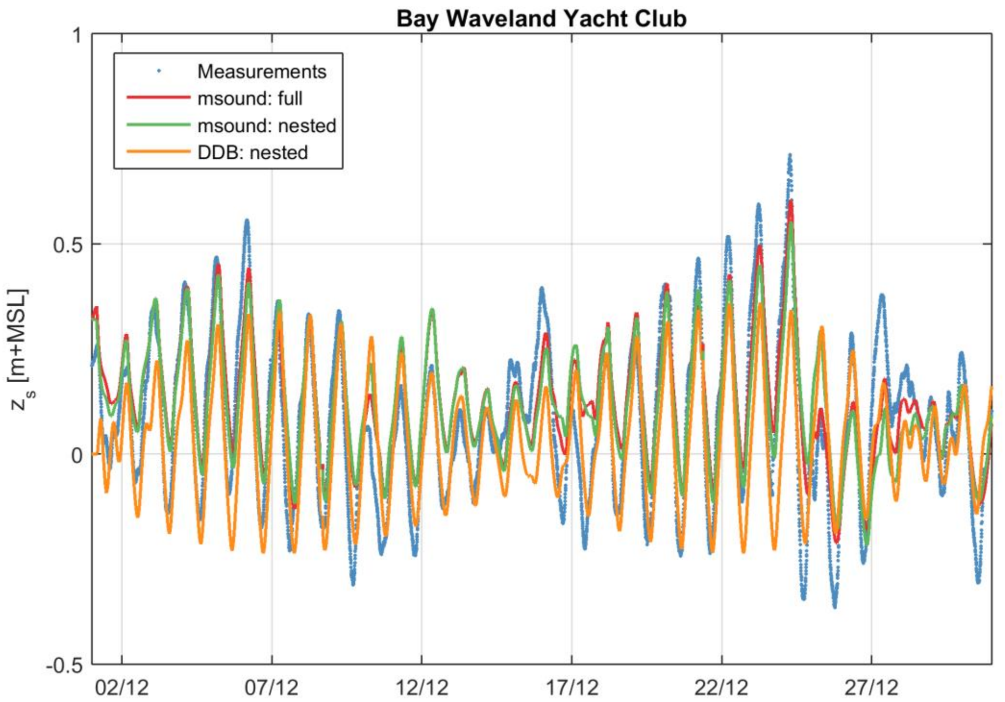


Figure 4.9 Water level observations (blue) and model results with msound full (red), msound nested (green) and DDB nested (orange) for Bay Waveland Yacht Club for the entire month of December, 2014

4.5.3 Include discharges

The second step of adding complexity in the Delft3D-FLOW model is by applying discharges in the detailed model. This will result in (fresh) water sources in the model domain. In order to make a fair comparison, the complexity of the msound model is reduced and only water level boundary conditions (through nesting) and discharges (so no meteo and/or waves) are applied. In this analysis the focus is on the reproduction of water levels and therefore the added value of stratified flows is not taken into account.

Qualitatively, adding discharges can result in an increase in the height of the modeled water levels . The total amount of water flow into the model domain is calculated to be 2.7 $*10^9$ m3. This value divided by the entire model area is about 10 cm. For some stations this results in an increase of the water level (e.g. Dog River Bridge). For other stations there is no impact (e.g. Bay Waveland Yacht Club, see Figure 4.11). However, the DDB model still underestimates the high water during December 24th since this is related to meteorological effects (most likely both on the large and smaller scale). For the msound, water levels were already and continue to be reproduced quite well.

Quantitatively, this msound model has a 4% lower R2 and a 13% higher RMSE than the full msound model. For the DDB model these differences increase to 7% for R2 and 11% for RMSE, see Table 4.5 and Figure 4.11. When comparing the results with and without discharges, the skill score decreases. This is related to two separate effects. First, hardly any observation points are located in close presence of a river. Including river discharges could have resulted in a better reproduction of the hydrodynamics, but this cannot be captured with the current distribution of observation points. On top of that, for stations where the water level was already overestimated, adding some extra water through the discharges results in higher water levels (and thus larger errors).

Table 4.5 Skill scores for msound full, msound discharges and ddb discharges. Skill scores for msound full, msound astronomic and ddb astronomic. Station-averaged values and do not include stations of Pascagoula NOAA Lab and Shell Beach

Model setup	R2 [-]	Bias [cm]	RMSE [cm]
msound: full	0,865	5,1	11,4
msound: discharges	0,824	6,1	12,8
DDB: discharges	0,800	-3,3	12,7

Figure 4.10 Skill scores for seven observations stations for three models: msound with all processes (blue), msound simplified with only nested boundary conditions and discharges (green) and DDB forced with nested boundary conditions and discharges (yellow)

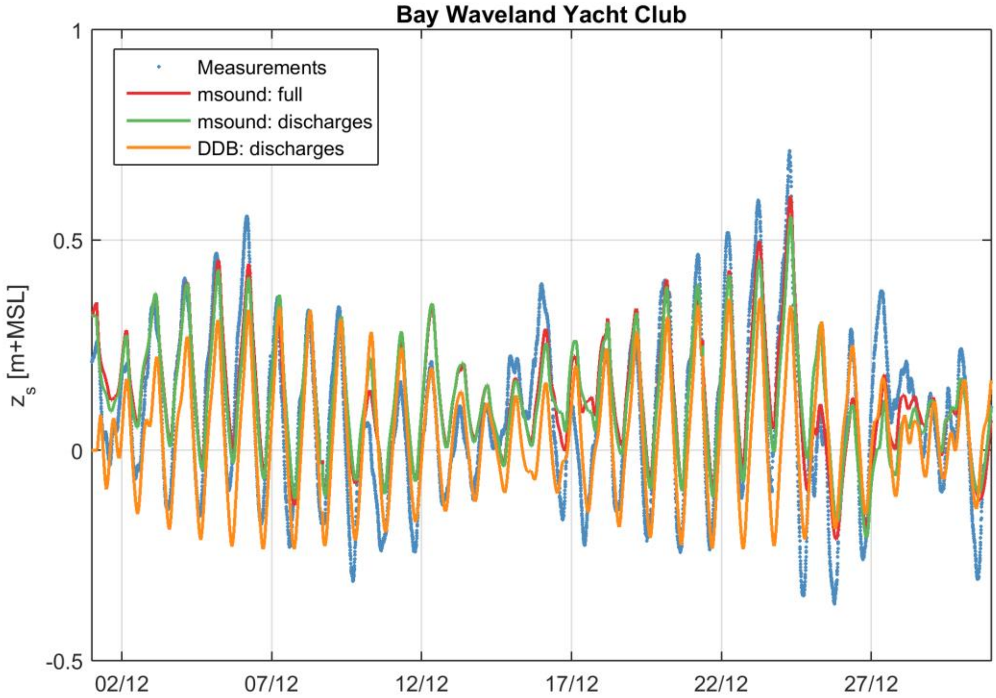


Figure 4.11 Water level observations (blue) and model results with msound full (red), msound with nested boundary conditions and discharges (green) and DDB with nested boundary conditions and discharges (orange) for Bay Waveland Yacht Club for the entire month of December, 2014

4.5.4 Meteo files: wind and pressure

The fourth step of adding complexity in the Delft3D-FLOW model is by applying meteorological forcing (e.g. wind and pressure) into the detailed model. The pressure fields and wind forcing may induce water level setup and set-down. In order to make a fair comparison the complexity of the msound is reduced and only water level boundaries (through nesting), discharges and meteo (no waves) are applied.

When local meteorological effects (e.g. wind and pressure) are taken into account the water level reproduction improves significantly. This is, for example, related to wind driven setup and set-down, as can be seen in Figure 4.13. For msound the differences between running Delft3D with and without waves are limited. This is related to the low offshore wave height (H_s < 1.0 meter). There are quite some differences between msound meteo and DDB meteo during the high water event of December 24th. This is most likely related to the difference in nesting, since the overall nesting model of msound contains meteorological forcing and the overall nesting model of DDB is only forced with tides, see also Section 4.5.2

This msound model has 0.2% higher R2 and a 1% lower RMSE than the full msound model. For the DDB model these differences increase to 0.6% higher R2 and 4% lower for RMSE. This means that both for the msound and the DDB setup the skill scores are better than the msound model with waves, see Table 4.6 and Figure 4.12. For the DDB model this is related to the overestimation of the water levels without waves. Taking into account waves will result in higher water levels due to wave induced setup.

Table 4.6 Skill scores for msound full, msound without waves and DDB forced with nested boundary conditions, discharges and meteorological files. Station-averaged values and do not include stations of Pascagoula NOAA Lab and Shell Beach

Model setup	**R2 [-]**	**Bias [cm]**	**RMSE [cm]**
msound: full	0.865	5.1	11.4
msound: meteo	0.866	4.8	11.3
DDB: meteo	0.870	-3.8	10.9

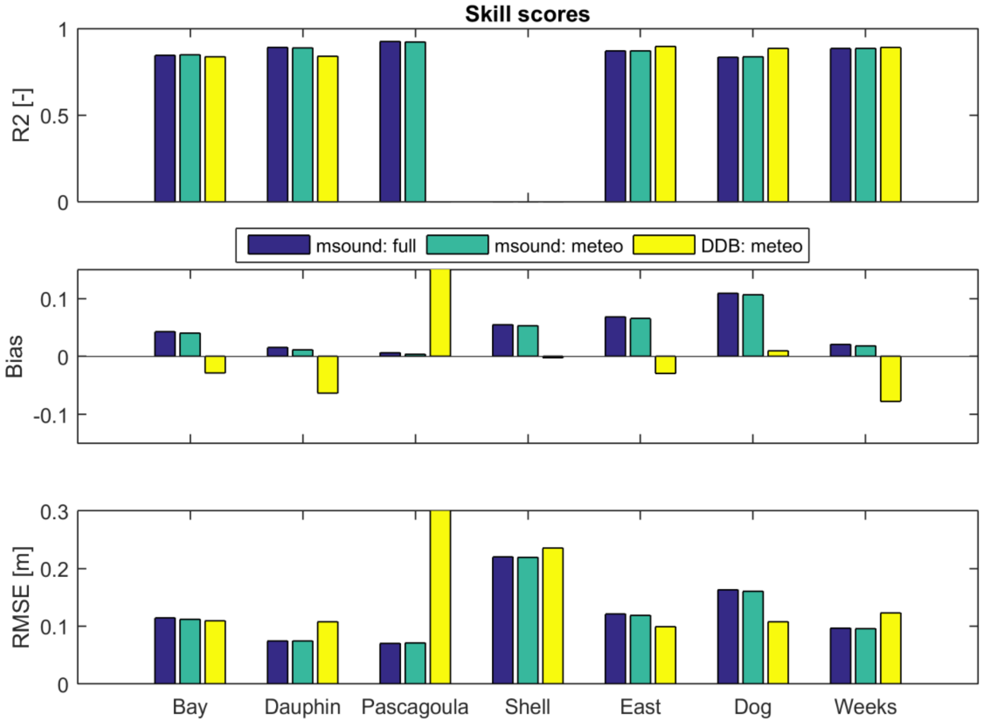


Figure 4.12 Skill scores for seven observations stations for three models: msound with all processes (blue), msound without waves (green) and DDB forced with nested boundary conditions, discharges and meteorological files (yellow)

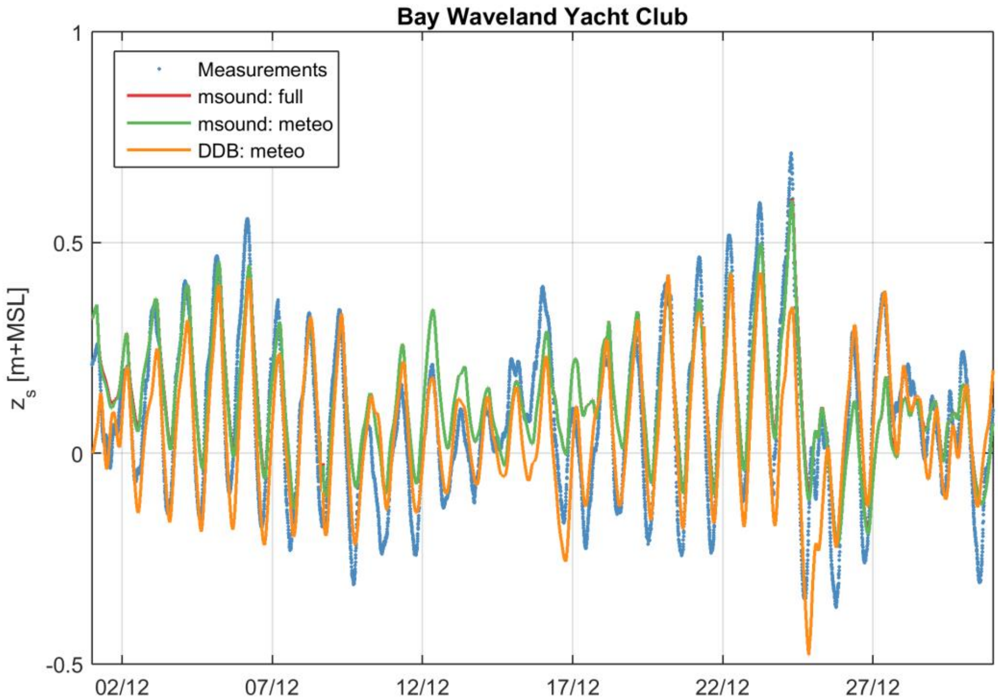


Figure 4.13 Water level observations (blue) and model results with msound full (red), msound without waves (green) and DDB forced with nested boundary conditions, discharges and meteorological files (orange) for Bay Waveland Yacht Club for the entire month of December, 2014

4.6 Analysis 2: added value per extra process

In the previous section (Section 4.5) complexity was added step-by-step per model setup (both msound and ddb). In this section the focus is on the added value per complexity step. This is carried out for both the msound model and the DDB model.

4.6.1 Mississippi Sound (msound) model

When applying the Mississippi Sound (msound) model with astronomic boundary conditions the Delft3D-FLOW model is already capable of reproducing the water levels for 5 stations in the model domain with reasonable skill (R2 of 0.82). Figure 4.14 shows that for Bay Waveland Yacht Club the msound model with only astronomical boundary conditions (green) the spring neap tidal cycle, seen in the measurements and msound full, can be reproduced.

The most positive contribution in order to enhance the R2 is by taking into account meteo files. This will result wind-driven setup and set-down and therefore a higher skill score. For the bias it is mainly important to apply nesting instead of applying astronomic boundaries based on TPXO 7.2 since there is a small offset compared to measurements when applying TPXO 7.2. This can be seen in Table 4.7 or in Figure 4.15 where ebb (i.e. low water) is better reproduced.

Applying discharges can result in an increase of the RMSE, but that was not observed here since the observation points were not located near main rivers. Moreover, the coupling with Delft3D-WAVE had in this specific case limited added value since the waves have a limited significant wave height (<1.0 m on sea and <0.1 m in sheltered areas), see Table 4.7 and Figure 4.14 for all the skill scores.

Table 4.7 Skill scores for all the complexity level of msound (full, astronomic, nested, discharges and meteo). Station-averaged values and do not include stations of Pascagoula NOAA Lab and Shell Beach

Model setup	R2 [-]	Bias [cm]	RMSE [cm]
astronomic	0.815	-6.5	13.2
nested	0.823	3.7	11.8
discharges	0.824	6.1	12.8
meteo	0.866	4.8	11.3
full (including waves)	0.865	5.1	11.4

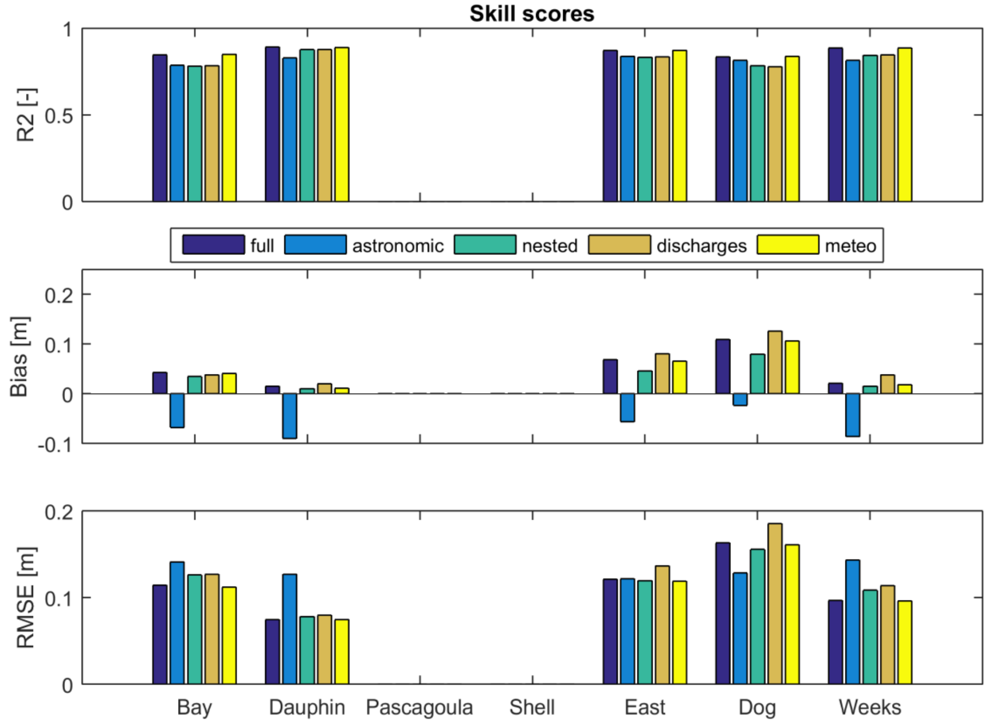


Figure 4.14 Skill scores for seven observations stations for msound models for multiple complexity levels (colors)

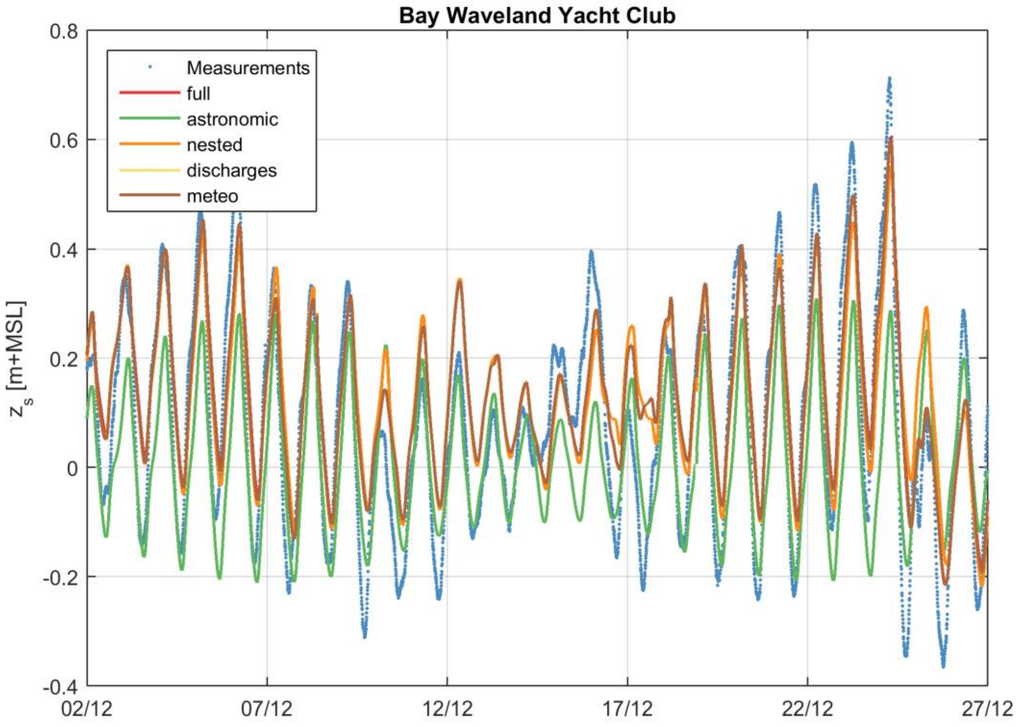


Figure 4.15 Water level observations (blue) and model results with msound models and multiple complexity levels for Bay Waveland Yacht Club for the entire month of December, 2014

4.6.2 Delft Dashboard (DDB) model

When applying the Mississippi Sound model made by DDB with astronomic boundary conditions, the model is already quite capable of reproducing the water levels for 5 stations in the model domain with reasonable skill (R2 of 0.81). However the skill is marginally lower compared to the msound with the same complexity (R2: 0.82). Figure 4.17 shows that for Bay Waveland Yacht Club the DDB model with only astronomical boundary conditions (green) the spring neap tidal cycle, seen in the measurements and msound full, can be reproduced.

Just like the msound setup, Section 4.6.1, the most positive contribution in order to enhance R2 is by taking into account meteo files. Reducing the bias is possible by applying nesting. The impact of taking into account both processes can also be seen in Figure 4.17. Meteorological effects result in a shift of the water level (brown line) with several dm (either positive or negative; i.e. setup or set-down). Nesting results in a slightly higher water level (e.g. see the increase of the water level during ebb) and therefore lower bias in Table 4.8. One is referred to Table 4.8 and Figure 4.16 for all the skill scores.

Table 4.8 Skill scores for all the complexity level of ddb (astronomic, nested, discharges and meteo). Station-averaged values and do not include stations of Pascagoula NOAA Lab and Shell Beach

Model setup	**R2 [-]**	**Bias [cm]**	**RMSE [cm]**
astronomic	0,807	-6,1	13,3
nested	0,805	-5,0	12,9
discharges	0,800	-3,3	12,7
meteo	0,870	-3,8	10,9
msound: full	0,865	5,1	11,4

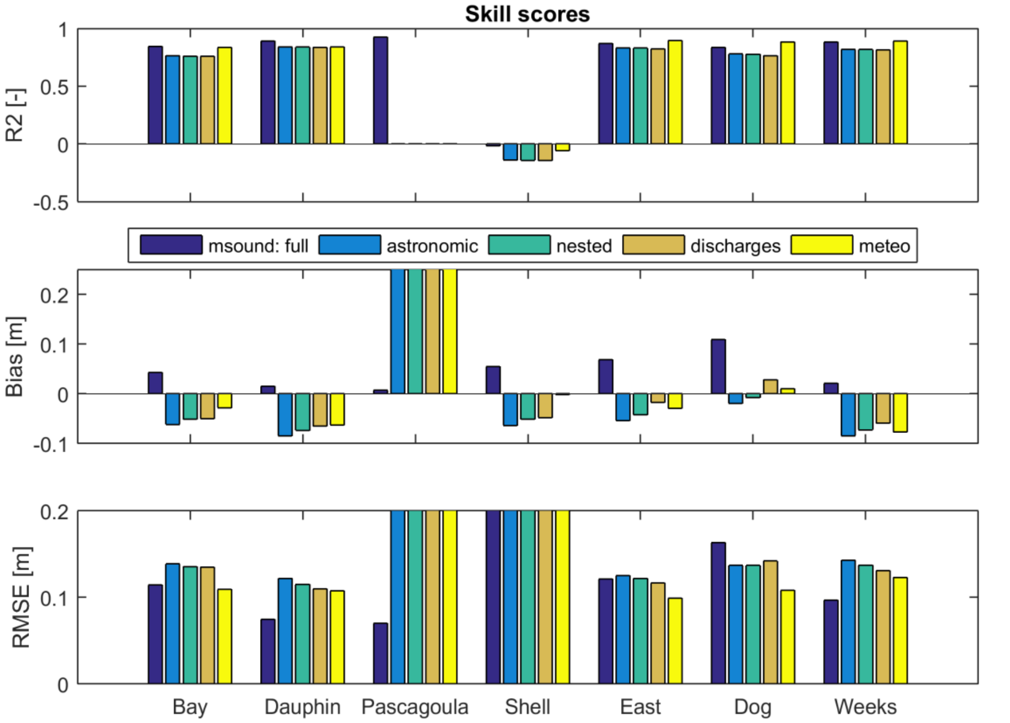


Figure 4.16 Skill scores for seven observations stations for DDB model for multiple complexity levels (colors)

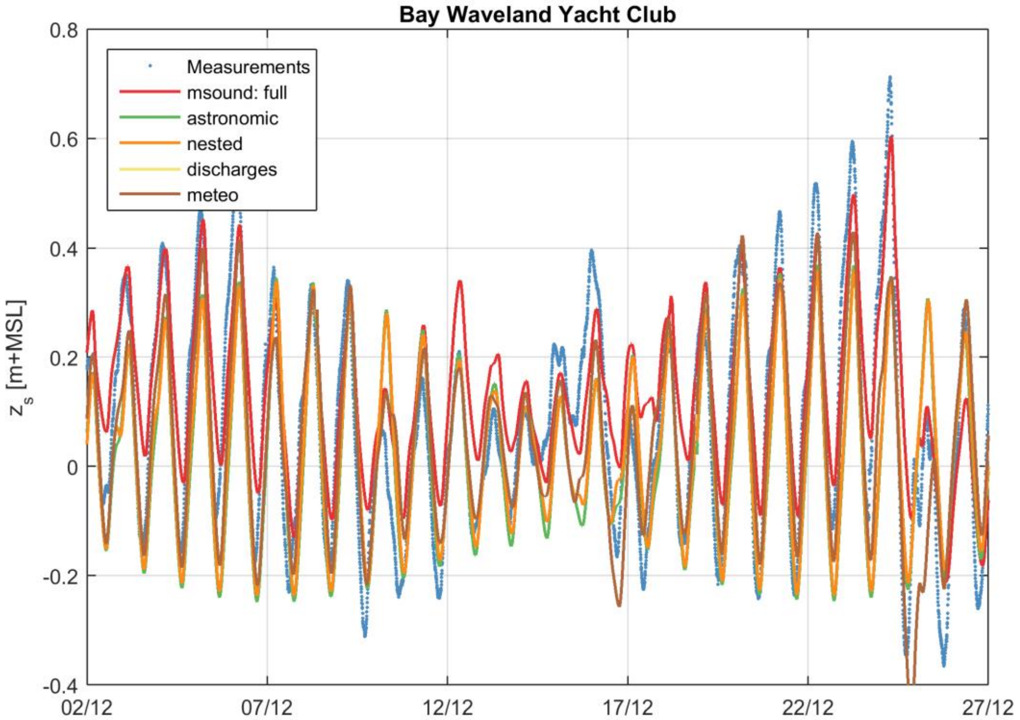


Figure 4.17 Water level observations (blue) and model results with DDB model and multiple complexity levels for Bay Waveland Yacht Club for the entire month of December, 2014

4.7 Conclusion

In this chapter a well-calibrated Delft3D model (Mississippi Sound model, msound) is compared with a quickly generated model within Dashboard (DDB). The focus was the reproduction of the water levels for the stations within the area of interest.

1. **What are the differences between the well-calibrated model and the Delft Dashboard model in reproducing the water levels (both in skill and spatial patterns)?**
   The differences between the well-calibrated model (msound) and the Delft Dashboard model (DDB) are limited. Compared to the most elaborate msound model, simple models forced with astronomic boundaries have a 7% lower R2 and a 16% higher RMSE (both msound and ddb).

2. **What is the added value of each step per complexity (eg. nesting, meteo-files) in reproducing the water levels both for the msound model and for the ddb model?**

When adding more complexity to the models one should focus on nesting (lower bias) and include meteo files (lower RMSE). The added value of taking into account discharges and waves was, in this specific case, limited due to the fact there was no measurement stations near rivers and there were low wave heights (Hs <1.0 m).

5 North Sea model

5.1 Introduction

The North Sea is a marginal sea in North-west Europe and is part of the shelf which connects the Atlantic Ocean through the English Channel in the south and the Norwegian Sea in the north. For water level forecasting this is a complex, but also often modeled area. The main flow pattern in the North Sea is characterized by a counter-clockwise and a semidiurnal Kelvin wave. The ocean currents mainly enter via the north and exit along Norwegian coast. Some of the energy travels through the English Channel into the North Sea (Pugh, 2004). The spatial pattern of the M2-tide is characterized by three amphidromic points, one located in the Southern Bight (between the Netherlands and Belgium) and two in the main basin (Dyke, 2007).

In this chapter the performance of Delft3D-FLOW models made by Delft Dashboard in reproducing the hydrodynamics (water levels due to tide) is analyzed. The fundamental question is what the quality of the model setup is and how that relates to current state-of-the-art operational models like the sixth version of the Dutch Continental Shelf Model (DSCMv6; Zijl et al., 2013) and to inverse tide models (e.g. TPXO 7.2).

Figure 5.1 The North Sea in perspective. Source: http://www.decomworld.com/

5.2 Model setup

5.2.1 Dutch Continental Shelf Model (DSCMv6; Zijl et al., 2013)

DSCMv6 is developed using the WAQUA software package (Stelling 1984). The model grid covers the northwest European continental shelf and has a uniform grid cell size of 1/40° in east–west direction and 1/60° in north–south direction, yielding approximately to 10^6 computational cells. The model bathymetry is mostly based on the North-West Shelf Operational Oceanographic System (NOOS) gridded bathymetry dataset, but changes have been made to the initial model bathymetry to improve the water-level representation. The bed friction was initially modeled by with a uniform Manning coefficient of 0.028 $m^{1/3}/s$. However a spatially varying roughness field was later applied based on a data assimilation with the tool OpenDA (Kurniawan et al. 2011). The amplitudes and phases of the eight main diurnal and semi-diurnal constituents have been derived from an inverse tidal dataset. Meteorological forcing is taken into account. For meteorological surface forcing the model uses time- and space varying wind speed (at 10 m height) and air pressure (at MSL) provided by the Numerical Weather Prediction high-resolution limited area model (HiRLAM). It is estimated that the total setup time is about 50-100 days which is mainly spend at model calibration.

5.2.2 Delft Dashboard (DDB)

Several Delft3D-FLOW models have been created with Delft Dashboard. The models are depth-averaged (2DH) and forced with water levels from TPXO at the boundaries. Tidal forces (all components possible) and bed roughness (Manning value of 0.028 $m^{1/3}/s$; similar to DSCMv6) are activated. The simulation is started with a constant water level which is set at mean sea level (MSL). Waves, wind and pressure are not taken into account.

The standard settings applied in the model are listed below.

- **Grid size**:
  - *Standard*: 1/20° in east–west direction and 1/30° in north–south direction. This results in 500 x 631 grid cells.
  - '*Finer'*: 1/40° in east–west direction and 1/60° in north–south direction. This results in 1000 x 1262 grid cells
- **Bathymetry** data is either based on
  - *Standard*: Vaklodingen + EMODnet (Greater North Sea and Celtic sea) + GEBCO
  - only *GEBCO*
- **Boundary conditions** are based on the TPXO 7.2 dataset
- **Simulation time** is one year (2007) with a time step of 2 minutes.

An individual DDB model is generated within 10 minutes by using Delft Dashboard as a tool for pre-processing.

5.3 Goodness of fit criteria

The performance of the model in reproducing water levels is based on:

1. <u>Tidal propagation over the shelf</u>. A harmonic analysis is carried out on 258 altimeter points (TPXO 7.2), see Figure 5.2 (red circles). For this analysis the bias and RMSE of the tidal amplitude and phases are determined. The VD is determined to take into account frequency, since it describes the difference per constituent in modeled and observed amplitude and phase.
2. <u>Reproduction of in-situ observations.</u> A water level analysis is carried out on 23 in-situ stations, see Figure 5.2 (green circles). For this analysis the RMSE is determined. Note: processes likes wind-driven setup and set-down are taken out of the measured signal. This is both done for the DSCMv6 and DDB model.

One is referred to Section A for all the definitions and formulas.

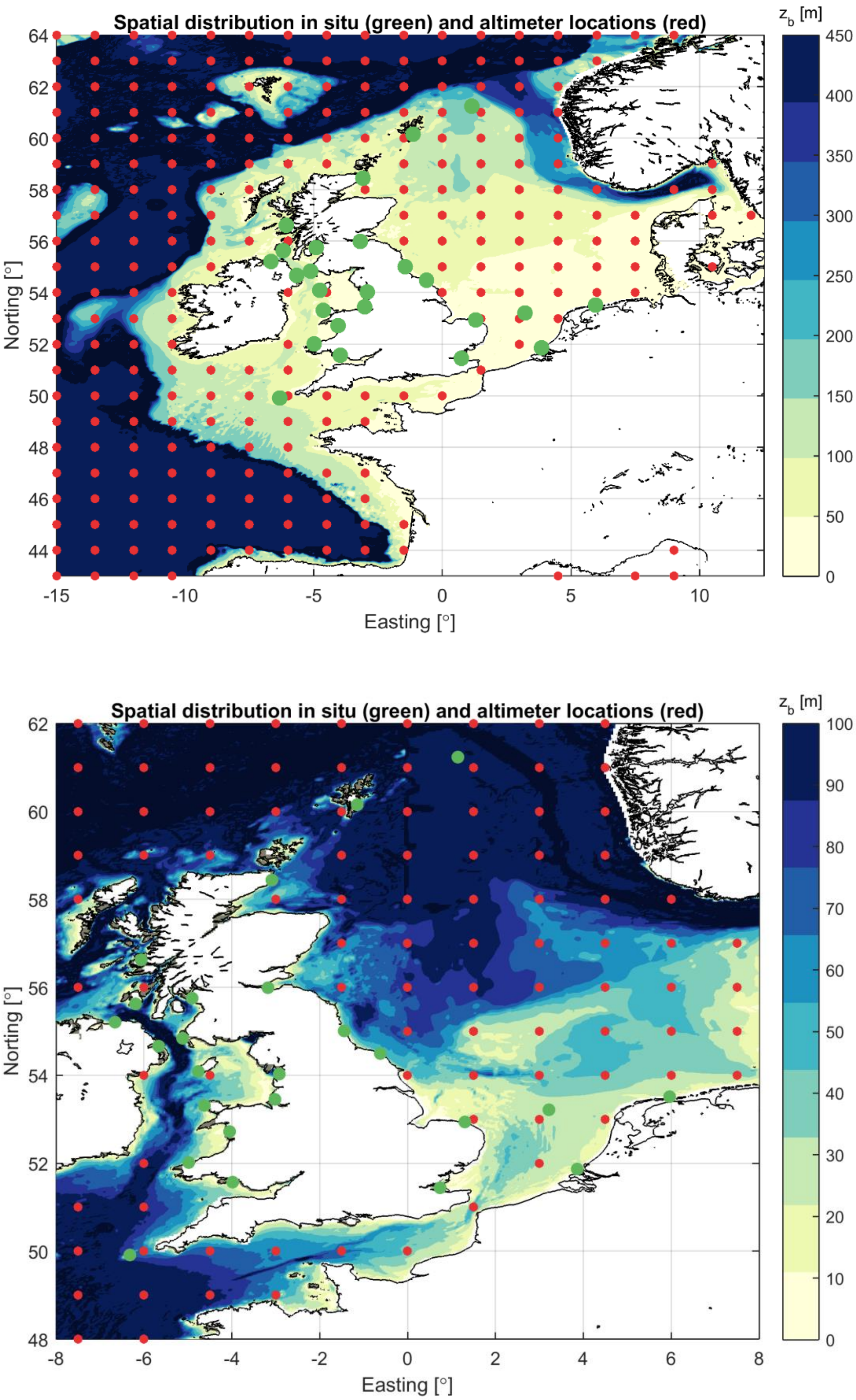


Figure 5.2 Model bathymetry (overview: upper panel; detail: lower panel) and spatial distribution of available in-situ (green) and radar altimeter locations (red). Positive values indicate the depth.

5.4 Analysis 1: reproduction tidal propagation over the shelf

Figure 5.3 shows the M2 amplitude (upper panel) and phase (lower panel) as calculated by the model created with DDB. The different constituents are determined via a Fourier analysis of the full time series of water level elevation and the colors (from white to black) indicate the value of, respectively, the amplitude in centimeters and phase in degrees. The circles indicate the results from the inverse tide model TPXO 7.2. The color difference between the colored field and circles can be used to assess the relative error made (i.e. qualitative evaluation). On top of that, the RMSE of the model for all circles is determined (i.e. quantitative evaluation). Since the tidal elevation in the North Sea is dominated by the M2 constituent, this section will focus on the results of this constituent.

In the model the M2 tidal wave travels in counter-clockwise direction along the Dutch coast, which is in agreement with literature (Pugh, 2004). The errors made are in the order of a few centimeters on the ocean and start to increase on the more shallow areas on the shelf. This is both the case for errors made in the amplitude and phase (i.e. phase errors in the order of a few degrees). One sees however that the large-scale characteristics of the tide in the northwest European shelf are well represented by the DDB model since there are hardly any color differences between the colored field and the colored circles. Close to the boundary, the errors are almost zero. This is logical since one is comparing the model with the imposed signal.

In general the model overestimates the amplitude of the M2 tidal wave. The error is the largest around Great Britain, since the tidal amplitude is the largest here too. Errors in phase are mainly made in the North Sea where the model is lagging compared to the TPXO results (i.e. phase is larger meaning the tidal wave arrives too late). Near Denmark, however, the phase starts to be leading compared to observations. This means the propagation speed of the M2 tidal wave is overestimated in the model.

Compared the model results of DSCMv6, the DDB model performs well. The M2 amplitude RMSE is similar (8.5 cm versus 6.4 cm), but the M2 phase RMSE is larger (21.3 degrees versus 5.1 degrees). The error in phase is directly related to the error made with the model bathymetry. DSCMv6 makes use of the NOOS bathymetric which is a dataset collected by all the national hydrographical offices and merged into one accurate bathymetric set. Additionally, the bathymetry has been locally deepened to reduce the errors made in the phase. In the DDB model only different open source data were combined. There was no tuning of the bathymetry involved. Amplitude errors are linked to the applied roughness. The DSCM v6 applies a spatial varying roughness value which is optimized with an open source data assimilation toolbox (openDA). In the DDB model one uniformly applied value of 0.028 $m^{1/3}/s$ is applied

For the other tidal constituents (i.e. K1, N2, M4), one sees a similar pattern as with the M2 tide where the errors in the amplitude and phase are only of a few centimetres and degrees. The amplitude errors are in the same order as DSCMv6. The phase errors are generally larger.

Figure 5.4 shows the VD for the M2 constituent (upper panel) and all constituents (RSS; lower panel). The VD can be used to evaluate the model performance in frequency space by applying both the observed and computed phase plus amplitude. Again, compared to the model results of DSCMv6, the DDB model performs fairly well. The largest difference is the error made in the M2 tidal wave (RMS VD of 13.4 cm compared to 7.8 cm; respectively for DDB compared to DSCMv6). The relative difference between the two models does not increase when all the constituents are taken into account (RMS RSS VD of 14.6 compared to 8.1 cm).

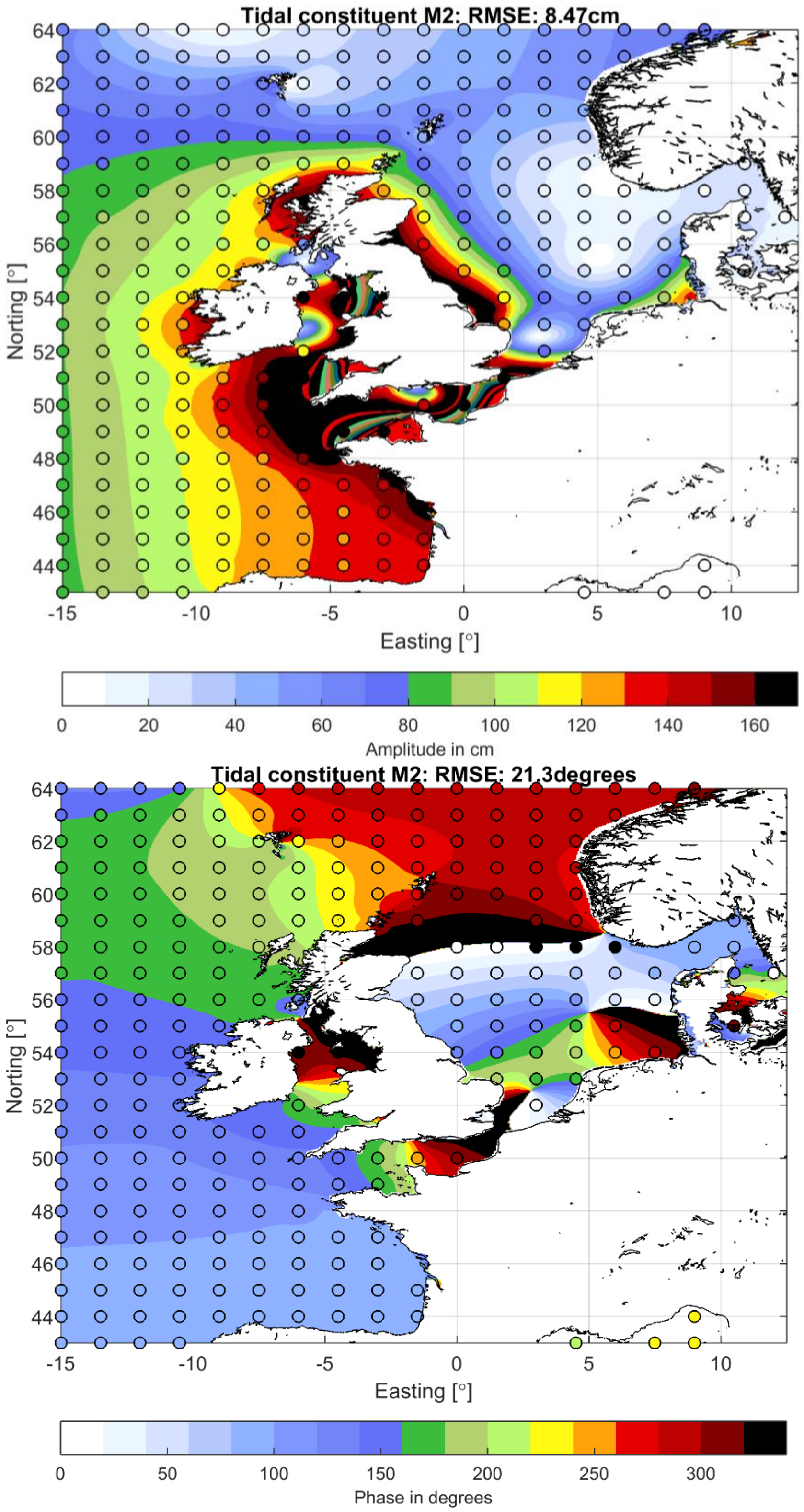


Figure 5.3 Reproduction of the M2 amplitude (upper panel) and phase (lower) with the 'standard' model setup. Circles are TPXO resuts.

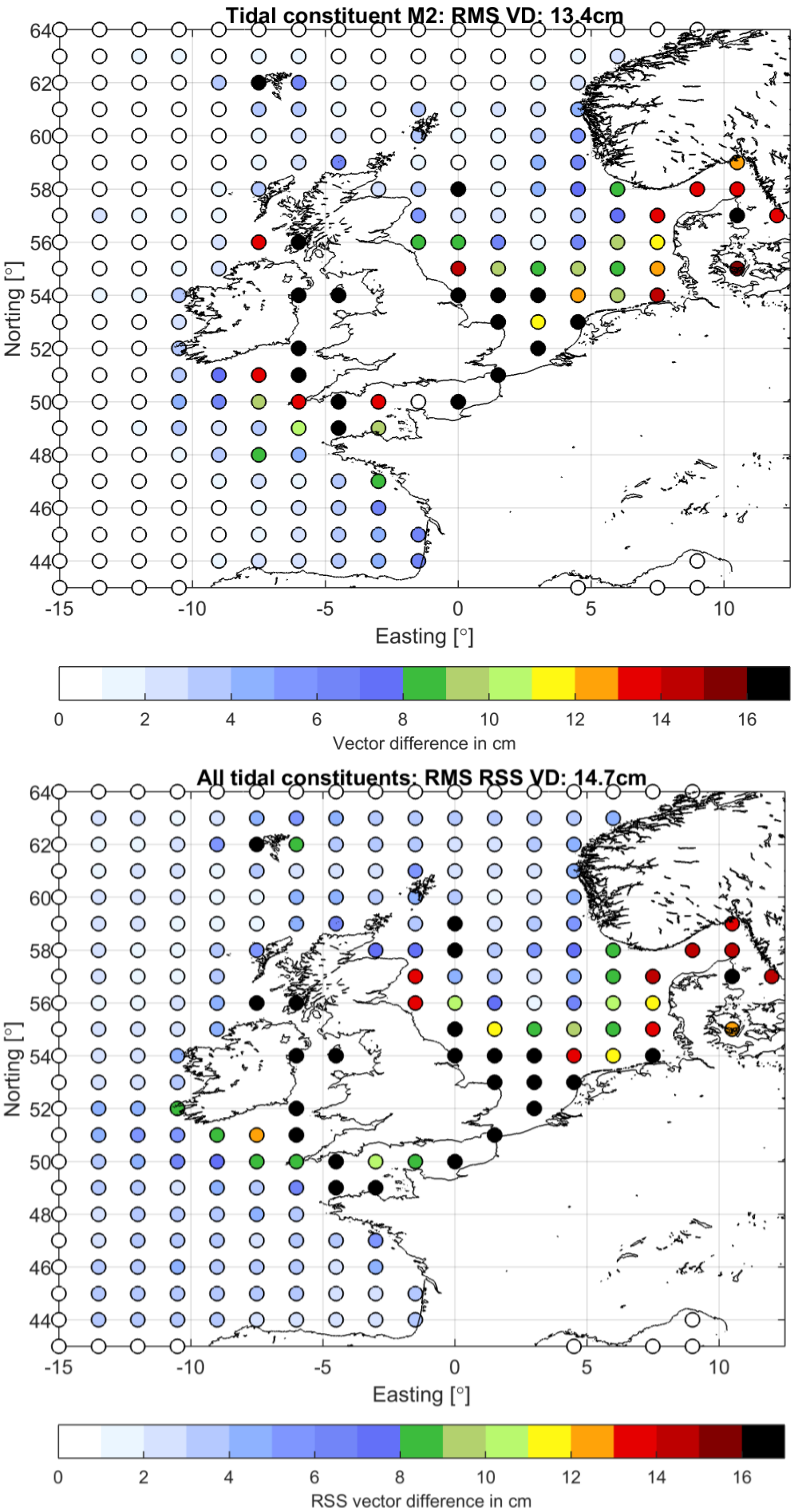


Figure 5.4 VD for the M2 tidal wave (upper panel) based on the difference between the model results and altimeter derived amplitude and phases. Lower panel the RSS VD over the available major tidal constituents.

5.5 Analysis 2: reproduction of in-situ observations

Eventually one would like to be able to reproduce the tidal movement at several locations. The error in the water level reproduction is determined by calculating the RMSE from the model compared to measurements from the full calendar year of 2007. Processes likes wind-driven setup and set-down are taken out of the measured signal, since this is not modelled either. The colors (from white to black) indicate the RMSE of each station in the DDB model. Moreover, all the errors are combined by calculating the average and the RMS.

The skill of the DDB model (and any model) depends on the location. Half of the stations (10 in-situ locations) are reproduced with a RMSE of less than 20 centimeters. However, there are also 3 stations where the RMSE exceeds 95 centimeters. This large RMSE is most likely related to the complexity of the bathymetry, geometry and roughness which are not captured well enough in the DDB model. It is argued that this could be related to either the model resolution (which is lower), the quality of the bathymetry or the constant bed roughness. Overall the RMSE for all the stations is 44.9 centimeters, however the tidal range is also a few meters.

Comparing the individual results with DCSMv6, one sees that the RMS of the RMSE of individual in-situ stations is 5.3 times higher for the DDB simulation compared to the state-of-the-art operational model (44.9 centimetres compared to 8.4 centimetres, respectively for DDB compared to DSCMv6). The error is driven by an incorrect reproduction of the M2 and S2 tidal wave. There is no clear pattern of over- or underestimation of the amplitudes. The differences vary locally. However, one could see a pattern of too low amplitudes near the Dutch coast, east part of Britain and near the Irish Sea. Near the Bristol Channel and Ireland, amplitudes are generally too low. This gives ideas where to calibrate the bed roughness. Something similar can be distinguished for the phases where, for example, the M2 tidal wave is lagging at Holland. For the full list of skill scores refer to Table 5.1.

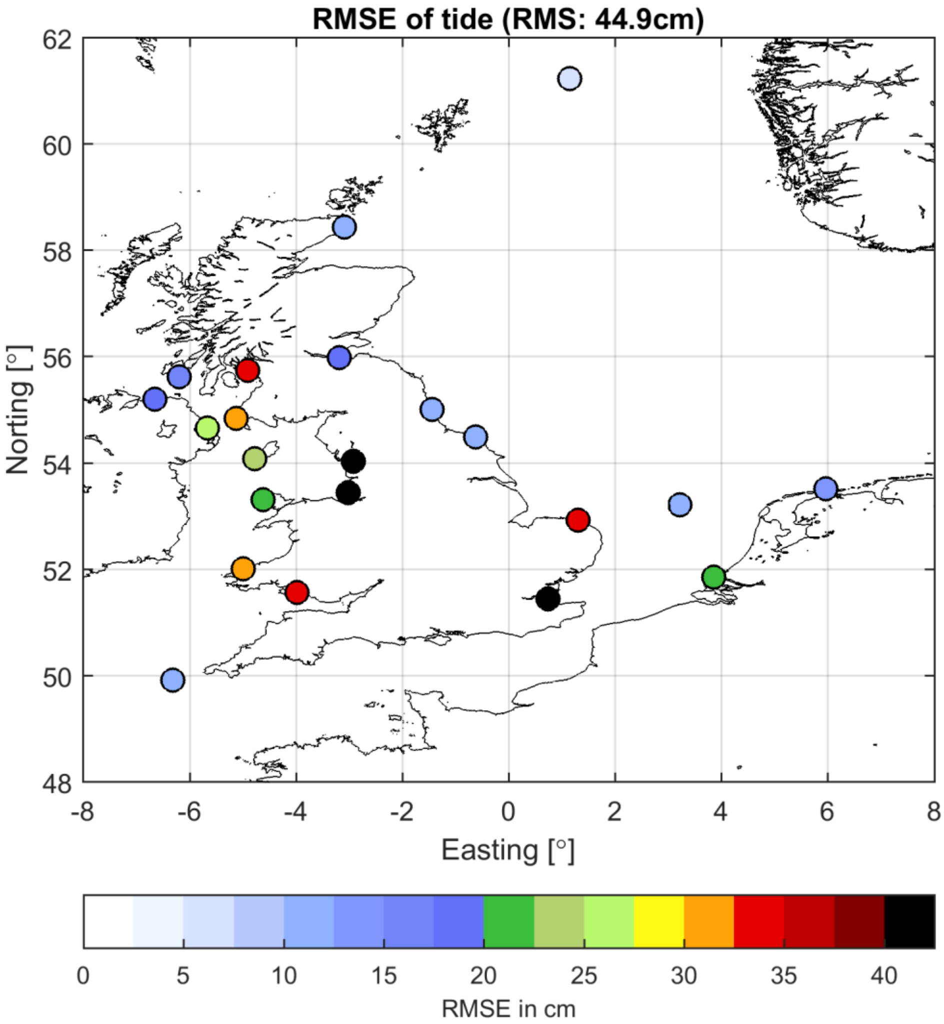


Figure 5.5 RMSE of the entire tidal signal for 23 in-situ observations for the ‘standard’ DDB model compared to a year of measurements in 2007.

Table 5.1 RMSE of the M2 amplitude, M2 phase, VD of M2, RSS VD and RMSE of tide

Station	RMSE of M2 amplitude [cm]	RMSE of M2 phase [degrees]	VD of M2 [cm]	RSS VD [cm]	RMSE tide [cm]
Bangor	35.8	8	37.9	42.9	30.5
Cromer	1.1	-16	41.9	48.8	34.7
Fishguard	-27.5	4	29.4	36.3	25.7
Heysham	37.8	-27	138.3	160.4	113.9
Holyhead	6.0	7	21.9	27.9	19.9
PortErin	34.1	1	34.2	39.3	28.0
PortEllen	-15.8	-50	24.1	28.4	20.1
Leith	-20.6	-4	24.5	31.9	22.6
Liverpool	32.7	-23	117.8	143.0	101.5
Millport	42.4	0	42.4	52.3	37.2
Mumbles,	-5.5	-5	29.5	42.5	30.1
Northshields	-9.6	-2	10.6	16.3	11.6
Portpatrick	44.8	0	44.8	49.8	35.4
Portrush	-16.9	17	24.1	28.3	20.0
Sheerness	41.2	-43	135.5	147.7	104.8
StMarys	0.9	-2	7.1	14.6	10.5
Whitby	-14.5	-3	16.3	21.1	14.9
Wick	-12.9	5	15.4	19.4	13.7
Haringvliet 10	4.3	-13	21.6	28.0	19.9
K13a platform	-0.1	-15	13.3	16.5	11.7
North Cormorant	-1.1	5	4.3	10.0	6.7
Wierumergronden	4.2	-9	14.3	20.1	14.3
K13a platform	-1.1	5	4.3	10.0	11.7
North Cormorant	4.2	-9	14.3	20.1	6.7
Wierumergronden	35.8	8	37.9	42.9	14.3
Mean	6.8	7.9	36.2	44.0	31.2 (7.5)
RMS			54.4	63.4	44.9 (8.4)

5.6 Analysis 3: resolution and bathymetric set

So far the simulations have been carried out with a bathymetry based on a combination between the Vaklodingen (Dutch bathymetry), EMODnet (Greater North Sea and Celtic Sea) and GEBCO. Surprising result is that only applying GEBCO results in a small increase of the RMS RSS VD on the shelf of 14.2 versus 14.6 centimeters compared to the combined bathymetric set. Apparently the accuracy of GEBCO is fairly high in this area. It is not an issue related to the resolution since the model has a resolution of 3 x 5 km and GEBCO a resolution of +/- 1 kilometer. Overall one can conclude that the tidal propagation is marginally similar between the two.

Differences start to emerge when looking at the reproduction of the in-situ measurements (Table 5.3). The mean RMSE at the in-situ stations increases from 31.2 to 42.9 centimeters. The model resolution of the DDB model is two times as coarse compared to DCSMv6, but refining the grid resolution to a similar resolution as DCSMv6 (i.e. 1/40° in east–west direction and 1/60° in north–south direction) results in a limited increase in model skill for the DDB model. The tidal propagation over the shelf decreases (e.g. mean RSS VD increases from 14.6 cm to 17.6 cm; see Table 5.2). However, the reproduction of the in-situ stations increases (e.g. RMSE of tide decreases from 31.2 cm to 28.6 cm).

Table 5.2 Mean skill scores for the tidal reproduction on the shelf

Criteria	DDB ‘Standard’	DDB ‘GEBCO’	DDB ‘Finer’
M2 amplitude [cm]	8.5	9.0	13.9
M2 phase [°]	21	18	19
VD of M2 [cm]	13.4	12.8	15.9
RSS VD [cm]	14.6	14.2	17.6

Table 5.3 Mean skill scores for the tidal reproduction of in-situ stations

Criteria	DDB ‘Standard’	DDB ‘GEBCO’	DDB ‘Finer’
M2 amplitude [cm]	6.8	21.0	-12.4
M2 phase [°]	7.9	3.4	12.5
VD of M2 [cm]	36.2	50.1	31.2
RSS VD [cm]	44.0	60.4	40.4
RMSE [cm]	31.2	42.9	28.6

5.7 Conclusion

Delft3D-FLOW models created with Delft Dashboard are capable of reproducing the tidal propagation on the continental shelf. The errors made in the phase are the most important driver for VD. For example for the M2 constituent: the amplitude error of the DDB model is 30% higher and the phase error is 200% higher than with DCSMv6. The general patterns of tidal propagation on the North Sea were still reproduced when running the DDB model with a different resolution or less detailed bathymetric datasets.

For the reproduction of the 10 in-situ observations, the differences between the DDB model and DCSMv6 increase. The RMSE of the water level is 3 to 4 times as high compared to DCSMv6. The error in amplitude and phase of the M2 tidal wave are the most important contributors to this error. There is no clear over- or underestimation and simply more detailed calibration is needed to improve the skill of the model. A DDB model with a finer resolution decreased the RMSE with 20%. For a DDB model with only the GEBCO bathymetry, the error increased with 40%.

6 Conclusions

Deltares has developed Delft Dashboard (DDB) as a tool for the rapid setup of coastal and estuarine hydrodynamic numerical models. However, it is not a priori known which settings to use in DDB and what the quality of a 'quick-and-dirty' model is. The central question of this study is: *What is the quality of a numerical model created with Delft Dashboard (DDB) in comparison to observations and/or other well-calibrated models in reproducing water levels and which settings in DDB should be applied to maximize the performance of the model created by DDB?*

Based on the three case studies presented in this study the following conclusions related to the two parts (i.e. 1) quality of the created model with DDB; 2) which settings should be applied in DDB) of the central question can be made.

6.1 Quality of a model setup made by Delft Dashboard

Numerical models created with Delft Dashboard have a good skill in the reproduction of the tidal propagation in the ocean or on the continental shelf. For example the combined error of amplitude and phases of all the constituents in the North Sea is the in order of 15 centimeters. This was in the same order compared to state-of-the-art, well-calibrated process-based models (+- 8 centimeters).

The reproduction of in-situ observations, which are usually obtained near the coast, is more difficult. This is typically related to errors in topography, bathymetry and roughness. For stations in larger oceanic basins, the model skill of a DDB model and a well-calibrated model is similar. For example the RMSE for in-situ observations in the Gulf of Mexico, the RMSE was in the range of 5 to 15 centimeters for both the DDB and the well-calibrated model. For in-situ observations on a more complicated (i.e. more shallow) shelf (e.g. the North Sea) the errors increased. The RMSE for the well-calibrated model varied between 10 and 20 centimeters. For the DDB model the error increased between 35-60 centimeters.

In order to improve the quality of the water level reproduction with a DDB model, the resolution can be increased and more accurate bathymetric information can be used. Note: GEBCO ’08 has a resolution of 1/20° x 1/20°. When using a dataset with a finer resolution, the model resolution can also be increased.

6.2 Recommendations regarding the use Delft Dashboard

It is recommended to define a model grid which is marginally larger (factor 1.5) than the area of interest. When making a grid smaller, the semi-diurnal constituents are generally not completely reproduced. When making a grid larger, the diurnal constituents will generaly be overestimated.

When applying Riemann boundaries the spin-up time can be reduced. The spin-up time between water level boundaries and Riemann boundaries can reach a factor of 8 to 10. It is not recommended to intersect islands, since this will increase the spin-up time. An intersection of islands does not affect the performance, however.

A good starting point will be to apply 1 to 5 Riemann boundary sections based on TPXO 7.2 with a resolution of 0.1 x 0.1 degrees, GEBCO bathymetry, Manning roughness of 0.02 $m^{1/3}/s$ and a time step of 2 to 5 minutes. Sometimes a higher/lower bed roughness or different (higher resolution) bathymetric datasets can result in a better tidal reproduction. However, which settings to use in Delft3D-FLOW and DDB strongly depend on the case study which is modeled.

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A Goodness of fit criteria

In order to evaluate the outcome of numerical models, an objective evaluation method is needed. According to Sutherland et al. (2004), performance of numerical models can be assessed by calculating the bias, accuracy and skill. In this section all the different equations used in this study are presented.

A.1 Time domain

To measure the performance of a model in the time domain, three evaluation criteria are used: R-squared (R2), bias and the root-mean-square error (RMSE).

The R-squared (R2) is a statistical measure of how close the model results are to the measurements. An R2 of 1 indicates that the model explains all the variability of the measurements. An R2 of 0 indicates that the model does not explain any of the variability. The R2 can be calculated with Equation (1.1) in which SSE is the sum of squared error, and SST is the sum of squared total.

$$R^2 = 1 - \frac{SSE}{SST} \tag{1.1}$$

The bias is the difference in central tendencies of the computed values (X) and the observations (Y). Bias is used for hydrodynamic models in order to analyze the systematic error. A positive bias means that the water is higher in the computed data set than the measurements. The bias can be calculated with Equation (1.2).

$$bias = \frac{1}{N}\sum_{i=1}^{N}(Y_i - X_i) \tag{1.2}$$

Accuracy can be seen as the average size of the difference between a set of computed values (X) and the observations (Y). A commonly used measure for accuracy is the RMSE which can be calculated with the equation below. Accuracy is mainly used for water levels. The RMSE can be calculated with Equation (1.3).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y_i - X_i)^2} \tag{1.3}$$

A.2 Frequency domain

For the assessment of tide representation, it is insightful to evaluate model performance in the frequency domain as well. Besides looking separately at amplitude and phase errors of individual tidal constituents, one can use a so-called vector difference (VD) to assess the combined effect of the errors made (Provost et al. 1995). The VD per constituent describes the difference per constituent in the modeled and observed amplitude and phase. To provide a combined picture of these errors, the root-summed-square (RSS) vector difference (over the eight main constituents) is also calculated. The VD can be calculated with Equation (1.4) in which Hc is computed amplitude, H0 is observed amplitude, Gc is computed phase and Go is observed phase.

$$VD = \sqrt{\left[H_c \cos G_c - H_o \cos G_o\right] - \left[\left[H_c \sin G_c - H_o \sin G_o\right]\right]} \quad (1.4)$$

The root-summed-square (RSS) vector difference can be calculated with Equation (1.5) in which

$$RSS = \sqrt{\sum_{i=1}^{n} \left|X_i\right|^2} \quad (1.5)$$

A.3 Averaging over data

Averaging over multiple data points is done both by simply taking the average or by calculating the root-mean-square (RMS) of the errors made. The RMS can be calculated with Equation (1.6) in which x are values and N are the number of values.

$$RMS = \sqrt{\frac{x_1^2 + x_1^2 + \ldots + x_n^2}{N}} \quad (1.6)$$