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Modeling storm surges in the Belgian coastal area: preliminary work

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Modeling storm surges in the Belgian coastal area: preliminary work

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Abstract— **This document aims to present preliminary work carried on in the framework of the development of a storm surge model for the Belgian coastal area. The PUG Matlab toolbox for pre- and post-processing of unstructured grids is first presented along with an open source strategy to design triangular, unstructured grids. Then, the ongoing development in the Beluga branch of the TELEMAC source code is briefly discussed. It aims to read space- and time-varying wind velocity and air pressure fields in the open NetCDF format.**

I. Introduction

A storm surge is an offshore rise of water, which is primarily caused by winds pushing on the sea surface. In shallow water areas, storm surges can be particularly damaging when they occur at the time of a high tide, potentially causing devastating coastal flooding. This phenomenon is one of the major natural threats for the Belgian coastal area and the region surrounding the tidal part of the Scheldt basin (Fig. 1). It is therefore a subject of high interest in terms of long-term coastal protection and sustainable development in Belgium.

Studying local impacts of storm surges is a rather multi-scale problem as the latter are formed at the scale of the entire North Sea. The use of an unstructured grid model seems therefore to be a natural choice, thanks to the ability of such models to simulate various scale processes in a rather flexible way.

There are many software solutions to generate triangular, unstructured grids, e.g. Blue Kenue and Janet, which are recommended on the TELEMAC website, Gmsh [1, 2], which is used in this project, and ADMESH [3], to name a few. All of them have pros and cons, but none of them offer satisfactory built-in functionalities to define the contour of the domain, which can be painful to obtain. Indeed, most of the time, available data come from several sources of different kinds, and their combination is handmade, so that everything has to be done each time from scratch. Another issue is the lack of a standard file format to save unstructured grids or model outputs. As a result, many different file formats coexist, and the choice of a specific mesh generation program is often driven by its possible output file formats rather than its mesh generation capabilities.

The PUG[1] Matlab toolbox is developed with the aim to offer a solution to those problems encountered by many unstructured grid model users. Indeed, it gathers several functionalities to define domain contours in an integrated framework, and it generates TELEMAC input files from Gmsh grids. The latter functionality will be extended to other file formats in the future. Used together with Gmsh and Inkscape, which is a computer aided-design (CAD) software program, PUG offers an original open source procedure to define domain contours (Section II) and design unstructured grids (Section III).

Finally, to perform realistic storm surge simulations on those unstructured grids, a slightly modified version of TELEMAC-2D is used. Indeed, in its standard version, the model cannot be forced with wind velocity and air pressure fields that vary both in space and time. The Beluga branch of the source code is being developed to take these meteorological conditions into account through NetCDF files (Section IV).

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[1] PUG stands for "(pre- and post-) Processing Unstructured Grids," it can be downloaded on http://www.oliviergourgue.net/download.

Figure 2. Contour data from GSHHG describing the coastlines of North-Western Europe; low (l) resolution is used far from the area of interest, intermediate (i) resolution in the Eastern part of the Channel, and full (f) resolution along the Belgian and Dutch coastlines.
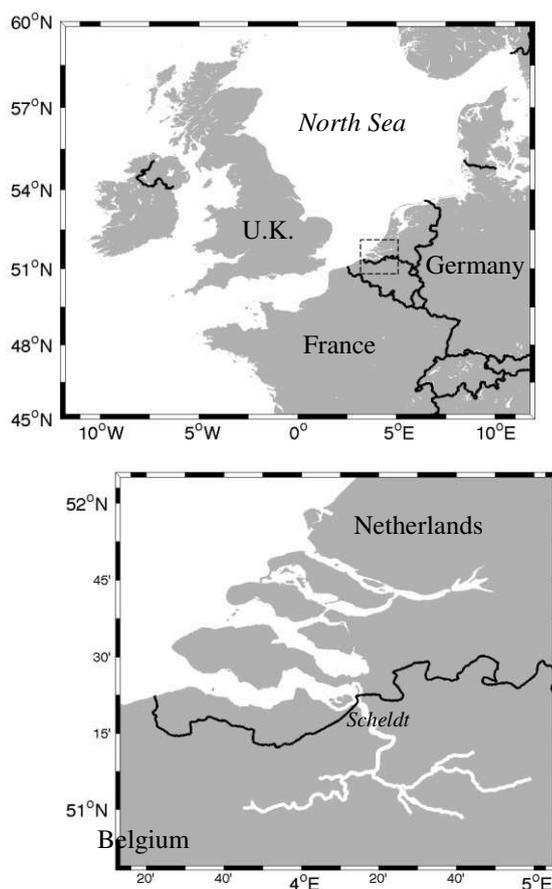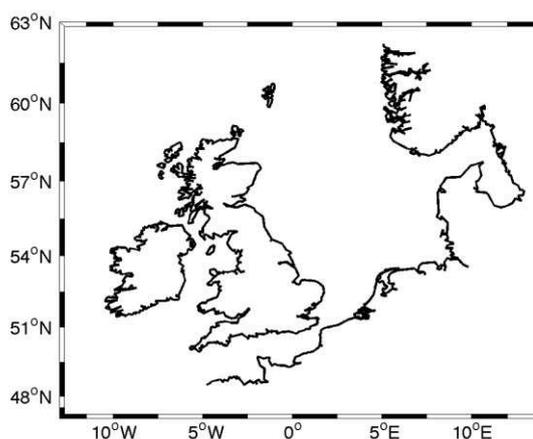

Figure 1. Map of the North-Western Europe (upper panel), with zoom on the tidal part of the Scheldt basin (lower panel).

II. Domain contour definition using PUG and Inkscape

A. Contour data from GSHHG

PUG uses the Global Self-consistent, Hierarchical, High-resolution Geography (GSHHG) database to define the shorelines of a model domain. GSHHG is a high-resolution geography data set, amalgamated from two databases in the public domain: World Vector Shorelines (WVS) and CIA World Data Bank II (WDBII). The data have undergone extensive processing and are supposed to be free of internal inconsistencies such as erratic points and crossing segments [4]. The M_Map mapping package[2] for Matlab is used to access the data.

GSHHG comes in five different resolutions, i.e. crude (c), low (l), intermediate (i), high (h), and full (f), so that the user can select the most appropriate regarding the expected grid resolution in the area. For the storm surge model of the Belgian coastal area, low resolution is used far from the area of interest, intermediate resolution is used in the Eastern part

of the Channel, and full resolution is used along the Belgian and Dutch coastlines (Fig. 2).

However, even the full resolution of GSHHG lacks details in some areas. PUG offers two alternatives to overcome this problem (Subsections B and C).

B. Contour data from KML files (Google Earth)

Usually, GSHHG does not include manmade coastal constructions such as ports, artificial islands, dams or sluices. Sometimes also, GSHHG is simply not accurate enough in some locations where fine grid resolution is required.

If the area to correct is not too large, it is quite convenient to define the coastline by creating a path in Google Earth, and pointing and clicking along the land boundary. Then, if the path is saved into a KML file, PUG can read it and add it to the domain contour.

For the storm surge model of the Belgian coastal area, this technique is used to include many details of the Belgian and Dutch, such as, for example, a fine description of the port of Zeebrugge (Fig. 3).

C. Contour data from a point cloud alpha shape

Sometimes, the area to include is too large to consider a "point-and-click" procedure in Google Earth. That may be the case for example when fine grid resolution is needed in estuaries, rivers or embayments. However, it is usually in the area of major interest of the model that so fine grid resolution is required, and it can be assumed that a large amount of data is available there. PUG takes advantage of that by computing an external contour of any point cloud of data. This is done efficiently using the concept of alpha shape, which is a concave generalization of a convex hull. The Matlab package Alpha shapes3 is used to compute those contour domains.
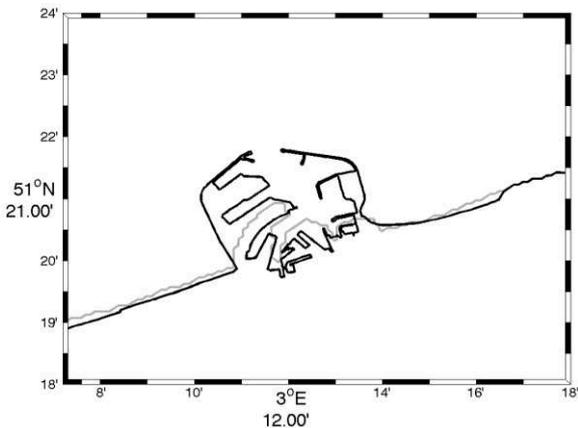

Figure 3.   Contour data from a KML file (in black) is used to represent the port of Zeebrugge, Belgium, because the full (f) resolution of GSHHG (in gray) is not accurate enough.
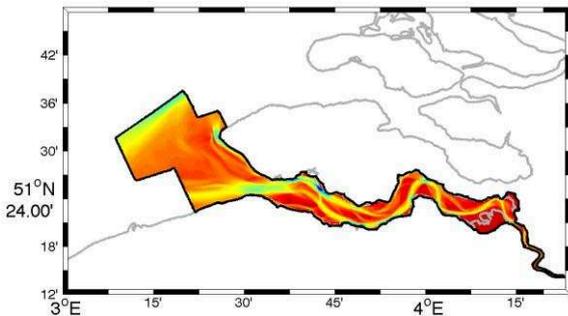

Figure 4.   The alpha shape (in black) from a bathymetry data point cloud (in colors) is computed to complete contour data from GSHHG in full (f) resolution (in gray) in the Scheldt basin.

This technique is used to include the tidal part of the Scheldt basin in the computational domain of the storm surge model of the Belgian coastal area (Fig. 4).

D.   Contour data from ETOPO1

Subsections A to C describe procedures to define land boundaries. However, unless the computational domain is the entire world ocean, it is necessary to define an open boundary offshore as well. Open boundaries can be drawn manually, for example by using Google Earth (Subsection B). However, in some cases, it may be useful to define them following physical criteria. For example, it is not uncommon to place the offshore open boundary at the shelf break, i.e. at the end of the continental shelf, usually because the tidal forcing signal is well know there [5, 6].

The shelf break is generally defined as a contour line at a specific depth. Therefore, PUG is implemented with the ability to extract contour lines from a bathymetry data set and add them to the domain contour. For that, it makes use of ETOPO1, which is a 1 arc-minute global relief model of Earth's surface built from numerous global and regional data sets [7]. For the storm surge model of the Belgian coastal
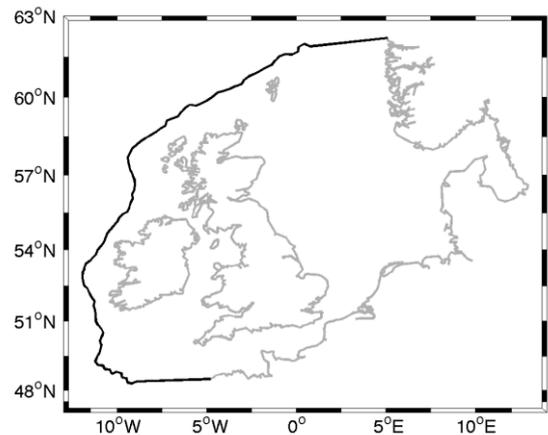

Figure 5.   The contour line 200 m below the mean sea level (in black) is extracted from the bathymetry database ETOPO1 to close the domain contour made up with coastlines from different sources (in gray).

area, the open boundary is defined as the contour line 200 m below the mean sea level (Fig. 5).

E.   Manipulation of raw contour data using Inkscape

Grid design is not possible without a well-defined domain contour, which consists of one closed external contour, and possibly several closed internal contours describing island coastlines. However, raw data uploaded as described in the previous subsections usually do not form a well-defined domain contour. A few manipulations are therefore still necessary before considering mesh generation, such as remove entire or part of lines, remove individual points, join lines, etc.

When dealing with a large number of points, such manipulations are not really convenient in Matlab. On the other hand, that is exactly what CAD software is made for. Among various alternatives, the professional quality vector graphics software Inkscape[4] presents several advantages: it is open source, runs either on Windows, Mac OS X or Linux, and uses the open standard SVG (Scalar Vector Graphics) as its native format. That is why PUG is implemented with the ability to read and save contour data in SVG files.

The procedure to define a domain contour using PUG and Inkscape is therefore the following:

- load raw contour data and save them in a SVG file using PUG (Subsections A to D),

- manipulate raw contour data using Inkscape to obtain a well-defined domain contour,

- load the well-defined domain contour and convert it into the appropriate grid design software input format using PUG.

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[4] http://www.inkscape.org

III.   GRID DESIGN USING GMSH

Once the domain contour is properly defined, the open source software Gmsh[5] is used to generate unstructured triangular grids. Gmsh also runs on Windows, Mac OS X and Linux, and is widely used in many branches of engineering because of its high flexibility in defining variable mesh densities [1, 2]. However, it remains poorly known within the TELEMAC user community, probably because it does not support grid exportation to selafin files. This should not be a problem anymore, since one of the functionality of PUG is to write selafin files for TELEMAC from Gmsh grid files.

Gmsh reads the domain contour from an ASCII file, which is called the geometry (GEO) file. The latter can be generated by PUG. Then, two different methods can be used to design a grid. It can be done through the Graphical User Interface (GUI), but, as every manipulation made through the GUI is transcribed into the GEO file, grid design can also be done by editing the latter directly. This second approach offers an efficient solution for small changes, or to script frequently used sequences. In practice, both methods are often used complementarily.

Fig. 6 presents a grid designed for the storm surge model of the Belgian coastal area, whose mesh density is a function of the following criteria:

- distance to coastlines (mesh density increases when getting close to coastlines, to have a good representation of them without increasing the computer cost offshore),

- distance to areas of interest (mesh density increases when getting close to the Belgian coast and the Scheldt estuary),

- bathymetry in the Belgian continental shelf (mesh density increases in shallow areas of the Belgian continental shelf, to have a good representation of the top of the sand banks, which play an important role in the damping of wind wave energy towards the coast),

- bathymetry and its gradient in the Scheldt estuary (mesh density increases in deep and steep areas of the Scheldt estuary, to have a good representation of the main channels where most of the tidal energy transport takes place).

Figure 6.   Unstructured grid generated by Gmsh, made up with 261926 triangles, with a characteristical length ranging from 100 m in the port of Zeebrugge (middle panel) and some parts of the Scheldt basin (lower panel) to 5 km offshore.

IV.   STORM SURGE MODELING USING TELEMAC-2D

The key factor responsible for storm surges is the evolution of the marine meteorological conditions, i.e. wind velocity and, to a lesser degree, air pressure. Therefore, to simulate the development of storm surges, the model must be able to take those forcings into account. However, to date, in its standard version, TELEMAC is only able to consider wind and air pressure varying in time, but not in space.
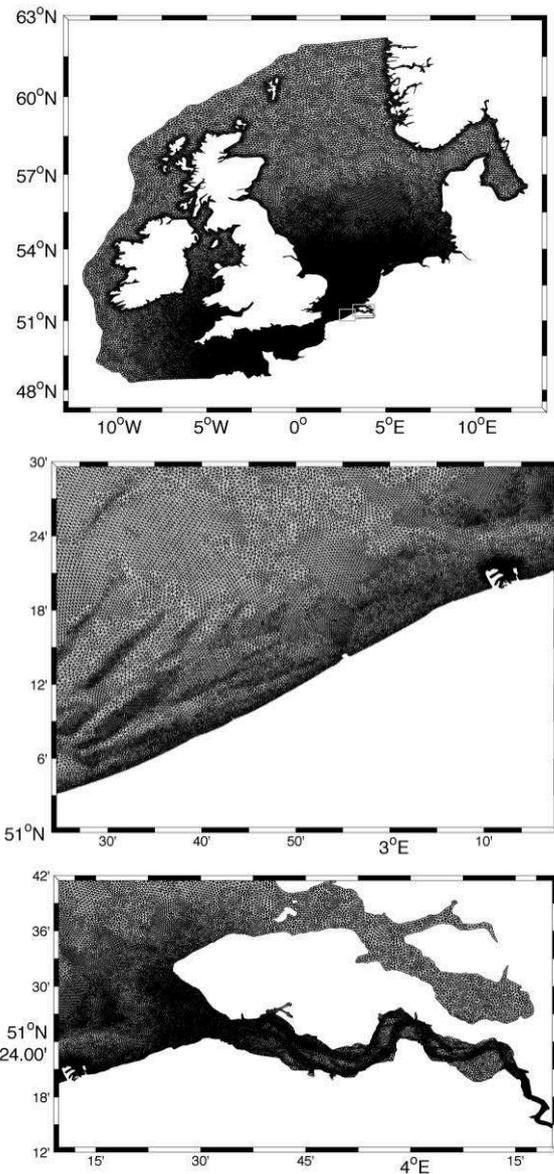
The development of the Beluga branch of the TELEMAC source code aims to impose meteorological forcing through NetCDF files. Provided they fulfil the Climate and Forecast (CF) convention, doing so ensures that the forcing files are self-describing. In practical terms, the user defines the NetCDF file in the steering file, and the data are interpolated in space and time by TELEMAC to provide meteorological conditions at each grid node and at each time step.

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[5] http://geuz.org/gmsh

To date, it is already possible to perform two-dimensional hydrodynamic simulations with wind velocity and air pressure varying in space and time. However, the
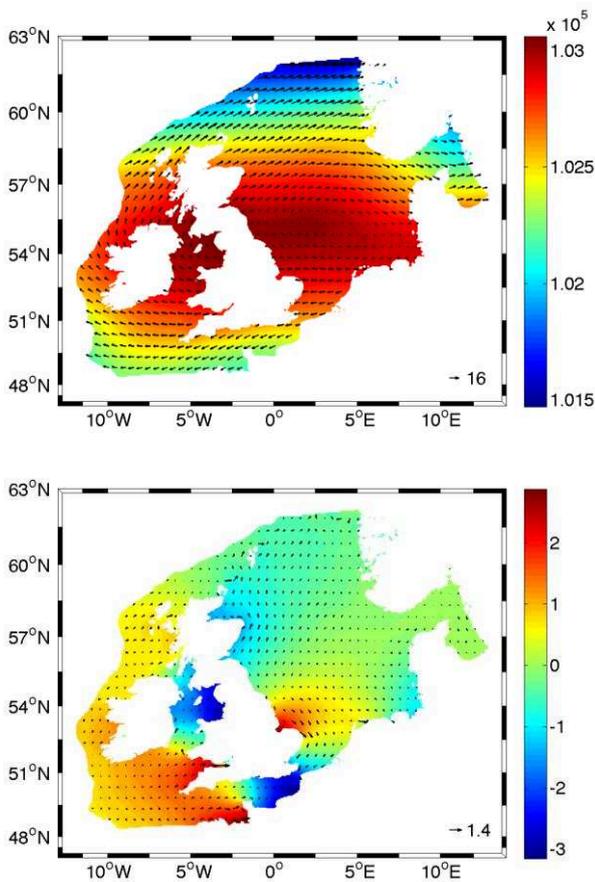

Figure 7. Upper panel: Air pressure [Pa] (colors) and wind velocity [m/s] (arrows) fields on the 5th of January 2013 at midnight. Lower panel: Water elevation [m] (colors) and depth-averaged velocity [m/s] (arrows) computed by the model at the same moment.

elevation and depth-averaged velocity are shown on the lower panels of Fig. 7 and Fig. 8 for illustration.
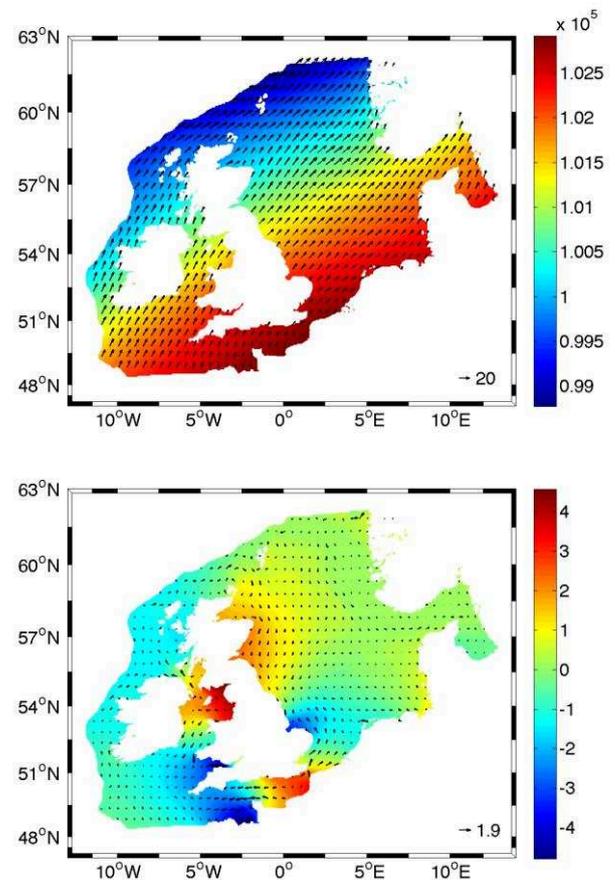

Figure 8. Upper panel: Air pressure [Pa] (colors) and wind velocity [m/s] (arrows) fields on the 10th of January 2013 at midnight. Lower panel: Water elevation [m] (colors) and depth-averaged velocity [m/s] (arrows) computed by the model at the same moment.

developments are not mature enough to consider merging the branch to the trunk. Some part of the code is still hard coded, and the NetCDF FORTRAN library functionalities are still not exploited to their maximum.

The current version of the model uses the triangular grid of Fig. 6 with a time step of 60 s, and it is driven by tides and marine meteorological conditions. The tidal forcing is imposed at the shelf break using the European Shelf OTIS Regional Tidal Solution dataset, which provides amplitudes and phases of eleven major harmonic constituents for water elevation and transport, with a spatial resolution of 1/30° [8]. The computer time is about 40 min for one month of simulation on sixteen processors.

Snapshots of very different and heterogeneous meteorological conditions in the North Sea are presented on the upper panels of Fig. 7 and Fig. 8 to illustrate the need of the above-mentioned developments in the Beluga branch of TELEMAC for this project. The corresponding water surface

V. CONCLUSIONS AND PERSPECTIVES

The development of the PUG Matlab toolbox offers an almost open source strategy to design unstructured grids, when used together with Inkscape and Gmsh. However, to really offer a complete open source experience, compatibility with GNU software like Octave should be ensure in the future, to avoid the use of a Matlab license.

The developments in the Beluga branch of the TELEMAC source code to impose meteorological forcing through standard NetCDF files are promising. However, some effort has still to be made before they can be useful for other applications in a wider community.

which has been used extensively to generate all the figures of the present document.

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