Circulation pathways in Thermaikos Gulf based on field and model Lagrangian experiments

Y. Androulidakis[1,2,*], C. Makris[1], Y. Krestenitis[1], V. Kolovoyiannis[2], V. Baltikas[1], Z. Mallios[1]

[1]Division of Hydraulics and Environmental Engineering, School of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Central Macedonia, 54124, Greece
[2]Laboratory of Physical and Chemical Oceanography, Department of Marine Sciences, University of the Aegean, Mytilene, Lesvos Island, 81100, Greece
[*]Corresponding author: iandroul@civil.auth.gr

Abstract

The Northern Thermaikos Gulf (NTG; Figure 1a) is a semi-enclosed coastal region of the Aegean Sea facing severe pollution events, characterized by anthropogenic and natural stresses such as intense industrial and agricultural activities, urban outflows, and several nutrient-rich river discharges. The hydrography and the hydrodynamic circulation patterns of NTG are revisited in this paper based on the findings of an integrated observational-modeling study, conducted during an annual cycle from June 2021 until May 2022. The main goal of the study is to investigate the environmental conditions that determine the renewal and water quality of the semi-enclosed basin. An operational system for predictions of ocean circulation and Lagrangian pathways to support search and rescue and first responders during pollution accidents over NTG was also developed providing daily 3-day forecasts.

Keywords Drifters, Hydrodynamic circulation, Delft3D, Operational system.

1 INTRODUCTION

The Northern Thermaikos Gulf (NTG) is located at the tip of the northwestern Aegean Sea (eastern Mediterranean Sea; Figure 1a). Thessaloniki, the second largest city in Greece with population of 1.1 million habitants, is located along the gulf's northern coast. Two large (Axios and Aliakmonas) and two smaller (Gallikos and Loudias) rivers (Figure 1a) supply freshwater into the NTG along its western coast, containing large quantities of nutrients (Karageorgis et al. 2005). Several smaller outflows (e.g., the Halastra irrigational drainage channel network and Anthemountas intermittent river; Figure 1a) periodically discharge overflowing waters, containing agricultural (drainage), urban (treated and untreated wastewater) and industrial (liquid chemicals and heavy metals) pollutants. The main pollution pressure of NTG, related to these inputs, is eutrophication, which is strongly controlled by the mesoscale circulation patterns and the renewal capability of the gulf (Androulidakis et al. 2021). The principal objective of this study is to describe the seasonal distribution of the water masses' physical properties, the main circulation patterns, and the variability of the physical connectivity pathways, based on a systematic observational approach (six field campaigns with a 2-monthly temporal step) supported by outputs from three-dimensional (3-d) numerical simulations combined with Lagrangian particle modeling, covering a recent annual cycle (June 2021 - May 2022).

Figure 1. (a) Location of NTG, river system, drainage basins, and Delft3D-Thermaikos model domain. Components of the observational platform: (b) "AEGEAN" drifter, (c) "CARTHE" drifter, (d) Workhorse ADCP, and (e) SBE 19plus CTD

2 METHODS AND DATA

2.1 Field observations

The monitoring period covered an annual cycle from June 2021 to May 2022 with a 2-monthly temporal step (6 campaigns). The near-surface circulation pathways investigation was based on 12 Lagrangian experiments with autonomous, satellite-tracked, and free-drifting floats (drifters) for the recording of ocean current velocities at different times and locations during the observational campaigns. Two types of drifters were used: a) nine AEGEAN drifters (Figure 1b; Zervakis et al. 2009), developed by the Laboratory of Physical and Chemical Oceanography in the Department of Marine Sciences (University of the Aegean; https://www.mar.aegean.gr/), and b) three CARTHE drifters, developed by the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE; http://carthe.org; Novelli et al. 2017, Androulidakis et al. 2018). A network of seven measurement stations (temperature, salinity, density, and current velocity measurements; Figure 1) was also employed to investigate the distribution of physical properties over the NTG during the Lagrangian experiments.

2.2 Numerical simulations of meteorological, ocean and river conditions

The meteorological conditions were obtained from the operational system for met-ocean weather forecasts, Wave4Us (Krestenitis et al. 2017, http://wave4us.web.auth.gr). Simulations of regional-scale, high-resolution, atmospheric circulation are conducted with the Weather Research and Forecasting model's Advanced Research dynamic solver (Wang et al. 2010), developed in the Department of Meteorology and Climatology of the Aristotle University of Thessaloniki (WRF-ARW-AUTh; Pytharoulis et al. 2015). The ocean circulation conditions during 2021-2022 were reproduced by numerical hydrodynamic simulations with the Delft3D modeling system, implemented over the broader Thermaikos Gulf (Delft3D-Thermaikos; Androulidakis et al. 2021; Figure 1a). The boundary conditions along the open southern boundary of the model, are derived by the Mediterranean Forecasting System model (Clementi et al. 2019; http://medforecast.bo.ingv.it/) embedded into Copernicus CMEMS Mediterranean Sea Physical Reanalysis dataset (Simoncelli et al. 2019). Androulidakis et al. (2021) discuss in detail the model setup (e.g., initial, boundary, and forcing conditions; parameterization and river input) and its performance capabilities. The simulated current fields were used to support the prevailing circulation patterns derived from the drifter experiments and current measurements. The main freshwater NTG input comes from four rivers (Gallikos, Axios, Loudias, and Aliakmonas) *in tandem* with a complex system of irrigation canals and trench drains (e.g., Halastra, Anthemountas) (Figure 1a). The daily river outflow rates of the two large rivers of Aliakmonas and Axios (Figure 1a) were derived from available observational datasets. Daily discharges of the smaller rivers, canals and trenches were not available (Loudias, Gallikos, Halastra and Anthemountas; Figure 1a). Therefore, the Hydrologic Modeling System (HEC-HMS; https://www.hec.usace.army.mil/software/hec-hms/) was implemented to simulate the hydrologic processes of the river basins (Figure 1a) and their discharges into the NTG.

2.3 Lagrangian numerical experiments

The simulated fields of currents derived from the Delft3D-Thermaikos model were used to develop Lagrangian particle experiments based on an advection-dispersion model (TracerModel2D; Krestenitis et al. 2007). Nine sources of particles input (100 particles) were used, located at the mouths of the main freshwater discharges in the coastal zone of NTG: 1) Axios, 2) Aliakmonas, 3) Dendropotamos, 4) Loudias/Mylovou, 5) West Halastra, 6) Gallikos, 7) Anthemountas, 8) Rema Dikaston, 9) East Halastra. Twelve simulation cycles were executed associated to the 5-day periods of the maximum river discharges of each month during the annual cycle (June 2021 - May 2022). The results of the particle experiments were used to estimate the main connectivity pathways between the land pressure sources and the NTG sub-basins. Additional Lagrangian experiments were also executed covering the periods of the field drifter deployments and current measurements (ADCP) to compare the simulated trajectories to the realistic conditions (drifter tracks and measured currents).

3 RESULTS

3.1 Comparison between drifter and numerical experiments

The spreading of the simulated particles (TracerModel2D) agrees with the surface currents derived from the ADCP measurements and the overall drifter trajectories (Figure 2). Field and numerical experiments reproduced the prevailing circulation conditions over the NTG during 6 study periods of the annual cycle. The drifter trajectories show that the ocean currents may transfer the surface water masses at long distances in less than 10 days. For example, Drifter D8 moved cyclonically in the inner-Gulf (Gulf of Thessaloniki) in 8 days of March 2022, in agreement with the simulated particles that were confined in the Gulf of Thessaloniki. The particles moved around the coasts after their release in the same location with the drifter (eastern coast). This trajectory also highlights the connectivity pathway between the most polluted area of NTG (northern tip) and the eastern coasts of the central-Gulf.

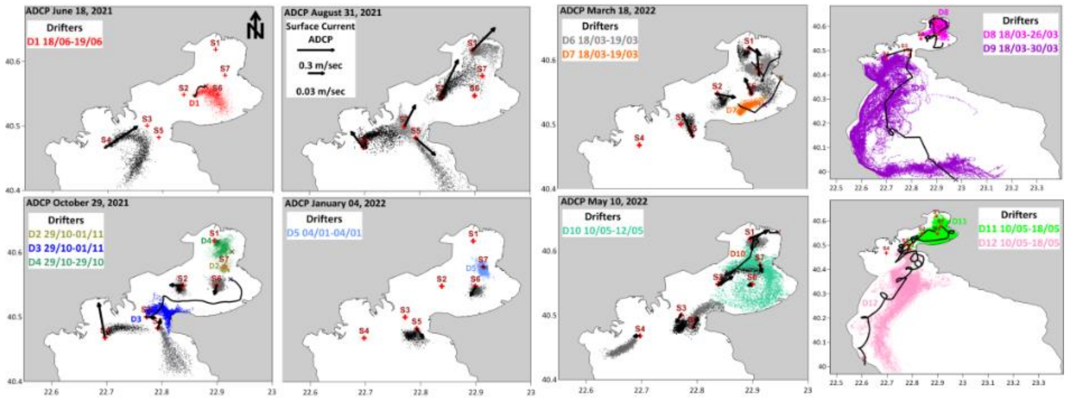

Figure 2 ADCP surface currents (vectors), trajectories of 12 drifters (black lines), and positions of 100 simulated particles (for each experiment) during the same periods

3.2 Distribution of Lagrangian particles over the NTG

The NTG was divided in 29 sub-areas to estimate each source impact at different parts of the Gulf. The June 2021 experiment is presented in Figure 3 showing the distribution of the particles spreading from each of the 9 potential coastal sources of seawater pollution.

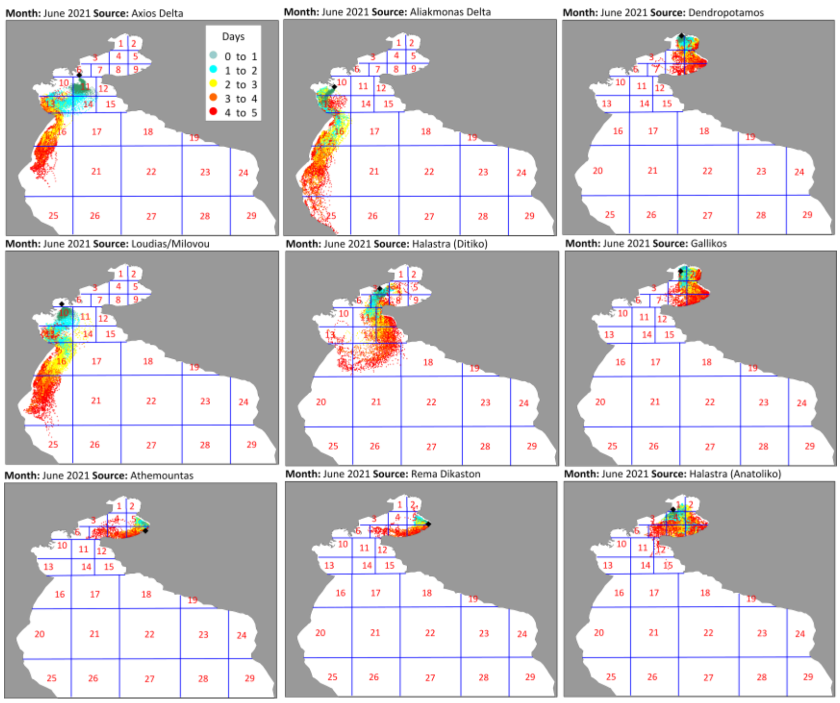

Figure 3 5-day distribution of simulated particles in NTG originated from the 9 sources during the maximum river discharge rates of June 2021

To compare the impact at each sub-domain that are characterized by different size, the number of particles ($N_{i,j}$) at each domain was weighted by the respective area ($A_{i,j}$). The impact percentage ($P_{i,j}$) of each source was then computed for all 29 sub-areas:

$$P_{i,j} = \hat{N}_{i,j} \Big/ \sum_j \hat{N}_{i,j} \times 100 \qquad (1)$$

where $\hat{N}_{i,j} = N_{i,j}/A_{i,j}$, $N_{i,j}=M_j \times t$, i=1,29 (areas), j=1,9 (sources), M_j=1,100 (particles), t=120 hours (5 days). The $P_{i,j}$ represents the impact of each source based on the prevailing circulation conditions derived from the Delft3D-

Thermaikos simulations. To take into account the discharge rate of each source as well, the R_D index was computed:

$$R_{Di,j} = P_{i,j} \times {Q_j}/{\sum Q_j} \quad (2)$$

where Q_j is the monthly maximum discharge rate of each j source. High (low) R_D values indicate strong (weak) impact of the source at each sub-domain (Figure 4). Due to the high discharge rates of Axios and Aliakmonas rivers, the respective R_D are significantly high along the western coasts and in the broader southwestern area of NTG. The stronger impact of the northern NTG areas is related to Gallikos and Dendropotamos sources, however it is restricted in the northern basin (Thessaloniki Bay) and is weaker than the impact of the large rivers in the southern areas of the gulf. At the coastal areas of the eastern NTG, which are characterized by urban facilities, sanitary utility infrastructure, and extensive touristic activities, the main impact is related to both more polluted northern sources (e.g., Dendropotamos, Gallikos) and the large deltas of the western coast (e.g., Axios).

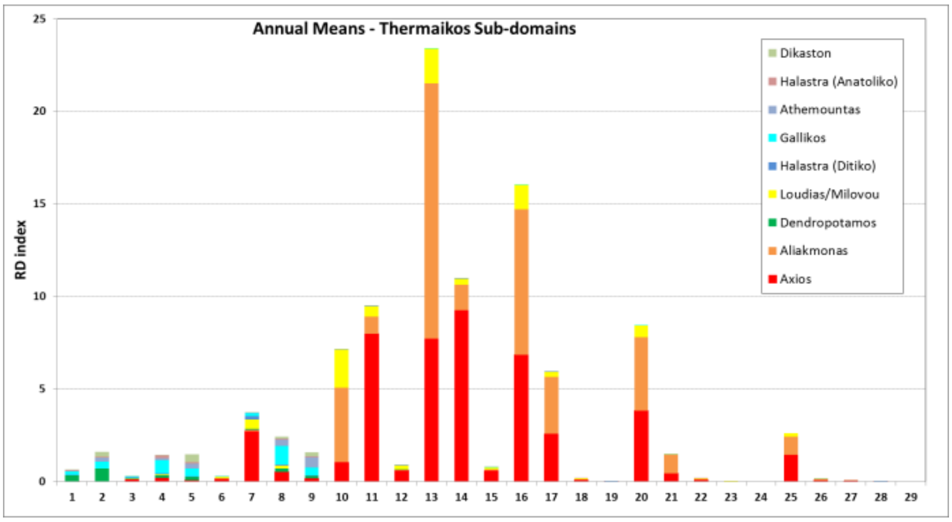

Figure 4. R_D index per source at the surface layer of the 29 sub-areas of NTG

3.3 Operational mode

The operational system Wave4us provides 3-day forecasts of sea level, wave conditions, temperature, salinity, density, and horizontal currents at different depths. The simulated forecasts are distributed freely to the general public through the system's website every day at 8:30 am after the preparation of the boundary and atmospheric conditions from the Copernicus service and the WRF-ARW-AUTh model, respectively. The system also includes the Lagrangian component that can quickly (in approximately half an hour) operate on demand to provide estimations of water mass spreading in the case of a polluting accident in the marine environment of Thermaikos Gulf. An example during a recent oil spill that was detected near the port of Thessaloniki (03/04/23; https://greekcitytimes.com/2023/04/07/thessaloniki-marine-pollution/) shows the theoretical spreading of the polluted water masses during the following hours after the accident, assuming that no clean-up countermeasures were taken (Figure 5).

4 CONCLUSIONS

An integrated observational and modeling study was conducted, with measurements of thermohaline and current profiles, drifter experiments, combined meteorological-river-ocean numerical simulations to describe the hydrography and the main circulation patterns of the Northern Thermaikos Gulf (NTG). It is the first time that drifter trajectories were used to describe the physical connectivity in NTG, representing the near-surface circulation pathways under variable wind regimes. The coupled meteorological, river, hydrodynamic and Lagrangian particle simulations provided information about the connectivity pathways between the environmental stress sources located along the NTG coastline and the several sub-basins of the Gulf. The spreading of the simulated particles (Delft3D-Thermaikos/TracerModel2D suite) agrees with the surface currents derived from the ADCP measurements and the overall drifter trajectories. Field and numerical experiments reproduced the prevailing circulation conditions over the NTG during 6 study periods of the annual cycle. The coupled model suite is also used in the operational system Wave4Us, providing daily forecasts of ocean conditions and spreading of water masses that can be used in the case of polluting accidents in the marine environment of NTG. Furthermore, the operational system, whose products are freely available to the public, is an important tool both for first-level responders during a pollution incident or search-and-rescue teams during maritime transportation accidents, and for stakeholders and authorities responsible for the integrated management of the coastal zone.

Figure 5 Snapshots of particles´ spreading derived from the Wave4us forecast during an oil spill accident in the port of Thessaloniki (03/04/23)

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