OCEAN CIRCULATION EFFECTS ON EUTROPHICATION IN THERMAIKOS GULF

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Abstract
One of the most significant environmental problems of Thermaikos Gulf is the occasional formation of extended eutrophication phenomena (red tides, mucilaginous aggregates). Herein, we investigate the contribution of hydrodynamic processes on the formation of such events, under the effects of different meteorological and river discharge conditions. We conducted field observations (physical-biological measurements), microscopy analysis of phytoplankton samples, satellite ocean color image analysis, and implemented high-resolution numerical hydrodynamic simulations with updated river discharge outflows to detect eutrophication events and relate them with the prevailing physical processes and ocean circulation patterns. The eutrophication events were mainly associated with the dominance of southerly winds. Northerly winds contribute on the renewal of the Gulf imposing a two-layer flow, especially along the eastern coasts.
Keywords: *Ocean Dynamics, Red Tides, Ocean Modeling, Observations*
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1. Introduction

Thermaikos Gulf is a typical, river-fed, microtidal, semi-enclosed, coastal inlet of the east-central Mediterranean Sea. It is an important coastal ecosystem susceptible to several anthropogenic pressures, strong river discharges and variable meteorological and ocean (met-ocean) conditions. One of the most significant environmental problems of the region is the occasional formation of extended eutrophication phenomena (phytoplankton blooms, red tides, mucilaginous aggregates), especially over the Northern Thermaikos Gulf (NTG). The hydrodynamic circulation of the NTG is characterized by two seasonal patterns, one during the winter and the other during summer (Hyder *et al*. 2002; Krestenitis *et al*. 2012). The intrusion of the denser Aegean Sea Waters (ASW) usually takes place through the deeper layers along the eastern coasts of the Gulf while the water masses of the Gulf exit towards the open sea through the surface layers (Balopoulos & Friligos, 1993; Krestenitis *et al*. 2012). The major lateral freshwater input of NTG consists of four rivers (Gallikos, Axios, Loudias, and Aliakmonas) together with a large complex system of canals and trench drains, mainly located at the western coast (Vokou *et al*. 2018). The hydrography of the region, the major circulation patterns, and several physical processes (e.g., coastal upwelling, dense water formation, renewal, river plume dynamics, vertical mixing) play a significant role on the variability of the ecological and biogeochemical characteristics, the pollutants transport, and furthermore the water quality of the Gulf. Eutrophication events are very common, especially pronounced over the northern region, and have recently raised great concern among the public, municipal, and regional authorities, and the scientific community. The main motivation of this study is to investigate the influence of the predominant circulation patterns on the appearance of eutrophication events based on an integration of satellite, in situ and modeling data.

2. Material and Methods

The seasonal in situ measurements refer to the physical (temperature and salinity) and biological (chlorophyll-a: chl-a) parameters, whereas water samples for phytoplankton microscopy analysis were also collected in the water column of three sampling stations, located at the inner- (Station S2), central- (Station S1), and outer- (Station S3) Gulf (Figure 1a). The observational period covered three seasons in 2017. Phytoplankton samples were examined using an inverted epi-fluorescence microscope (Nikon Eclipse TE 2000-S, Melville, MSA) with phase contrast. Phytoplankton identification was based on taxonomic keys and papers and counting was done using the inverted microscope method following the same protocol described in Stefanidou *et al*. (2019). For biomass estimation, the dimensions of 30 individuals of each abundant species were measured using a digital microscope camera (Nikon DS-L1). Mean cell volume estimates were calculated using the appropriate geometric formulae. Satellite ocean-color data were also used to derive the chl-a concentrations over the entire study region. All the collected raw satellite images refer to Sentinel-2 and Sentinel-3 datasets, derived from EU's Earth Observation Programme platform, Copernicus (https://scihub.copernicus.eu/). The numerical simulations were implemented with the FLOW module of the Delft3D (Delft3D-FLOW) modeling system (https://oss.deltares.nl/web/delft3d) in a 3-dimensional (3-D), sigma-layer configuration for the investigation of the NTG hydrodynamic circulation (Delft3D-Thermaikos model; Androulidakis *et al*., 2021). Information about the model set-up (e.g., initial, boundary, forcing conditions, river parameterization and input) and its good performance were discussed by Androulidakis *et al*. (2021).

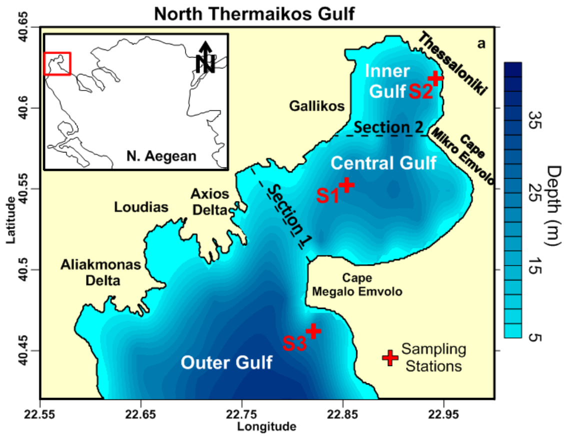

Figure 1. (a) Bathymetry of the Northern Thermaikos Gulf, located in the Northwestern Aegean Sea (insert in the upper left). The major topographic features of the Gulf are shown: inner-, central- and outer-Gulf, Cape Megalo Emvolo, Cape Mikro Emvolo, city of Thessaloniki, Gallikos, Axios, Loudias and Aliakmonas rivers. The locations of three sampling stations are also marked with red crosses. Dashed black lines indicate the borders between the three sub-regions (Sections 1 and 2).

3. Results

The distribution of chl-a in the water column and the phytoplankton biomass concentration at specific depths for each campaign and sampling station are presented in Figure 2. The chl-a water column distribution derived with the CTD broadly agrees with the distribution of the phytoplankton biomass derived from processing of collected water samples in three depth levels (surface, pycnocline, near-bottom). The peak values and the distributions between the two variables qualitatively agree in all cases despite the very low chlorophyll content of phytoplankton biomass reflecting the physiological state of dominant diatoms and the mixotrophy of other phytoplankters on their chl-a content (Genitsaris *et al*. 2019).

The respective horizontal distribution of chl-a, derived from the satellite ocean color images, is presented in Figure 3. The highest near-surface chl-a values among the three stations were detected over the inner-Gulf (Station S2) in early-December 2017. The phytoplankton biomass also revealed the highest values (extreme value of 85 mg/L) during December, while smaller, but very high concentrations were detected in July (20 mg/L) in agreement with the chl-a concentrations (2-4 mg/m^3). In all seasons, Station S3 (outer-Gulf) revealed very low and homogenous vertical distribution of chl-a (~1 mg/m^3) and phytoplankton biomass (<5 mg/L) indicating lower primary production of nano- and micro-phytoplankton over this area, located closer to the open sea boundary (influence of ASWs).

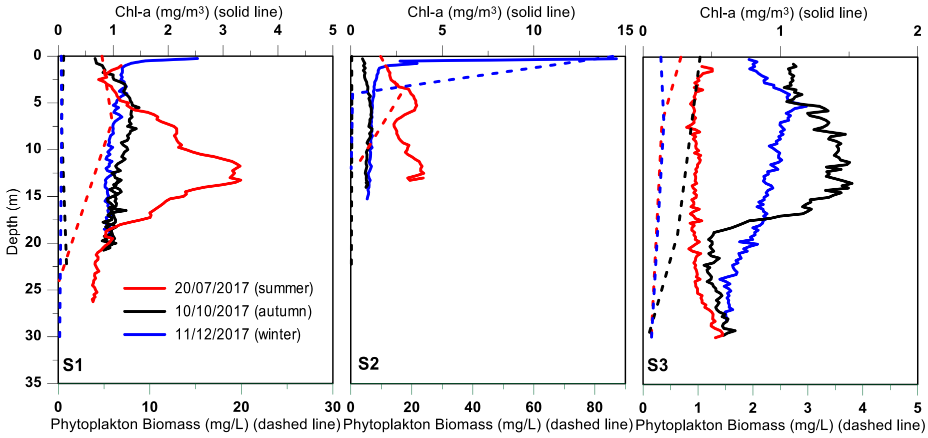

Figure 2. Seasonal vertical profiles of chl-a measured by SBE 19plus CTD (mg/m^3; solid lines) and phytoplankton biomass (mg/L; dashed lines) at S1 (red line), S2 (black line), S3 (blue line) stations.

High chl-a concentrations were detected by the satellite ocean-color sensor in early-July 2017 (Figure 3a). Different surface distribution of satellite-derived chl-a was observed in the ocean color satellite images between the two campaigns of summer 2017 (5 and 20 July). The eutrophication event in late-June and early-July was related to an extensive phytoplankton bloom in spring/early-summer 2017 and *Noctiluca* red tides that contributed to a "dirty sea" phenomenon of mucilaginous aggregates (Genitsaris *et al*. 2019). The December 2017 red tide event was also discussed by Genitsaris *et al*. (2019), which was related to the autotrophic ciliate species *Mesodinium rubrum*. Based on the ocean color images, the chl-a concentrations were significantly high south of the Axios Delta on 5 December (Figure 3d) but were also increased in the inner-Gulf a few days later, on 10 December (Figure 3e), in agreement with the field observations. Generally, both in situ (Station S3) and satellite data support the lower eutrophication state over the southeastern part of the NTG, while the higher chl-a concentration values usually appeared in the inner-Gulf and especially along the western coasts, where the river deltas are located. The year of 2017 was unique, with two very intense eutrophication events (late-June to early-July 2017 and December 2017) and two periods (renewal events) characterized by clear waters (late-July 2017; October 2017) over the entire NTG.

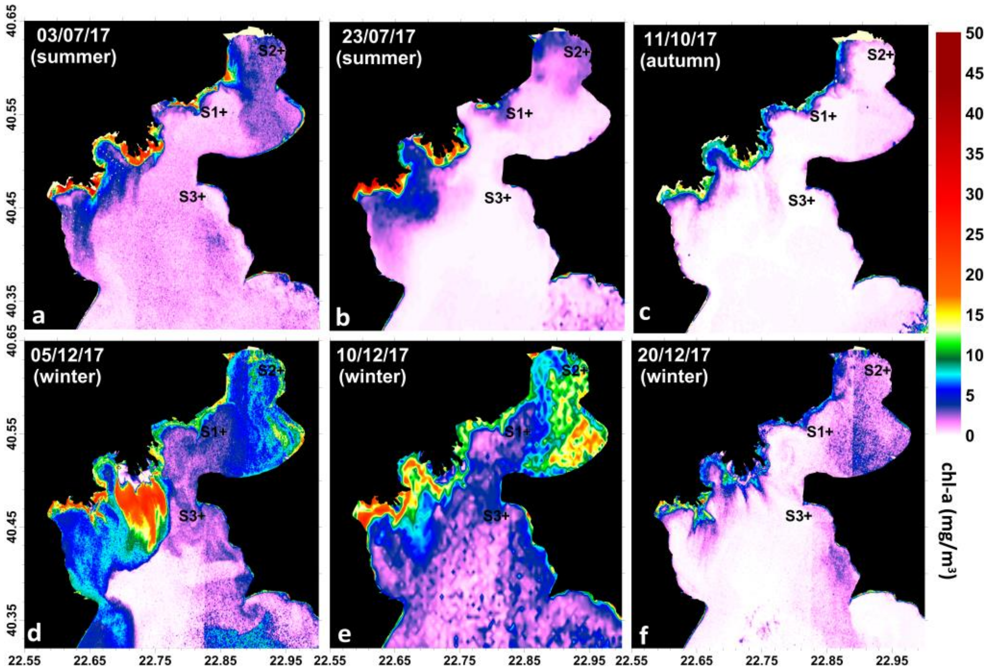

Figure 3. Horizontal distribution maps of chl-a concentrations (mg/m^3), derived from the available Sentinel-2 and Sentinel-3 satellite on (a) 03/07/17, (b) 23/07/17, (c) 11/10/17, (d) 05/12/17, (e) 10/12/17, (f) 20/12/17.

The Delft3D-Thermaikos model simulated the ocean circulation during a full annual cycle in 2017, covering the two major eutrophication events in late-June and early-July, and December and the two renewal events in late-July and October. The southerly winds induced a general northward spreading of surface waters imposing an anticyclonic circulation in early-July (Figure 4b). Two distinct circulation features emerged from the surface current fields; an anticyclonic pattern in the central- and inner-Gulf and a second anticyclonic eddy in the outer-Gulf, keeping the two water masses separated. A similar anticyclonic circulation pattern prevailed in the central-Gulf a few days later (Figure 4d), on 20 July, under weak northerly winds (Figure 4c), with smaller river discharge rates (Figure 1b) and limited spreading of brackish waters, especially over the central-Gulf. Stronger northerly winds that prevailed in mid-July (not shown) played a role on the southward advection of the riverine plume, away from the northern central- and inner-Gulf regions. The small period of strong northerly winds that occurred in mid-July played a role on the different eutrophication levels and physical distribution between the two campaigns. Significantly strong northerly winds (>10 m/s; Figure 4e) prevailed in October over the entire study region imposing a respective southwestward spreading of surface waters with currents higher than 0.5 m/s. During the eutrophication event in early-winter 2017 (11/12/17), the prevailing southerly winds induced a respective northward surface circulation pathway. The simulated Sea Surface Temperature (SST) distribution indicating two separate water masses between the inner- (colder and less saline) and outer-Gulf (warmer and saltier). Although southerly winds may drive surface waters towards the North, they can also confine the inner-Gulf surface waters and enhance eutrophication phenomena especially when riverine brackish waters are trapped in the northern part of the NTG.

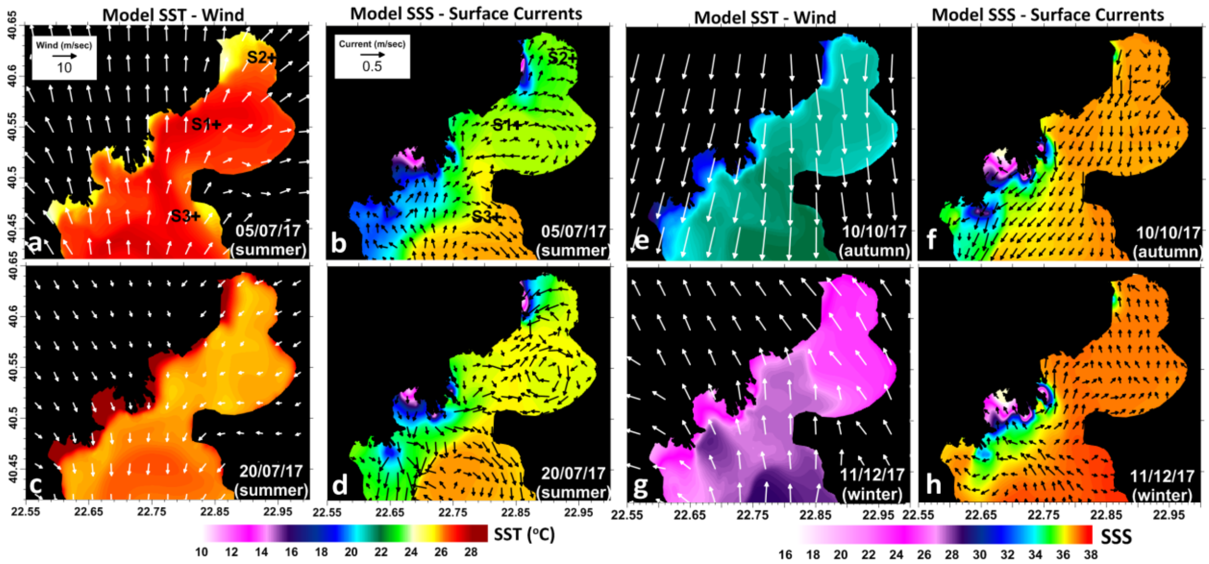

Figure 4. Horizontal distribution of Sea Surface Temperature (SST; °C) and Sea Surface Salinity (SSS), derived from the Delft3D-Thermaikos simulations, overlaid with wind vectors (WRF-METEO-AUTh; m/s) and simulated surface current vectors (m/s), respectively on (a)-(b) 05/07/17, (c)-(d) 20/07/17, (e)-(f) 10/10/17 and (g)-(h) 11/12/17.

4. Conclusions

The eutrophication events (e.g., "Dirty Sea mucilaginous aggregates" in June-July 2017 and "Red Tide" in December 2017), described in the study, were mainly associated with the dominance of southerly winds, which affect the ocean circulation over the NTG in three ways: 1) they confine the surface waters in the northern parts of the NTG (central- and inner-Gulf) separating the waters masses between the northern and southern regions, 2) they contribute to the northward spreading of nutrient-rich brackish waters towards the northern parts of the Gulf, originated from the main rivers of Thermaikos (Axios and Aliakmonas); the phytoplankton species of the different habitat communities of S1, S2 and S3 were highly connected while S1, located closer to the river deltas showed the largest species pool including nutrient opportunists (Vallina *et al*. 2014), and 3) they impose an anticyclonic circulation, especially in the inner- and central-Gulf weakening their renewal process, which is mainly associated with cyclonic circulation that supplies the NTG along the eastern coasts with clearer Aegean Sea Waters (ASW; Hyder *et al*. 2002; Krestenitis *et al*. 2012; Androulidakis *et al*. 2021). The renewal events were mainly related to northerly winds that enhance the spreading of the coastal waters and dispersing abundant phytoplankton towards the southern parts of the NTG (outflow) and eventually towards the open sea of the Aegean. More data and analyses over the 2017-2020 period are also available confirming the prevailing met-ocean conditions during the eutrophication and renewal periods.

References

Androulidakis Y., Kolovoyiannis V., Makris C., Krestenitis Y., Baltikas V., Stefanidou N., Chatziantoniou A., Topouzelis K., Moustaka-Gouni, M. (2021). Effects of ocean circulation on the eutrophication of a Mediterranean gulf with river inlets: The Northern Thermaikos Gulf. Continental Shelf Research 221, 104416.

Balopoulos E.T., Friligos, N.C. (1993). Water circulation and eutrophication in the northwestern Aegean Sea: Thermaikos Gulf. Journal of Environmental Science & Health Part A 28(6), 1311-1329.

Genitsaris S., Stefanidou N., Sommer U., Moustaka-Gouni M. (2019). Phytoplankton blooms, red tides and mucilaginous aggregates in the urban Thessaloniki Bay, Eastern Mediterranean. Diversity 11(8), p.136.

Vallina S.M., Follows M.J., Dutkiewicz S., Montoya J.M., Cermeno P., Loreau, M. (2014). Global relationship between phytoplankton diversity and productivity in the ocean. Nature communications 5(1), 1-10.

Hyder P., Simpson J.H., Christopoulos S., Krestenitis Y. (2002). The seasonal cycles of stratification and circulation in the Thermaikos Gulf Region of Freshwater Influence (ROFI), north-west Aegean. Continental Shelf Research 22(17), 2573-2597.

Krestenitis Y.N., Kombiadou K.D., Androulidakis, Y.S. (2012). Interannual variability of the physical characteristics of North Thermaikos Gulf (NW Aegean Sea). Journal of Marine Systems 96, 132-151.

Stefanidou N., Genitsaris S., Lopez-Bautista J., Sommer U., Moustaka-Gouni, M. (2019). Response of a coastal Baltic Sea diatom-dominated phytoplankton community to experimental heat shock and changing salinity. Oecologia 191, 461–474.

Vokou D., Giannakou U., Kontaxi C., Vareltzidou S. (2018). Axios, Aliakmon, and Gallikos Delta Complex (Northern Greece). In: "The Wetland Book", Finlayson C., Milton G., Prentice R., Davidson N. (eds). Springer, Dordrecht. p. 1137–1147. doi:10.1007/978-94-007-4001-3_253