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Impacts of a buoyant strait outflow on the plankton production characteristics of an adjacent semi-enclosed basin: A case study of the Marmara Sea

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A B S T R A C T

As documented by observational studies, the buoyant outflows emanating from straits and rivers with large amounts of nutrients and biogenic materials cause marked changes in the biochemical characteristics of the adjacent receiving water bodies. Here, using a three-dimensional biophysical model of the Marmara Sea-Bosphorus Strait two-layer exchange flow system and configuring it for the winter phytoplankton blooming period with limited top-down control, we show that complex buoyancy-induced basin-scale circulation is driven by the buoyant jet emanating from a strait, which sustains enhanced production even in the absence of any nutrient flux from its upstream source region and lateral point sources around the sea. In the supercritical flow regime downstream of the strait exit, strong upward motion introduced by the hydraulically controlled outflow dynamics injects subsurface nutrients into the upper layer. Those accumulated within the adjacent anticyclonic bulge to the right of the outflow plume then support relatively high phytoplankton production, whereas strong currents limit phytoplankton production along the main jet axis. Furthermore, topographically controlled anticyclonic circulation within the lower layer around the deep northern basin induces upwelling due to the divergence of cross-isobath, uphill flow and causes the nutrient enrichment of the upper layer. This cumulative response, together with the additional contribution of nutrient recycling and the horizontal distribution of nutrients and biota by the mesoscale-dominated circulation system, maintain a highly productive system within the sea, which is consistent with previous observations.

1. Introduction

Buoyant outflows issuing from straits and rivers represent complex dynamic systems featuring marked changes in their momentum, density and vertical mixing, as well as their biogeochemical properties. Further variability is introduced in receiving water bodies as outflows are advected in the form of meandering offshore jets and/or coastally attached boundary currents. A number of theoretical studies have elaborated upon their mixing and transport characteristics in idealized estuary-river systems for cases of small Kelvin numbers (i.e., narrow rivers and straits). In particular, the dynamics of a hydraulically controlled buoyant outflow issuing from strongly stratified estuaries were studied by Geyer and Ralston (2011). Hetland (2010) considered the relative importance of the mixing and spreading of river plumes, whereas Horner-Devine et al. (2015) provided a comprehensive description of the different processes that play roles in the development of plumes. Yankovsky et al. (2001), Fong and Geyer (2002), Narayanan and Garvine (2002), Choi and Wilkin (2007), Schiller and Kourafalou (2010) and others examined the alongshore transport characteristics of river plumes in terms of the upstream flow conditions at the river mouth, the presence or absence of an ambient current, the degree of the bottom slope, horizontal and vertical mixing, wind forcing, etc. However, studies of the dynamics of buoyant outflows issuing from straits are more limited. In addition to the first theoretical modeling study performed by Wang (1987), other examples include studies of the Gibraltar outflow into the Alboran Sea (Wang, 1989), the Dardanelles outflow into the Northern Aegean Sea (Androulidakis and Kourafalou, 2011), and the Bosphorus outflow into the Marmara Sea (Gerin et al., 2013; Sannino et al., 2015).

Nutrients fuel phytoplankton productivity in coastal and shelf sea systems, once they are supplied by the buoyant outflows from rivers (e.g., Rabalais et al., 2002; Kudela et al., 2010; Schofield et al., 2013; Hoshiba and Yamanaka, 2016) and straits (Macias et al., 2010; Souvermezoglou et al., 2014; Sanchez-Garrido et al., 2015; Oguz et al., 2016). The anticyclonic bulges formed to the right of the outflow plumes may trap large amounts of fresh water and macronutrients to serve as sources of nutrients (Kudela et al., 2010). On a broader scale,

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their horizontal distributions, which are controlled by local circulation systems, may contribute to basin-wide plankton productivity further away from the outflow plume regions (Fennel et al., 2011). Nutrients may also be supplied from deeper, nutrient-rich layers by intense vertical turbulent mixing and local upwelling processes.

Employing a coupled physical-biological model, the present study examines the impacts of a surface-intensified buoyant jet emanating from a strait on the development of complex buoyancy-induced basin-scale circulation and the nutrient enrichment and plankton production characteristics within the adjacent basin. In particular, it identifies the outflow plume zone and the topographically induced upwelling regions as the major sources of nutrient enrichment and plankton production. We use the Bosphorus Strait-Marmara Sea two-layer exchange flow system as a case study and focus on the most productive winter phytoplankton blooming season with limited zooplankton grazing. Below, we first provide a brief overview of the oceanographic characteristics of the Marmara Sea in Section 2 as background information. We then describe the general features of the physical and biochemical models and their implementations to the region (Section 3). This is followed by the results of the model describing the hydraulic adjustment of the upper-layer flow at the strait exit, the characteristics of the buoyant jet further downstream and its contributions to nutrient enrichment and plankton production within the Marmara Sea proper (Section 4). Finally, Sections 5 and 6 contain a discussion of the results and observational supports for the model features as well as concluding remarks, respectively.

2. An overview of the oceanographic characteristics of the Marmara Sea

The Marmara Sea is a small, semi-enclosed basin (~11,000 km^2) that is linked to the Black and Aegean Seas by the Strait of Istanbul (the Bosphorus Strait) and the Strait of Canakkale (the Dardanelles Strait), respectively. Its main topographic features include the shelf region (<100 m) that covers the southern half of the basin, its connection to the approximately 1000 m deep northern basin through a steep topographic slope structure, and the shallow (~60 m deep) junction regions to the Bosphorus and Dardanelles Straits(Fig. 1). The former is also referred to as the Bosphorus-Marmara Junction (BMJ) region. The Marmara Sea is a densely stratified marine system where the brackish water mass of the Black Sea origin (σ_t < 18.0 kg m^{-3}) moves southwestward towards the Aegean Sea within the upper ~20 m over the more saline, denser water mass of the Aegean Sea origin (σ_t > 28.0 kg m^{-3}),which flows northeastward towards the Black Sea at depths below ~40 m (Unlüata et al., 1990; Beşiktepe et al., 1994). These two distinctly different water masses are separated by an interface layer of ~10–20 m (i.e., the pycnocline) and have a density contrast of ~5–8 kg m^{-3} (Beşiktepe et al., 1994; Polat and Tuğrul, 1995).

The upper layer flow of the Marmara Sea experiences a hydraulic control at the southern exit section of the Bosphorus Strait, as was documented by the Acoustic Doopler Current Profilers (ADCP) measurements performed from September 2008–February 2009 (Jarosz et al., 2011). Downstream of the exit section, the jet is directed towards the south with a typical speed of 1.0 m s^{-1}; it then veers anticyclonically towards the northern coast and proceeds at a speed of 0.2–0.3 m s^{-1}towards the Dardanelles Strait as a topographically controlled boundary current system (Beşiktepe et al., 1994; Gerin et al., 2013). The interior of the anticyclonic jet comprises an anticyclonic eddy. The details of this system may vary depending on the wind force and the intensity of the Bosphorus outflow (Beşiktepe et al., 1994; Chiggiato et al., 2012; Gerin et al., 2013; Sannino et al., 2015). In the case of the weaker upper layer transport of the Bosphorus, the buoyant jet tends to veer to the right, closer to the junction region. In the case of the strong jet transports, such as those produced during strong northwesterly wind episodes, the southward path of the jet may extend up to the southern coast and be followed by its broader anticyclonic meander towards the northwest. Under moderately intense southwesterly winds, on the other hand, the jet weakens and is attached closer to the northern coast. Under even stronger southwesterlies, which may occur for a few days several times a year, the Bosphorus upper layer flow may be temporally blocked inside the strait and the buoyant jet will not exist at the Bosphorus-Marmara junction region for several days. Mesoscale eddies with sizes of ~50 km or smaller accompany this buoyant jet flow pattern more frequently in the southern shelf and within the vicinity of Marmara Island. These are mostly transient features driven by flow instabilities as well as by the spatial variability of the wind stress (Chiggiato et al., 2012).

The Marmara Sea is one of the most eutrophic eco-regions in the European Seas (Chassot et al., 2007). Its main biological production occurs within the upper layer and the pycnocline. The lower layer is permanently hypoxic, recording oxygen concentrations of approximately 50 ± 10 μM and nitrate concentrations of 9 ± 1 mmol m^{-3}(Polat and Tuğrul, 1995), which are contrary to the low nutrient availability (<1 mmol m^{-3}) of the upper layer. The presence of a strong pycnocline limits turbulent exchanges between the layers. Monthly variations in surface chlorophyll concentrations, compiled from long-term mean (2002–2016) satellite ocean color data, record a well-defined winter–early spring peak followed by lower surface concentrations in summer. The enhanced autotrophic production in winter-spring is followed by the mesozooplankton bloom in spring, the heterotrophic dinoflagellate red tide species *Noctiluca scintillans* bloom in May–June, and the gelatinous ctenophore species *Mnemiopsis leidyi* bloom in August–October (Yılmaz et al., 2005).

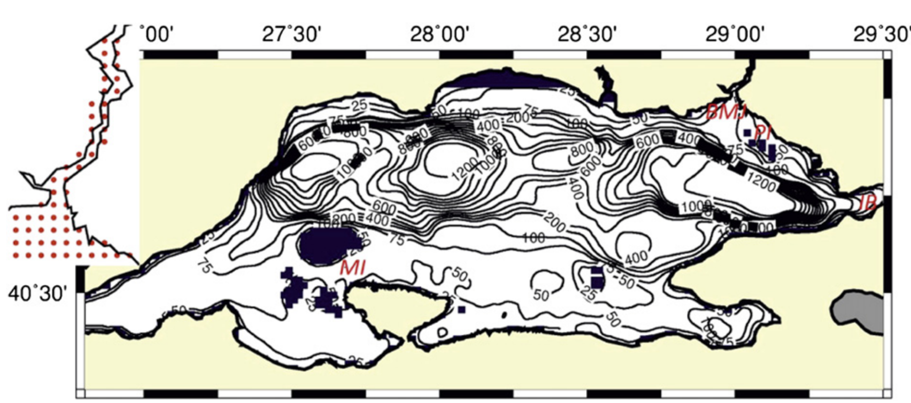

Fig. 1. Bottom topography of the Marmara Sea characterized by the northern deep basin and the southern shelf region. The insert represents the idealized grid structure for the southern half of the Bosphorus Strait. The BMJ refers to as the Bosphorus-Marmara Junction region, MI the Marmara Island, PI the Prince Islands, IB the Izmit Bay.