APPLICATIONS OF WAVE4US OPERATIONAL PLATFORM TO SUPPORT FIRST-LEVEL RESPONSE ACTIVITIES IN THERMAIKOS GULF

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Abstract
Thermaikos Gulf is an environmentally fragile coastal environment characterized by numerous anthropogenic and natural pressures. The environmentally protected areas along its western coasts and the large number of inhabitants that live over its northern and eastern coasts raise the need for systematic monitoring and prediction of the marine environment concerning the ocean circulation, weather conditions, sea level and wave characteristics, pollution events, coastal flooding, and freshwater input. Herein, we present recent advances of the Wave4Us operational platform that provides short-term forecasts of all the above conditions, freely accessed by local authorities, the research community, and the broader audience on a daily basis. Specified marine predictions (e.g., about pollution, flooding, and heatwaves) provide useful real-time information to first-level responders and managerial stakeholders during hazardous events that may threaten the quality of the coastal environment and the safety of the population residing on Thermaikos Gulf's littorals.
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1. Introduction

Thermaikos Gulf (TG) is a semi-enclosed coastal area in the NW Aegean Sea frequently facing adverse conditions of seawater pollution, induced by numerous anthropogenic and natural factors. The high social and environmental impact of TG is mainly related to: a) the dense population together with the accompanying infrastructure that are located along the coastal zone, and b) the environmentally protected areas, mainly along its western coasts, where large river deltas and NATURA 2000 areas are located (Kaberi *et al*. 2023). Thus, the knowledge of the prevailing environmental conditions such as weather and marine characteristics on a daily basis, and moreover their short-term prediction, are of very high importance and demand. Such estimations and forecasts may provide useful information to all stakeholders involved with the marine environment (e.g., authorities and professionals), the scientific community, and of course to the citizens of the coastal zone. Their quality of life and safety level are both strongly determined by the state and quality of the sea, especially under the context of climate change conditions. Herein, we present the most recent advances of an integrated numerical forecasting platform that operates over the marine environment of the TG and offers daily forecasts of several met-ocean parameters to support the prevention and mitigation of different natural hazards (e.g., coastal flooding, marine heat waves) and anthropogenic stresses or unfortunate events (e.g., pollution, marine accidents, loss at sea). Field and satellite observations were used to evaluate the performance of the different components of the platform's integrated modeling suite (Krestenitis *et al*. 2014; Pytharoulis *et al*. 2016; Androulidakis *et al*. 2021; 2023a; 2023b; 2023c; Makris *et al*. 2024).

2. Description of the operational system

The main modules of the Wave4Us operational system and the respective predicted parameters are presented in Figure 1a. Results are mainly presented as 2-D horizontal maps, but timeseries and/or spatial distributions along cross-sections are also provided in areas of interest that can be viewed using the 'Results type selection' menu in the Wave4Us website: http://wave4us.web.auth.gr. The 3-day forecast results are updated daily at 08:30 UTC. The atmospheric simulation, based on the WRF-ARW model (WRF-ARW-AUTh; Pytharoulis *et al*. 2016) covers the Central Macedonia region (1.67 km; Fig. 1b) with a simulation cycle that starts at 18:00 UTC of the previous day. WRF-ARW-AUTh provides the atmospheric forcing to the ocean model (Delft3d-Thermaikos; Androulidakis *et al*. 2023a) that covers the broader TG on a curvilinear grid and 15 vertical sigma-layers with horizontal spatial steps varying from 300 m in the northern part to 700 m offshore.

The freshwater input from six river sources around the TG is provided by HEC-HMS simulations (Androulidakis *et al*. 2021), associated with the respective drainage basins over Central Macedonia (Fig. 1b; Frysali *et al*. 2023). The Sea Level Height (SLH provided by HiReSS; Androulidakis *et al*. 2015; 2023b) and wave characteristics (provided by WAVEWATCH-III; Krestenitis *et al*. 2014) forecast simulations are forced by wind and sea level pressure fields (provided by WRF-ARW-AUTh), including an embedded parameterization for astronomical tides (Schwiderski 1980). The coastal inundation service of the Wave4Us platform provides hourly estimations of the potential flooding under combined SLH and extreme wave conditions along the coastal zone of TG with a high spatial resolution (5 m; DEM datasets by the Hellenic Cadastre; Androulidakis *et al*. 2023c), derived by 3-day simulations with CoastFLOOD model (Makris *et al*. 2023). The final module is based on Delft3d-Part and is forced by the system's hydrodynamic simulations (Delft3d-Thermaikos). The respective service covers the entire TG and is provided on-demand to predict the fate of tracers (lagrangian particles) in the unfortunate event of marine pollution accidents (e.g., oil spills) and pollutants' intrusion from land sources (e.g., flash floods and polluted freshwater input). It can further support the needs of search-and-rescue actions in the marine environment by predicting the potential areas of search.

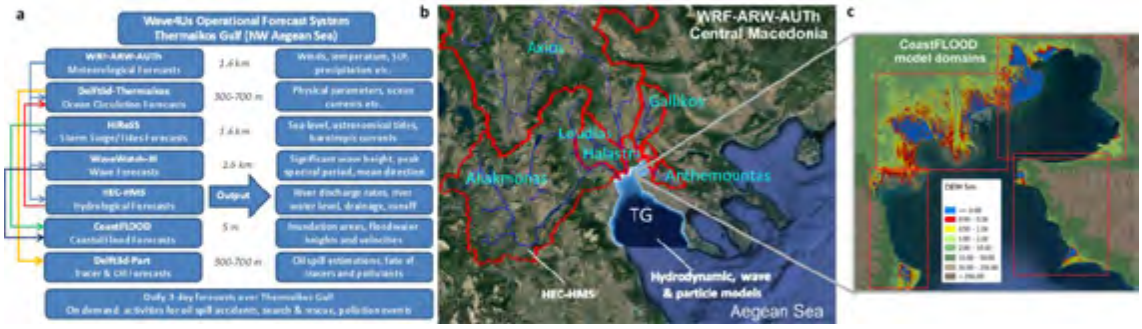

Figure 1. (a) Forecast modules and parameters of the Wave4Us operational platform, (b) domains of the WRF-ARW-AUTH, HEC-HMS (rivers), and Delft3d models, and (c) domains of CoastFLOOD simulations (5 m DEM).

3. Results

The main hazards of TG are primarily related to pollution events associated with significant environmental stresses due to impactful human activities taking place on the coastal zone (e.g., agriculture, aquaculture, industrial and port operations, urban effluent discharge, oil refineries, marine transportation, etc.). Furthermore, coastal flooding under extreme meteorological events (storm surges) is also an important hazard. Four examples of such events that were efficiently estimated by the Wave4Us system are presented below.

An oil spill of almost 5,000 m^2 was detected in the northern part of TG due to an oil mass release at the docking location of the permanent hydrocarbon supply pipeline outside of Thessaloniki port in the morning of 4/11/2017 (https://www.ertnews.gr/ert3/thessaloniki/petreleokilida-entopistike-ston-thermaiko/). South and southeasterly winds prevailed after the accident (Fig. 2) that induced a cyclonic circulation over the central and eastern part of the Thessaloniki Bay, while northward currents prevailed along the western coasts in agreement with the general patterns under southerlies, shown by Androulidakis *et al*. (2023a).

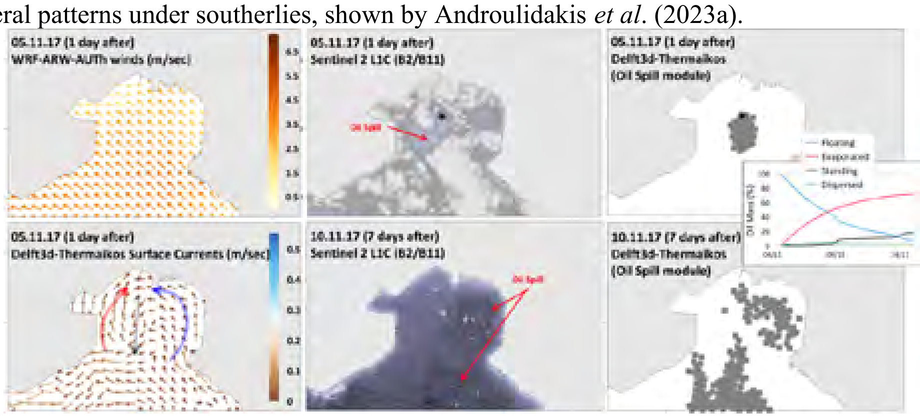

Figure 2. Wind and current distribution during an oil spill accident in November 2017 (left panels). Distribution of the B2/B11 band ratio (Sentinel 2 1LC images for two dates; middle panels). Snapshots of the oil spill simulations and oil mass evolution (right panels).

The oil spill, released at the central gulf, expanded southward as derived by the Bands 2 and 11 (B2/B11; Kolokoussis & Karathanassi 2018) of the Sentinel 2 L1C image on 05/11/17 (10 m resolution; https://dataspace.copernicus.eu/). A similar oil mass expansion was efficiently simulated by the Delft3d-Part (Oil mode), while oil patches were also detected along the prevailing cyclonic circulation along the eastern and northern coasts during the following week. A small portion of the released oil was also beached after 09/11, according to particle simulations, while most of the oil mass (80%) was evaporated during the first 10 days. The initial oil mass was set equal to 10 t, while Ekofisk type was chosen. Note that precise information (not available) about the oil's type, release mass, and possible mitigation measures applied after the accident, would improve the accuracy of the simulations. However, the coupled meteo-ocean-oil model provided efficient estimations about the fate of the specific oil spill.

During the same month (November 2017), a severe low pressure system (Medicane Numa; 12-19/11/2017) evolved over the central Mediterranean and resulted to 21 fatalities and approximately US$100 worth damages in Greece (Toomey *et al.* 2022). The increased precipitation led to strong discharge rates of freshwaters into the coastal marine environment. In the case of TG, our HEC-HMS simulations estimated river outflows especially for Aliakmonas that peaked over 200 m^3/sec on 20/11 (not shown). The large amounts of riverine waters contain high concentrations of nutrients and other pollutants and are usually responsible for the formation of eutrophication events, depending on TG's prevailing circulation conditions (Androulidakis *et al.* 2021). Fig. 3a shows the evolution of the river plume spreading based on the Normalized Difference Turbidity Index (NDTI; Lizcano-Sandoval *et al.* 2022) derived from Bands 3 and 4 of the Sentinel 2 LIC satellite images.

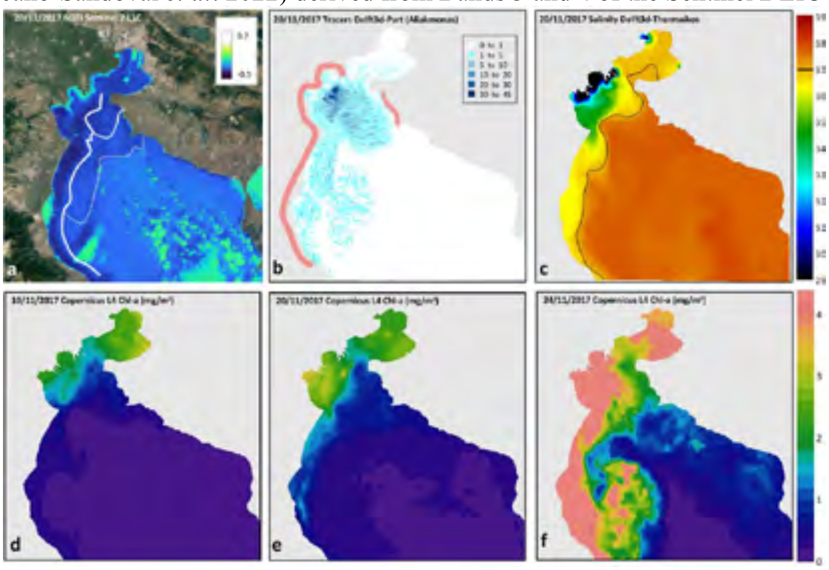

Figure 3. Distribution of (a) NDTI (Sentinel 2 1LC), (b) Passive tracers (Delft3d-Part), (c) salinity (Delft3d-Thermaikos) on 20/11/2017. Copernicus multi-sensor satellite-derived Chl-a concentrations (mg/m^3) on (d) 10/11 (before), (e) 20/11 (during), and (f) 24/11 (after).

A southward along-coast river plume extended along the entire western coast of the outer TG, while brackish waters were also detected over the central TG and the neighboring eastern coasts. The simulated salinity distribution (Delft3d-Thermaikos) confirmed this pattern showing salinity less than 37 along the western coast (Fig. 3c). The Delft3d-Part (Tracer mode) simulation shows that the passive particles released on the mouth of the Aliakmonas delta (continuous release 10-20/11) spread over the same coastal areas; the red lines indicate the potentially affected coastal zone (Fig. 3b). The spreading of the nutrient-rich waters formed favorable conditions of increased primary production, which was relatively low before the study period under lower river discharges (Figure 3d). A Chlorophyll-a (Chl-a) increase was observed on 20/11 (Figure 3e) which was even higher (>4 mg/m^3) a few days later (Fig. 3f). The high levels detected over the offshore area in the southwestern TG (Figure 3f) agree with the spreading of the simulated tracers (Figure 3b). Note that similar predictions can also guide search-and-rescue activities in the case of human or object loss in the marine environment.

Coastal inundation due to storm surges under low pressure atmospheric systems is also a known hazard of the TG coastal zone, especially over the low-lying areas of the western coast (Androulidakis *et al.* 2023b). Herein, we examine the storm surge-induced flooding derived from the Wave4Us predictions during Medicane Daniel in early-September 2023 (Fig. 4). Meteorological (WRF-ARW-AUTH), SLH (HiReSS), and coastal inundation (CoastFLOOD) simulations were combined to estimate the potential seawater flooding during the storm (04-08/09/23). A peak of SLH was detected on 07/09/23 00:00 (Fig. 4a) that affected several areas of the TG (Fig. 4b). The estimation of the most extended inundation during the storm period is presented in Fig. 4c. Several coastal areas of the deltas (west) and the low-lying peninsula of Epanomi (east) are affected by relatively extended floods, while only a few land cells along the coastline were flooded in the rest of the region. Fig. 4d shows the estimated inundation for a theoretical extreme case of SLH = 1 m, for which the flood is significantly larger over the entire western coastal zone, with floodwater heights over low-land areas.

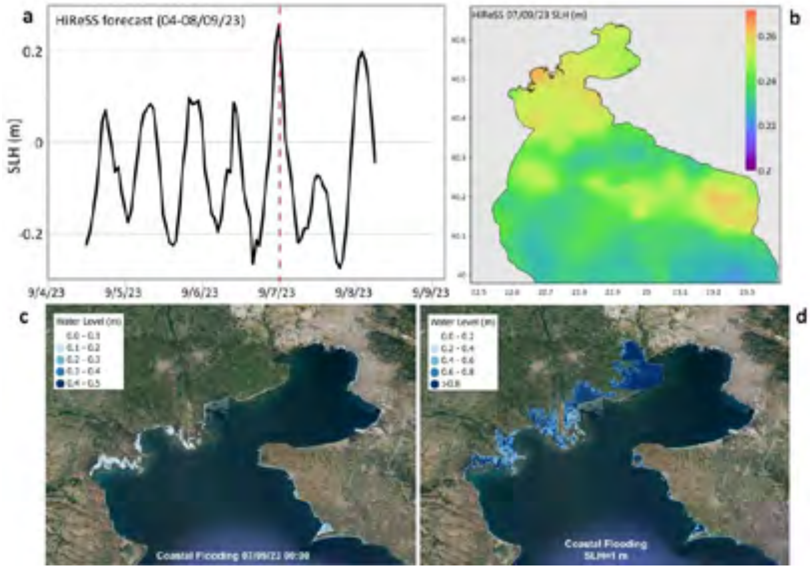

Figure 4. (a) 3-day SLH forecast, (b) map of SLH during the highest storm surge, maps of coastal flooding (c) under the strongest storm surge (07/09/23), and (d) under an extreme scenario (SLH=1 m).

The prediction of Marine Heatwaves (MHWs) is an additional valuable service provided by the Wave4Us system based on the Sea Surface Temperature (SST) forecasts of Delft3d-Thermaikos and the methodology provided by Hobday *et al*. (2017). TG is characterized as a MHW "hot spot" (Androulidakis & Krestenitis 2022). The model predicted most of the MHWs (5 out of 6) that occurred in 2017 (Fig. 5) with the strongest one in June (Mean intensity > 2ºC) as confirmed by the AVHHR satellite observations (1982-2017).

A/A	MHW start	MHW end	Duration (days)	Mean Intensity (°C)	Cumulative Intensity (°C x days)
Predicted (Delft3d-Thermaikos)					
1	23/03/2017	27/03/2017	5	1.23	6.13
2	15/04/2017	17/04/2017	3	1.61	4.83
3	30/06/2017	03/07/2017	4	2.18	8.70
4	09/08/2017	12/08/2017	4	1.39	5.56
5	17/09/2017	21/09/2017	5	1.46	7.31
Observed (AVHHR)					
1	21/03/2017	27/03/2017	7	1.61	11.26
2	01/04/2017	05/04/2017	5	1.48	7.38
3	13/04/2017	16/04/2017	4	1.54	6.17
4	27/06/2017	03/07/2017	7	2.40	16.79
5	07/08/2017	13/08/2017	7	1.96	13.73
6	19/09/2017	21/09/2017	3	1.32	3.95

Figure 5. Observed and predicted SST and MHWs for 2017 over TG (MHW info are shown in the table).

4. Concluding remarks and future steps

The Wave4Us operational platform provides near-future forecasts of the TG sea-state on a daily basis and is able to support a large range of activities related to the protection and management of the marine and coastal environment of the gulf. Marine pollution and other coastal hazards (e.g., floods, MHWs) are very common in the area, and their prediction contributes to the efficient mitigation of their adverse effects on both the coastal environment and population. For example, the on-time prediction of the fate of a potential oil spill may support first-level responders to quickly implement successive measures for the restriction of the spill's expansion, reducing its impacts on the marine environment. The detection of the areas where land-originated pollutants might spread after their discharge in the sea in combination with the prevailing met-ocean conditions can provide estimations of possible eutrophication effects related to nutrients' accumulation. Note that other biological processes that are not currently included in the system's suite will be added in the future with the development of an operational biochemical model, coupled to the existing simulations. The estimation of the riverine waters' connectivity patterns is a good indicator for the detection of the potentially impacted coastal areas during an extreme event of fluvial outflows. Finally, the operation of a coastal flooding model, coupled to sea level simulations, provides near real-time forecasts of potentially inundated coastal areas, especially during the passage of strong low-pressure systems over the TG. The compound flooding from both sea (storm tides and waves) and inland sources (i.e. due to precipitation, runoff, and flash floods in watersheds) will also be included to the Wave4Us platform in the future, based on the coupling of the existing HEC-HMS model with a 2-D flood routing hydraulic model.

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