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Physical and biogeochemical variability in the Gulf of La Spezia (Eastern Ligurian Sea, Italy): insights from a new high-resolution coastal observatory

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Highlights

- A warming trend of 0.045 °C per year in the area with long-term temperature records.
- Increased frequency and intensity of Marine Heatwaves (2022–2023).
- Altered local hydrodynamic regime due to the dam.
- Enriched carbonate environment promoting biological calcification.
- Area as an active carbon sink especially in winter and spring months.

Abstract

Coastal marine shallow sites exhibit high biological richness and diversity while experiencing substantial fluctuations in seawater physical and chemical variables. The complexity of coastal processes and dynamics, exacerbated by the climate change effects, are making difficult to predict the fate of marine coastal systems.

High-resolution observatories enable big data acquisition through continuous monitoring, improve the real-time detection of oceanic changes, especially at local scale, and provide essential data for marine system predictions and early warning capabilities for maritime activities. However, comprehensive long-term, high-resolution datasets in coastal areas are still limited.

Smart Bay Santa Teresa underwater observatory, a new high-resolution system located in the Eastern Ligurian Sea, provided physical and biogeochemical data continuously from 2021 to 2024. Physical data confirmed a warming trend of 0.045 °C per year in the study area, consistent with global climate change patterns, and increased frequency and intensity of Marine Heatwaves, especially in 2022–2023. Biogeochemical data revealed an enriched carbonate environment, despite the short-term perturbations, and a shift of biogenic and thermal control of the carbonate system through seasons favoring biogenic carbonate development (i.e. mussels' reefs). Interestingly, the balance between CO_2 stock and release, derived from biogenic calcification, revealed that the area as an active carbon sink, especially in winter and spring.

The ecological value and biodiversity of the coastal marine ecosystems coexisting with highly anthropogenic areas make the site ideal to monitor the interacting effects of global warming, local hydrodynamics, and seasonal biogeochemical processes through integrated monitoring approaches.

Introduction

Marine coastal shallow sites are complex systems, characterized by biological richness and diversity (Freestone et al., 2024), fluctuations in seawater physical and chemical variables (e.g. temperature, salinity, dissolved oxygen, nutrients, light and carbonate environment (Wolfe et al., 2020)), and shallow depths (i.e., shore habitat, rocky shores, or seagrass beds (Hurd et al., 2011)).

To improve the understanding of coastal marine systems and their strength or vulnerability to climate change, the ocean big data collection represents a priority (Cristini et al., 2016; Freestone et al., 2024; von Jackowski, 2025). High-resolution coastal observatories with high frequency data acquisition are powerful tools for validating satellite data and models, providing real-time data necessary for making predictions on seawater changes, and thus providing early warnings for maritime activities. Currently, ocean observatories have expanded far beyond their traditional scientific research functions and now serve as critical connections between ocean science and society, addressing the demand to understand the connections between ocean processes, their changes and thus planning sustainable developmental strategies for its resources (Sustainable Development Goal (SDG) 14 in UNFCCC Agenda 2030 (United Nations, 2015); Ruhl et al., 2011), according to Blue Growth objectives.

Recognized the strategic importance of long-term ocean observation, the European Community has been funding the creation of several Research Infrastructures under the frameworks of either the European Strategy Forum on Research Infrastructures Roadmap (see ESFRI, 2021 as a reference) or the Horizon Infrastructural (INFRA) calls (e.g. JERICO). Besides addressing specific scientific questions, these infrastructures provide the base line to address Europe's policy demands for sustainable use of the seas, ecosystem-based management and establishment of environmental status indicators, as expressed by the EU's Marine Strategy Framework Directive (MSFD) and the Nature Restoration Law.

Among ocean data, physical-biogeochemical observations are becoming increasingly urgent given the need for quantifying the current characteristics and trends of physical and biogeochemical states. Relevant at global, regional and local scales (Fennel et al., 2019), such data provide estimates of the carbon cycle, acidification, primary production, and oxygen and nutrient availability affecting local ecosystems. However, long term, high-resolution and comprehensive data are still very rare especially in some areas of the Mediterranean Sea.

Under this framework, this study presents a new high-resolution underwater coastal observatory from the Eastern Ligurian Sea (Mediterranean Sea) by analysing three years of physical-biogeochemical data driven by climate change.

The Mediterranean Sea is a semi-enclosed basin with highly variable orography, physical, biogeochemical, and ecosystem characteristics (Pinardi et al., 2015; Siokou-Frangou et al., 2010). Furthermore, the ongoing direct and indirect anthropogenic impacts are affecting such properties and the way they interact at different scales (Micheli et al., 2013; Giorgi, 2006). Physical data have been extensively described for the basin as well as the tendencies and projections by combining data and models (Darmaraki et al., 2019; Pisano et al., 2020; Somot et al., 2016). In particular, an average warming trend of $0.041 \pm 0.006\,^{\circ}$C/year was reported for the entire Mediterranean, from 1982 to 2018 with non-uniform spatial pattern: from $0.036 \pm 0.006\,^{\circ}$C/year for the Western Mediterranean, to higher values in other regions (Pisano et al., 2020). Significant trends of warming and an increase in heat content are also observed, especially for the surface layers (0–700 m) (Ciuffardi et al., 2024). Marine Heatwaves are reported to become stronger and more intense especially towards the end of the century with clear impact to the vulnerable Mediterranean Sea ecosystems (Darmaraki et al., 2019). In contrast to these well-documented climate trends, high-resolution biogeochemical data from in situ observations are very limited, tendencies are almost absent and generally related to single variables (such as chlorophyll-a (Chl-a)). Satellite data for the period 1998–2009 revealed significant positive Chl-a trends in most of the western Mediterranean and negative trends in the northern Adriatic Sea (Colella et al., 2016) highlighting different regional and local dynamics. In the Mediterranean basin, the carbonate system is unique due to the intrinsic seawater characteristics: warm waters and high Total Alkalinity (TA > 2500 μmol/kg) associated with a permanent and rapid thermohaline circulation loop with a residence time of nearly 100 years (Millot and Taupier-Letage, 2005). On average, the TA in the Mediterranean Sea is 10% higher than that of the global ocean (Palmiéri et al., 2015) thus giving a key role to the Mediterranean Sea in carbon sequestration.

Located in the northwestern part of the Mediterranean, the Ligurian Sea represents a key basin with a geological history closely connected with the evolution of the Western Mediterranean Sea (Migon et al., 2020). Physical observations, including current measurements and temperature-salinity (T/S) profiles, started in 1960's- '70s in the Ligurian Sea, mainly on the western part including the Gulf of Genova, and they consisted of regular monitoring campaigns from ship stations. Recently, long-term monitoring infrastructure have been established using buoys and profiling floats in areas ranging from shallow to deep waters, including the DYFAMED station and the BOUSSOLE or W1M3A buoys (Migon et al., 2020). Data acquired during the last 40 years in the Ligurian Sea have shown an increase in both temperature and salinity (the latter starting at the end of '80s), in both shallow and deep stations (Prieur et al., 2020). The origin of this trend could be explained by the waters entering the Ligurian Sea along western Corsica, confirming historical ship observations (Goffart et al., 1995; Gostan, 1967; CNRS, 1973, CNRS, 1975) and recent profiling floats and gliders (Bosse et al., 2015). From a biogeochemical point of view, observations in the Ligurian Sea started in 1998 with surveys up to 2016 and were successively integrated with permanent observatories with autonomous sensors for surface and deep measurements. Despite the extended knowledge on the Western Ligurian Sea, which reveals a marked seasonality of the carbonate system (Coppola et al., 2020; Migon et al., 2020), the biogeochemistry of the Eastern Ligurian Sea is still poorly known. Western monitoring stations systematically monitor physical parameters (temperature, salinity), biogeochemical variables (nutrients, trace metals, atmospheric inputs), and biological components (phyto and zooplankton). This provides comprehensive understanding of seasonal cycles, interannual variability, and long-term trends - data that are currently largely unavailable for the Eastern Ligurian Sea.

To fill this knowledge gap, in 2021 we established Smart Bay Santa Teresa underwater observatory, a new in situ coastal high-resolution system located in the eastern Ligurian Sea. Physical and biogeochemical data were collected from 2021 and 2024 with the aims to: (1) describe physical and carbonate environments, (2) detect effects of physical and biological components on the carbonate environment, and (3) identify changes in marine heatwave patterns.

High-resolution Smart Bay Santa Teresa dataset enables analysis of real-time changes at local scales, highlighting the complex dynamics and relevance of coastal sites where seawater, atmosphere, and biological systems mutually interact. Data are discussed with the perspective of the observatory empowerment (i.e., more stations and more variables measured) aiming at providing continuous, long-term datasets understanding the link between biogeochemical patterns and ecological responses and thus predicting the fate of coastal ecosystems under climate change.

Section snippets

The study area

The study area is located in the Gulf of La Spezia from 43.95°N, 9.64°E to 44.15°N, 10.05°E, with depth from 8 to 25 m (Fig. 1). The area is located between the Magra River mouth and the Cinque Terre National Park.

The continental shelf of the Ligurian Sea has a limited extension along the Liguria region until the Gulf of La Spezia. Its eastern deeper part is characterized by the Levante Canyon, almost parallel to the coast and hosting valuable and vulnerable ecosystems, such as the deep-living …

Temperature records and marine heatwaves

The 40-year satellite SST record close to the TI station, revealed an increase in temperature of 0.045±0.003 °C y^{-1} (Fig. 2).

Air and seawater temperatures displayed similar seasonal variations over the course of the year. In general, there was a good agreement between long-term seawater temperature measurements at three stations and satellite SST data from CMEMS (Fig. 3). SST records were particularly higher than all the SBST data in July–August 2022; mean daily air temperature (± standard …

Discussion

The Ligurian basin has a valuable role observing climate changes of the Mediterranean water masses (Prieur et al., 2020). Given the paucity of information available for the coastal areas of the Ligurian Sea, the multidisciplinary and integrated high-resolution Smart Bay Santa Teresa observatory of the Gulf of La Spezia represents a system to record seawater physic chemical patterns and variabilities both climate and ecosystem driven.

Anthropogenic climate change is causing deep modifications …

Conclusions and perspectives

This study reveals critical dynamics in the Gulf of La Spezia's carbonate reef environment under accelerating climate change. Four decades of temperature data confirm a relentless warming trend of 0.045 °C±0.003 °C per year, with Marine Heatwaves intensifying dramatically during 2022–2023. These thermal stress events now threaten calcifying organisms with unprecedented frequency, signaling a dangerous acceleration in climate impacts.

The presence of the dam fundamentally alters local …

CRediT authorship contribution statement

Tiziana Ciuffardi: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Silvia Becagli:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Data curation. **Giancarlo Raiteri:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Andrea Bordone:** Writing – review & editing, Validation, Software, …

Declaration of competing interest

None. …

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