A Big Data framework for Modelling and Simulating high-resolution hydrodynamic models in sea harbours

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Abstract— **The ability to reliably forecast sea states (most importantly sea level, wind and wave conditions) within or close to the entrance of ports is a critical tool for all involved stakeholders. In this paper we present our work on a prototype decision support system capable of providing accurate sea state forecasts based on three high-resolution hydrodynamic models, i.e. a spectral wave model (model A), a mild-slope equation wave model (model B) and a barotropic hydrodynamic circulation model (model H). We present an end to end novel data processing pipeline, capable of handling the challenges posed by the volume of related data and capable of providing high resolution wave forecasts by exploiting parallelization.**

Keywords— *Big Data; Safe navigation in ports; Decision support systems*

I. Introduction

Sea level elevation due to meteorological conditions and tidal effects, wave agitation, currents and high winds can heavily affect vessel maneuverability. Port operations can be severely hampered by bad weather conditions especially when large vessels are attempting to safely berth, load and dredge. Strong coastal currents and sea waves can induce excessive horizontal movements to the ship while at a port terminal that may disrupt loading and unloading operations and cause damage to the ship itself, port infrastructure, and even nearby ships [1]. If the ship is sailing across the port entrance or inside the harbour, sea waves may cause large vertical movements of the ship that evidently leads to contact between the ship's hull and port structures. [2]. Harbour pilots are employed to bring vessels safely in and out of ports or whenever navigation may be considered hazardous. Amongst the main challenges faced by pilots are getting on board a large vessel in bad weather conditions and carefully navigating it (and its cargo) to dock safely.

Recently, autonomous vessels have been developed to transfer pilots to waiting ships either under remote control or without any human interaction. Wave characteristics in conjunction with wind and currents speed and direction information heavily affect their decision to come alongside a big tanker or to bring a small barge carrying oil into port during harsh weather conditions. It is clear that the ability to reliably forecast sea states (most importantly sea level, wind and wave conditions) within or close to the entrance of ports is a critical tool for seaport authorities, the ship's master, pilots and other implicated parties [2].

Global scale open sea forecasts are available from various sources but lack the resolution and accuracy in the vicinity of ports, required for safe port navigation. Numerical models for hydrodynamic circulation, sea level variation and wave forecasting at a regional level can produce quite accurate estimates of the sea state characteristics in and around any given port [2]. Although there is a plethora of wave and ocean models capable of simulating sea wave propagation and hydrodynamics over large areas in a computationally efficient way integrating different numerical models in coupled mode can improve simulation accuracy [3].

Large scale, real world implementations demand the constant data flow across the network and the scheduling of hundreds of jobs running concurrently and exchanging large amounts of data. Typically, the raw input data (originating from numerous sources including National Oceanic and Atmospheric Administration (NOAA), Copernicus Marine Environmental Monitoring Service (CMEMS), Bathymetric data) is 15GB, while the different phases of the simulation-analysis pipeline produce 30GB on a daily basis. Consuming and producing such massive datasets with traditional approaches is highly inadequate due to strict time constraints. In this paper we present our work on a prototype decision support system [1] capable of producing improved accuracy forecasts based on three high-resolution hydrodynamic models [2], *i.e.* a spectral wave model for wind-induced irregular wave fields (model A) [4,5,6], a mild-slope equation wave model (model B) [7, 8], and a barotropic hydrodynamic circulation model (model H) [9, 10]. We present an end to end novel data processing pipeline, capable of handling the challenges posed by the volume of related data and capable of providing high resolution wave forecasts by exploiting parallelization.

This paper presents a complete framework which includes intelligent data management, fusion and simulation execution, exploiting parallelism, to achieve large-scale volume of data integration, post-processing, consumption and visualization.

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II. Background and System Architecture

Decision support tools (DSTs) aid the decision maker in solving unprogrammed, unstructured or semi-structured problems [1, 2]. The key elements of such systems are: a) incorporating complex numerical and data processing models into the automated decision-making process, b) providing a simple intuitive interface for investigation and querying, and c) supporting the decision activity with presentation of results in a structured format. A reliable DST for safe navigation in port areas, needs to support members of the port community (seaport authorities, the ships' masters, pilots, etc.) in their decisions about harbour approach, safe ship docking or offshore mooring. The basic idea behind this tool is the potential of estimating the offshore and coastal wave characteristics, near-surface currents and sea level around and inside the port area up to 72h in advance, and to transfer the respective information to the port managing system.

In sum the main required functionalities of the system include:

- High resolution forecast of sea states in 3 hours intervals for 3 days for port and areas in proximity via tailor made configurations per area.
- Visual representation of high-resolution forecasts for sea level elevation, wave height and direction and sea currents that facilitates decision making for pilots and port authorities.
- Consistent comparison of forecast data with in situ observations available within areas of interest.
- Database to store all relevant information.

Recently similar works have appeared in the related literature, see e.g. [11, 12, 13]. Different from previous works, in this paper we present an approach capable of being applied automatically to large number of ports (>50) in a computationally efficient way.

A. *Input Data*

Necessary bathymetric information in the relevant sea areas of the selected port sites (e.g. Figure 1) were digitized by nautical maps of National Hydrographic Services, British Admiralty, Navionics platform, GEBCO database etc., and transformed into a georeferenced appropriate format and resolution for models H (spherical coordinate grids), A (triangular finite element mesh) and B (high-resolution, Kriging-interpolated, staggered orthogonal grids).

Fig. 1. Selected locations of 50 important ports around the globe and their corresponding data acquisition areas and bathymetries for each model (green for model H, purple for model A and densified near port area for model B.

The sea state and weather input data needed for implementing this project are forcing, initial and boundary conditions for models H, A and B. These include large-scale forecast values of wind intensity/direction and atmospheric pressure at sea level; sea level elevation due to meteorological conditions and tidal effects, and respective ocean currents' intensity/direction; wind-induced wave and swell characteristics. Particularly, sea and weather conditions are represented by the following parameters: significant wave height, peak spectral period, and main direction; for tides, global-scale sea level anomalies, atmospheric pressure, current velocities and directions are collected; winds are represented by wind speed and direction. The sources used to obtain the above forecasts are the CMEMS, used for wave [22] and tidal data [23]; and the NOAA, for atmospheric data [24].

B. *Numerical Simulation and Wave modeling*

The model integration setup was performed as follows. Model H is forced using boundary and initial configuration data from the aforementioned sources (incorporating storm surge and astronomical tide effects [10]), providing to Model A the sea level elevation and mean current speed and direction. The latter information in conjunction with wave and wind data are fed into Model A to simulate wave generation and propagation from offshore to the vicinity of the port covering an area a few dozens of kilometers across [2]. Results obtained from model A in terms of wave height, period and direction are then extracted along the wave generation line of model B to further simulate wave propagation inside the harbour basin [8]. In general, the three aforementioned numerical models tackle different needs in terms of area coverage and accuracy; schematics of the sequence of model interaction are provided in the following Figure 2.

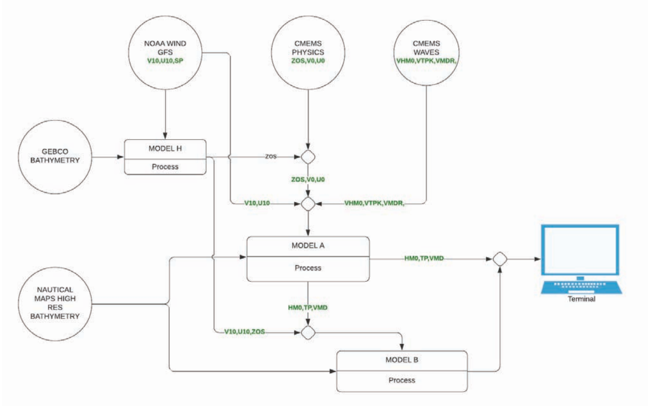

Fig. 2. Data flow diagram depicting each variable's sequence of model executions, starting from external sources or local storage till the final calculation delivered to end user.

HiReSS (Model H) is a high-resolution storm surge numerical model developed in the Laboratory of Maritime Engineering at Aristotle University of Thessaloniki (LME-AUTh) simulating 2-DH barotropic hydrodynamic circulation based on the shallow water equations [10, 14]. It can predict the free surface elevation and the depth-integrated sea currents due to storm surge (combined wind and inverse barometer effects) and astronomical tides through the static tidal model [15]. It has been developed, calibrated, verified and applied on a number of actual sites for both long-term [16] and short-term severe weather conditions [5, 17].

TELEMAC-based Operational Model Addressing Wave Action Computation – TOMAWAC (Model A) [4] is an open-source code for a 3rd generation, phase-averaged, directional, spectral wave model, developed by Électricité De France R&D's Laboratoire National d'Hydraulique et

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Environnement [5, 6]. It simulates the evolution in space and time of the spectrum of sea surface elevation in waters of any depth. The numerical calculations are executed by the Finite Elements Method over an unstructured mesh. TOMAWAC is suitable for both offshore and nearshore applications, where high computational resolution is required. The model captures processes of wind wave generation and propagation; energy dissipation due to white-capping, bottom friction, wave shoaling and depth limited breaking; non-linear triad and quadruple wave–wave interactions, wave-structure interaction (diffraction), wave-current interaction.

WAVE-L (Model B) is a 2-DH solver of the mild-slope equation based on the hyperbolic approximation [7]. It has been developed by LME-AUTh [8, 19, 20] to cope with quasi-irregular wave propagation in coastal waters of mildly sloping beds and capture wave modifications due to several processes in very fine resolution: currents; wave shoaling, refraction and diffraction; wave reflection at solid boundaries; energy dissipation due to bottom friction; depth-limited wave breaking [19, 20]. The numerical solution of the equations is based on an explicit scheme applied on a grid staggered between the cell values of surface elevation and mean velocities. Along the open sea and lateral boundaries sponge layers are placed [8, 19].

C. Job orchestration and parallel execution

As discussed in the previous section, models A and H require both static (regional bathymetry) and dynamic data (global-scale forecasts) availability. Moreover, the execution plan for each port varies, due to different local characteristics (such as its location and orientation, coastline diversity, local bathymetry, etc.). The execution plan and static data are stored in the filesystem and database respectively, while dynamic data are acquired each day. We develop a framework in Python that handles job orchestration relying on Dask [25] for parallel and asynchronous execution, while daily execution is monitored with Airflow [26].

Combining daily forecast data from multiple sources and orchestrating the model execution for each port along with their respected offshore areas is a challenging task. To tackle it, we identify common tasks for multiple ports and models and then we break down the rest of the execution plan into smaller components and jobs (micro-services), that could be executed and processed in parallel as soon as all their common preprocessing requirements are met.

First task to be parallelized is data acquisition. Each source is handled separately; firstly we acquire the global GFS forecast from FTP in GRIB2 format and extract data for areas of interest then, we call CMEMS API (motu) for waves and physics products for each port. As soon as all data, required for Models A and B in a specific port or aquatic body (for Model H), is available, the execution process starts (Figure 3).

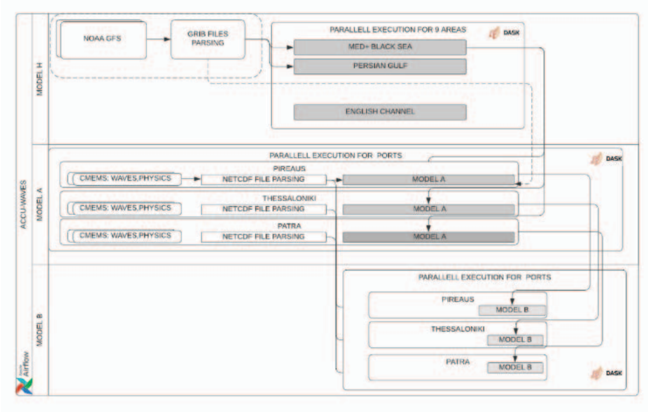

Fig. 3. Architecture of model integration. High level representation of job orchestration and parallelization capabilities of the system.

III. Testing and Validation

Each hydrodynamic model has been thoroughly evaluated in both standalone and integrated mode by comparisons of model output against experimental data and model hindcasts and forecasts against *in situ* observations [3]. Specifically, the efficiency of Model H has been evaluated in the past [9, 14, 16, 17]; however, case-related numerical setups have also been tested and calibrated within Accu-Waves [1], *e.g.* against *in situ* measurements in several ports of the Mediterranean Sea with quite high forecast skill scores [3, 10]. Evaluation of the ability of wave model A to capture wave breaking due to a strong opposing current, an adverse situation for safe navigation, was carried out by comparing model results to the experimental measurements of [21], showing very good agreement. Additionally, the operational efficiency of Model A has been assessed in a worst-case scenario for navigation [18] related to wave breaking due to a strong opposing current for the port of Le Havre, France. Model B has been setup and fundamentally evaluated in the past [19, 20], yet has also been validated against field data at Thessaloniki port [3, 8], including results by integration of all three models at the three largest Greek ports (Patra, Piraeus and Thessaloniki).

Figure 4 presents validation of Models H and A+B recent forecast implementations in Thessaloniki port for weather-/tide-induced sea levels and characteristic wave height, respectively. Comparisons range from acceptable to good and refer to timeseries and scatter plots of modelled data against field observations performed from October to December of 2019. Figure 5 presents the integrated models' output of wave height in a high-resolution map of the inner Thermaikos Gulf and the coastal area inside and near the Thessaloniki port. Wave attenuation by the harbour's breakwater is evident and wave conditions are depicted in high detail at different berth locations on the waterfront of several piers.

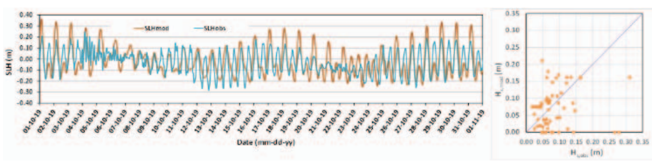

Fig. 4. Comparisons of Sea Level Height, SLH (m), by Model H output (mod) against in situ observations (obs) [left graph] and Significant Wave Height, H_s (m), by Models A and B [right graph] in Thessaloniki port (Thermaikos Gulf, NW Aegean Sea, Greece) during Autumn-Winter 2019.

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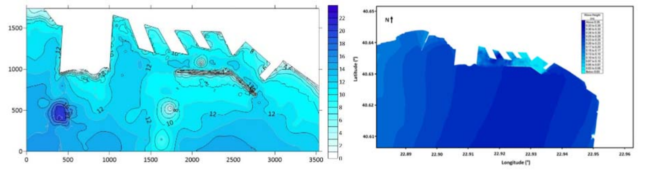

Fig. 5. Characteristic operational forecast results of significant wave height by the integrated A and B wave models (left graph) in Thessaloniki port (Thermaikos Gulf, NW Aegean Sea, Greece) during a SW-S sector light wind event in December 2019 (right graph).

Figure 6 illustrates the spatial distribution of wave heights for an extreme case of Hs (>3.5 m) by integrated simulations with models A and B, in the vicinity of an open-sea port, i.e. the new Patra port (southern Ionian Sea, Greece), for strong winds blowing from the northwestern-northern sector.

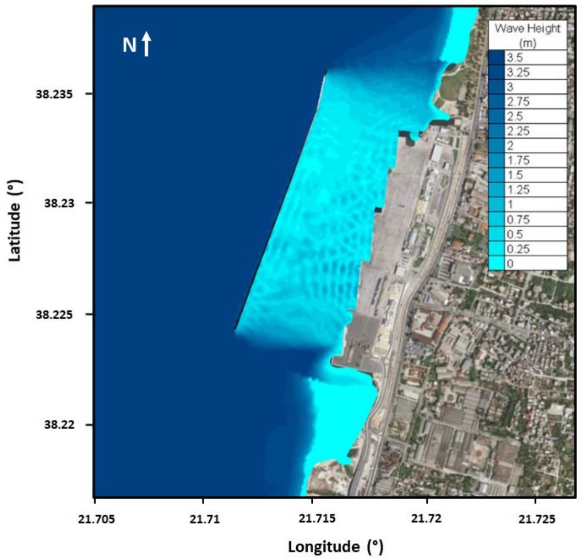

Fig. 6. Operational forecast results for spatial distribution of significant wave height H_s (m) by integrated simulation with models A and B inside and in the vicinity of the new Patra port for strong winds from the NW-W sector.

A further example of Model H forecasts in operational mode is presented in Figure 7 for the Mediterranean and Black Sea basins. On 25/05/2020, a strong Low Barometric Pressure (LBP) system was detected along the NW African coast that increased sea level elevation over the western Mediterranean. The rest of the basin remained unaffected with rather low sea levels. During the second forecasting day, the atmospheric cyclone characterized by LBP propagated towards east-central areas resulting to high seas levels over the central Mediterranean (early-morning of 26/05/20) and over the Aegean and the western Black Sea (noon of 26/05/20).

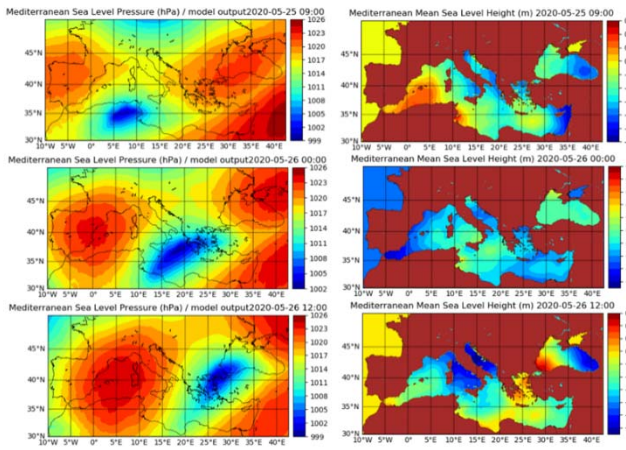

Fig. 7. Characteristic snapshots of a 3-day forecasts of Sea Level Pressure (left panels) derived from NOAA and respective Sea Level Height (right panels) derived from Model H in operational mode over the Mediterranean and Black Seas during 25-26 May 2020.

IV. Discussion and Conclusions

In this paper a prototype decision support system capable of providing accurate sea state forecasts based on three high-resolution hydrodynamic models, i.e. a spectral wave model (model A), a mild-slope equation wave model (model B) and a barotropic hydrodynamic circulation model (model H), has been presented.

Overall, the validation of ocean and coastal, hydrodynamic, spectral and phase-resolving wave models seems promising in port areas. The software architecture of model coupling, and integration is also presented supporting the implementation of a robust scalable operational forecast platform for wind, wave, sea level and current data in and around ports with high traffic load. Presented pilot applications concern European regions of the Mediterranean and Black Seas. Various tests of the combined model suite are currently performed in order to tackle communication, performance and data dissemination issues by site-specific verification of the operational platform.

A new integrated modelling application is introduced to address significant needs of Ports Safety Management Systems in secure navigation and berth positioning driven by high-resolution sea-state forecasting. The goal is to assist the reduction of in-port marine accidents and consequent port downtime. The integrated model results can form a novel complete body of information on sea states and weather conditions able to support pilotage guidance and, in general, safe approach procedures of ships to port and harbour basins.

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