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Delft Dashboard: a quick set-up tool for hydrodynamic models

Maarten van Ormondt, Kees Nederhoff and Ap van Dongeren

ABSTRACT

The open-source program Delft Dashboard (DDB) is a graphical user interface designed to quickly create, edit input parameters and visualize model inputs for a number of hydrodynamic models, using private or publicly available local and global datasets. It includes a number of toolboxes that facilitate the generation of spatially varying inputs. These include new model schematizations (grids, bathymetry, boundary conditions, etc.), cyclonic wind fields and initial tsunami waves. The use of DDB can have significant benefits. It can save modellers considerable time and effort. Furthermore, the automated nature of both data collection and pre-processing within the program reduces the likelihood of errors that could occur when setting up models manually. Three case studies are presented: simulation of tides in the North Sea, storm surge and wave modelling under tropical cyclone conditions and the simulation of a tsunami. The test cases show that models created with DDB can be set up efficiently while maintaining a predictive skill that is only slightly lower than that of extensively calibrated models.

Key words | Delft Dashboard, GUI, hurricanes, hydrodynamic models, tides, tsunamis

Maarten van Ormondt (corresponding author)
Deltares, Marine and Coastal Systems,
Boussinesqweg 1, 2629 HV Delft,
The Netherlands
E-mail: *maarten.vanormondt@deltares.nl*

Kees Nederhoff
Deltares-USA,
8601 Georgia Ave #508, Silver Spring, MD 20910,
USA

Ap van Dongeren
Deltares, Marine and Coastal Systems,
Boussinesqweg 1, 2629 HV Delft,
The Netherlands

INTRODUCTION

High quality data, tools and hydrodynamic software are crucial in successfully executing hydraulic engineering and impact assessment studies (Van Koningsveld *et al.* 2010). These studies require data that is both spatially accurate and up-to-date and typically include bathymetric and/or topographic data, as well as boundary forcing data (e.g. tides and wind-generated waves) and atmospheric forcing data (e.g. wind and barometric pressure fields). Mesh generation tools are used to define the geometry, extent and resolution of hydrodynamic models. Various other pre-processing tools are often required to convert and interpolate raw data. Hydrodynamic model simulations themselves also produce output data in the form of time series or maps. These may serve to force nested models or be analysed and visualized using post-processing tools. In practice, modellers spend a significant amount of time and effort collecting input data from various sources and converting these to appropriate model formats. The manual nature of both data collection and pre-processing increases the likelihood of errors that may be reduced or eliminated by automation of the process. Another, equally important, advantage of automated input processing is that it can ensure reproducibility of research.

This automation has been achieved in Delft Dashboard (DDB), an open-source software package (under GNU (L) GPL license) to rapidly set up hydrodynamic and basic morphological numerical models. It should be noted that, whereas the DDB code is available as open source, the code is written in Matlab®, which is proprietary software that requires a license. DDB gives modellers the capability to set up and edit hydrodynamic models within minutes, for any location in the world. However, this effectiveness

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in terms of model generation does not release the user of the responsibility to construct a qualitative model (e.g. correct resolution for relevant physics, logical topographical location, etc.). DDB currently supports (but is in principle not restricted to) Delft3D (Lesser *et al.* 2004), XBeach (Roelvink *et al.* 2009) and WAVEWATCH III (Tolman 2009) software. DDB uses publicly available online datasets for bathymetry, topography and tidal constituents to generate model geometries (mesh and bathymetry files) and ocean boundary conditions. Additional toolboxes allow the modeller to force these models with parameterized cyclonic wind fields and initial tsunami waves, nest models in publicly available ocean models or force them with outputs from meteorological models. DDB supports most of the geographic and projected coordinate systems of the EPSG database (http://www.epsg.org/). Existing software systems that offer functionality similar to DDB include PCTides (Posey *et al.* 2008) and the Surface Water Modeling System (SMS; Aquaveo 2017). PCTides is a global, relocatable, tide/surge forecast system developed by the Naval Research Laboratory (NRL). It has a rudimentary graphical user interface (GUI) and supports only one two-dimensional (2D) barotropic ocean model. SMS (like DDB) does support a variety of different hydrodynamic solvers (such as ADCIRC, TUFLOW and STWAVE). SMS also offers post-processing functionality, whereas DDB mainly serves for model input preparation. Unlike PCTides and SMS, DDB is available as an open-source package. Additionally, DDB is directly linked to a large number of online available global and local bathymetry databases, and it offers a number of toolboxes (such as the Tropical Cyclone toolbox and Tsunami toolbox) not available in either PCTides or SMS.

In this paper, we first describe the different elements of DDB (user interface, supported models, data sources and toolboxes). Then, three case studies are presented that illustrate the use of DDB. The effectiveness and skill of model set-up with DDB are briefly evaluated. One case study focuses on a tidal propagation model in the North Sea; the second case study on the impact of Hurricane Ike in the Gulf of Mexico in 2008 and the third case study on the impact of the tsunami that resulted from the 2011 Tohoku earthquake. The model results will be validated against results from well-established models and against field observations.

METHODS

DDB, part of the OpenEarth initiative (De Boer *et al.* 2012), is a tool to quickly create, edit and visualize model inputs (grids, bathymetry, boundary conditions, etc.) for a number of hydrodynamic models, using publicly available datasets. It comprises a set of toolboxes that assist with these tasks. Its user interface and underlying functions were developed in Matlab®. An executable version that does not require a Matlab license® is available for Windows® operating systems and may be obtained from the DDB website (https://publicwiki.deltares.nl/display/DDB/Delft+Dashboard). The source code (SVN) and the user manual can also be found on this website. The software can run on any Intel or AMD x86-64 processor and requires at least 1 GB of RAM and 1 GB of disk space.

The user interface contains a top menu, a primary tab panel, an edit panel and a zoomable map (Figure 1). Different models, toolboxes, bathymetry datasets and coordinate systems can be selected from the top menu. The left-hand tab of the primary tab panel gives access to the selected toolbox, whereas the other tabs allow the user to edit specific model inputs in the edit panel. The map panel shows the selected bathymetry/topography data and can be used to interactively insert or edit specific data such as the extent of a new model by dragging a box over the area of interest, or the location of a cyclone track. For details on the use of DDB, we refer to the online user manual.

Models

The main purpose of DDB is to allow a modeller to create new or edit existing hydrodynamic model schematizations. The user can generate rectangular model grids or load in existing grids created with DDB or other grid generation software (e.g. RGFGRID (Deltares 2016)). DDB provides default values for all relevant input parameters (such as start and stop times, time step, open boundary types, bed roughness) that can be altered by the user in the GUI.

Currently, the following models are supported:

- Delft3D (Lesser *et al.* 2004). An open-source flexible integrated modelling suite for 2D (in either the horizontal or the vertical plane) and 3D flow, sediment transport and

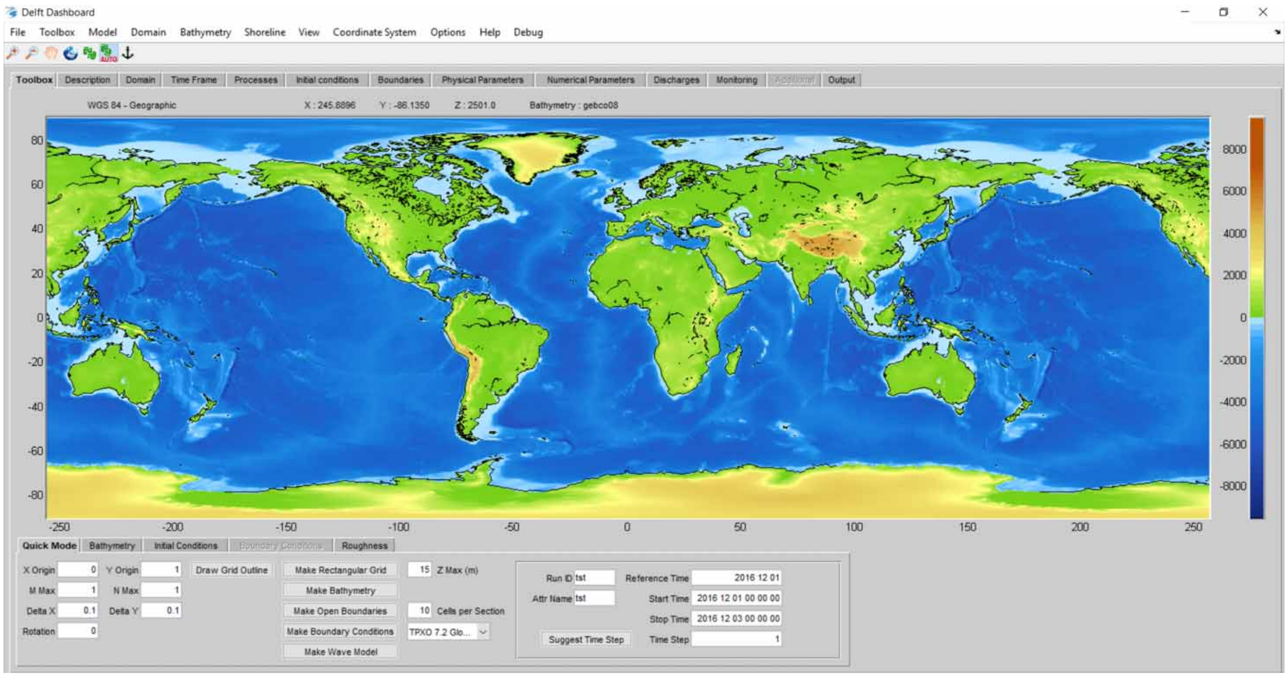

Figure 1 | DDB user interface. Ellipses indicate (a) top menu (yellow), (b) primary tab panel (green), (c) zoomable map (red) and (d) edit panel (blue). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/hydro.2020.092.

morphology, waves, water quality and ecology and is capable of handling the interactions between these processes. Delft3D-WAVE is a shell around SWAN (Booij *et al.* 1999). SWAN is a third-generation wave action model, which computes the wave action density in geographical, directional and frequency space.

- XBeach (Roelvink *et al.* 2009, 2017). An open-source 2D model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and back-barrier during storms.
- WAVEWATCH III (Tolman 2009). An open-source third-generation spectral wave model for simulating wave propagation on a global and regional scale.

The modular nature of the DDB code allows for the extension of the list of supported models. Extension with a new model typically requires programming the Matlab functions for reading and writing the relevant input files (grid, bathymetry, boundary files, etc.) for that model. Additionally, information needs to be provided (in XML format) on the position and type of GUI elements (edit boxes, popup menus, etc.) that are needed to manually edit input parameters.

Data

DDB uses online open-source datasets as input, which is stored in NetCDF (Network Common Data Form) files on the OPeNDAP (Open-source Project for a Network Data Access Protocol) server of Deltares. One advantage of NetCDF in combination with OPeNDAP is that it allows users to only extract the required data, thereby avoiding the need to download entire (large) data files.

For **bathymetric and topographic data**, DDB uses global (e.g. General Bathymetric Charts of the Ocean, GEBCO (http://www.gebco.net/) and Shuttle Radar Topography Mission 4.1, SRTM (http://www2.jpl.nasa.gov/srtm/)) and local datasets (e.g. Coastal Relief Model (https://www.ngdc.noaa.gov/mgg/coastal/crm.html)). Bathymetric data are stored on regular grids and are saved as tiles at increasing spatial resolutions. This approach has the advantage that data can be easily cached on the user's PC.

When zooming in or out on a specific area on the globe, DDB first checks whether the required tiles (those within the zoom area at the appropriate resolution) are already available in the cache on the user's PC. If not, these tiles are automatically downloaded to the cache from the OPeNDAP server. DDB subsequently reads the data from the required tiles in the local cache and merges these into a larger regular matrix (covering the entire zoom area) that is used for visualization. Users can also add their own datasets. In order to do so, the raw data has to be stored on a regular mesh (in either a geographic or projected coordinate system) in a commonly used file format (such as binary or ASCII ArcInfo grid or GeoTIFF). Metadata containing information on the horizontal coordinate system and the vertical datum needs to be provided. The bathymetry toolbox in DDB can tile the raw data and store these locally in NetCDF files.

Aerial imagery of Microsoft Bing Maps offers worldwide orthographic satellite, map and hybrid imagery. Coverage varies by a region, with the most detailed coverage in the USA and UK. Aerial imagery can also be exported for application in post-processing, e.g. in plotting model results on top of an aerial image. Aerial imagery is automatically adjusted to the selected coordinate system.

For **tidal information,** DDB uses inverse tide models like TPXO (6.2, 7.2 and 8.0) (Egbert & Erofeeva 2002) for global forecasting. **Observation data** in the form of tidal predictions based on a constituents database (e.g. IHO and XTide (http://www.flaterco.com/xtide/)), tide gauges (e.g. CO-OPS (https://tidesandcurrents.noaa.gov/)) and buoys (e.g. NDBC or DART (http://www.ndbc.noaa.gov/)) are also supported in DDB. Observational data can be downloaded and the stations can be added as observation points in the models.

Toolboxes

The data required to set up hydrodynamic models often come in a format that is not directly compatible with the model software. Modellers, therefore, typically spend a great deal of time and effort converting raw data. DDB provides a number of toolboxes to facilitate or fully automate this process.

The most important toolbox is the **Model Maker Toolbox**. It allows a modeller to select an area of interest, create a model set-up for that area and save all the model inputs that were generated in the process. The area selection occurs by dragging, moving and/or rotating a box on the map. Alternatively, the user may enter the values for box location, dimensions and rotation manually, which ensures that the exact same model set-up can be reproduced at a later stage. The user then needs to supply the required horizontal grid spacing (in metres or degrees, depending on the selected coordinate system) for the model grid. DDB can subsequently generate a rectilinear model grid within the box. Curvilinear grid generation is currently not supported by DDB, but it does allow for importing of such grids generated with other software packages. In the next step, DDB downloads bathymetric data from an OPeNDAP server (or read them from the local cache) at a model-appropriate resolution and interpolates these onto the model grid, using a bilinear interpolation method. The model bathymetry can be made up of data from one or more user-defined sources. The latter option is particularly useful when the highest resolution or most recent bathymetry dataset does not cover the entire model domain. For circulation models (currently Delft3D-FLOW and Delft3D-FM), the Model Maker Toolbox can also generate tidal boundary conditions. First, the boundary sections are automatically defined along the model grid's ocean-facing perimeter. Next, DDB downloads tidal constituent data (from the selected TPXO database) from the OPeNDAP server and interpolates these onto the boundary locations. For the creation of WAVEWATCH III models, DDB makes use of the Matlab grid generation scripts by Chawla & Tolman (2007) that include the effects of wave blocking by small islands not resolved in the model bathymetry.

Hydrodynamic simulations of water levels, currents and waves frequently involve the use of nested models. In this numerical technique, large-scale coarse models are used to generate boundary conditions for smaller but higher-resolution models that cover the area of interest. These boundary conditions can be time series of water levels and/or currents for circulation models, and time series of wave parameters (wave height, period and direction) or wave spectra for wave models. The typical procedure for nesting involves two steps. In step 1, output locations in the larger model need to be defined along locations of the boundary sections or points of the smaller model.

The simulation of the large model is then executed. In step 2, the boundary conditions for the smaller model are extracted from the output of the larger model. This step includes reading in the outputs and converting the data to a new boundary conditions file that is to be used by the small model. The **Nesting Toolbox** facilitates both nesting steps. Nesting is not limited to two models of the same type. It is, for example, possible to generate tide and surge conditions for XBeach from Delft3D-FLOW or wave conditions for Delft3D-WAVE from WAVEWATCH III.

Hydrodynamic models are often used to simulate storm surge or extreme waves under tropical cyclone conditions. Wind and atmospheric pressure fields associated with these extreme events may be directly obtained from numerical weather prediction (NWP) models. These are, however, not always available or they are too coarse to accurately describe the shape and size of a tropical cyclone. In those cases, storm surge modellers frequently resort to the use of cyclone track data in combination with parametric wind models to generate time- and space-dependent wind and pressure fields. The **Tropical Cyclone Toolbox** can be used to generate these, based on cyclone track data, and parametric wind field models. Currently, the wind profile relations of Holland (1980), Holland *et al.* (2010) and Fujita (1952) are implemented. DDB allows the user to create one's own hypothetical cyclone track or to download track data from a number of sources: the IBTrACS database (Knapp *et al.* 2010) that contains historical data from as early as 1848, as well as the latest forecasts from the Joint Typhoon Warning Center (JTWC), the National Hurricane Center (NHC) and the Australian Bureau of Meteorology (BoM). In order to generate wind and pressure fields, the parametric wind profile relations require at least the following data at each point along a cyclone track: time, position (latitude and longitude in degrees), maximum sustained wind speed V_{max} (in knots), radius of maximum winds R_{max} (in NM) and central pressure P_c (in Pa). Additionally, the wind speed radii of 35, 50, 65 and 100 knots (R35, R50, R65 and R100 in NM) may be provided for the four quadrants (NE, SE, SW and NW). If the Holland *et al.* (2010) wind profile is selected, this information is used in addition to V_{max}, R_{max} and P_c, which typically yields a more accurate representation of the storm size and asymmetry. The databases from which cyclone tracks can be downloaded do not contain information on R_{max} and P_c for each storm. When these values are missing, the user may choose to estimate them with empirical relations (Vickery & Wadhera (2008) for R_{max} and Holland (2008) for P_c). Asymmetry in the wind fields due to the forward motion of the storm is taken into account with the method of Schwerdt *et al.* (1979). The Tropical Cyclone Toolbox creates wind and pressure input files in the native format of the selected model. For Delft3D-FLOW, the data are written to a so-called spider web grid, i.e. radial grid that moves in time with the eye of the cyclone. For WAVEWATCH III, they are written to file on a regular grid.

The **Tsunami Toolbox** can be used to generate an initial tsunami wave for Delft3D-FLOW models using the method of Okada (1985). For each fault line segment, the Okada model requires the earthquake parameters: width (in km), depth (in km), dip (in degrees), slip/rake (in degrees) and slip (in m). The user can define the location of an earthquake along a fault line by clicking one or more fault line segments on the map. The magnitude of the earthquake (in Mw) can either be specified as input data based on information provided by USGS (https://earthquake.usgs.gov/earthquakes/map/) or GfZ (http://geofon.gfz-potsdam.de/eqinfo/eqinfo.php) on which the fault area dimensions can be determined using different relations that have been published in the literature (Wells & Coppersmith 1994; Papazachos *et al.* 2004). Optionally, one can manually adjust the fault area dimensions and the associated slip (in m) on which DDB will determine the earthquake magnitude using those same relations referred to above. Also, the earthquake parameters (slip, strike and rake angles) can be manually adjusted by the user. All fault segment inputs can be stored in a text file that can be read in at a later stage in order to ensure reproducibility. Using the fault segment data and Okada (1985), DDB computes a spatially varying vertical water level displacement along each fault segment. This information is then interpolated onto the Delft3D-FLOW grid, resulting in an initial conditions file of water levels for the model that includes the initial tsunami wave.

The **Meteo Data Toolbox** allows for easy downloading (e.g. from NOAA's NOMADS servers (http://nomads.ncep.noaa.gov/)) of weather data such as wind speeds, atmospheric surface pressure, precipitation, solar radiation, cloud coverage, relative humidity and surface air temperature.

These are model output parameters typically produced by meteorological models. The downloading is done by dragging a bounding box on the map over the area of interest and providing a start and stop time for the data to be downloaded. The data are first downloaded and stored on the user's PC in binary MAT files (native Matlab format). The user can subsequently use this toolbox to convert these data and create atmospheric forcing files in the native format of the selected model (Delft3D or WAVEWATCH III). The list of available weather data for downloading is continuously evolving and currently includes the Global Forecast System (GFS; Moorthi *et al.* 2001) by NOAA and North European High Resolution Limited Area Model (HIRLAM; Källén 1996) by the Dutch meteorological service KNMI.

Similarly, the **Ocean Models Toolbox** enables the user to download 3D data (surface elevation, current velocities, salinity and temperature) from ocean models (HYCOM; Bleck 2002) and convert these to initial and boundary conditions for Delft3D models. The coverage consists of the entire database of HYCOM experiments (http://tds.hycom.org/thredds/catalog.html).

The **Tide Stations Toolbox** and **Observation Stations Toolbox** allow the user to quickly include existing tide stations and wave buoys as observation points in the models. Additionally, the Tide Stations Toolbox provides online access to XTIDE and IHO tide databases, which contain tidal constituents for thousands of stations around the globe. It can be used to generate time series of predicted water levels for a selected station over a user-defined time interval (using the T_TIDE libraries of Pawlowicz *et al.* 2002) and store these in a number of file formats. Similarly, the Observation Stations Toolbox allows the user to download historic and current observational data from CO-OPS (https://tidesandcurrents.noaa.gov/) and NDBC (http://www.ndbc.noaa.gov/) servers. Time series of both predicted water levels and observations can then be used for model validation.

RESULTS

Case study: tidal propagation in the North Sea

In this case study, we demonstrate the skill of a DDB-generated model in reproducing the tidal hydrodynamics compared against observations. The spatial pattern of the M2 tide is characterized by three amphidromic points, one located in the Southern Bight (between Holland and Belgium) and two in the main basin (Dyke 2007).

The Delft3D model (Figure 2) created with DDB contains 500×630 grid cells and has a resolution of 0.05 by 0.033° (~5 by 3.3 km). The bathymetry is based on Vaklodingen (https://svn.oss.deltares.nl/repos/openearthrawdata/trunk/rijkswaterstaat/vaklodingen/), European Marine Observation and Data Network (EMODnet (http://www.emodnet.eu/)) in combination with GEBCO. Areas below mean sea level (e.g. large parts of The Netherlands) have been excluded from the model.

The model is forced along the sea boundaries with astronomical boundary conditions from the TPXO 7.2 database. Tide-generating forces in the model are activated. The simulation is started with a constant water level at mean sea level (MSL) and runs with a constant Manning roughness coefficient of 0.028 $s/m^{1/3}$ for the duration of 1 year (2007) with a time step of 2 min. The performance of the DDB-generated model and the DSCMv6 model in reproducing the tidal propagation is evaluated by comparing the computed versus the predicted tidal harmonics at 258 TPXO points (pink dots in Figure 2). Moreover, validation of seven water level stations around the North Sea is presented (orange dots in Figure 2). These stations are Northshields, Whitby, Wick, Haringvliet, K13A platform, North Cormorant and Wierumergronden.

The computed M2 amplitude and phase (Fourier analysed from the DDB-generated model results) agree well with the TPXO 7.2 predictions (Figure 3). The mean absolute error (RMS) amplitude errors determined at each of the observation points are in the order of a few centimetres in the ocean and start to increase on the more shallow areas on the shelf. Similarly, the phase errors are in the order of a few degrees. The largest phase deviation occurs in the North Sea where the model is lagging compared to the TPXO observations. Near Denmark, however, the phase starts to be leading compared to observations. For the other tidal constituents, similar patterns as for the M2 tide are observed. The overall M2 amplitude RMSE is 8.5 cm and the phase RMSE is 21°.

Amplitude and phase errors are in the order of a few centimetres and degrees. The average RMSE amplitude

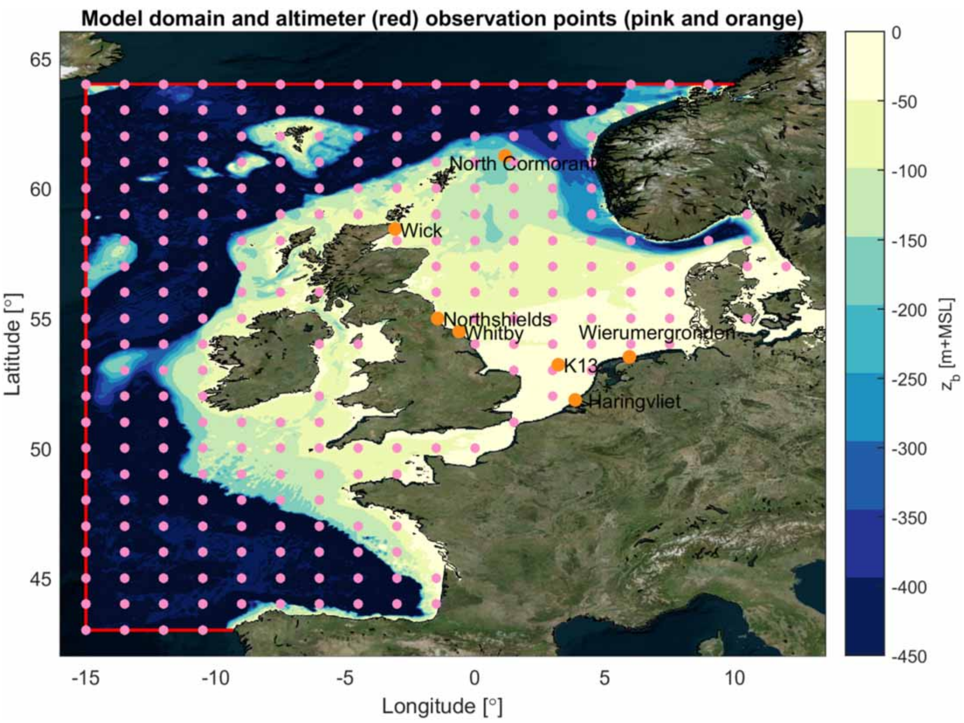

Figure 2 | Model domain, bathymetry, model boundary (red line), the spatial distribution of radar altimeter locations (pink dots) and water level gauges (orange dots). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/hydro.2020.092.

and phase errors for the seven observation stations are given in Table 1. Amplitude errors for the DDB-generated model are in the same order as for other numerical models (e.g. O'Dea *et al.* 2012). O'Dea *et al.* (2012) report amplitude errors of 10–2 cm and phase errors of 15° and 17° for, respectively, M2 and K1.

This validation shows that a DDB-generated model, even without any calibration, can reproduce the complex tidal dynamics in a shallow shelf sea reasonably well. It can, therefore, be a viable alternative in tide-dominated shelf seas where a well-calibrated model is not available.

Case study: Hurricane Ike

Here, we will analyse the performance of a Delft3D model made by DDB in reproducing the storm surge and wave heights during Hurricane Ike (2008). Several previous modelling attempts of Hurricane Ike have been carried out (e.g. Hope *et al.* 2013; Huang *et al.* 2013; Veeramony *et al.* 2017). In this section, the DDB simulation, forced with a parametric wind field, will be compared against field observations and a DDB simulation forced with wind and pressure field based on data assimilation techniques.

Hurricane Ike struck the Texas coast near Galveston on 13 September 2008. Despite being 'only' a category 2 hurricane, its large size in combination with the broad continental shelf resulted in high surge levels that impacted over 1000 km of coastline (Hope *et al.* 2013). At landfall, the surge reached its peak in excess of 5 m approximately 50 km east of Galveston. The storm's most intense winds to the east of the eye produced significant wave heights in excess of 10 m.

The coupled Delft3D-FLOW/WAVE models created with DDB are a basin model (178 × 128 grid cells, Figure 4(a)) and a nested coastal model (461 × 301 grid cells, Figure 4(b)) with spatial resolutions of 0.1° (~10 km) and 0.02° (~2 km), respectively. The model bathymetries are compiled with data from Southeastern Universities Research Association, SURA (http://gcoos.tamu.edu/)), Coastal Relief Model and GEBCO.

The Delft3D-FLOW model is forced with tides from TPXO 7.2 at its open boundaries. Wind forcing and atmospheric pressure are provided by a parametric hurricane

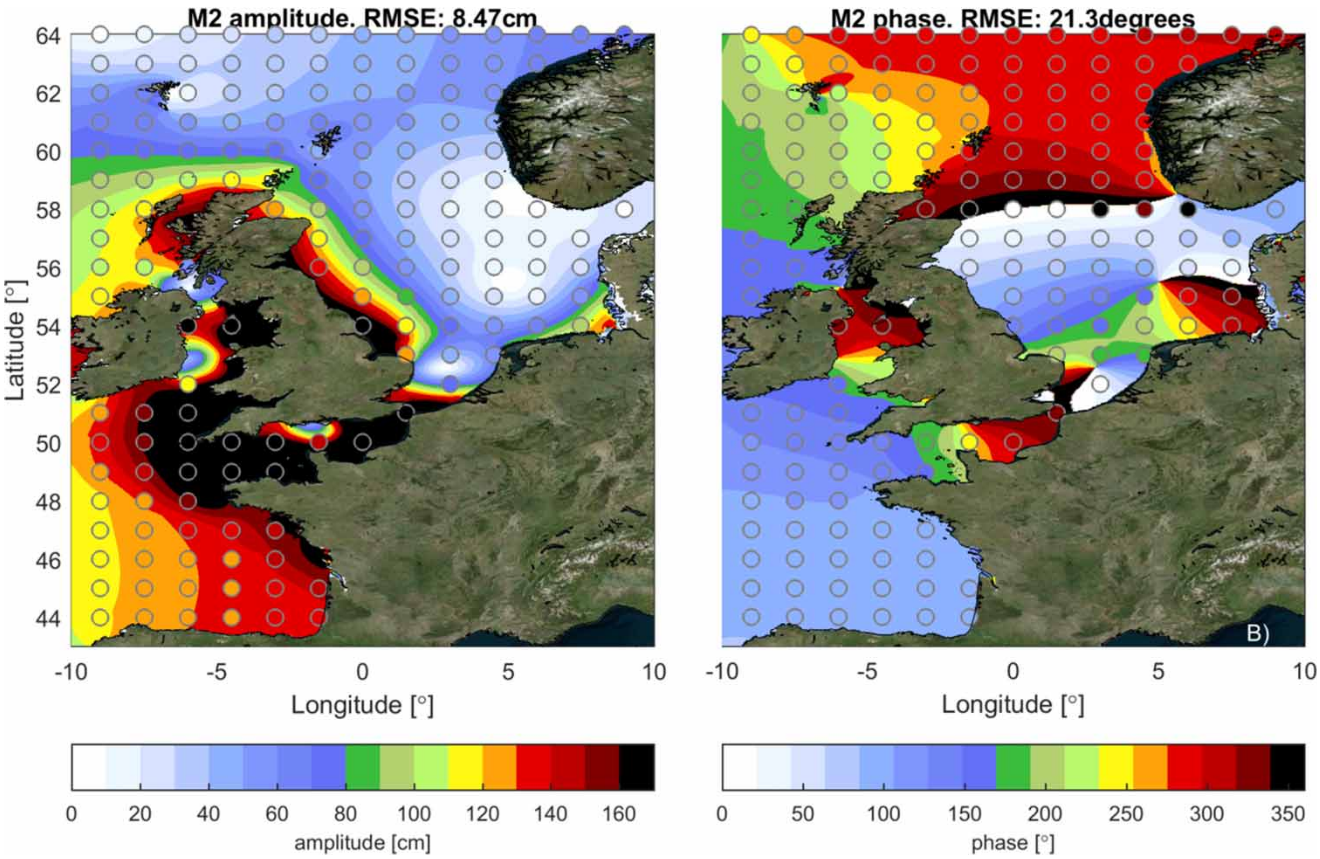

Figure 3 | (a): Computed and TPXO predicted (in circles) M2 amplitude. (b): Computed and TPXO predicted (in circles) M2 phase.

Table 1 | Mean tidal amplitude and phase errors at seven stations for semi-diurnal components

Constituent	Amplitude error (m)	Phase error (°)
M2	0.085	21
N2	0.017	11
S2	0.027	13
K2	0.092	21

model. The wind drag relation of Vatvani *et al.* (2012) is applied. A uniform Manning roughness of 0.012 $s/m^{1/3}$ (characteristic for the muddy bottom of the shelf) is applied in open waters. This relatively low friction was found to be critical for developing the fast flows that generated the large forerunner observed during the storm (Kennedy *et al.* 2011). The simulations run from 8 September 2008 until 15 September 2008 with time steps of 2 min (overall domain) and 0.5 min (detail domain). Delft3D-WAVE (SWAN) is run in a non-stationary mode. Wave forces are computed based on radiation stress gradients. Coupling between Delft3D-FLOW and Delft3D-WAVE occurs at 30-min intervals. At these coupling intervals, the FLOW model passes water level, current and wind data to the WAVE model. The WAVE model passes wave forces and wave orbital motion to the FLOW model.

NDBC wave and wind data (circles in Figure 5(a)) are used to validate the model's ability to reproduce observed wave and wind characteristics. Water level observations from NOS stations and temporary USGS gauges are used to validate the model performance in reproducing tide and surge levels (circles in Figure 4).

After setting up the hydrodynamic models, a parametric wind field is generated by DDB using the methodology of Holland *et al.* (2010). Best track data from the HURDAT2 database (Landsea *et al.* 2015) are downloaded by DDB and used to provide the necessary inputs for the Holland

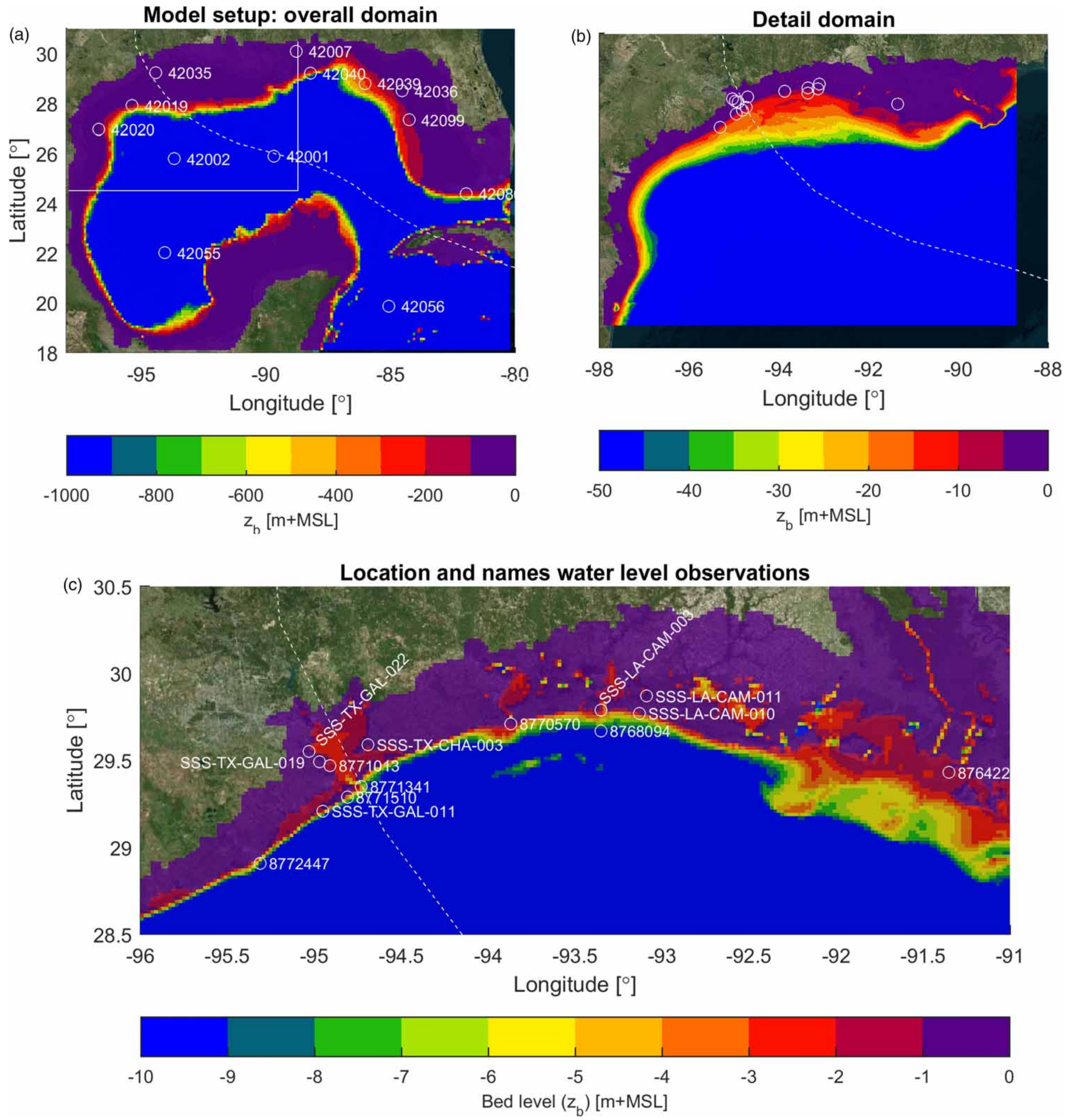

Figure 4 | Model bathymetry (overall model: (a); detail model: (b)) and the location of NDBC wave buoys (a) and water level stations (b). Names of the water level stations are shown in (c).

wind profile. The resulting time-varying wind and pressure fields serve as input to the hydrodynamic models.

In the remainder of this section, the simulation results from the DDB model are compared against field observations and against the results obtained from a reference model forced with a wind and pressure field created based on data assimilation techniques (Veeramony *et al.* 2017). This latter wind field is created by NOAA's Hurricane

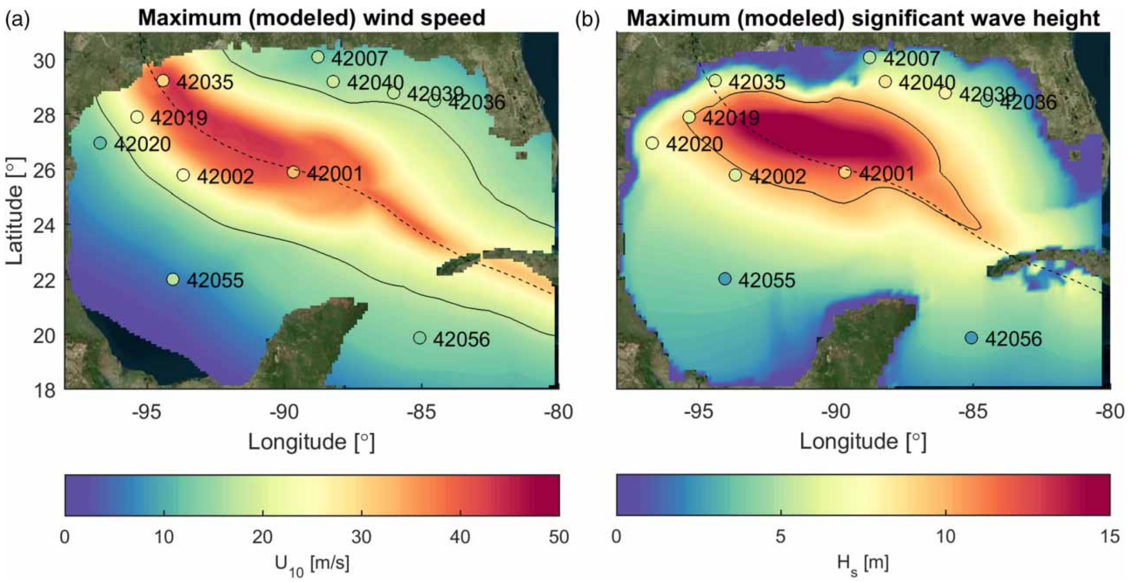

Figure 5 | (a) Maximum (modelled) wind speed during Hurricane Ike (2008). Circles are NDBC observations. The dashed black line is the track of Hurricane Ike. The solid black line is 35 knots (17.47 m/s) contour. (b) Maximum (modelled) significant wave height during Hurricane Ike (2008). Circles are NDBC observations. The dashed black line is the track of Hurricane Ike. The solid black line is 10 m wave height contour.

Research Division Wind Analysis System (H*WIND, Powell *et al.* 2010) and is considered a more accurate description of the wind and pressure fields in hurricane conditions.

The maximum wind speeds in the parametric model are overestimated with respect to NDBC observations (e.g. 42035 and 42001 in Figure 5(a)), suggesting a mismatch between the buoy observations and the HURDAT2 database. The far-field wind structure appears to be reproduced more accurately, as further away from the hurricane eye maximum observed wind speeds are similar compared to the modelled wind speeds.

The wind speeds near the radius of maximum winds are overestimated, resulting in overestimation by the model of significant wave heights in deep water near the eye of the hurricane compared to the buoy data (Figure 5(b)). In the north-eastern Gulf, however, shallow water NDBC buoys 42035 and 42020 recorded significant wave heights of 6 m which is similar to the computed wave height.

The observed time series (Figure 6) of wave height, period and direction are fairly well reproduced, although for buoys 42001 and 42019 the wave height is significantly overestimated, which is again attributed to the wind speed overestimation. Computed patterns in wave heights, wave periods and directions are similar to those computed by the reference model.

The maximum water level, as computed by the DDB-generated model, is presented in Figure 7. The circles in this figure indicate observed high water levels from the 7 NOS and 59 USGS stations. In marshes and wetlands around the Mississippi Delta (8764227), the low surge levels (±1–2 m) are reproduced correctly. Closer to the location of landfall, just east of Galveston Bay, the surge is underestimated by the DDB-generated model by 0.5–1 m. The computed peak water level here is around 4.5 m + MSL, whereas data from the temporary USGS gauges show peak water levels of 5–5.5 m + MSL in this area. The forerunner surge west of the hurricane eye towards Freeport is underestimated, but the model does reproduce the correct water level (limited surge) further away from the eye at Matagorda Bay. For all gauges combined, the model with parametric wind forcing shows a bias of −0.36 m (indicating underestimation of the surge) and an RMSE of 0.67 m. When forced with H*Wind, the model results improve (bias: 0.05 m, RMSE: 0.57 m).

In Figure 8, the water level time series at 14 permanent and temporary gauges are presented of the observations and both the DDB and reference models. In general, both models are capable of reproducing the time of maximum surge during landfall. The results of the DDB model are similar to those of the reference model, indicating that the

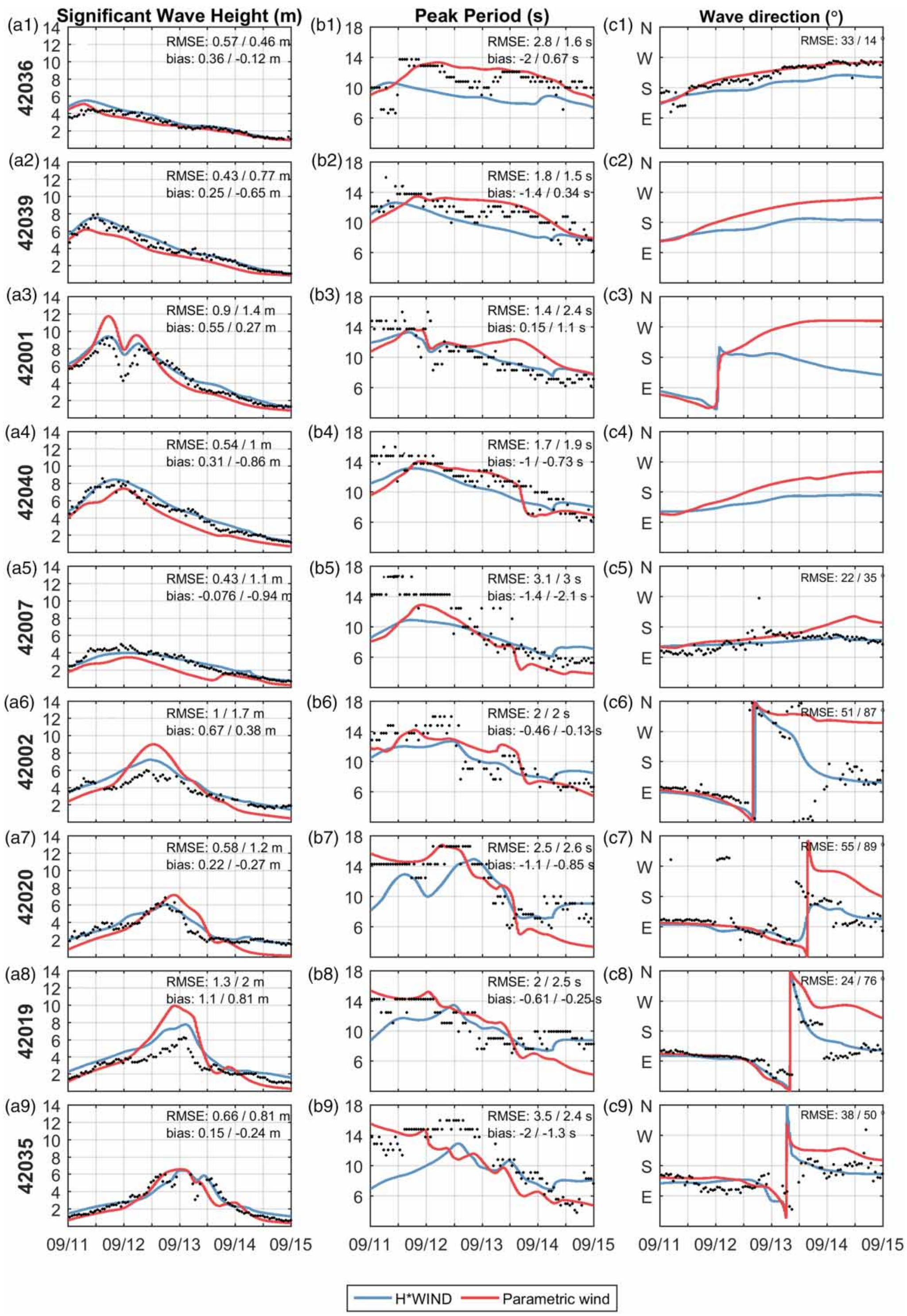

Figure 6 | Time series of wave heights (left panel), peak wave period (middle panel) and wave direction (right panel). Results from the reference model are indicated in blue. The DDB model results are indicated in red. Skill scores in each panel are calculated using the reference and DDB model, respectively. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/hydro.2020.092.

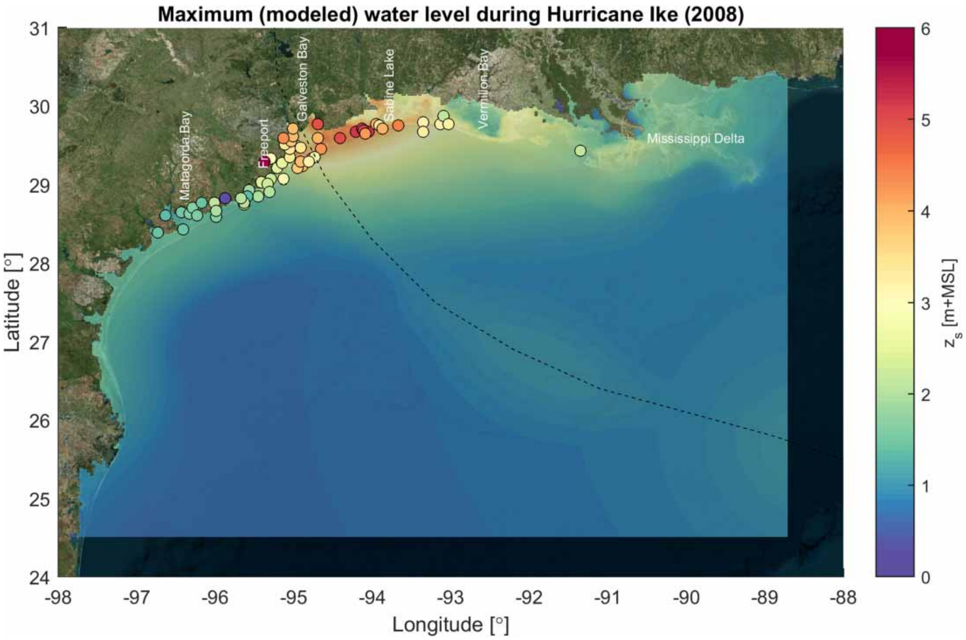

Figure 7 | Maximum (modelled) water levels during Hurricane Ike (2008). Observations (NOS and USGS) are indicated as circles. The dashed black line is the track of Hurricane Ike.

parametric wind model based on Holland *et al.* (2010) yields a reasonable representation of the actual wind fields. The reference model with analysed winds does show somewhat better error statistics. Averaged over all stations, the DDB model has an RMSE and bias of 76 and −38 cm compared to 55 and −8 cm for the reference model. The largest errors in both models are made inside Galveston Bay, e.g. at stations TX-GAL-022 (DDB RMSE: 110 cm compared to 63 cm), TX-GAL-011 (DDB RMSE 130 cm compared to 82 cm) and TX-CHA-003 (DDB RMSE: 120 cm compared to 98 cm). This is largely attributed to the relatively coarse spatial resolution of the models (~2 km), which is insufficient to resolve the complex geometry of the bay.

The results of this case study show that the DDB-generated model has reasonable skill in predicting both offshore wave characteristics and surge levels at the coast. Somewhat better results are however obtained when (more accurate) analysed wind fields are applied. Both models perform well at the NOS stations that are situated along the open coast (left column in Figure 8). At the inland USGS gauges (right column in Figure 8), the performance is less good. The relatively coarse resolution of the models limits the models' ability to correctly reproduce surge levels at the inland USGS water level gauges. This is not so much a limitation of DDB (which does allow for the set-up of higher-resolution models), but the result of choices made by the modellers when setting up this experiment.

Case study: tsunami modelling of the Great Tohoku Earthquake

In this case study, we investigate the performance of a Delft3D model made by DDB in reproducing the tsunami amplitude and inundation after the Great Tohoku Earthquake in Japan. The Tohoku earthquake occurred on 11 March 2011 with a magnitude of 9.1 on the moment magnitude scale (Mw). It resulted in a devastating tsunami that had a dramatic impact in terms of lives lost and property damage.

The Delft3D models created with DDB are an overall model of part of the Pacific Ocean and land measuring 951×782 grid cells with a resolution of 0.05° (approximately 5 km) and a nested detail model of 1002×402 grid cells for the inundation (both shown in Figure 9). The bathymetry and topography are based on GEBCO (below MSL) and SRTM (above MSL). The model is forced from an initial water level displacement generated by the earthquake. Riemann boundaries are applied in order to absorb any

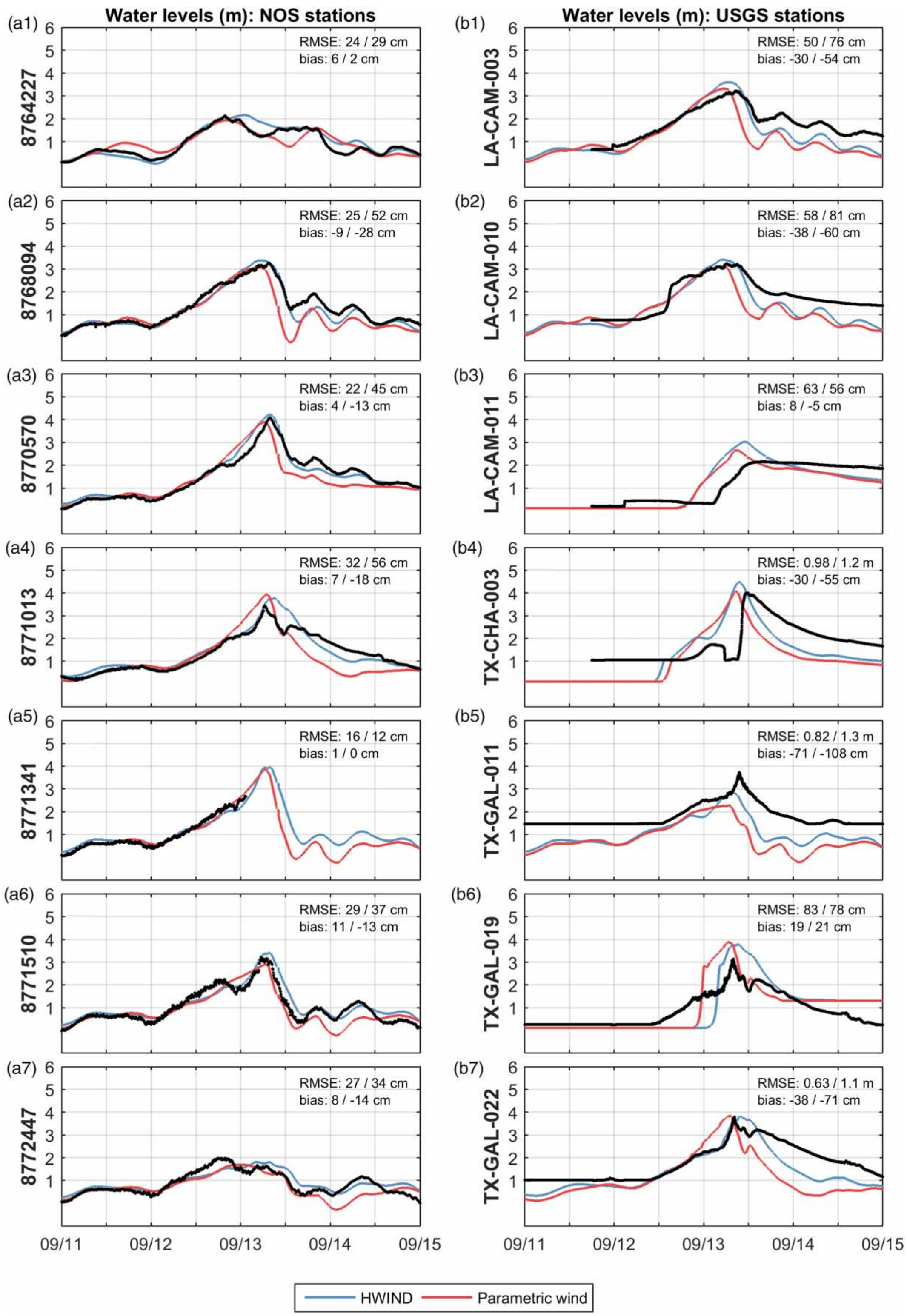

Figure 8 | Time series of surge (water level in m + MSL). The reference model results are indicated in blue, the DDB model results are given in red. The skill scores in each panel are calculated using the reference and DDB model, respectively. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/hydro.2020.092.

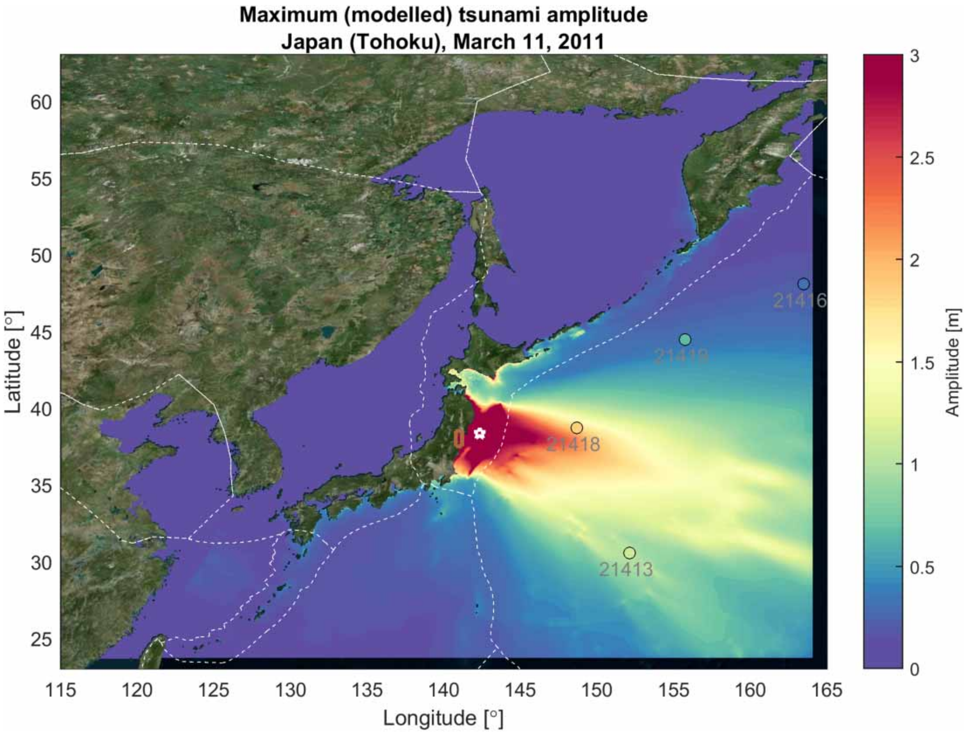

Figure 9 | Maximum computed water level above MSL. Circles indicate maximum tsunami amplitude observed by the DART buoys. Also shown are the tectonic plates (dashed white) and epicentre earthquake (white star). Detail (inundation) model outline is shown in brown. Slip varies between 0 and 20 m; Depth = 22.9 km; Width = 149 km; Dip = 10; Rake = 88 and Magnitude = 9.1 Mw. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/hydro.2020.092.

outgoing waves at the open seaward boundaries. A spatially varying Manning roughness of 0.020 below MSL and 0.04 above MSL (characteristic of developed land) is applied. The simulation starts with a constant water level (at MSL) and runs for 7 h with a time step of, respectively, 0.5 and 0.05 min. The time step of 0.5 min is applied in the overall model to accurately describe the propagation of the tsunami on deep water. A time step of 0.05 min is applied in the detailed model to ensure numerical stability.

The initial water displacement as a result of the earthquake is generated with DDB using the Okada model (1985). The Okada model is a set of analytical expressions to calculate the surface deformation (in two dimensions, x and y) due to fault displacement. Input parameters in DDB are provided along the fault line. In this application, the depth, strike, dip and width are kept constant. The slip varies with the fault line based on averaging the slip of Shao *et al.* (2011) along the fault line.

The performance of the model in reproducing the tsunami (amplitude over time) is assessed at 4 Deep-ocean Assessment and Reporting of Tsunami buoys (DART (https://www.ngdc.noaa.gov/hazard/dart/2011honshu_dart.html)). The inundation is compared at 620 high water marks (Mori *et al.* 2011) at Sendai.

The initial pulse at the epicentre propagates outward as a radial wave in a north-westerly to the south-easterly direction (Figure 9). Maximum water levels at the fault line are 7–8 m (based on the Okada model) resulting in a tsunami amplitude at the coast of Japan around 10 m, which is consistent with other modelling attempts (e.g. Løvholt *et al.* 2012 or Yamazaki *et al.* 2013).

In general, the model is capable of reproducing the instance and amplitude of the tsunami wave (Figure 10). Water levels at DART buoys 21418 and 21413 are well reproduced in height and period. DART buoys 21419 and 21416 are underestimated in amplitude. For an exact reproduction of the tsunami wave (both in amplitude and in period), the exact rupture is of importance which cannot be created with the Okada model, but rather a finite-fault rupture model should be used as demonstrated by Yamazaki *et al.* (2013).

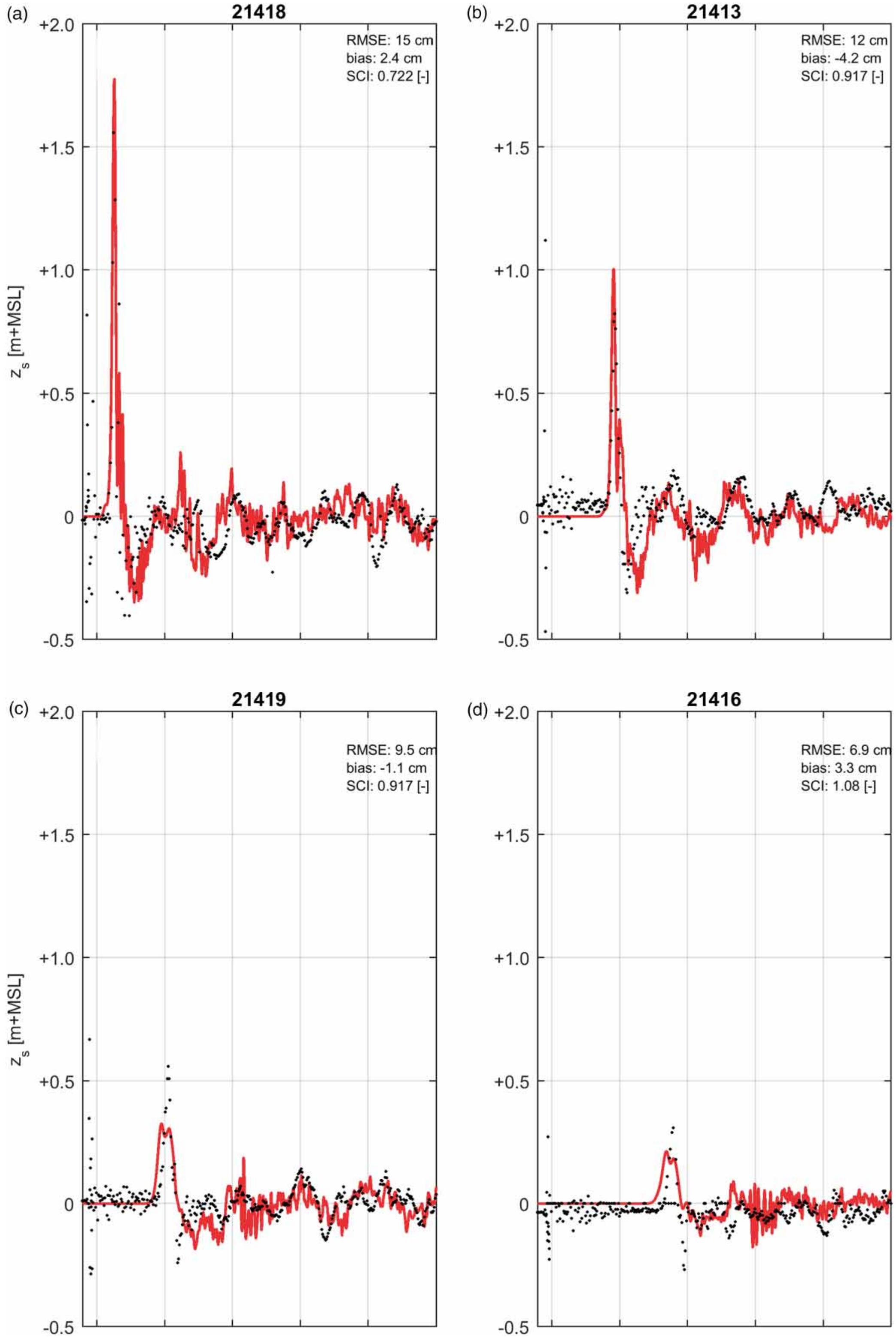

Figure 10 | Time series of the tsunami amplitude over time at DART buoys 21418 (a), 21413 (b), 21419 (c), and 21416 (d). Time is of March 11, 2011 in GTM. Skill scores (RMSE, bias and SCI) are determined over the presented tsunami amplitude time series.

The computed overland flood depth agrees reasonably well with the observations (Figure 11). On average, the water depth is somewhat underestimated by the model (bias of −0.9 m). The authors believe that there are two likely sources for this error. Firstly, it may be the result of inaccuracies in the initial tsunami wave (generated by the Okada model). Secondly, it may stem from possible inaccuracies and offsets in the underlying SRTM model topography. The flood extent is well reproduced, although it must be stated that this is mainly topography-driven with a clear low-lying delta that is inundated up to the mountains.

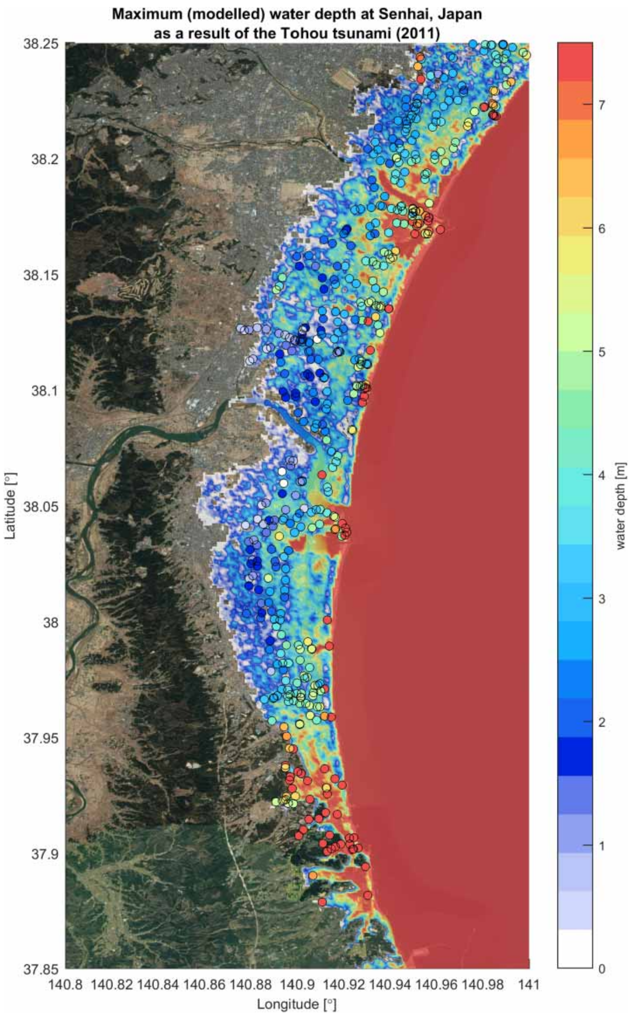

Figure 11 | Maximum (modelled) water depth as a result of the Tohoku tsunami (2011). Observations from Mori *et al.* (2011) are shown in circles.

DISCUSSION AND CONCLUSIONS

DDB is a standalone Matlab-based user interface, which supports modellers in setting up new and existing models. DDB employs a large number of coupled toolboxes for fast and easy model input generation. For any location in the world, a hydrodynamic model can now be set up in a matter of minutes, an operation which used to take weeks of work until a short time ago.

The three case studies presented show model set-ups created using DDB. For the case of tidal hydrodynamics, the DDB model has a predictive skill which is only slightly lower than the state-of-the-art operational model, but the efficiency (years of development versus a model set-up within 10 min) is much higher. In the case study of Hurricane Ike (2008), the DDB model predicts surge and wave heights reasonably well with deviations that were due to the use of a parametric wind field. In the tsunami case, the model showed good results for both deepwater propagation and coastal inundation. Improvements in overland flood predictions may be achieved by including (global or local) land use datasets, from which spatially varying roughness values may be obtained. DDB does currently not yet support the use of these datasets. However, these examples demonstrate that a DDB-generated model is a viable alternative for prediction or impact assessment, if a well-calibrated model is not available.

DDB is intended to save a modeller time in setting up a model by replacing the tedious, routine operations with a semi-automated system, drawing from online databases. Besides saving time, it also reduces the risk of model set-up errors, especially with respect to grid and bathymetry generation and applying forcing conditions (i.e. nesting in the large-scale model or generating initial conditions). However, while this tool can help to make a working model *quickly*, it does not release the user of the responsibility to construct a *quality* model, which represents the system the user wants to simulate. The latter still requires system knowledge and modelling experience by the user. For instance, one aspect that DDB does not prevent is the incorrect definition of the offshore boundaries. Placing boundaries too close to the area of interest or in topographically illogical places (i.e. sea straits, through islands) may affect the water motion in the interior domain and thus the accuracy/quality of the model results. In addition, the user should verify that the DDB-derived model represents the relevant physics and that these processes are modelled with adequate resolution. For instance, a short wave runup problem cannot be solved with a relatively coarse storm surge model.

In our experience, the largest source of error in hydrodynamic simulations often stems from inaccuracies and/or insufficient resolution in the underlying bathymetric data. DDB makes bathymetric datasets available to the user without improving upon shortcomings in the data that these contain. The global GEBCO08 dataset, for example, is known to be inaccurate in many coastal seas. Furthermore, it may lack the resolution to serve as input for high-resolution coastal models with grid spacing less than a few hundred metres. Users of DDB currently only have a limited number of high-resolution coastal datasets at their disposal. The usefulness of tools like DDB increases with the number of bathymetric datasets available. This could be achieved by linking these tools to databases hosted by third-party agencies (government agencies, research institutes, universities and commercial companies). This is currently complicated by the lack of a unified standard for storing and (online) hosting of bathymetric datasets (including important metadata regarding accuracy, horizontal and vertical datum) at different resolutions.

A potential downside to this tool is that hydrodynamic modelling becomes too easy and encourages the practice of 'black box' modelling. Although these concerns are certainly valid, the benefits do outweigh the drawbacks. The time gained in setting up a model can thus be spent on improving the calibration and carrying out a more comprehensive validation, thereby improving system understanding.

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