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Integrated modeling of sea-state forecasts for safe navigation near and inside ports: the Accu-Waves platform

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ABSTRACT

This paper presents a novel initiative for reliable high-resolution forecasts on prevailing sea states at 50 important ports worldwide (Accu-Waves; http://accuwaves.eu/). Its goal is to support safe navigation, unhampered vessel approaching to busy harbored areas, and secure ship maneuvering in ports. Accu-Waves[1] is based on integrated, high-resolution, ocean and coastal modeling that uses data from global scale, open-sea forecasts as boundary conditions. The models' setup, coupling, nesting, calibration, verification, and application are reported herein, concerning areas near and inside globally significant port basins. Thus, we present the automated operational setup of the Accu-Waves service for three-day forecasts at three-hourly intervals.

KEY WORDS: Port; sea-state; wave; sea level; modeling; forecast; navigation.

INTRODUCTION

The feasibility of maritime transports and the safety of port-related navigational processes may be undermined by severe weather conditions and consequent rough sea states. According to the International Maritime Organization (https://www.imo.org/en), the determination of Certified Navigation Pathways (CNPs) in port areas, within the recent *e*-Navigation strategy, requires reliable forecasting of prevailing continental shelf, nearshore, and in-port sea states. The latter are imperative in preventing or minimizing port downtime, transportation delays, vessel approach stoppage, halt of berth-load-dredge operations, damages to port infrastructures, ship accidents, etc.

Short Review of Recent Efforts on Met-Ocean Forecasts

Open-sea oceanographic forecasts in global or regional scales are freely provided by various platforms worldwide; however, they lack the required resolution in harbor areas for reliable met-ocean predictions to increase port navigation safety. Thus, the existing literature about ocean and coastal modeling applications of Marine Weather Forecasts (MWF) is unlimited, yet herein we focus only on recent research for short-term sea-state predictions specifically in port areas, which is rather scarce. Tintoré et al. (2019) recently presented a comprehensive review of the established operational MWF systems in the Mediterranean basin, mainly concentrating on fit-for-purpose "downstream" services, such as the Copernicus Marine Service (CMS; http://marine.copernicus.eu) platform. Nevertheless, these platforms mostly contribute to bridging the science-policy gap, rather than providing fast-track services targeted at real-time operational management to port authorities and maritime industry stakeholders.

The SAMOA (https://www.spasamoa.ws/projects; Sotillo et al., 2019) initiative is more focused on port sector needs for tracking and forecasting of marine physical parameters (wind, waves, and sea level). It involves ensemble MWF modelling (e.g., 29 high-resolution atmospheric, hydrodynamic and wave models). The goal is to deliver a user-customized Operational Forecast System (OFS) for the aid of the Spanish Port Authorities on navigation safety, environmental management of harbored areas, and port-operation decision making. The services are restricted to national and local interest (Spain, western Mediterranean, and Iberian Atlantic). Heslop et al. (2019) presented an integrated strategy based on sector-focused products and services within the SOCIB MWF platform (https://www.socib.eu/) at regional and local scales. The portal supports MWF data-sharing by an OFS for open-sea waves, but with rather crude resolution (>0.5 km), focusing on maritime safety agencies and operators (e.g., coastguard, oil-spill response managers, maritime emergency managers, naval security officers, etc.). Bonino et al. (2015) focused on the Northern Tyrrhenian and Ligurian Sea and presented a pilot sea-state (wind and wave) forecast platform, aiming at real-time MWF around the main ports of the study region. Their Wave Forecast System (WFS) is based on MIKE21's phase-averaged Spectral Wave model, cross-validated by comparisons with *in situ* wave buoy recordings. They showed that a local MWF system is reliable, maintainable, and cost-effective, yet the implemented resolution is considered to be of medium range, varying from 16 km offshore to 200 m near port entrances. Rusu and Soares (2013) also presented the thorough evaluation of a high-resolution OFS for open-sea irregular wave fields. The tested models (SWAN and WAM) should provide reliable real-time information about sea states around Portuguese ports. In all previous efforts, only national/local large coastal areas of rather coarse resolution were investigated. However, higher spatial analysis and phase-resolving model approximations are needed in order to properly simulate the wave penetration in port areas, diffraction due to jetties and breakwaters, and reflection from piers and waterfronts.

Nonetheless, in all previous efforts, only national/local large coastal areas of rather coarse resolution were investigated. Similarly, MED-MFC (https://marine.copernicus.eu/about/producers/med-mfc) produce an open-sea wave component within its OFS services referring to a resolution of 1/24° (~4 km) on a daily basis in a 5-days hourly prognostic mode in the Mediterranean Sea. The resolution of sea-state depictions, provided by the CMS platform, is rather low for port areas. Other similar OFS tools comprise the Poseidon (https://poseidon.hcmr.gr/) state-of-the-art MWF platform, Portus (http://portus.puertos.es) and WaveForUs (Krestenitis et al., 2017; http://wave4us.web.auth.gr/) forecasting components. These operate at both local and Mediterranean basin scales, with sea level and wave products, covering also some port and coastal areas. However, the highest spatial resolution of wave models can hardly reach dx=250 m.

Scope of Research

Severe marine weather conditions can decisively influence port operations and maritime transport by balking ship maneuvers, towage services, and vessel docking procedures. All concerned parties (port traffic headquarters, navigators, towing servicers, shipping companies and owners, harbor masters, ship pilots, captains, seafarer staff, fishermen, coastguard, diving technicians, etc.) are interested in reliable forecasts of sea states on CNPs and port entrances. Therefore, we consider the daily delivery of comprehensible and detailed MWF data to navigational traffic control and vessel operatives through a user-friendly OFS platform to be a novel product for MarineTraffic (https://www.marinetraffic.com/). It should significantly enhance navigation safety in big cargo ports with high traffic loads (Memos et al., 2019). Our goal is to introduce fine-resolution forecast modeling of wave agitation inside and in the vicinity of ports *in tandem* with Sea Level Elevation (SLE) and hydrodynamics due to meteorological forcing and tidal effects. Thus, our approach implements one-way coupled simulations by nested dynamic downscaling into super-fine grid resolutions near and inside ports.

This paper presents the ongoing development of the Accu-Waves MWF platform towards the assistance of OFS-based Decision Support Tools (DST) for 50 selected important ports worldwide. The app will support port approaching procedures for any type of vessel calling to harbor facilities. It will be offering reliable data and detailed interactive maps of prevailing sea-state characteristics in and around port basins in a 3-hourly provision mode for a full 3-day forecast, updated every day. Herein, we are concerned with the integration of three high-resolution, hydrodynamic and wave models fed with input data from global scale meteorological forecasts, and boundary/initial conditions by ocean scale MWFs (Makris et al., 2021).

The prototype MWF software suite comprises mature (calibrated and verified) solvers, *i.e.*, a spectral wave model A (Benoit et al., 1997; Papadimitriou et al., 2021), a mild-slope equation wave model B (Copeland, 1985; Makris et al., 2019b) and a barotropic hydrodynamic circulation model H (Androulidakis et al., 2015; Makris et al., 2019a). These are intertwined and finetuned via *Python* language control codes, designed for automation of the nested simulations on all ports. The latter are executed in parallel, allowing translation of model H output and optimal delivery of input data to downscaled high-end wave modules (Spiliopoulos et al., 2020). Thus, we hereby also present the end-to-end computational processing route of the integrated MWF model suite. It is created to intelligently manage (i.e., retrieve, translate, handle, fuse, simulate, integrate, post-process, validate, and visualize) georeferenced numerical big data. The daily storage volumes are in the order of hundreds of GB. We also provide scientific proof of pre-operational models' verification and characteristic depictions of typical model applications out of the official bulletins of evaluation by experienced port engineering consultants.

METHODOLOGY

The Accu-Waves methodological framework follows the operational data flow schematics of Fig. 1. The sequence of the implementation components in the OFS comprises retrieval of patrimonial, open-access, forecast input data from: a) NOAA (https://www.ncdc.noaa.gov/; meteorological forcing), b) CMS (hydrographic boundary conditions), c) GEBCO (https://www.gebco.net/), national map agencies, and Navionics (https://webapp.navionics.com/; bathymetric data), and d) Aviso+ (https://www.aviso.altimetry.fr/; tidal components of sea level). Next, all necessary data is stored, catalogued, and archived in a contingency plan side-route. Then, all data are inserted to the transformation-translation component led by a series of built-in *Python* and *NumPy* scripts to navigate and operate all input and output of the model processing component. The latter runs in an integrated way, based on *Python* control of *Fortran* main codes within CPU-paralleled job executions. The MWF products are then conditionally validated against field observations, where available, by CMS *in situ* sub-datasets (stage *b*). After that, all model output is post-processed (interpolation, filtering, etc.), and automatically visualized via *Matplotlib* coding. The ultimate step of dissemination to end-users relies on web-GIS services.

Numerical Models

Integrated applications of three nested numerical models (H, A, B) are presented for engineered coastal areas with significant harbors and port facilities, considering: i) SLE driven by barotropic hydrodynamics, ii) wave propagation in port-neighboring open seas, and iii) wave interaction with coastal works and wave agitation in harbored waters.

Model H HiReSS is a 2-DH "storm surge" numerical code for the simulation of barotropic hydrodynamic circulation and sea level variations, based on the depth-averaged shallow water equations (Makris et al., 2019a). It is applied over the continental shelf, considering combinatory effects of barometric systems, wind stress on the sea surface, geostrophic Coriolis forces, bottom friction, eddy viscosity, and wave-induced mean flows (Stokes's drift) in open seas (Androulidakis et al., 2015; Makris et al. 2016). It reproduces SLE and depth-integrated ocean currents due to meteorological conditions (wind setup and inverse barometer effect; Krestenitis et al., 2017) combined with astronomical tides by a static model (Krestenitis et al., 2015).

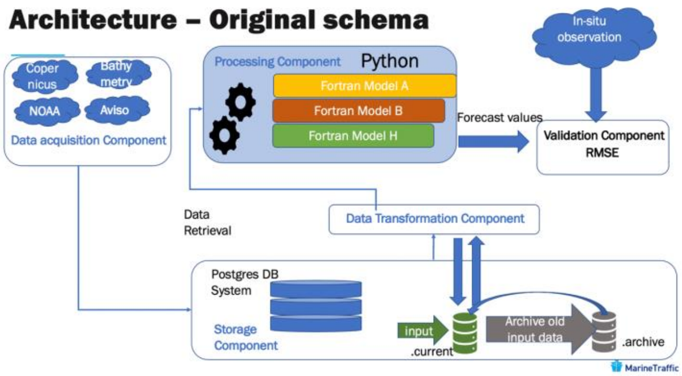

Fig. 1. Operational data flow schematics depicting the sequence of several components in Accu-Waves OFS, from open-access data retrieving to model processing, validation of MWF products, output data post-processing, and local storage and dissemination to end-users.

Model A TOMAWAC (http://www.opentelemac.org/) is a 3rd generation spectral solver that simulates the generation and propagation of wind-induced irregular wave fields on triangular finite element meshes (Benoit et al., 1997). It is a phase-averaged, directional, spectral wave action model that can reproduce the irregular wave shoaling and depth-limited breaking, the energy dissipation due to white-capping and bottom friction, the non-linear triad and quadruple wave-wave interactions, rudimentary wave-structure interaction. Model A runs on diverse computational resolutions, i.e., finer meshes as the waves travel into shallower coastal waters, thus densified near ports (Makris et al., 2021; Papadimitriou et al., 2020). The model can also capture wave-current interaction processes; herein we capitalize on the recent work of Papadimitriou et al. (2021). Therefore, we parameterize model A to simulate mean wave direction disturbance from wind- and surge-induced barotropic currents (by model H) in coastal areas around ports.

Model B WAVE-L is based on the hyperbolic mild-slope equation and it simulates the transformation of wave fields in the vicinity of ports with rapidly varying bathymetries. It includes shoaling, refraction, diffraction, reflection from structures, energy dissipation due to wave breaking and bottom friction in a combined way (Karambas and Samaras, 2017; Makris et al., 2019b). Makris et al. (2021) have analytically presented an evolved version of the model to cope with quasi-irregular wave generation and propagation from any incoming direction (i.e., both the "model-south" and lateral boundaries with surrounding sponge layers) in coastal waters with very fine resolution ($dx \geq 2.5$m). An advanced approach to incorporate partial and full reflection from structures is also followed (Karambas and Bowers, 1996). The numerical scheme is based on an explicit staggered-grid solver (Karambas and Samaras, 2017; Makris et al., 2021).

The model integration follows the subsequent steps of implementation. NOAA weather forecasts of atmospheric (wind and Sea Level Pressure; SLP) fields feed model H, which is driven in its boundaries by CMS prognoses of SLEs and tidal currents. In turn, model H provides high-resolution estimates of SLE and depth-averaged current speed and direction to model A. CMS wave forecasts on its mesh boundaries and NOAA wind predictions over the entire field of application force model A runs to simulate spectral wave propagation and transformation from offshore regions towards the port areas (Memos et al., 2020). Model B is then nested to model A domain and runs based on wave height, period, and direction input from model A forecasts in order to simulate wave penetration inside the port basins (Makris et al., 2021).

Case Study Areas

The list of 50 ports selected for Accu-Waves application is given in Table 1. Commercial importance, shipping transport load and global navigational correspondence of port-visiting vessels were the main selection criteria. The harbor sites are depicted in Fig. 2, together with the surrounding areas of model H implementation on a global map. This indicates the different delivery expectations by the three models in terms of area coverage, forecast accuracy, and topographical impact.

Bathymetric Data We put a great deal of work in creating very detailed bathymetric grids in the relevant sea areas of all selected port sites (Table 1). These were semi-automatically digitized and interpolated by Kriging method in QGIS, after being drawn via data-mining algorithms by available nautical maps of National Hydrographic Services and the Navionics platform. The latest GEBCO database was also used for georeferenced format of fine-resolution model H bathymetric grids.


Fig. 2. Global chart depicting the locations of the selected 50 important ports of Table 1 (marked with purple dots). Green hatched areas correspond to model H domains. Zoomed windows refer to model A and B domains in the continental shelf and the port of Algeciras.

Spatial Extents Model H is applied at large domains covering aquatic bodies, such as the entire Mediterranean and Black Seas (Makris et al., 2019a; 2021) or the northwestern part of the Atlantic Ocean (coastal zone of central and northern Americas; Fig. 2) in order to include the effects of synoptic scale meteorological processes on the sea level. Hence, 9 relevant areas were selected including smaller marginal seas and large gulfs, i.e., Persian Gulf, English Channel, Java Sea, Osaka, Tokyo and Finland Gulfs, Yellow Sea, and Red Sea. Model A's domain covers all offshore areas of 50 ports (Table 1) on the continental shelf, up to 45 km away from ports, in order to capture the wind-induced wave generation or amplification in gulfs and bay areas with sufficient fetches (Memos et al., 2020). Model B is for now applied to 22 of the 50 ports (Table 1), in harbored areas where a rational computational domain can be installed in terms of processing resources. Model B's spatial configuration contains all the port infrastructure and the nearby part of the port approaches routing to the ports' entrances. Thus, the port-approach part of the CNPs is treated by overlapping simulations of both models A and B. Ad hoc nesting of the two models was performed by choosing a characteristic wave generation line for model B (where model A output is attached) with mainly homogeneous water depth.

Model A simulates wave fields in surrounding port domains of <1600km^2 with variable triangular mesh resolution down to dx=25m in coastal and port areas. Therefore, adequately high resolution of wave data is achieved even without model B runs. Model H runs in "hot" initial condition mode and provides input data to both models (A, B).

IMPLEMENTATION SYSTEM

Computational System

A robust DST for safe navigation in harbors needs to hinge on reliable MWF products and a user-friendly OFS platform in order to help the operational management for port authorities, ship masters, pilotage controllers, and vessel captains, up to 72h in advance. The foundational concepts of Accu-Waves refer to: unhindered operability of computations; continuity of data-streaming; forecasts' security against contingencies; transferability of high-focus MWF to end-users.

Implementation The operational MWF platform runs on a *Linux*-based multi-CPU server with 128GB of RAM. The stream of individual processes is coordinated by open-source software based on *Python* programming language. A general schematic of the operational I/T system layout in Accu-Waves OFS is given by Memos et al. (2019). The main functionalities of the OFS include: a) communication and data retrieval protocols with existing MWF global-scale databases; b) integrated high-resolution modelling of marine hydrodynamics in regional and port scales; c) consolidation of sea-state forecasts in 3-hourly intervals for a 3-days product; d) visualization of products for port managers and navigators via tailor-made configurations; e) on-the-fly evaluation of the disseminated product by comparison of forecast data with *in situ* observations (if, where, and when available); f) management and maintenance of storage and database for all the aforementioned sets of information (Spiliopoulos et al., 2020).

Storage – Database The Data Storage Units (DSU) for the immense information volumes, created every day by the Accu-Waves OFS platform, refer to several TBs on SSD hard disks. CPU-DSU communication is operated via a data transformation block with parallel acquisition and processing cycles. The first cycle involves raw data storage and backup for MWF support, while the second cycle involves raw, post-processed, and visualization data, leading to simulation and management output data storage within a daily OFS time-limit (of 12h). Maximum storage capacity threshold may be reached, especially in cases of realization of contingency plans. Thus, a dual monitoring scheme of the logical procession in Accu-Waves OFS big-data implementation is needed. In order to reference, save, manage, and exploit the used and produced data of the MWF system, an advanced open-source relational database for model suite systems' developers is designed to back up the forecast and dissemination processes (*PostgreSQL*; https://www.postgresql.org/; Spiliopoulos et al., 2020).

Input Data

Models H and A need forcing weather data and/or and sea-state input as boundary conditions to perform accordingly.

Forcing and Boundary Conditions All sources refer to freely available, rather coarse resolution, global- or regional-scale forecasts of: a) wind speed/direction and atmospheric SLP from NOAA's GFS; b) SLE from CMS; c) Sea Level Anomalies (SLA) due to astronomical tides from Aviso+; d) ocean currents' intensity/direction by CMS and Aviso+ (as boundary condition and as alternative where model H does not apply); e) wind-induced wave characteristics (significant wave height H_s, peak spectral period T_p, and main wave propagation direction φ_w) from CMS; f) swell wave characteristics from CMS.

Table 1. List of selected important ports for MWF within Accu-Waves.

A/A	Port Name	Country	Lat, Lon (in decimal °)
1*	Fujairah	UAE	25.18449, 56.376976
2	Jebel Ali	UAE	25.115958, 54.992612
3*	Buenos Aires	Argentina	-34.408068, -58.217592
4	Port Hedland	Australia	-20.295223, 118.579852
5	Antwerp	Belgium	51.761809, 3.584792
6	Paranagua	Brazil	-25.553207, -48.268124
7	Santos	Brazil	-23.983137, -46.286548
8*	Halifax	Canada	44.589519, -63.521229
9*	Cartagena	Colombia	10.4012, -75.684413
10	Bremerhaven	Germany	53.634542, 8.432954
11	Hamburg	Germany	53.970308, 8.598527
12*	Algeciras	Spain	36.103713, -5.376105
13*	Barcelona	Spain	41.323029, 2.197049
14*	Le Havre	France	49.486063, 0.06775
15	Immingham	UK	53.554267, 0.107858
16*	Patra	Greece	38.251791, 21.690261
17*	Piraeus	Greece	37.929029, 23.587359
18*	Thessaloniki	Greece	40.448321, 22.829513
19*	Hong Kong	China	22.248463, 114.133737
20	Jakarta	Indonesia	-6.041035, 106.859654
21*	Dublin	Ireland	53.333206, -6.10403
22*	Haifa	Israel	32.854963, 35.00941
23	Mumbai	India	18.888354, 72.824252
24	Cochin	India	9.95638, 76.225454
25*	Genova	Italy	44.364064, 8.857234
26	Osaka	Japan	34.481998, 135.215596
27	Tokyo	Japan	35.358128, 139.721075
28	Kobe	Japan	34.481998, 135.215596
29*	Busan	Korea	35.040455, 128.777307
30	Incheon	Korea	37.382372, 126.518003
31*	Colombo	Sri Lanka	6.958612, 79.819435
32*	Tanger Med	Morocco	35.896937, -5.531744
33	Klang	Malaysia	3.017965, 101.172777
34	Lagos	Nigeria	6.423271, 3.378338
35*	Ijmuiden	Holland	52.470833, 4.52835
36	Rotterdam	Holland	51.998589, 3.980189
37*	Callao	Peru	-12.040148, -77.178332
38	Ras Laffan	Qatar	25.916437, 51.694296
39	St Petersburg	Russia	59.923369, 30.121587
40*	Novorossiysk	Russia	44.655115, 37.824991
41*	Jeddah	Saudi Arabia	21.455015, 39.127487
42	Singapore	Singapore	1.160392, 103.747156
43	Bangkok	Thailand	13.492719, 100.593242
44*	Ambarli	Turkey	40.949147, 28.676802
45*	Keelung	Taiwan	25.163773, 121.762476
46	Los Angeles	USA	33.715401, -118.188251
47	Dalian2	China	38.990992, 121.931578
48	New York	USA	40.517758, -73.95194
49	Dalian	China	38.921425, 121.748244
50	Shanghai	China	31.288889, 121.927287
** Ports where both A and B wave models are applied.*			

The 68% of CMS input data are obtained from the Global-scale package (1/12° resolution). The rest of the CMS datasets are retrieved from the NW European and Mediterranean, finer resolution (1/24°), regional components of the Copernicus platform. Wave characteristics are obtained from the respective global and regional packages.

Solid Boundaries in Ports Following the fully detailed mapping process for numerical bathymetric grids, we also made a great effort to create an inventory of solid boundaries and depict them in all necessary detail on all the selected port sites for model B runs (Fig. 3). Thus, both fully and partially reflective boundaries in all coastal areas were identified, based on the classification of ranges for the reflection coefficient C_r corresponding to typical harbor structures, by Thompson et al. (1996). The latter was set as: a) $C_r \leq 0.15$ for natural beaches, b) $C_r \leq 0.45$ for absorbing piers or rough armored slopes and rubble mound breakwaters (acropods, dolos, rocks), and c) C_r=0.9-1.0 for vertical quay walls (blocks/caisson) (Fig. 3). The relevant model B grid cells in these areas were assigned with respective values of C_r for the advanced numerical computation of wave reflection by an extra turbulent eddy viscosity (dissipation) term. The latter is modeled based on an updated version of the Karambas and Bowers (1996) approach via a system of complex number equations (Makris et al., 2021).

Fig. 3. Illustrative example map of reflection coefficient assignment on the perimetric solid boundaries in Ijmuiden, NL, port 35 of Table 1, based on type of waterfront; a) natural beaches (blue color), b) absorbing jetties, rough armored slopes, and rubble mound breakwaters (yellow color), and c) fully reflective vertical quay walls (red color).

In Situ Data

The MWF reliability check and the integrated OFS product quality control rely on available field data of sea-states in and near ports.

Field Observations We therefore performed *in situ* observations of sea level and wave characteristics in 2 Greek ports (Thessaloniki and Patra) during the "cold" period of 2019. The equipment was Sea-Bird Electronics (https://www.seabird.com/) SBE26 Seagauge Wave and Tide Recorder[22]. All details of recording setup and post-processing methodology for sampled measurements are presented analytically by Makris et al. (2021). Concurrent local information about atmospheric conditions from the nearby meteorological station of Aristotle University of Thessaloniki (https://meteo.geo.auth.gr/en/meteo-obs), were also used for tide-gauge calibration. The two datasets refer to wave, tidal and sea level records during parts of September-December 2019.

Available Hydrographic Data Moreover, longer datasets of past wave- and tide-gauge measurements were also retrieved from available web sources, such as GLOSS (https://www.gloss-sealevel.org/), ISPRA (http://www.isprambiente.gov.it/), HNHS (https://www.hnhs.gr/en/), and Poseidon. These mostly refer to SLE and wave data, where available, information at several Mediterranean stations (e.g., Algeciras, Barcelona, Genova, Trieste, Venice, Alexandroupoli, Mykonos, Lefkada, Chios, Piraeus, and Haifa; Makris et al., 2019a; 2021). Observational output was used to validate both hindcast and initial operational simulations of models H and A. The record periods are from 1995 to 2005, 2012 to 2015, and 2017 to 2019. All datasets have undergone severe post-processing (filtering, de-tiding, etc.) to exactly account for modelled cases.

We have also created an automated filesystem controller to update our Accu-Waves database of field data near a few of the selected ports (Table 1). We use data-mining codes, via a highly efficient and robust webserver to treat oceanographic data, i.e. the *Python*-motu client (https://github.com/clstoulouse/motu-client-python), to retrieve CMS near real-time (NRT), *in situ*, quality-controlled observations. The latter are hourly updated and distributed by INSTAC (In Situ Thematic Centre; https://marine.copernicus.eu/about/producers/insitu-tac), within 24-48h from acquisition in average. Data are inherently pre-tested as they are collected mainly through certified global networks and the pre-World Meteorological Organization Global Telecommunication System (pre-WMO-GTS; https://public.wmo.int/). Thus, we refer to the wave buoy datasets of NRT-CMS observations (1/30° resolution), e.g., in Los Angeles and Antwerp ports, for model A validation.

Operational System Architecture

Except from its integrated numerical modeling aspect, the Accu-Waves OFS deals with systematic big data management in a daily schedule. The job orchestration and parallel execution of modeling and management tasks stand on a *Python* framework relying on *Dask* (https://dask.org/) for parallelized and asynchronous execution, while daily MWF tasks are controlled with *Apache Airflow* (https://airflow.apache.org/). The integrated model data flow architecture and orchestrated job monitoring is presented in Fig. 4.

Big Data Management The management of interconnections for all models applied to every port (A and/or B), its surrounding coastal area (A), and the continental shelf region (H or CMS/Aviso+ available data) are a complex task. Specifically, models A and H rely on static (bathymetries) and dynamic data (global-scale MWF boundary conditions). The availability of the latter is scrutinized during job orchestration, before model run, in order to update upon contingency alternative routes. Therefore, a separate execution plan for each port is created on a daily basis, respecting a pre-defined dossier of harbor information (georeferenced location and orientation, coastline depiction, local bathymetric data, weather metrics, *in situ* data coverage, etc.). This also contains specific characteristics of computational setups, estimated runtimes, model-run availabilities, data inflow/outflow, and interactions within all levels of implementation. This way, the flowing data are stored in the Accu-Waves database, while the execution plan is saved in the filesystem for future transcriptions and easy-tracing for upcoming implementations. Within Accu-Waves we try to run a truly large scale, real world macro-implementation that demands constant dataflows on the web and concurrently schedules and runs hundreds of jobs with big data exchange. Typically, model H is executed in 9 jobs covering most of the ports with very large areas in continuous 72h forecast mode per run. Model A involves another 50 consecutive runs also referring to 72h forecasts per implementation, covering the need of fine-scale wave data in all harbor areas, CNPs and port approaches. Conclusively, the model B runs need to achieve steady-state conditions per any 3-hourly implementation. Thus, for a 3-day MWF, 22 ports × 24 3h sea-states produces 528 jobs. A total maximum of 587 model runs may be called each day notwithstanding the intermediate communication jobs. This setup can produce raw input/output data within the different phases of simulation – processing – analysis pipeline of a few hundreds of GB daily. The massiveness of consumed and produced datasets in such an OFS makes it necessary to employ new non-traditional I/T and software engineering techniques to fulfil on-time (within 12h from incipient system run) a complete 3-day forecast.

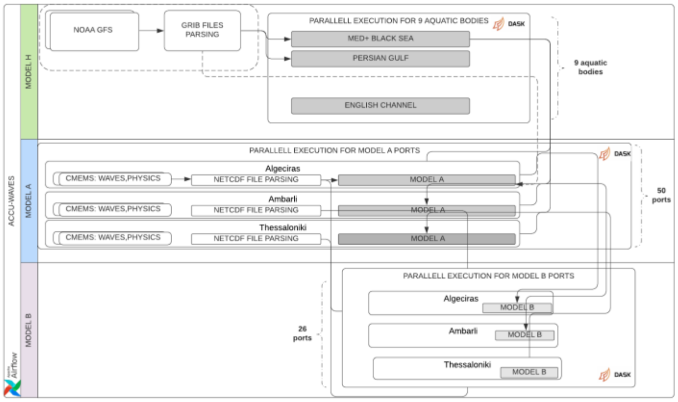

Fig. 4. *Airflow*® controlled model integration data flow architecture with *Dask*® orchestrated parallelization of job assignments in Accu-Waves OFS platform.

Time Scheduling and Automation We programmatically author, schedule, and monitor all workflows with *Airflow*. Within it, the *Dask* data frames scale the *Python* panel data analysis (pandas) workflows, enabling applications in a feasible and clever time series while munging big data. This way, common preparation or model tasks for any harbor or a multitude of ports are identified. Thus, the rest of the execution plan can be discretized into further independent processing micro-components and specific jobs executed in parallel. The dynamic data are downloaded every day, discarded if not used for the sake of space-saving, and stored in bilateral structures of the OFS database for easy future queries. In general model H runs for all 9 areas in a few hours. Concomitant model A runs in locations, where model H is not run, are completed crudely together with the storm surge model to save time. The rest of model A implementations usually take another 4-5h to deliver the main Accu-Waves output of wave and sea level characteristics in all port areas. Upon the latter, the most time-consuming implementation of a 3-day forecast with model B is set in asynchronous mode to catch-up with the rest of the data currently being prepared for visual dissemination. If all model B ports are run, it may take up to half a day to finalize the integrated job executions. Automation algorithms for all the aforementioned are built on *crontab* commands (https://www.computerhope.com/unix/ucrontab.htm). An automated contingency plan secures MWF on-line data sharing and OFS delivery to any port DST for 3-day periods in case of functional problems or any communication fails with the patrimonial databases (CMS, NOAA, and Aviso+). Job orchestration and parallelization stands on and supports the above, respectively.

Job Orchestration and Parallelization We use the *Dask* data frame by parallelizing pandas that remain on disk for larger-than-memory computing on a single server with large capacity. We also use the *Dask* application programming interface (API) to achieve multi-core speed-ups at least during scheduling, integrating, pre- and post-processing model data, and finally preforming scalar model runs simultaneously. This upscaled workflow enables some adequate level of multi-dimensional data analysis in our coastal models. For example, the parallelization process starts with data acquisition from patrimonial MWFs of NOAA-GFS and CMS *ftp* repositories in GRIB2 and NetCDF formats, respectively. *In tandem* with the latter, all nested H→A→B model runs are prepared and commenced in asynchronous mode, taking advantage of the available system resources.

SYSTEM EVALUATION

The evaluation of the Accu-Waves OFS has been separated in the pre-operational phase with multi-parametric validation per model setup and the operational phase with both testing for standalone models and critique of MWF results by experienced port engineering consultants.

Model H HiReSS model has been extensively validated in the past at the Mediterranean Sea basin for long-term hindcasts (Androulidakis et al., 2015; Makris et al., 2016). Furthermore, model H has been tested specifically for the combined astronomical tide and storm surge effects (Krestenitis et al., 2015), for short-term extreme weather conditions during downscaled and nested operational forecasts (Krestenitis et al., 2017). The Accu-Waves setup of model H has been calibrated with *in situ* SLE records on several ports throughout the Mediterranean basin (Makris et al., 2019a; 2021). The simulation skill scores range from adequate to high, reaching up to 0.78 and 0.85, for Pearson correlation and Willmott index, respectively. Relative bias and errors were occasionally found to be small enough, i.e., a root-mean-square error down to 10 cm (12.5% of SLE_{max}) in pre-operational hindcast model runs (Fig. 5).

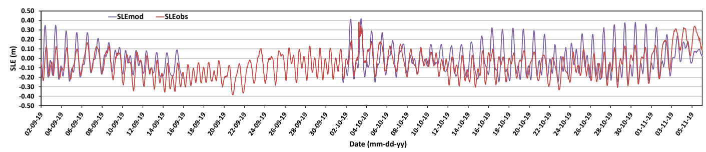

Fig. 5. Comparisons of SLE (m) by model H output (mod) against *in situ* observations (obs) in Ancona port (Italy) during Autumn 2019.

Model A TOMAWAC is a well-established spectral wave model tested against experimental data and real-life problems. Within Accu-Waves, we have tried to parametrize model A and evaluate its ability to capture spectral wave transmission, refraction and breaking due to strong opposing currents (Papadimitriou et al., 2020; 2021). The latter are crucial to safe navigation tactics near ports and harbor structures. Verification against experimental measurements was carried out yielding quite satisfactory results. Testing cases referred to a worst-case scenario at the port of Le Havre, in France (Papadimitriou et al., 2021).

Model B WAVE-L has been upgraded from its previous versions (Karambas and Samaras, 2017) and further evaluated in a fundamental laboratory scale approach (Makris et al., 2019b). Wave penetration through breakwater gaps, wave diffraction by semi-infinite jetties, and refraction by abrupt shoals were tested by comparisons with experimental data, and results were promising. A quasi-irregular wave generator is now incorporated in model B, while reflection from solid boundaries, diffraction at breakwater roundheads and through port entrances was revisited for real-life applications (Makris et al., 2021).

Feasibility, accuracy, and robustness of the Accu-Waves MWF results, near ports and along CNPs, are thoroughly discussed by Makris et al. (2021) in terms of the general consensus about the possible accuracy of modelled wave predictions at offshore, coastal, and nearshore areas. The operational performance of the integrated model suite was verified based on in situ records (SBE26+ wave-tide pressure-gauge) in a Greek port (Makris et al., 2021). Fig. 6 presents validation of combined model H and A/B's MWF results. Comparisons against field observations, taken in December 2019, range from very good for sea level to acceptable for modelled wave data. The integrated model suite for port sea-states is found to perform satisfactorily in operational MWF mode.

Preliminary quality assessment of the OFS products is currently being set up on automated NRT comparisons of model A to CMS wave buoy data, e.g., in Los Angeles and Antwerp ports (not shown for brevity).

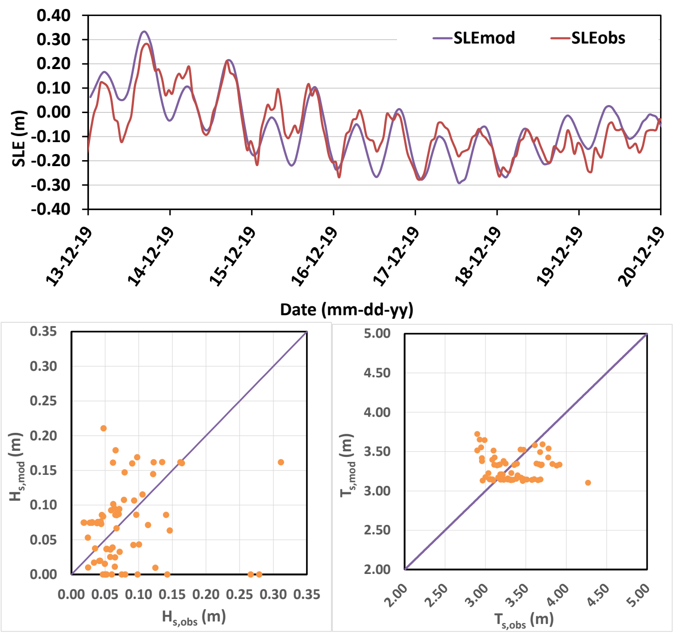

Fig. 6. Comparisons of SLE (m) timeseries by model H (upper graph) output (mod) against *in situ* observations (obs); and correlation scatter plots of H_s (m) and T_s (s) by integrated A and B models (lower graphs) in Thessaloniki port (Greece) during Winter 2019.

RESULTS

The work to disseminate all the completed integrated H→A→B model simulations in 9 large-scale areas, containing 50 ports worldwide, and 22 refined port-scale runs is still ongoing. The operational web-GIS Forecast Demo (https://accuwaves.eu/forecast/index.html) of Accu-Waves presents pilot output for 11 ports for the time being, yet new implementations are currently added for full operability within 2021.

Model H Spiliopoulos et al. (2020) and Makris et al. (2021) recently presented examples of HiReSS forecasts in operational mode. Sea level response to propagating Low Barometric Systems (LBS) and large-scale deep depressions in southern Europe were portrayed and discussed. The inverse barometer effect was reproduced well, while the effect of water accumulation due to onshore winds was also plausibly predicted. This was the case, especially in coastline alcoves, such as Algeciras, near the Gibraltar strait, and semi-enclosed Gulf of Gabes.

Model A Fig. 7 presents model A results about a case of W-NW sector waves of H_s=3.8m, T_p=10s, and winds blowing with speed 20m/s (9Bf; strong/severe gale) from the Atlantic Ocean. The modelled wave fields appear to be plausible in the port approach area, and specifically over the dredged pathway leading to wave focusing before the port basin entrance. Peculiarities in the shallow foreshore of the Seine estuary may seem rather pronounced, but this area is considered to be far from crucial for the developed prognostic tool. The rate and spatial expansion of energy dissipation for such long waves might seem overestimated at a first glance, yet the diverse shallowness of waters in the wider Le Havre port area, allows us to rate the overall depiction of the wave field as satisfactory. In other similar applications (not shown) the wave penetration in the port basins looks very good, as well as the directionality of spectral wave propagation is very well reproduced, especially along dredged bed channels in port approaches. Similar wave conditions for Patra port are also presented. The wave field behavior is satisfactory in the port entrances and wave blocking by the breakwaters is predicted. Diffraction is not well reproduced as expected by a phase-averaged model (WAVE-L tackles that).

Model B Fig. 8 presents model B results about two cases of W and NW sector medium seas with waves of H_s=1m, T_p=8s, and winds blowing with speed 20m/s (9Bf; strong/severe gale) from the Ionian Sea. In the case of transverse wave impact on the breakwater, model B seems to behave very well in terms of wave energy dissipation and minor to no diffraction predicted about the right and left roundheads, respectively. This is plausible, due to their topographic layout, i.e., the slight onshore and offshore horizontal tilts, respectively. Wave attenuation by the harbor's breakwater is evident in the NW case, too. There is a very high detail depiction of the wave height evolution in the leeward side of the structure and near the scaffolding berth positions and the unprotected waterfront. Reflection is numerically assigned to a C_r=0.45 according to "Input Data" Sub-section parameterizing, and this also plausibly depicted by the windward wave height map, i.e., H_s=1.4-1.6m, compared to the offshore deep water significant wave height H_{so}=1m.

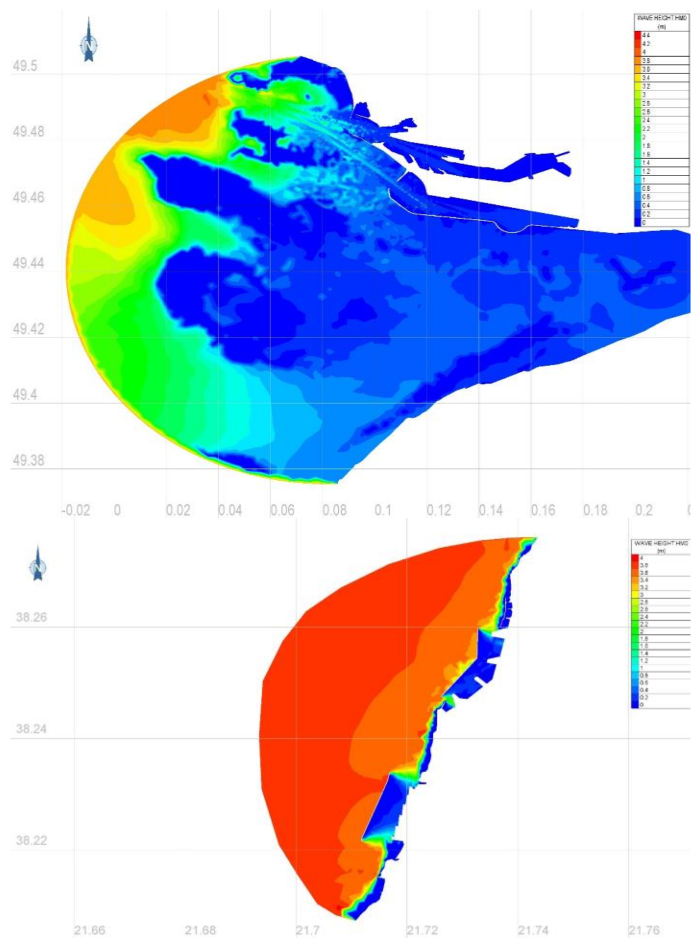

Fig. 7. Characteristic operational MWF results of Hs (m) by model A in Le Havre (France) [upper] and Patra (Greece) [lower] ports during W-NW and W-SW sector high wave conditions, respectively.

CONCLUSIONS

A new fine-resolution OFS for sea conditions in and around ports is presented. Accu-Waves is a prototype MWF tool that can uphold DSTs for harbor shipping operations and port navigation management. An end-to-end integrated software suite of three high-resolution ocean and coastal models, for spectral waves, sea level and barotropic circulation is therefore detailed. The system incorporates complex numerical and data processing within automated, upscaled, parallel frameworks. It is built in MarineTraffic's web-app and can provide an intuitive interface for coastal- and port-scale met-ocean data investigation and querying.

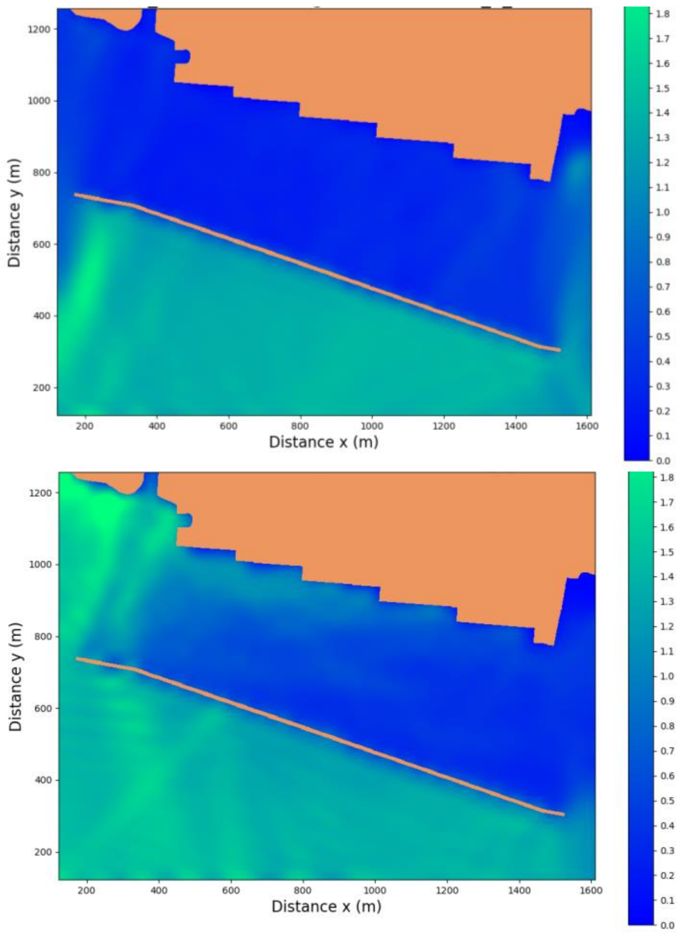

Fig. 8. Characteristic operational MWF results of H_s (m) by model B in Patra (Greece) port during W (upper) and NW (lower) sector incoming waves of H_s=2m (port orientation is turned 90° counterclockwise).

To sum up, useful validation and critique of both the standalone and integrated models' performance is achieved. The use of a high-resolution phase-averaged model supported by a hydrodynamic solver for storm surges is proved to be a robust approach. The OFS system is completed by a fine phase-resolving wave model application, which seems very promising in redefining the MWF paradigm for port areas. The operational system's architecture is schematized in detail and big data management needs and difficulties are also discussed. The straining job orchestration framework is intelligently programmed with modern open-source applications fit-for-purpose within the available computational setup and resources. The new OFS product also tackles issues concerning the extent of global-scale applications in 50 ports, contingency and back-up plans, database communication, model performance, results' dissemination, site-specific verification, and GIS platforming. Accu-Waves hopefully introduces state-of-the-art MWF in Ports Safety Management Systems for secure navigation towards and inside ports, vessel collision avoidance in offshore mooring on port approaches, safe ship docking, and clever berth positioning. Future steps of Accu-Waves OFS refer to alerting mechanisms, capitalizing on threshold excess tracking algorithms for extreme waves, winds, etc.

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