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Evaluation of different meshing criteria for areas exposed to flooding

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ABSTRACT

This paper investigates the relationship between criteria used for the unstructured mesh generation of two dimensional shallow water models and model result convergence. A physically based, localized truncation error remeshing method is recursively applied to an ocean to estuary domain. The adapted meshes are tested in a tidal study with the wet and dry option turned on: their quantitative performance, made at three stations within the estuary, shows that the method improves the reproduction of the measured flow velocity, especially at the upstream station, as a consequence of an increased mesh resolution within the estuary.

A comparison between four alternative discretization criteria (coarse estuary discretization; fine estuary discretization, multi-criteria approach and its a-posteriori, error adapted mesh) is made under the same model conditions of the previous test. Although the study does not identify a best mesh, it is possible to see how the coarsest estuary discretization has the lowest performance indices, while the finest uniform estuary discretization outperforms the other meshes just in reproducing the water elevation. The a-posteriori, error adapted mesh gives a more accurate representation of the of the wetted area extension than the multi-criteria mesh it is derived from.

1. Introduction

The objective of this work is to assess the response of a shallow water model when different meshing criteria are applied to an ocean to basin, multi-scale domain, including an estuarine region and its adjacent flood plains, subject to the river flow and the covering and uncovering of the tide: particular attention is given to the relationship between meshing criterion/criteria used and model output convergence, with regard to the measured water elevation, currents and flooded area extension inside the estuary.

In inundation studies, the domain discretization of all the physical and hydrodynamic spatial scales plays a critical role in relation to the efficiency and accuracy of the model prediction, as the gradient of each input or modelled variable has to be properly reproduced. Shallow water models, associated to finite element or finite volume resolving schemes, allow adopting a varying degree of spatial resolution through the use of unstructured meshes, from a coarse deep water discretization to localized refinements nearshore and in the areas at risk of flooding [1]. Moreover, the coupling of hydrodynamic models requires that the resolutions of each model grid/mesh in the overlapping regions are similar, to avoid the loss of information [2,3].

Mesh sizing criteria can be broadly divided into a-priori and a-posteriori. Recurrent a-priori criteria used for ocean and coastal areas, not exposed to inundation events, are the wavelength to grid side ratio [4], the topographic length scale [5], the maximum bathymetric gradient [6], the coastline resolution [7,8], and the spatial gradient of the input forcing function [8,9]. As the mesh resolution needed for the result convergence is generally not known a-priori, adaptive re-meshing techniques have been developed, where the re-meshing is done by optimizing an error based function: mesh refinement is introduced in regions where the error indicator is large, while coarsening or no action is applied where the error is small. The error may be derived from the discretization of the bathymetry/topography field [10], or more generally, from the residual of the flow solution on a per element basis [11,12]. The localized truncation error analysis (LTEA) is a recent a-posteriori meshing approach [13–17] which estimates the error from the discretization of the linearized shallow water equations. The latest version of the method, called localized truncation error analysis with complex derivatives (LTEA + CD) [18–20], introduces, in the error expression, the estimation of the spatially variable bottom stresses and of the Coriolis force.

However, for intertidal and low-lying areas exposed to inundation, discretization criteria are more difficult to be expressed analytically, due to the complex bathymetry/topography and to the local scale processes. Jones and Richards [21], Bunya et al. [22] and Westerink et al. [23] recommend including into the discretization all relevant hydraulic features likely to convey or stop the inland water propagation. A minimum number of mesh elements per waterway cross

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section is required [23,24] in order to guarantee the proper system conveyance: this parameter is set according to the modeller's needs and application options (with or without wet and dry; with or without slip boundary condition). Specific algorithms have been developed to extract significant features or objects from a high resolution elevation data set, such as those derived from airborne laser altimetry (LiDAR): significant horizontal length scales are determined through variograms and topographical significant points through filtering processes [25]. An image segmentation system from LiDAR dataset has been used to approximate vegetation hedges and individual trees [26]. Coggin [27] developed an automatic methodology where raised natural and manmade features, high and long enough to obstacle or convey flood propagation, are extracted from a high resolution digital elevation model (DEM). The methodology is then applied to a floodplain LiDAR dataset [28]. For urban flood inundation modelling with unstructured grids, buildings and vegetation are detected and separated according to the combined information of height and ortophoto colours [29]. In Mazzolari et al. [30] sudden elevation changes are detected by the inverse of the bathymetry gradient, and are saved as active fronts in an advancing front method meshing algorithm. Xu et al. [31] instead directly convert the points of a high resolution DEM into the nodes and sides of the mesh elements. Mesh design is also subject to computational constraints, like the Courant condition [6], topological conditions at the nodes [32], and geometrical empirical rules for adjacent elements, as the area transition coefficient [13].

Comparison between discretization can be done in terms of convergence of the results and relative computational cost. However, mesh convergence studies have been performed normally only for fully wetted domains [4,8,13,14,16,33]. Similar tests have not been conducted yet for computations where a wet and dry algorithm is present. Within the recent modelling works to predict the extent of coastal inundation, Bilskie and Hagen [34] compare storm surge water levels and extension of the flooded areas for meshes of different resolutions, but without a model validation with field data. Chaouch et al. [35] developed a method to integrate information from different remote high resolution sources to define the limits of inundated areas, which is then applied for validation in a coastal modelling study [36].

The present work is an attempt to evaluate, on a quantitative basis, different discretization approaches for areas heavily influenced by wetting and drying hydrodynamics.

The paper includes, after this introduction, a description of the chosen study site (Section 2) and the meshing methods used to perform the discretizations (Section 3); in Section 4 a brief outline of the shallow water model used is given, while Section 5 presents the methodology chosen for assessing the model output performance. In Section 6 two mesh convergence studies are carried out on the basis of the LTEA + CD method, adapted to bathymetries exposed to flooding. In Section 7, four estuary discretizations, corresponding to alternative meshing criteria, are used in a wet and dry tide modelling study and the model output convergence is quantified. In the last section, some conclusions are drawn.

2. Study site description

The area chosen for the following modelling applications is a multi-scale domain, encompassing part of the North Atlantic Ocean shelf, of the shelf break and of the Western Iberian continental shelf (Fig. 1). The Lima estuary, with its adjacent floodplains and river course are included as well until the upstream tide propagation limits, located around 20 km upstream the river mouth (Fig. 2). The Lima estuary is tidal dominated, with a spring tidal range of 3.8 m and neap range of 1.1 m, while the river discharge is controlled by the presence of two hydraulic power plants. The lower part of the estuary is occupied by the Viana do Castelo harbour facilities, while the middle

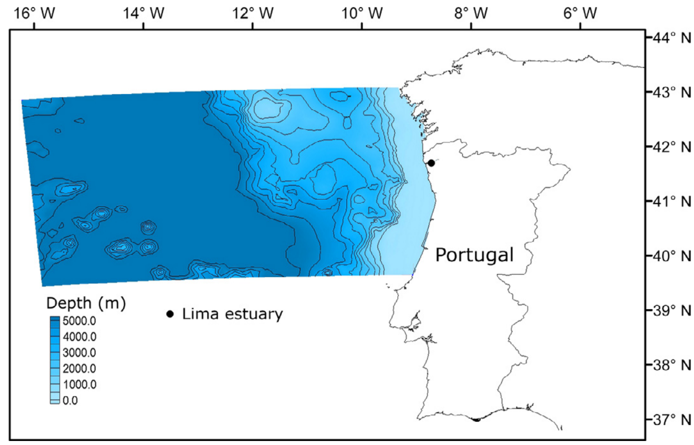

Fig. 1. Oceanic domain extension, bathymetry, and location of the Lima estuary.

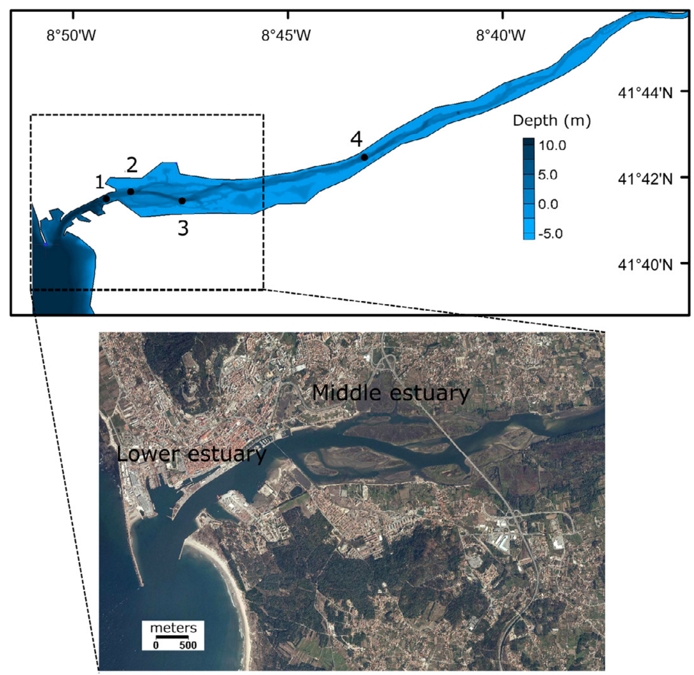

Fig. 2. Top: Estuary domain extension and bathymetry (depths are positive if below mean sea level), with the four ADCPs location; bottom: aerial view of the lower and middle estuary and its adjacent areas.

estuary present one main and several secondary river channels, separated by mud and sand banks covered by vegetation. The river banks include revetments and rip-raps, while the nearby flood plain region has mild slopes, which make it exposed to the risk of river and storm inundation.

The DEM has been obtained from several sources: for the oceanic domain, the 1:150 000 and 1:1 000 000 nautical charts of the Portuguese navy were digitized up to the bathymetric contour 4000 m, while the 1' resolution Global seafloor bathymetry of Smith and Sandwell [37] was used for deeper depths. The estuary bathymetry was obtained during a survey campaign [Hidrodata, unpublished], in the form of regularly spaced scatter sets with resolution of 5 m for the lower estuary and 25 m $\times$ 10 m for the middle and upper estuary [38]. The bathymetric information was completed with the digitalization of the 1: 25 000 topography map of the Portuguese Army Geographical Institute for the nearby flood plain region and intertidal areas.