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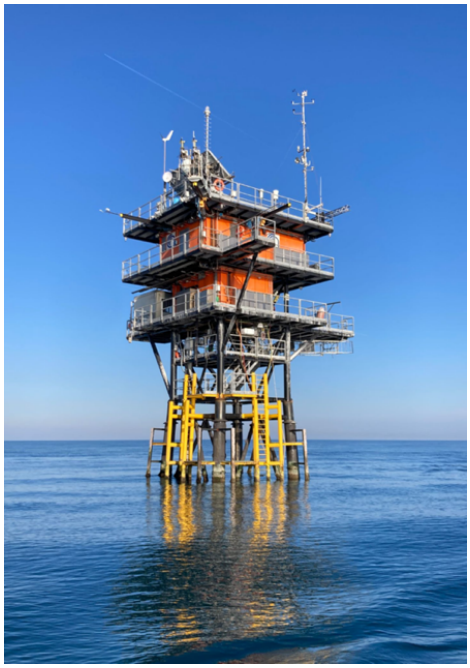

"ACQUA ALTA" OCEANOGRAPHIC RESEARCH TOWER

PIATTAFORMA DI RICERCA OCEANOGRAFICA "ACQUA ALTA"

Adriatic Sea, Italy
45.314° N, 12.508° E

Italian National Research Council (CNR)

- BULLETTIN 2025

With the contribution of: *Alvise Benetazzo, Francesco Barbariol, Mauro Bastianini, Fabrizio Bernardi Aubry, Luciana Bertotti, Vittorio Brando, Luigi Cavaleri, Silvio Davison, Christian Ferrarin, Stefania Finotto, Irene Guarneri, Alvise Papa (Venice Municipality), Angela Pomaro, Andrea Sabino, Marco Sigovini, Tihana Marčeta, Alessandro Bergamasco, and Davide Tagliapietra**

*Davide Tagliapietra passed away prematurely on 15/09/2023

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The anomaly of air temperature

Records from "Acqua Alta" show that 2025 North Adriatic air temperatures were systematically above the 2003–2022 climatology, with winter–spring values around +1.0 to +1.5 °C warmer than average and a pronounced June peak near +2.3 °C above the reference period. The seasonal cycle remains coherent with past years, but 2025 tracks consistently above the climatological mean (~25 °C in July–August), aligning with the Copernicus bulletin (https://climate.copernicus.eu/global-climate-highlights-2025) that 2025 was one of the hottest years ever recorded globally and in Europe, following 2024 and 2023 in the warmest sequence on record. From January to July, monthly anomalies range from +1.3 °C (January) to the June maximum, reflecting findings that January 2025 was the warmest January on record, and March–May were the second warmest globally for their respective months.

In the North Adriatic, the small negative anomalies in October (–0.4 °C) and November (–0.3 °C) are consistent with a regional late-year temperature variability, despite Europe still registering its third-warmest year on record in 2025, at +1.17 °C relative to 1991–2020. December returns to a positive anomaly (+1.3 °C), matching findings of a warmer-than-average December 2025 across Europe, contributing to the overall extreme warmth of 2025.

Overall, the figure captures a clear regional expression of the exceptionally warm 2023–2025 climate regime, driven by elevated greenhouse-gas concentrations and persistent marine and atmospheric warming.

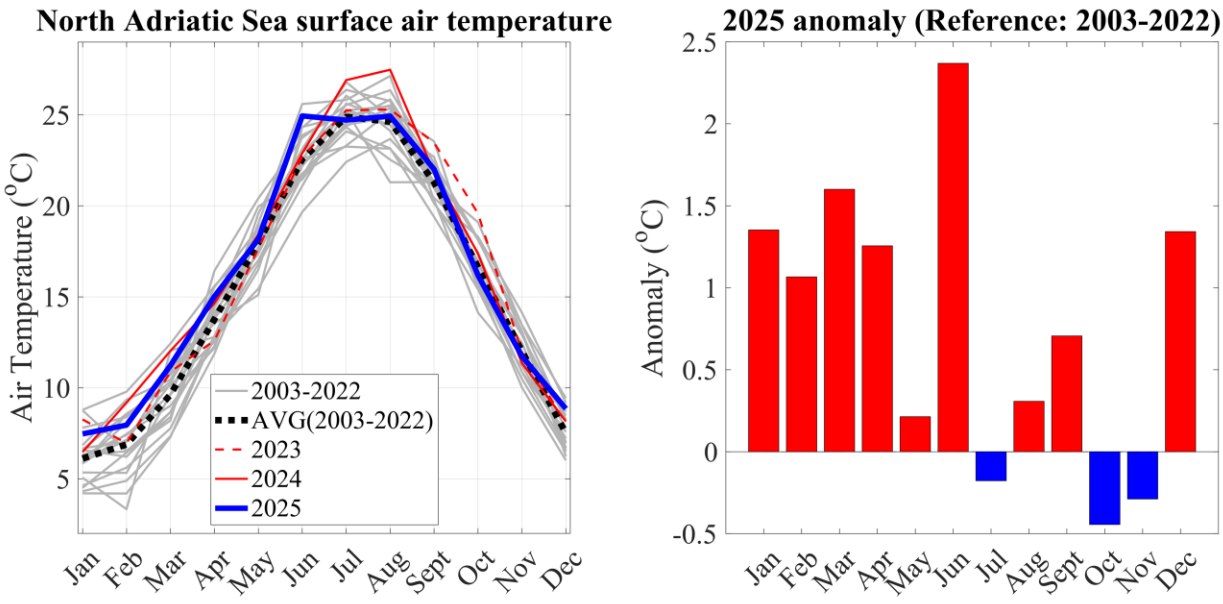

Figure 1 | (left) Sea surface air temperature, in the form of monthly averages, recorded at the "Acqua Alta" tower. 2025: solid blue curve; 2024: solid red curve; 2023: dashed red curve; Years 2003-2022: grey curves; Average of 2003-2022: dashed black curve. (right) 2025 Monthly anomaly relative to the reference period 2003-2022.

The sea level

The sea level data recorded at "Acqua Alta" does not indicate any exceptional conditions in 2025. The annual mean sea level was 37.5 cm, which ranks as the fifth-highest value since sea level measurements began in 1974, consistent with the ongoing positive mean sea level trend in the Northern Adriatic Sea. The detrended monthly mean sea levels were generally in line with the climatological data; the maximum and minimum values occurred in February and November, respectively.

The year 2025 was characterized by few and modest extreme sea level events, with the annual maximum of 125 cm - associated with a moderate Sirocco event - recorded on 28 January 2025. In total, only seven events exceeding 110 cm were observed in 2025, the majority of which occurred during the autumn months, reflecting the typical seasonal increase in sea level variability associated with meteorological forcing in the Northern Adriatic.

Data: https://www.comune.venezia.it/it/content/3-piattaforma-ismar-cnr

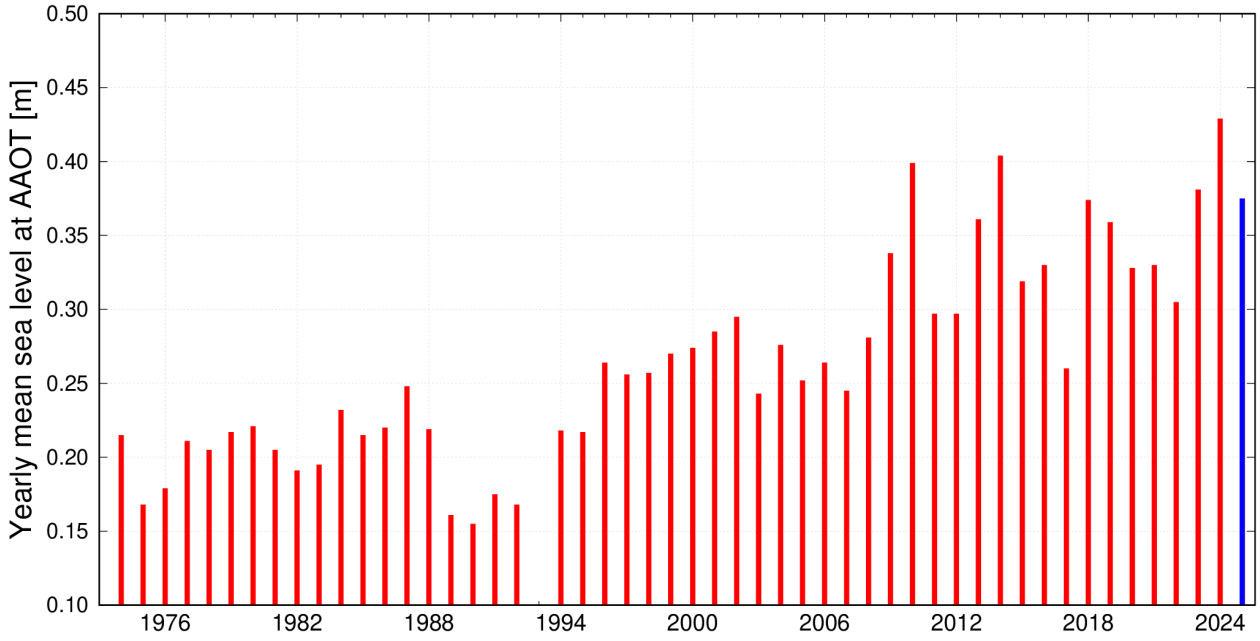

Figure 2 | Yearly mean sea level recorded at the "Acqua Alta" tower (AAOT). Years 1974-2024: red bars; 2025 blue bar.

Anomalies of wind and waves

Wind and wave conditions observed in the northern Adriatic Sea during 2025 were broadly consistent with the recent climatological reference. This agreement is particularly evident in the mean monthly conditions (upper panels), indicating that, despite some minor differences, ordinary wind and wave regimes in 2025 were generally close to climatological values.

A different picture emerges when considering the 99th percentile of U and H_s (lower panels). Extreme (stormy) winds show predominantly negative anomalies from March to September, contrasted by marked positive anomalies in January and December (with December 2025 standing out with the largest positive wind anomaly in the 2003–2022 record). In contrast, corresponding 99th percentile H_s in January and December remain near climatological values, showing only limited positive anomalies despite strong wind events.

This mismatch is explained by the dominant northeasterly storm winds during these months (not shown here): although characterised by very high U (occasionally up to 25 m/s), they produced fetch-limited sea states, resulting in moderate waves. Conversely, southeasterly winds, which typically drive severe non–fetch-limited waves, were less frequent. Finally, the positive wind and wave anomalies observed during autumn and winter storms in the northern Adriatic Sea were relatively uncommon within the broader Mediterranean context.

As it is shown, December 2025 was generally marked by below-average extreme wind and wave conditions across most of the basin, while the northern Adriatic—and a few localised areas—experienced above-average extreme winds, leading to locally enhanced but fetch-limited wave conditions.

This highlights the strong regional modulation of wind–wave coupling in semi-enclosed basins such as the northern Adriatic Sea.

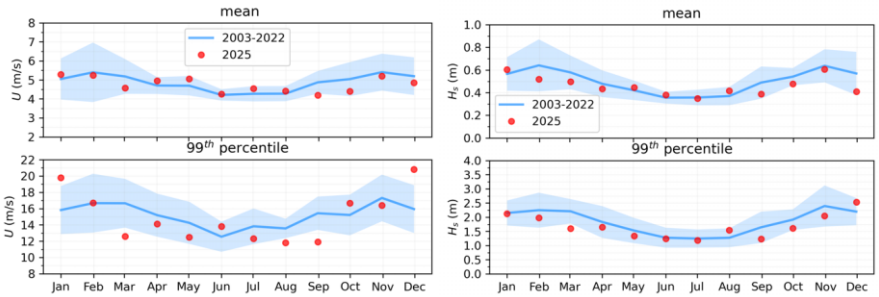

Figure 3 | Wind (left) and waves (right) in 2025, compared to 2003-2022 climatology, from measurements from "Acqua Alta". (left) monthly mean and 99th percentile of wind speed U. (right) monthly mean and 99th percentile of significant wave height H_s. Solid lines represent the 20-year average, and shaded regions the standard deviation above and below the average.

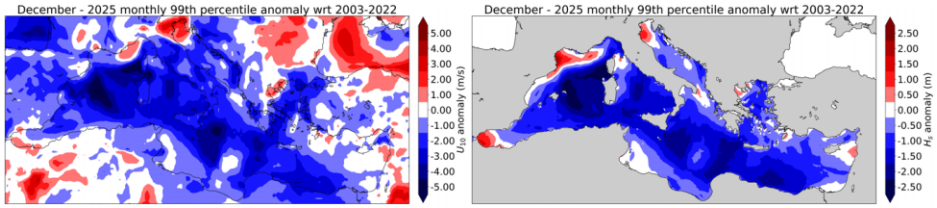

Figure 4 | December 2025 extreme (99th percentile) wind and wave anomalies in the Mediterranean Sea, compared to the 2003-2022 climatology. (left) 99th percentile anomaly of U from the ERA5 atmospheric model reanalysis. (right) 99th percentile anomaly of H_s from the CMEMS wave-model reanalysis.

Climatology (47 years) and trends of wind waves

An updated analysis of a 47-year directional wave time series recorded since 1979 at the "Acqua Alta" Oceanographic Tower in the Northern Adriatic Sea is obtained by extending the dataset by a full additional decade beyond what was previously published in (Pomaro et al., 2017). The extension of the time series, together with recent improvements in measurement techniques and data availability, allows for a re-evaluation of earlier findings and for the assessment of how these refinements affect the use of the dataset in climate change-related studies.

The new dataset provides a more detailed and reliable description of wave conditions in the North Adriatic and improves the identification of long-term trends and their connections with large-scale atmospheric circulation patterns.

The wave climate of this region is primarily shaped by two dominant wind regimes, bora and sirocco, whose characteristics are strongly influenced by regional orography. With the longer record now available, it becomes possible to distinguish more effectively between the local wind conditions, offering new insight into their differing meteorological signatures. This distinction strengthens the interpretation of changes associated with four key climate patterns: the North Atlantic Oscillation (NAO), the East Atlantic (EA), the EA/Western Russia, and the Scandinavian pattern, all of which modulate storm tracks and jet stream behaviour over broad areas of Europe.

The updated analysis does not confirm the previously reported marked decrease in the 99th percentile of significant wave height. Instead, negative trends are not statistically significant, while a seasonally consistent increase is observed in both the 50th and 75th percentiles. Further analyses are currently in progress to separately assess wind-forced contributions.

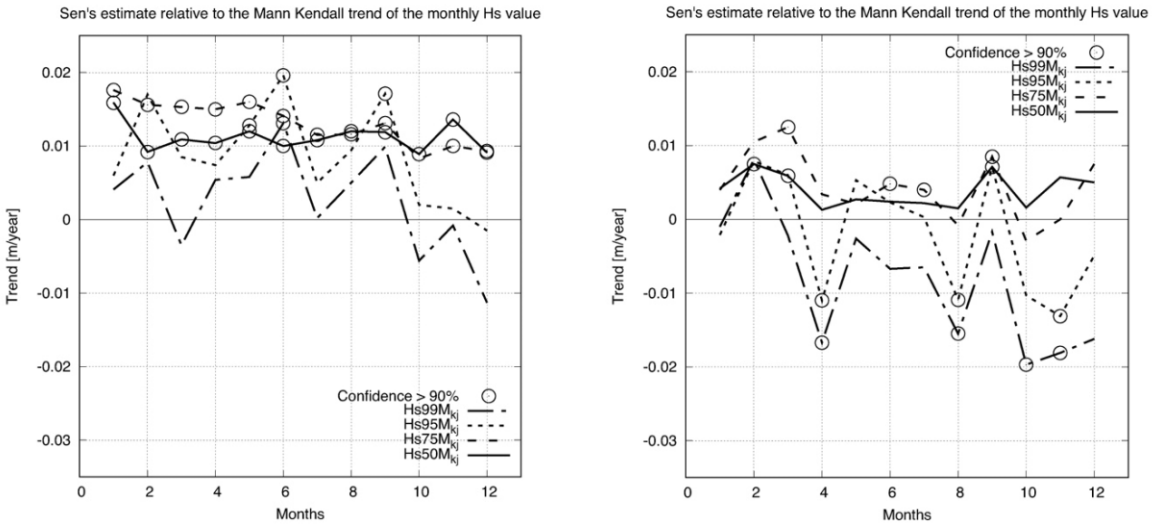

Figure 5 | (left) Updated monthly trends of the 50th, 75th, 95th and 99th *Hs* percentiles for all regimes. The circles identify trends statistically significant at the 90% confidence level. (right) Monthly trends for the period 1979-2016 (Pomaro et al., 2017).

Deployment of an “Italian National Wave Buoy Network” (RON) buoy: the second evaluation campaign

On 29 December 2025, the second experimental campaign aimed at evaluating the performance of a buoy from the Italian National Wave Buoy Network was launched at "Acqua Alta". This joint initiative—carried out by CNR-ISMAR, ISPRA (which is responsible for the network), and SIAP-MICROS (the buoy manufacturer)—builds on the first campaign completed in 2023. That initial effort enabled a detailed assessment of the buoy’s wave measurements at sea through comparison with simultaneous observations from ancillary instruments. Among these, a stereo-video system proved particularly valuable, as it allowed 3D tracking of the buoy’s motion and thus a characterisation of its dynamics during storm conditions. The results of this work were published in a joint scientific article (Benetazzo et al., 2025).

During this new six-month campaign, additional data will be collected by the buoy—now equipped with a broader and more advanced set of sensors—as well as by the tower instrumentation. These observations will enrich the validation dataset and support the development of a modulation transfer function designed to correct the buoy’s vertical motions, which may be influenced by factors such as inertia and mooring constraints. The ultimate goal is to improve the representation of the actual sea surface dynamics and, consequently, enhance the accuracy of wave measurements across Italian seas. The figure shows the buoy deployment near the tower, within the field of view of the stereo-video system.

For further information:
- https://www.mareografico.it
- Benetazzo et al. (2025). Evaluation of the 3D response and performance of an operational wave buoy for coastal wave monitoring. Coastal Engineering, 200, https://doi.org/10.1016/j.coastaleng.2025.104756.

Figure 6 | Deployment of a buoy of the “Italian National Wave Buoy Network” (Rete ondametrica Nazionale, *RON*). (left) The buoy with the floating hull (below, hosting wave and water column characteristics sensors) and its superstructure (above, supporting solar panels and meteorological sensors). (right) The buoy before the deployment. Photo credit: Thomas Pavan.

CO_2 air-sea flux

Building on the continuous monitoring initiated in 2024, high-resolution measurements of surface water CO_2 partial pressure at "Acqua Alta" have continued throughout 2025, allowing us to track seasonal and event-driven variability in air–sea CO_2 fluxes as the ocean alternates between periods of CO_2 uptake and outgassing. In parallel, acoustic backscatter (*Sv*) from a Nortek Signature 1000 ADCP is also recorded synchronously with the CO_2 data, providing a direct observational window into the near-surface mixing and bubble-mediated gas exchange.

This combined approach enables the investigation of individual high-wind and wave events in detail, quantifying the role of turbulence and bubble injection in enhancing gas transfer from the atmosphere to the ocean on an event-by-event basis.

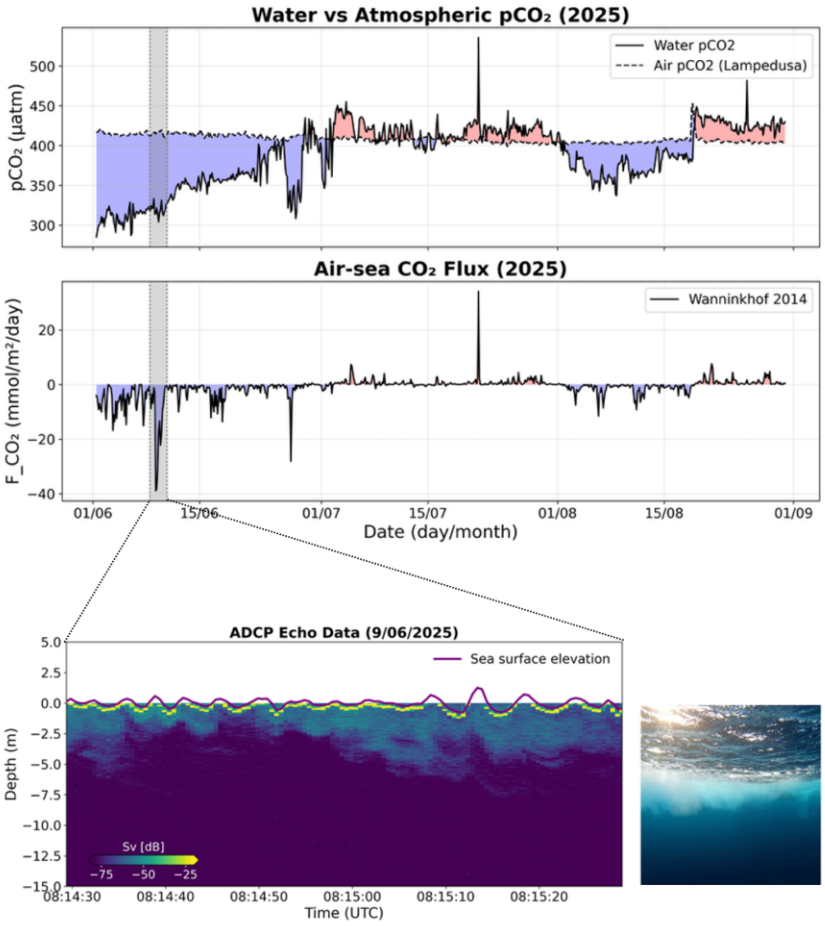

Figure 7 | CO_2 partial pressure (pCO_2) and resulting air–sea flux at "Acqua Alta" during summer 2025. (top) Seawater pCO_2 compared with atmospheric pCO_2 from Lampedusa station; shading indicates CO_2 sink (blue) and source (red) conditions. (middle) Air–sea CO_2 flux at "Acqua Alta" computed using the Wanninkhof (2014) parameterisation. (bottom) ADCP (Nortek Signature 1000) acoustic backscatter (*Sv*) snapshot for 9 June 2025 showing enhanced near-surface mixing and bubble-mediated gas exchange during moderate wind and wave conditions. (right) Example of an underwater image of a bubble plume during wave breaking.

Physical and biogeochemical parameters

Regular CTD (Conductivity, Temperature, and Depth) casts have been conducted at the "Acqua Alta" Oceanographic Tower since 2009 as part of the Italian Long-Term Ecological Research (LTER-Italy) program, documenting seasonal changes in water-column stratification and biogeochemical conditions. For 2025, monthly profiles of temperature, salinity, dissolved oxygen, and chlorophyll-a are shown, complemented by continuous measurements from a moored SBE37-SMP-ODO sensor at -3 m. Winter conditions featured colder surface waters and moderate vertical gradients intermittently deepened by wind-driven mixing (mainly Bora). From late winter to spring, surface freshening (~31 to 33 PSU) due to river discharge and rapid warming due to increasing light availability established stratification, with oxygen saturation frequently exceeding 110 to 120% and chlorophyll-a forming a subsurface maximum around 4 to 8 m in April.

This was also confirmed by microscopic analysis of phytoplankton abundance, which highlighted diatom blooms at both surface and bottom in the spring of 2025. In summer, stratification persisted, and surface chlorophyll-a declined significantly as a result of, e.g., grazing and nutrient limitation. In autumn, the combination of cooling and wind-driven mixing weakened vertical gradients again, producing a more homogeneous water column with lower oxygen levels and moderate chlorophyll-a concentrations.

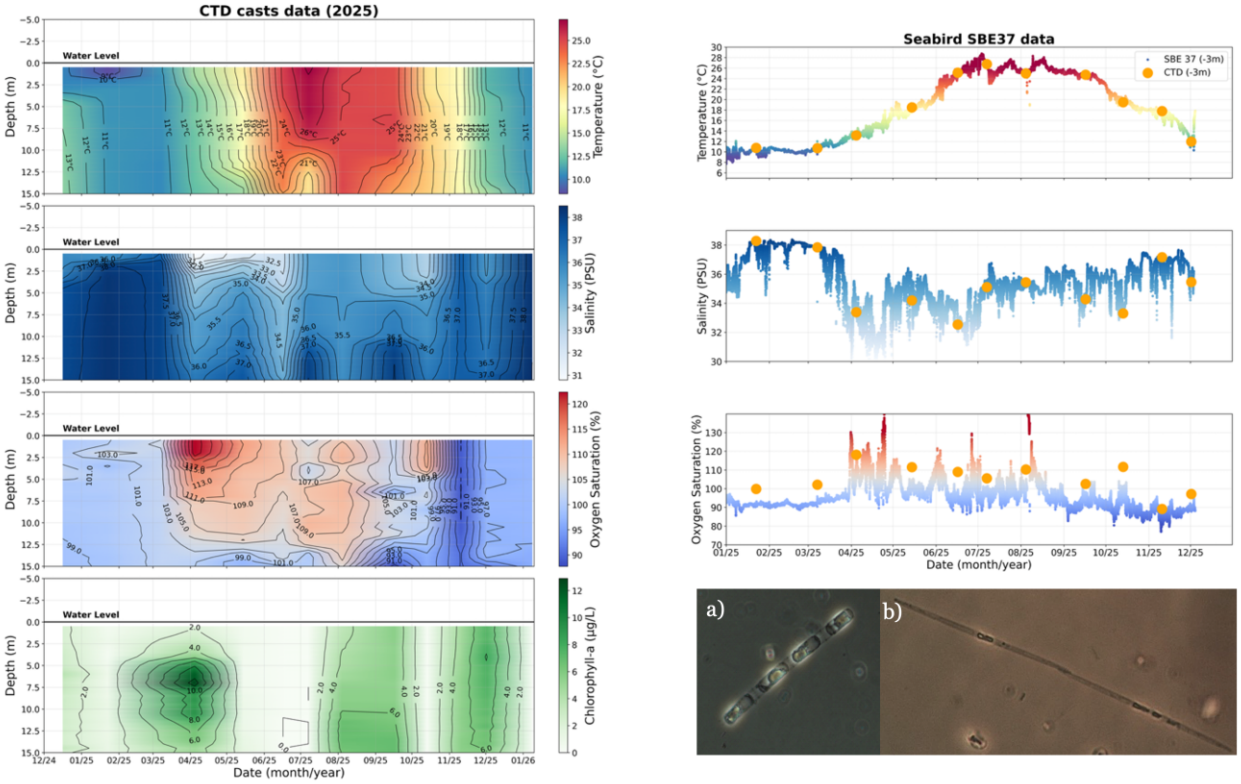

Figure 8 | Physical and biogeochemical conditions at the "Acqua Alta" Oceanographic Tower during 2025. Left panels show time–depth contour plots from CTD casts of (a) temperature (°C), (b) salinity (PSU), (c) dissolved oxygen saturation (%), and (d) chlorophyll-a concentration (µg L^{-1}). Depth is referenced to the sea surface water level (0 m), and contours highlight vertical structure and seasonal variability. Right panels show near-surface (−3 m) time series from a Seabird SBE37 moored sensor for temperature, salinity, and oxygen saturation, with concurrent CTD observations at −3 m overlaid as discrete markers for comparison. Two phytoplankton species responsible for bloom events in April are also shown: *Skeletonema marinoi* (a) and *Pseudo-nitzschia delicatissima* (b).

Wood durability study, ongoing experimentation

Wood degradation is driven by both abiotic and biotic factors. Unlike terrestrial and freshwater environments, where microorganisms such as fungi and bacteria play a major role, in marine and coastal environments the primary agents of wood degradation are crustaceans and bivalve molluscs. Among crustaceans, isopods of the genus *Limnoria* and amphipods of the genus *Chelura* are particularly relevant due to their ability to produce enzymes capable of digesting lignocellulosic material. Bivalve molluscs are mainly represented by the family Teredinidae, commonly known as shipworms, whose highly specialized morphology includes a reduced shell used as a drilling tool to excavate wood. Their capacity to feed on wood is enabled by the presence of endosymbiotic bacteria.

Wood durability and biodegradation processes in coastal and marine environment are commonly assessed based on standardized protocols, such as the EN 275 standard. These tests may also provide valuable information on the effectiveness of innovative and environmentally sustainable treatments, while offering the opportunity to investigate marine xylophages' diversity and ecology, including the presence of non-indigenous species.

Since 2021, an experimental evaluation has been conducted at the Acqua Alta Oceanographic Tower, initially within the framework of the DuraSoft INTERREG project, in accordance with the EN 275 standard. A total of 36 samples from five different tree species (*Abies alba* [silver fir], *Picea abies* [Norway spruce], *Pinus sylvestris* [Scots pine], *Pinus radiata* [Monterey pine], and *Quercus rubra* [red oak]) were installed on a pillar at a depth of 10 m. The samples were subjected to different treatments, including acetylation, thermal modification, and impregnation with specific formulations for coniferous wood. The tests are carried out simultaneously in different geographical areas of the North Adriatic Sea, allowing the assessment of material performance under diverse environmental conditions and exposure to different marine xylophagous communities. Samples are periodically retrieved and analysed using radiography, a non-destructive technique that enables continuous monitoring of the biodegradation process over time.

The untreated wood species have now reached EN 275 biodegradation level 4 (failure) and were therefore removed to allow the assessment of the xylophagous species involved in the degradation process. In contrast, the treated panels exhibited a high degree of durability, with limited evidence of biological attack. Given the scientific relevance of these results, the monitoring of treated materials will continue beyond the time limits established by the EN 275 standard, with the aim of providing predictive estimates of long-term resistance to macroinvertebrate xylophagous attack in the study area. This extended evaluation will contribute to a more robust understanding of wood performance and durability in marine environments.

Link: http://2014-2020.ita-slo.eu/it/durasoft; https://doi.org/10.1007/s11756-025-01964-x; https://link.springer.com/article/10.1007/s10530-021-02461-3; https://doi.org/10.26383/CNR-ISMAR.2025.08

Monitoring and research on the protected species *Pinna nobilis*: 2025 activity updates

The fan mussel Pinna nobilis (L. 1758) is an endemic species and the largest Mediterranean bivalve, distributed across various benthic habitats. Due to its ecological value and vulnerability, the species is protected under national and international legislation, including the Habitat Directive. Since 2016, an epidemic associated to the protozoan Haplosporidium pinnae has triggered Mass Mortality Events (MMEs), with mortality rates up to 100%, leading to a drastic decline of populations throughout the species distribution range. In the Northern Adriatic, MMEs have been recorded since 2019, causing a near-collapse of the species in the area. Nevertheless, some individuals survive in some locations, with the Lagoon of Venice hosting a particularly significant relict population. Since 2023, "Acqua Alta" has been included in the Northern Adriatic network for the monitoring of Pinna nobilis larval dispersal and recruitment by means of larval collectors, deployed at different depths. In 2025, during the spawning season, larval collectors were placed in the tower's surroundings on 1 August by the scuba team of the State Police.

Three types of collectors were deployed for intercalibration: a first type proposed by CNR-ISMAR (Marčeta et al. 2024, https://doi.org/10.5281/zenodo.14528163), a second type commonly used in Slovenian and Croatian waters, and a third type with biodegradable filler (jute) proposed by the Piran Marine Biology Station (NIB). The activity has initially been carried out within the framework of the INTERREG IT-SI TRECap project, and follows previous monitoring conducted in 2023 and 2024. The collectors were retrieved on 16 January 2026 and examined for the presence of settled juveniles. In contrast to the 2024 monitoring, where no individual, either dead or alive, was found, in the present monitoring, 8 juveniles were detected, 6 of which were alive. These results will be compared to those obtained at other Northern Adriatic sites, contributing to the understanding of the ecological dynamics and the status of the species, as well as to the optimisation of monitoring methods and to conservation strategies. In line with approaches developed during the TRECap project, the juveniles will be reared in a purpose-designed rearing system in the tower surroundings, a couple of meters above the seafloor. They will undergo regular inspections, with environmental conditions monitored continuously. The aim is to outplant the surviving individuals to the Tegnùe di Porto Falconera Natura 2000 site once they reach an adequate size, expected after next summer, replicating the procedure carried out in 2025, which resulted in the outplanting of three individuals settled on the tower collectors in 2024, one of which is still alive to date.

Figure 9 | (left) collector for *Pinna nobilis* planktonic larvae (CNR-ISMAR type); (right) juvenile found in January 2026 in larval collectors.

Copernicus FRM4SOC-2025 training in above-water radiometry

The Second EU Copernicus FRM4SOC Training for in situ Ocean Colour Above-Water Radiometry towards Satellite Validation was held in Venice from 6 to 20 July 2025. The training was held on the island of *San Servolo*, at CNR-ISMAR offices, and at the Acqua Alta Oceanographic Tower. Full details and links to presentations are provided at the event page https://frm4soc2.eumetsat.int/post/copernicus-frm4soc-2025-training-above-water-radiometry. This year, 24 PhD students, postdocs and early career researchers from Europe, US, South America, and Asia were trained in the principles of above water radiometry, derivation of uncertainty budgets, and protocols for matchup analysis with satellite data.

The course included expert lectures from the project team on the collection of FRM-quality measurements for satellite validation; practical experience collecting field measurements; hands-on tutorials for working with Copernicus Sentinel-3 from EUMETSAT, and PACE from NASA; and an introduction to, and practical exercises for working with the HyperCP processor and ThoMaS matchup toolkit. During the course, the participants also visited the Acqua Alta Oceanographic Tower, where a full instrument intercomparison exercise was being performed by OC experts. Participants took part in a group project on the data they collected and processed. They then presented their results on the gained hands-on experience towards the collection of FRM-quality measurements and on real validation against multiple ocean colour satellites.

Figure 10 | Field trips to the "Acqua Alta" tower for hands-on fieldwork training. (top) Dr Giuseppe Zibordi providing details on the radiometric instrumentation and measurements carried out on board; (bottom) group photo of trainers and trainees on board "Acqua Alta".

Validation of a local wave-forecasting model

The "Henetus" wave forecasting system in the Adriatic Sea has been operational since 1996. It provides once a day wave height, period and direction on the whole basin, using the up to five days ahead wind forecast of the European Centre for Medium-Range Weather Forecasts (Reading, UK). Combined with satellite data but based mainly on the wind and wave data recorded since 1979 on the "Acqua Alta" oceanographic tower, the long-term comparison has made it possible to correct the ECMWF modelled wind data of the known underestimate in enclosed seas. In turn, this has led to very high-quality wave model data, both as analysis and up to five days forecast.

The statistics for the 2025 performance of the model shows errors up to five days forecast of the order of, or less, than 1%.

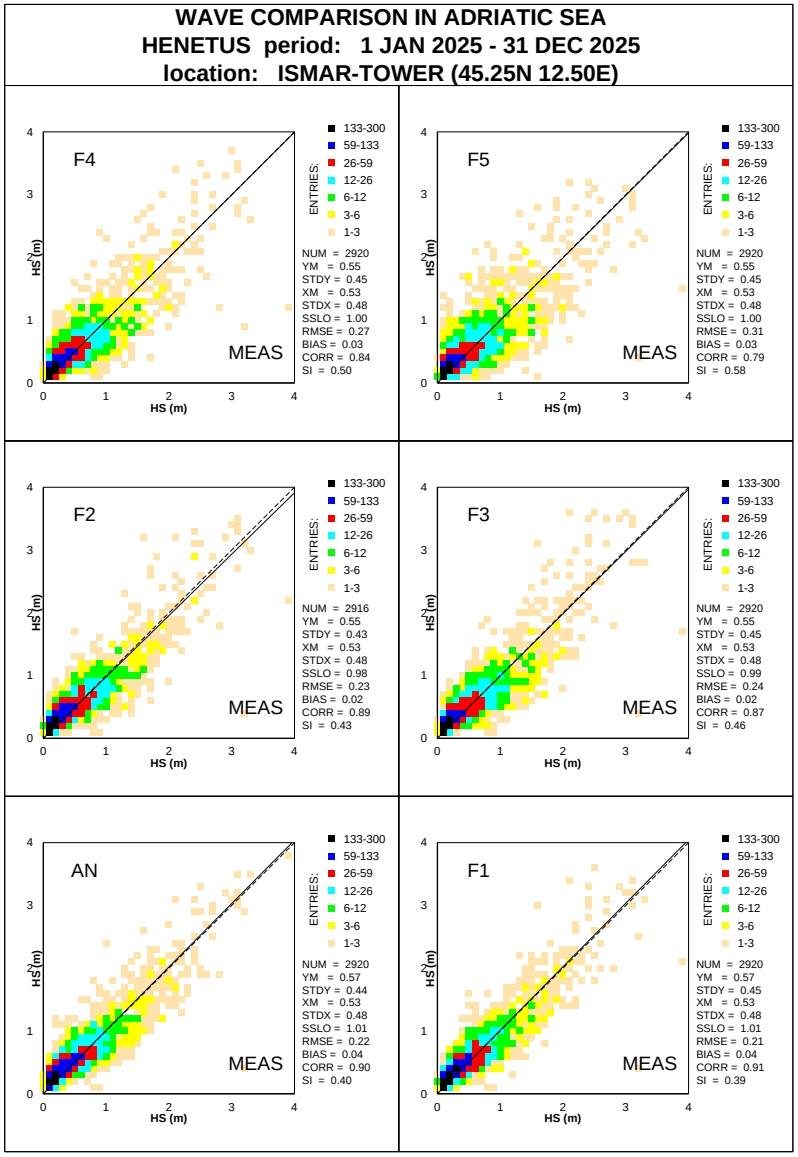

Figure 11 | Performance of the wave-model significant wave height H_s (horizontal axis of each panel) against the observed value (vertical axis of each panel). Panels represent the model analysis (AN) and forecast lead time from 1 (F1) to 5 (F5) days. Standard error metrics are provided in each panel.