Early Warning System for Coastal Hazards in Thermaikos Gulf (Aegean Sea)

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SCOPE OF STUDY

Thermaikos Gulf (TG) in the northwestern Aegean Sea (east-central Mediterranean) is a data-scarce area in terms of *in situ* monitoring. At the same time, it is a hotspot for significant anthropogenic pressures and natural hazards (Androulidakis et al., 2024a). This situation necessitates reliable metocean forecasts. To this end, the Wave4Us (https://wave4us.web.auth.gr/) Operational Forecast Platform (OFP; Krestenitis et al., 2015; Androulidakis et al., 2025) provides high-resolution model predictions for weather conditions, ocean circulation, Sea Level Elevation (SLE), wave characteristics, and river discharges (Figure 1). Based on these, it simulates coastal hazards like pollutant transport (oil spills and nutrients), Marine Heat Waves (MHW; Androulidakis et al., 2024b) and coastal flooding. This study presents the potential of the OFP's outputs and evaluates its predictive skill using satellite and field data, confirming its accuracy. The results highlight Wave4Us as a reliable tool for environmental impact assessment that can serve as the basis of an Early Warning System (EWS) for emergency response in the region.

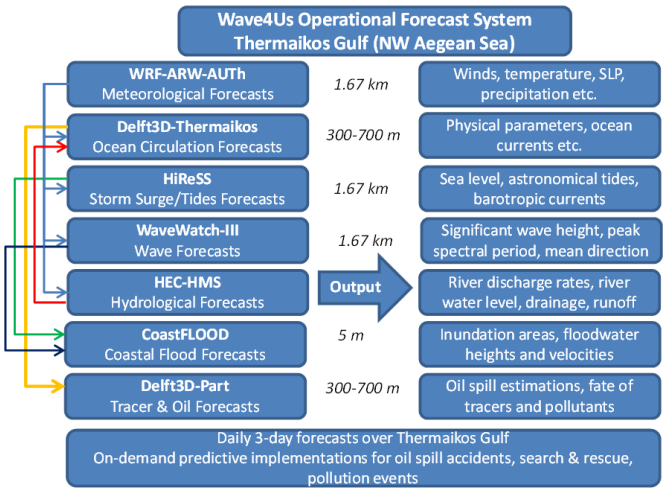

Figure 1. Wave4Us OFP work scheme and data flow (modules, interactions, coupling schematics, model resolution, and featured output).

METHODOLOGY

Study Area

TG is a naturally protected semi-enclosed coastal area influenced by anthropogenic stressors and meteorological and ocean dynamics. Major freshwater inputs from rivers and drainage channels shape the local hydrodynamics and hydrology, impacting seawater quality, ecosystem health, and circulation (Androulidakis et al., 2023). Intense urbanization, agriculture, maritime traffic, tourism, and industrial activities are sources of marine pollution, while extreme weather events (e.g., low-pressure systems, storm surge, high waves and flooding) also affect TG's vulnerability. Despite improvements in wastewater treatment, TG has yet to achieve a "good environmental state" (Androulidakis et al., 2024a). Limited field monitoring classifies it as a data-poor region. Given the projected climate change impacts, an integrated suite of high-resolution environmental forecasting is crucial for stakeholders, aiding decision-making in coastal management, hazard mitigation, and digital transformation initiatives (Makris et al., 2022).

Numerical Models

Wave4Us incorporates the following simulation models in an integrated way (1- and 2-way coupling; Figure 1): WRF-ARW-AUTh for meteorological forecasts (Krestenitis, et al., 2015a); Delft3D-Thermaikos and Delft3D-Part for coastal circulation, pollution transport and hydrodynamic connectivity (Androulidakis et al., 2023); HiReSS and WaveWatch-III for storm tides and wave dynamics (Krestenitis et al., 2015b), HEC-HMS for hydrological pluvial and fluvial flows (Androulidakis et al., 2023), and CoastFLOOD for littoral inundation (Makris et al., 2023).

RESULTS

The upgraded version of the Wave4Us system provides the following outputs regarding important coastal hazards. The OFP successfully simulated an oil spill of approximately 5,000 m² detected in the northern part of Thessaloniki Bay (northern TG) on 4/11/2017, due to a hydrocarbon leakage at the mooring point of the permanent refinery supply pipeline outside the Thessaloniki Port (Figure 2).

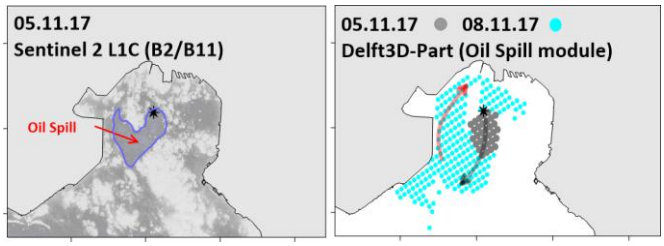

Figure 2. Oil spill spreading from Sentinel-2 L1C (observation) on 5/11 and from Delft3D-Part model (forecast) on 5/11 (gray) and 8/11 (blue) in the northern TG.

Figure 3 presents the forecast of the brackish water spread during Storm Numa (18-20/11//2017), which imposed large river discharges into the TG. During this event, primary production was enhanced in areas where the brackish waters expanded (Chlorophyll-a (Chl-a) increases). The observed

and predicted variability of Sea Surface Temperature (SST) shows strong agreement throughout the 2017 annual cycle, particularly during the summer months when MHWs (Hobday et al., 2016) typically occur (Figure 4). Five MHWs were identified in the simulations, exhibiting characteristics similar to those observed in the events. During the atmospheric cyclone Foivos in January 2019, a significant rise in SLE and intense wave-induced set-up were recorded, both successfully simulated by the individual OFP models (HiReSS and WaveWatch-III, respectively). The extent of coastal flooding due to the total water level from storm tides and waves in TG's coastal zone was ultimately assessed using the CoastFLOOD model (Figure 5).

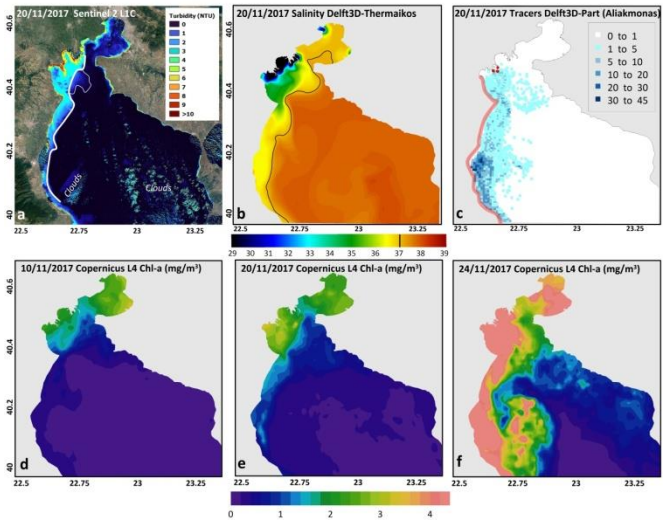

Figure 3. (a) Turbidity (Sentinel 2 1LC), (b) forecast salinity (Delft3D-Thermaikos) and (c) passive tracer spread (Delft3D-Part) on 20/11/2017. (d, e, f) Chl-a concentrations from satellite data (Copernicus CMS).

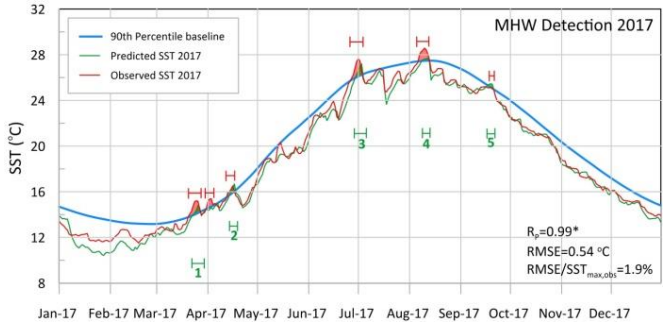

Figure 4. Satellite observations (Copernicus) and forecasts (Delft3D-Thermaikos) of SST and detection of MHWs for 2017 in the study area.

CONCLUSIONS

Wave4Us OFP provides specialized forecasts addressing key coastal hazards. It improves accuracy in extreme freshwater outflow predictions, which transport pollutants during storms, and enhances oil spill simulations, aiding first-level responder efforts. It contributes to better detecting pollutant dispersion risks, forecasting eutrophication, and predicting MHWs. A robust coastal flooding model can also offer quick early warnings of inundation hazards due to extreme weather events. These high-resolution forecasts can support coastal management, ecosystem resilience, and marine renewable energy planning.

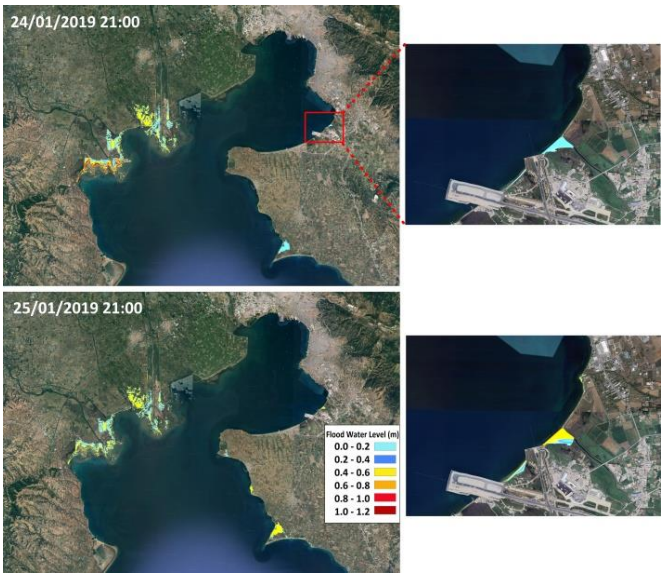

Figure 5. Forecast of flooded coastal areas and floodwater levels by CoastFLOOD model on 24-25/01/2019 (left). Zoom into the Macedonia Airport area (right).

ACKNOWLEDGEMENTS

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