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Assessing the impact of tides and winds on the circulation of the Gulf of La Spezia with high-resolution, three-dimensional simulations

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The Gulf of La Spezia (Ligurian Sea, Northwestern Mediterranean) is characterized by a complex geometry and delimited by the Tino and Palmaria islands on the west side and by the Punta Bianca promontory on the east. The Gulf extends along a Southeast-Northwest axis with maximum width and length of 9 and 13 km, respectively. Water exchanges between the inner and outer parts of the Gulf are limited to two openings of a breakwater. The latter is located in its southern portion and protects the harbor from rough sea conditions, mainly induced by southeasterly "*Scirocco*" winds. Inside the dam the mean depth is about 10-11 m while, in the outer portion of the Gulf, depth increases gradually offshore in the westward direction reaching maximum values of about 25 m close to the Palmaria isle. The Gulf is site of intense harbor activities and subject to significant urban and industrial discharges from the town of La Spezia.

Despite its importance, the three-dimensional circulation of the Gulf of La Spezia is not well established. Recent observational efforts suggest a mean circulation scheme, which is not fully in agreement with the hypothesized three-dimensional baroclinic response to wind forcing. Previous numerical studies are either bi-dimensional or neglect the complexity of the Gulf using idealized geometries.

In this study, the three-dimensional open-source DELFT3D model is setup to assess the dynamics and the circulation patterns in the Gulf. A high-resolution horizontal grid of 286 x 167 points (nominal spacing of about 50 m) is employed to fully resolve the complex real geometry of the region. The grid has two open boundaries, one at south and one at west while the high-resolution bathymetry is courtesy of the Hydrographic Institute of the Italian Navy. A number of 5 equally-spaced *"sigma"* layers are used to retain the same resolution in the vertical dimension.

Different simulations are run by varying the idealized forcing conditions. The first simulation aims at assessing the role of the semidiurnal tidal signal observed in the outer portion of the Gulf. It is forced at both open boundaries with a sinusoidal oscillation with a period of 12 h and 25 min and a sea-level amplitude of 15 cm. In the second simulation, another oscillation of 70 min and amplitude of 5 cm is superimposed to the tidal signal. This new signal mimics the local seiche, which is hypothesized to be due to a stationary wave fitting the length of the Gulf in its longitudinal dimension. A third simulation considers the addition of idealized sea breeze effects.

All simulations start at rest and with typical observed hydrographic initial conditions. The initial temperature (salinity) is uniform in the horizontal dimension and set to 25˚C (37.0) at the surface, while it linearly decreases (increases) in the vertical to reach 22˚C (37.3) at the depth of 10 m. No-slip conditions are applied at all material boundaries and a Chezy coefficient of C=50 is used for the bottom frictional term. Horizontal viscosity and diffusivity are both set to a 0.05 m2/s while a "k-?" turbulent closure scheme is used in the vertical.

Results and differences in the runs are quantified in terms of velocity at the two openings of the breakwater, residence times, erosion of the initial stratification as a measure of mixing, and location of typical Lagrangian Coherent Structures. Realism of the different scenarios is validated against the observations taken in the area.