REVISITING THE HYDRODYNAMIC CIRCULATION REGIME OF THERMAIKOS GULF, GREECE

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Abstract

The hydrodynamic regime of Thermaikos Gulf (NW Aegean Sea) is investigated through a high resolution 4-year modelling study (2017-2020 period). Validated, state-of-the-art modelling tools are employed to simulate the atmospheric conditions over the study area, the major river discharges, and the resulting circulation of the coastal ocean. Field observations are used to assess the performance of the hydrodynamic model and supplement simulation findings. Results provide a detailed description of the interannual variability of water column stability structure, while circulation patterns and ocean processes such as coastal upwelling and dense water formation are quantified with a high-resolution tool.

Keywords: enclosed coastal ecosystem, numerical simulations, Delft3D, Aegean Sea.

1. Introduction

The availability of high quality and high-resolution oceanographic information is key to the apprehension of the functioning of marine ecosystems. This is particularly true for semi-enclosed coastal systems sustaining human activities and being heavily affected by them, such as the Thermaikos Gulf (TG, NW Aegean Sea; Fig. 1), where there is an urgent need to maintain its health and mitigate adverse effects of anthropogenic pressure and climatic shifts. To this end, the work at hand describes an integrated approach in quantifying in a detailed manner the 3-D coastal hydrodynamics in this microtidal environment driven mainly by the variability of atmospheric conditions and river outflows (Androulidakis *et al.*, 2021). It combines aspects of field monitoring of oceanographic variables (Fig. 1; Androulidakis *et al.*, 2021; Petala *et al.*, 2018), river runoff modelling, downscaled atmospheric modelling (Pytharoulis *et al.*, 2015), and fine resolution hydrodynamic modelling of ocean circulation with a Delft3D implementation (Fig. 1; Androulidakis *et al.*, 2021) for the 2017-2020 period. This multi-platform approach produces detailed information on how the TG system works and reacts to various forcing, providing for the first time a multiyear insight on sub-mesoscale and mesoscale processes, on seasonality and evolution of river plume spreading and water column structure, and on water mass exchange and renewal times.

2. Material and Methods

2.1 Atmospheric modelling of meteorological conditions

The meteorological forcing of the coastal hydrodynamic model was derived from the met-ocean weather forecast operational system Wave4Us (Krestenitis *et al.*, 2015; Androulidakis *et al.*, 2022a). Simulations of regional-scale, high-resolution, atmospheric circulation were conducted with the Weather Research and Forecasting model's Advanced Research dynamic solver (WRF-ARW-AUTh). The produced 3-hourly atmospheric datasets (wind velocities, sea level pressure, air temperature, relative humidity, cloudiness, precipitation) cover the finer scale domain with a resolution of 1.67 km (Pytharoulis *et al.*, 2015; https://meteo3.geo.auth.gr/WRF/home.html).

2.2. River basin modelling

The main freshwater input comes from four rivers (Gallikos, Axios, Loudias, and Aliakmon, Fig. 1) along with a complex system of irrigation canals and trench drains located at TG's western coast. The Hydrologic Modeling System (HEC-HMS) was used to simulate the hydrologic processes of the river basins (Makris *et al.*, 2022). This led to detailed simulations of stream networks, robustly estimating the freshwater outflows in the TG, after evaluation by comparisons against *in situ* measured flow rates. The freshwater inflows are used as lateral input for the hydrodynamic simulations in TG (see Section 2.3).

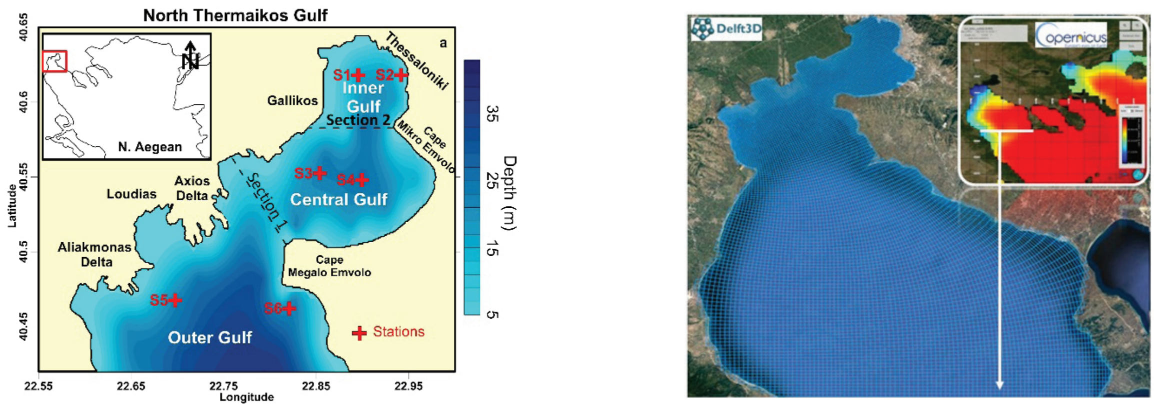

Fig. 1: Study area and monitoring stations S2, S3 and S6 (left), and hydrodynamic model computational domain, with open boundaries highlighted (right). At locations S1, S4 and S5 simulation output is also presented for a thorough insight of subbasin functioning.

2.3 Coastal ocean circulation modelling

The coastal circulation simulations were implemented with the FLOW module of the Delft3D (Delft3D-FLOW) modeling system in a 3-D, 15 sigma-layer configuration and a 110×126 curvilinear grid with a resolution step from 750 m offshore to less than 350 m in the inner gulf (Fig, 1.; Androulidakis *et al.*, 2021). The boundary conditions (open southern boundary) are derived from the Mediterranean Forecasting System model 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 performance.

2.4 Observations

Field measurements of oceanographic parameters (currents, temperature, salinity) over a network of sampling stations (S2, S3, S6; Fig. 1) during the 4-year period from 2017 to 2020 are used to calibrate and validate the ocean circulation model and map the plume dynamics of river outflows. Data were recorded along the water column with a Conductivity-Temperature-Depth profiler (SBE 19plus V2 SeaCAT). A total of 36 CTD casts at a minimum of 3 field trips per year were conducted at stations S2, S3 and S6 (Fig 1). Locations S1, S4 and S5 correspond to model grid points, where simulation output is also presented for a thorough insight of subbasin functioning. Vertical distributions of horizontal currents were also frequently derived with the use of an Acoustic Doppler Current Profiler (ADCP; Workhorse Sentinel by TELEDYNE MARINE) in a moored mode. River outflow rates were derived from HEC-HMS modelling (Section 2.2.) and from available field observations (Hellenic Agricultural Organization "DEMETER" and TERNA S.A.). Satellite observations were also derived from the Sea Surface Temperature (SST) set by the JPL OUROCEAN product (Group for High Resolution SST project; GHRSST; ftp://ftp.nodc.noaa.gov/pub/data.nodc/ghrsst/L4/GLOB/JPL_OUROCEAN/G1SST).

3. Results

3.1 Model Validation

Much effort has been invested into validating the individual components of the integrated met-ocean, hydro-weather modelling system (Androulidakis *et al.,* 2021; Makris *et al.,* 2021). Herein we present aspects of the Delft3D-Thermaikos evaluation and finetuning covering the period 2017-2020. The spatially averaged (over the entire TG) SST from model simulations against satellite data by GHRSST, with and without the seasonal cycle (a and b respectively) during 2017-2020 are presented. Model prediction skill is quite high for the 4-year hindcsast period. The correlation coefficients for both seasonal and non-seasonal comparisons are high and statistically significant (p-value<0.001). The RMSE is 0.96°C for the seasonal timeseries and approximately 0.5°C for the timeseries without the seasonal cycle. Increasing SST trends were derived for all timeseries. The effect of different river inflow parameterizations on model performance is also evaluated (Fig. 2c and 2d). The two Taylor diagrams summarize the effect of different Axios river discharge parameterization on standard deviation, correlation coefficient and RMS error for temperature and salinity (c and d, respectively).

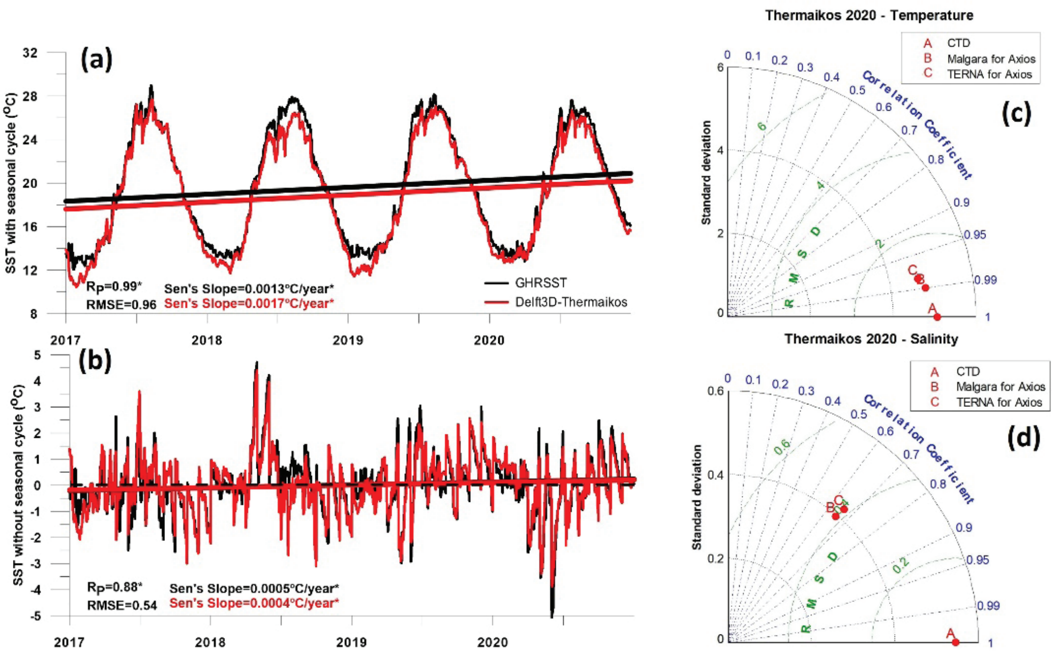

Fig. 2: Daily evolution of SST (a) with seasonal and (b) without seasonal cycle derived from GHRSST (black line) and Delft3D-Thermaikos, averaged over the model domain (2017-2020). Statistic metrics for each case are also shown. (c) Temperature and (d) salinity Taylor diagrams comparing different river inflow parameterizations.

3.2 Ocean circulation processes

The seasonality and interannual variability of water column structure together with the prevailing meteorological conditions are illustrated in detail in Figure 3.

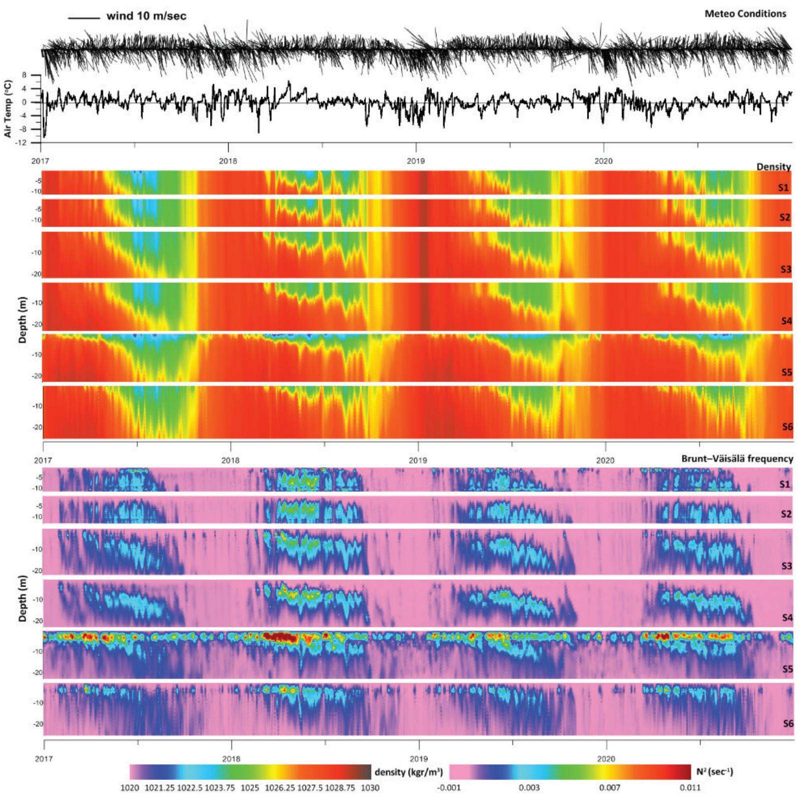

Fig. 3: Daily evolution of meteorological conditions (wind vectors, air temperature anomaly) derived at Station S3 from WRF-Thermaikos simulation, and Hovmöller diagrams of the temporal evolution of vertical density distribution and Brunt-Väisälä stratification frequency at S1, S2, S3, S4, S5, S6 as derived from Delft3d-Thermaikos simulation covering the 2017-2020 period.

The succession between mixing and stratification and its variability in time over different parts and subbasins of TG (locations in Fig. 1), are strongly depended on the atmospheric conditions and freshwater input. Notice the dense water formation incident at the beginning of 2019 that formed under strong northerly winds and low atmospheric temperature (deviating up to -6 or -8 °C from the mean monthly value). Water masses with density close to 1030 kg m^{-3} formed in Thessaloniki Bay and Central TG (S1, S2, S3, S4), gradually cascaded southward towards the outer parts of TG (S5, S6), occupying the deeper layers of the water column, during a 2–3-week period. Androulidakis *et al.* (2021), employing by and large the same modelling platform for the year 2017, established the association of eutrophication events (a major concern in TG), mainly with the dominance of southerly winds (not shown here). Northerly winds contribute on the renewal of the Gulf imposing a two-layer flow and cyclonic circulation, especially along the eastern coasts (Androulidakis *et al.* 2022b).

4. Conclusions

The implementation of a modelling system for the investigation of the hydrodynamic regime in Thermaikos Gulf is evaluated and discussed. The modelling platform consists of state-of-the-art and validated components that simulates the downscaled atmospheric conditions over the study area, the river discharges, and the coastal ocean circulation in a spatially high-resolution setup. The hydrodynamic model validation against satellite observations and field observations confirmed the good performance of Delft3d-Thermaikos in simulating both the seasonal cycle and the interannual variability of the physical properties. Results provide a detailed perspective on the evolution and interannual variability of water column stability structure as determined by meteorological forcing conditions and freshwater input, and new insight on the mesoscale oceanic circulation and the sub-mesoscale local hydrodynamic effects on marine eutrophication events.

5. Acknowledgements

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