

1 **Unveiling the Deep Ocean warming: observed bottom ocean dataset across Mediterranean Sea**

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9 **Abstract**

10 The deep ocean was long assumed to be in a quasi-stationary state, and therefore excluded from studies
11 on climate variability. The awareness of the unsteady state of the deep ocean is a fairly recent
12 achievement, but despite its pivotal role in the assessment of climate variability, the understanding of
13 abyssal ocean dynamics remains largely unknown, primarily due to the scarcity of observations. This is
14 why any observations below 2000 meters depth, although poor or widely dispersed, constitute valuable
15 knowledge that is mandatory to enhance and make available.

16 This work presents validated oceanographic time series collected by benthic multidisciplinary
17 observatories across key locations in the Mediterranean Sea region. It includes details on the data
18 processing and quality control methods used to ensure reliability and aims to deliver high-quality data, as
19 well as standardization in the quality control procedures for deep-sea measurements.

20 The dataset provides a comprehensive description of seafloor observations collected over different time
21 periods during the past decade, contributing to the long-term characterization and understanding of
22 abyssal ocean variability in the region.

23

24 **Short Summary**

25 We present a set of long-term, high-resolution oceanographic datasets collected by benthic observatories
26 across the deep Mediterranean Sea. These datasets provide valuable insight in the study of deep ocean
27 dynamics and its possible impact on climate variability. By applying standardized post-processing and
28 quality control procedures, we ensure the data's reliability and usability for further analysis and model

validation. This contribution addresses critical gaps in deep-sea monitoring and supports efforts aligned with the UN Decade of Ocean Science.

1 Introduction

The deep ocean is the largest, yet least observed, component of the Earth's climate system. For decades, it was assumed to be a quasi-stationary environment (*Stommel and Arons, 1960; Munk, 1966*) and thus was largely excluded from global monitoring strategies. The unsteady state of the deep ocean is a recent achieved knowledge (*Ferrari et al. 2016, MacKinnon et al, 2017, Polzin and McDougall, 2011*) that emphasizes the significance of abyssal processes in redistributing heat and energy, thereby influencing surface climate variability.

Recent findings (*Talley et al 2016., Desbruyères et al. 2016, Artale et al., 2018*) show that, all over, the deep ocean is far from being a stable environment; rather, it is an active part of the climate system, exerting measurable impacts on decadal time scales. The deep sea is indeed governed by physical and biogeochemical processes occurring on a wide range of temporal and spatial scales, resulting in a complex system. It is influenced by the continuous vertical exchanges across the water column and at the air-sea interface, as well as by lateral exchange with surrounding ocean basins, guided by morphological dynamics. Given the crucial role of the oceans in absorbing planetary energy imbalance (93%) (*Rhein et al., 2013*), understanding how and on what timescale deep-water masses redistribute this energy is essential for assessing long-term climate variability and ocean circulation dynamics (*Lo Bue et al., 2021*). Deep sea variability and the impacts of climate change on it are difficult to interpret, and it is difficult to disentangle the different contributions given the small number of available observations, as well as discriminate between local variability and climate change. These knowledge gaps are reflected in current global climate models, where abyssal processes are not well-represented, leading to important biases in the global climate variation estimates. Global climate models need observations for model design, tuning, and validation, so it is straightforward that the under-observed deep ocean results in being poorly represented (*Heuzè et al. 2022*). Recognition of observation as a critical element for ocean health and planet sustainability boosted observing efforts since 2000, but this has almost exclusively concerned the surface ocean (*Visbeck, 2018*). Therefore, the capacity to comprehend and quantify the energy redistribution in the deep ocean and its effects on climate variability will remain underestimated until enhancements in systematic monitoring across a substantial volume of (deep) ocean are achieved. Over the past decade, several global ocean observing programmes, such as ARGO, OceanSITES, GO-SHIP, OOI, ONC, and EMSO, have contributed to continuous monitoring of the deep ocean. In the

61 Mediterranean Sea, programmes such as HydroChanges (Fuda et al., 2007) and Med-SHIP (Schroeder et
62 al., 2015) have provided periodic observations since 2002 and 2013, respectively, documenting long-term
63 changes in thermohaline characteristics. However, these efforts still cover only a limited and spatially
64 scattered portion of the vast ocean (Levin et al., 2019). Currently, just 6% of hydrographic observations
65 extend below 2100 m in depth (*de Lavergne et al. 2016*), while the global mean ocean depth exceeds
66 4000 m.

67 As suggested by the UN decade (Howell, 2021), there is an urgent need to fill the knowledge gap about
68 the deep ocean and to better understand the rapid changes currently being observed, including those
69 occurring in the Mediterranean Sea (Chiggiato et al, 2023). This requires a collaborative, synergistic effort
70 that places priority on enhancing observation networks and monitoring programs across various domains
71 as well as delivering standardized, high-quality datasets to support both process studies and model
72 development. High-resolution, long-term datasets are essential not only for understanding deep ocean
73 variability but also for reducing biases in global climate models, which currently lack robust
74 parameterizations for abyssal processes (Heuzé et al., 2022).

75 In this context, we present a collection of validated, long-term oceanographic datasets acquired by benthic
76 observatories deployed at key sites across the deep Mediterranean Sea. These observatories provide
77 unique data for sampling strategies, heterogeneity, location, and endurance. The aim is to facilitate
78 knowledge sharing and promote a harmonized approach to deep-sea monitoring that supports broader
79 scientific efforts in climate research, model validation, and new ocean insight.

80

81 **2 Data acquisition system**

82 Accurate and continuous deep-sea monitoring requires advanced data acquisition systems capable of
83 withstanding extreme conditions and capturing a broad range of environmental variables over extended
84 periods. In this sense, benthic multidisciplinary observatories, such as GEOSTAR-type system (Favali et
85 al. 2006; Favali et al., 2009, Favali et al., 2013) (Fig. 1), are essential tools, integrating physical, chemical,
86 and geophysical sensors to acquire high-resolution data in challenging deep-ocean conditions, where
87 pressure, oxidation and temperature can affect the functioning of the system itself.

88 Benthic observatories can be broadly categorized into two types: autonomous (standalone) and cabled
89 systems. The choice between these configurations depends on monitoring objectives, site accessibility,
90 power and data requirements and logistical constraints.

91 Autonomous systems are designed to operate without external power or data transmission infrastructure.
92 Powered by onboard lithium batteries, these systems store data locally until physical recovery. Low-
93 power electronics are used to optimize battery life, and sensor data are timestamped using high-precision

rubidium clocks and stored in a central internal memory. Special attention is paid to sensor placement to minimize interference from the frame structure and to ensure optimal sampling conditions. Depending on the mission configuration, autonomous systems can operate for periods up to one year (*Embriaco et al., 2014; Marinaro et al., 2006; Favali et al., 2006; Beranzoli et al., 1998*). The autonomous nature of these systems makes them particularly valuable for deployments in remote areas where establishing a continuous power or data connection is impractical. However, their reliance on limited battery life and local data storage means that they require periodic recovery and maintenance, limiting their ability to provide real-time data.



Figure 1: Example of a GEOSTAR-type observatory integrating multidisciplinary sensors. The image shows the NEMO-SN1 benthic observatory during the GNDT-1 campaign (2002–2003).

Cabled observatories, by contrast, are connected to shore stations via electro-optical submarine cables, allowing for real-time data transmission and continuous power supply. A cabled observatory such as NEMO-SN1 (*Favali et al., 2013, Giovannetti et al., 2016*) incorporates an electro-optical jumper and a 28 km-long submarine cable that connects the system to a dedicated onshore acquisition system. This setup enables uninterrupted data collection, remote control of sensors, and real and near-real-time quality control (depending on the type of data acquired). Time synchronization is achieved via a GPS signal received at the shore station, ensuring high temporal accuracy across all measurements. Cabled systems

are ideal for deep long-term monitoring in accessible regions requiring high-frequency, real-time data. Table 1 summarizes the observatories, deployment sites, and sensor configurations described in this study.

3 Dataset, processing, and quality control

Monitoring the deep sea presents significant challenges, from instrument deployment and data recovery to ensuring the accuracy, quality and comparability of measurements, primarily due to its remote and extreme environment. Harsh environmental conditions, logistical complexity, and technological variability across observatories result in heterogeneous datasets requiring robust processing and harmonization. This section outlines the datasets, their characteristics, and the quality assurance (QA), the standardized post-processing, and quality control (QC) procedures adopted to enhance data integrity, reliability, and interoperability.

3.1 Datasets

Between 2002 and 2014, eight long-term multidisciplinary time series were collected by four different benthic observatories strategically located across the Mediterranean Sea (Fig. 2). Each observatory hosts a wide array of geophysical sensors. However, for the purposes of this paper, we focus only on those measuring physical and biogeochemical parameters, notably: temperature, conductivity, pressure, turbidity, and ocean currents. Sensor operation varied across deployments, with sampling intervals depending on the sensor type and mission objectives. A central data acquisition unit guarantees time synchronization among sensors that operate with different sampling intervals, ranging from hourly to a frequency as high as 5 Hz. Table 1 provides a summary of each observatory, including deployment periods, sensor types and models, sampling frequencies, and overall sensor efficiency, defined as the percentage of successfully recorded data relative to the total expected data acquisition load. Below, we present a detailed description of the datasets acquired at each site.

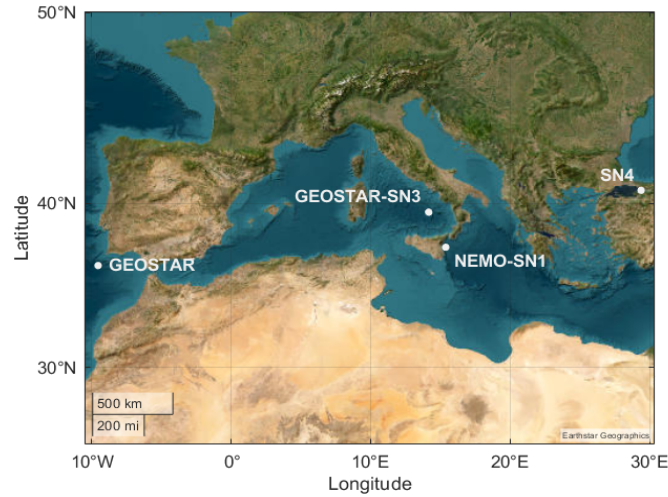


Figure 2: Location of the benthic multidisciplinary observatories: GEOSTAR (Gulf of Cadiz), GEOSTAR-SN3 (Tyrrhenian Sea), NEMO-SN1 (Ionian Sea), and SN4 (Marmara Sea), (from Google Earth).

NEMO-SN1 observatory (Western Ionian Sea, 2100 m), located ~25 km off the coast of Eastern Sicily (37.5° N, 15.4° E), yielded two different monitoring campaigns: October 2002–February 2003 and June 2012–June 2013 (Favali *et al.* 2006, Favali *et al.* 2011, Favali *et al.* 2013). The first deployment included a CTD probe (SBE 37SM) sampling every 12 minutes, and an acoustic punctual current meter (Falmouth 3D-ACM) operating at 2 Hz. This sensor payload was then improved for the second campaign (2012–2013) by adding an ADCP (RDI WorkHorse, 600kHz), sampling current profiles every 30 minutes. Also, a new punctual acoustic current meter (Nobska MAVS-3 3-axis) replaced the previous one, maintaining the same sampling frequency, while the sampling rate of the CTD was changed to 1 sample per hour. This site is a key transition zone for water mass exchange between the Levantine Basin, Adriatic Sea, and Western Mediterranean, and plays a central role in deep thermohaline circulation of the Eastern Mediterranean (Malanotte-Rizzoli *et al.*, 1997; Lascaratos *et al.*, 1999; Gacic *et al.*, 2010, Budillon *et al.* 2010).

GEOSTAR-SN3 (Southern Tyrrhenian Sea, 3320 m), located on the Marsili abyssal plain (39.5° N, 14.2° E), GEOSTAR-SN3 represents the first long-term pilot deployment at this site. This observatory was implemented to act as the main node of an underwater network of deep-sea observatories (Favali *et al.* 2009). It operated in two consecutive missions: 2003–2004 and 2004–2005. The observatory was

equipped with a CTD (SBE 16plus), a transmissometer (Chelsea Alphasacka II), an ADCP (RDI WorkHorse 300 kHz), and a point current meter (Falmouth 3D-ACM), all sampling at hourly intervals, except for the last sensor that operated at 2 Hz. Due to the presence of the Marsili Volcano, which represents one of the largest European underwater volcanoes of the Plio-Pleistocene age, this area is key for addressing both geophysical and oceanographic topics (*Beranzoli et al. 2009*).

GEOSTAR (Gulf of Cadiz, Iberian Sea, 3200 m), an updated version of the GEOSTAR seafloor observatory, was then deployed between 2007 and 2010 near shore in the Gulf of Cadiz (Iberian Sea - 36.4°N, 9.5°W). This deployment was part of the CE NEAREST project (Integrated observation from NEAR shore sourceS of Tsunami: Towards an early warning system) (*Favali et al. 2009*), which aimed to enhance the near-real-time detection of signals through a multiparameter seafloor observatory designed to characterize potential sources of tsunamis, contributing to the development of a prototype Early Warning System (EWS). From an oceanographic perspective, this site is significant for monitoring interaction between the North Atlantic current and the Mediterranean outflow, contributing to the oceanographic characterization of a key interbasin exchange zone (*Alves et al. 2011, García-Lafuente et al. 2006, Ochoa et al. 1991*). The sensor suite included a CTD (SBE 16plus), a turbidimeter (Wet Labs ECO BB), an ADCP (RDI WorkHorse 300 kHz) sampling every 10 minutes and a punctual current meter (Nobska MAVS-3) sampling at 5 Hz.

SN4 (Marmara Sea, 166 m), deployed along the North Anatolian Fault in the Gulf of Izmit (40.7° N, 29.4° E), SN4 monitored seismic activity and its coupling with environmental parameters. Campaigns were conducted in 2009–2010 and 2013–2014, with durations of 5 and 7 months, respectively. Although SN4 is one of the smallest GEOSTAR-class observatories, its instrumentation includes both geophysical and oceanographic sensors (*Favali et al. 2009, Marinaro et al. 2006*), hosting CTD (SBE 16plus), a turbidimeter (Wet Labs ECO NTU), an oxygen optode (AADI 3830), and a point current meter (Nobska MAVS-3), with sampling frequencies ranging from 1 sample every 10 minutes (CTD, turbidity) to 1 Hz (oxygen) and 5 Hz (currents). The observatory's purpose is to investigate potential correlations between seismic activity and gas methane emissions in the surrounding environment, given the area's status as an active seismic zone (*Embriaco et al., 2014*).

3.2 post-processing and quality control

The long-term deployment of observatories, along with the evolution of instrumentation over the years, has resulted in variability in data formats and metadata structures. Consequently, a tailored post-processing procedure for each observatory was required to face these discrepancies. To provide a more

reliable comparison for future dissemination and usage of the data, in compliance with the FAIR (Findable, Accessible, Interoperable, and Reusable) principles for data sharing, the post-processing workflow consisted of several steps: converting raw data into usable formats, harmonizing metadata, and applying quality checks. Preliminary analysis was always conducted, as the first step, to evaluate the data storage efficiency (Table 1). The raw data extracted from the deck unit were converted into a readable format using custom-designed software tailored for each specific observatory, whereas certain types of data, such as ADCP data, required conversion using the manufacturer's software. Each dataset underwent post-processing utilizing specific multi-step standardized procedures following the manufacturer's recommendation. This process enhances the accuracy, reliability, and interpretability of the raw data, refining its quality and facilitating better interpretation. The QC procedures were guided by recommendations from international frameworks such as GOOS (*IOC, 2010; Pouliquen et al., 2011*) and QUARTOD (*Bushnell et al., 2019*). Tests included checks for time consistency, value ranges, rate of change, and internal consistency across sensors. Data were flagged based on severity and usability (Table 2), with bad or missing data replaced by NaNs to maintain data integrity.

3.2.1 post-processing

The first stage aimed to collect, convert, and verify the data gathered by different acquisition systems, considering the diverse types of sensors and the relative data format, to enhance the quality and reliability of the collected information. A thorough post-processing phase was undertaken to refine and further validate the data. This involved primarily an inspection of the efficiency of the sensors and their proper functioning through meticulous post-calibration and validation procedures to ensure the integrity of the data, providing a solid foundation for subsequent analysis and interpretation. Table 1 reports the efficiency for each sensor and mission elaborated, where the overall acquisition efficiency is calculated as the percentage of data recorded on the total acquisition load. The efficiency of the oceanographic sensors was generally greater than 90%, with a few exceptions, most notably in the Marmara Sea (Table 1), where the Nobska MAVS-3 sensor stopped functioning relatively early in the mission. Subsequently, several checks were performed to verify timestamp validity, ensure alignment of multivariable measurements, and assess instrument efficiency.

Table 1: Overview of the benthic observatories, including site location, deployment period, sensor types and models, sampling frequency, and acquisition efficiency.

Observatory name, depth, and geographical site	Acquisition period	Sensor type	Sensor model	Sampling frequency	Sensor efficiency (%)
NEMO-SN1 (2100 m) Western Ionian Sea	2002-2003 and 2012-2013	CTD	SBE 37 SM	1 sample/12'	100% (2002-2003) 95.3% (2012-2013)
		CURRENT METER	Falmouth 3D-ACM (2002-2003) Nobska MAVS-3 (2012-2013)	2Hz	99.9% (2002-2003) 98.4% (2012-2013)
		ADCP	RDI WH 600 kHz	2 samples/h	98.7% (2012-2013)
GEOSTAR SN3 (3320m) South Tyrrhenian Sea	2003-2004 and 2004-2005	CTD	SBE 37 SM	1 sample/h	99.5% (2003-2004) 98.5% (2004-2005)
		TRANSMISSOMETER	Chelsea Alphasracka II	1 sample/h	99.5% (2003-2004) 98.5% (2004-2005)
		CURRENT METER	Falmouth 3D-ACM	2Hz	100% (2003-2004) 99.9% (2004-2005)
		ADCP	RDI WH 300 kHz	1 samples/h	100% (2003-2004) 99.7%(2004-2005)
GEOSTAR (3200) Gulf od Cadiz	2007-2008 and 2009-2010	CTD	SBE16plus	1 samples/h	91.4% (2007-2008) 96.1% (2009-2010)
		TURBIDIMETER	Wet Labs ECO BB	1 samples/h	91.4% (2007-2008) 96.1% (2009-2010)
		CURRENT METER	Nobska MAVS-3	5Hz	90.5%(2007-2008) 36.8%(2009-2010)
		ADCP	RDI WH 300 kHz	1 sample/h	90.5% (2007-2008) 36.8% (2009-2010)
SN4 (166 m) Marmara Sea	2009-2010 and 2013-2014	CTD	SBE16plus	1 sample/10'	99.5% (2009-2010) 99.7% (2013-2014)
		TURBIDIMETER	Wet Labs ECO BB	1 sample/10'	99.5% (2009-2010) 99.7% (2013-2014)
		CURRENT METER	Nobska MAVS-3	5Hz	99.9% (2009-2010) 17.7% (2013-2014)
		OXYGEN	AADI Optode 3830	1 Hz	99.9% (2009-2010)

Table 2: Definitions of quality flags applied to datasets. Missing and Bad data (flag 9) are not retained and replaced in the new QC datasets with NaNs.

Code	Definition
1	Good data
3	Suspect data potentially correctable or high-interest data
9	Missing value or bad data

Moreover, regression analysis was employed to verify internal consistency, particularly between current meters and ADCPs. For instance, the eastward velocity component (U) measured by the punctual current meter and by the ADCP deployed at GEOSTAR-SN3 during the 2003–2004 mission showed moderate agreement ($R^2 = 0.28$, Fig. 3). This result should be interpreted in the light of the differences in functioning, and positioning: the ADCP samples the open water column, whereas the punctual current meter operates within the observatory frame. Also, The current-meter record, acquired at 2 Hz, was smoothed using a 1-hour moving average and sampled at hourly intervals to allow comparison with the ADCP data.

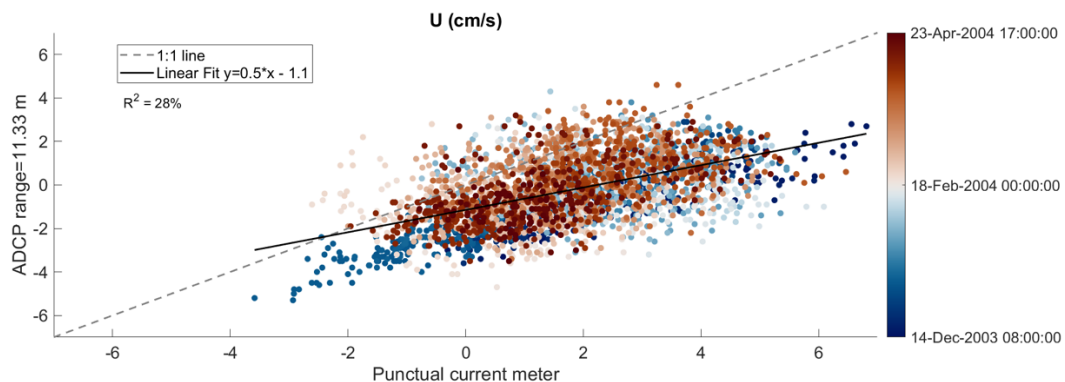


Figure 3: Comparison of the horizontal (U) velocity components from punctual current meter (located approximately 1 m above the seabed) and ADCP (data refers to measurements taken at 11.33 m above the seabed) at GEOSTAR-SN3 (2003–2004). To match these two different types of data we considered the hourly time series.

The RDI Workhorse 300 kHz ADCP measurements correspond to ensemble-averaged profiles (100 pings per ensemble, 6 s ping interval), which produce one velocity profile per hour. This moderate consistency was observed despite differences in their operating principle, measurement accuracy and installation height from the seafloor. The ADCP profiles a section of the water column above the observatory (up to 20 – 30 m in this example), while the punctual current meter captures velocity close to the sensor itself, close to the bottom. This comparison helps confirm the reliability of the collected data.

3.2.2 Quality Control Procedures

Before any QC procedure can be meaningfully applied, however, rigorous Quality Assurance (QA) is essential to ensure that the sensors themselves provide measurements within their expected accuracy and long-term stability specifications (i.e., limited drift over time). In these cases, QA included pre-deployment sensor calibration and in situ verification through dedicated CTD casts performed using high-accuracy shipborne CTD systems (e.g., SBE 911plus) and conducted both immediately before the observatory deployment and after recovery. These steps establish the baseline performance of each instrument, allow the identification of sensor drift or malfunction. Ensuring robust QA is fundamental, as even the most sophisticated QC procedures cannot fully compensate for poorly calibrated or improperly functioning sensors (*Bushnell et al., 2019; Waldmann et al., 2022*); rather, effective QA provides the foundation upon which reliable real-time and delayed-mode QC can be built. Whether performed in real-time or in delayed mode, QC data is crucial for ensuring the accuracy, reliability, and consistency of the data collected. For cabled observing systems, real-time QC serves as necessary tool for assessing, monitoring sensor performance and developing possible real-time applications. It also helps prevent the storage and analysis of erroneous data, while enabling prompt corrections that can minimize data gaps or inaccuracies during critical monitoring periods.

In contrast, delayed mode QC provides a more comprehensive review to improve data accuracy. It involves comparing measurements with reference datasets, historical records, or model outputs, allowing the detection and correction of errors missed during real-time processing. Sensor recalibration and cross-referencing with nearby instruments are commonly applied. By applying advanced statistical and tailored threshold-based techniques (e.g. range tests, spike and outlier detection), together with time series

287 methods (e.g. low-pass/high-pass filtering, trend analysis, autocorrelation), delayed mode QC can
 288 effectively address issues such as missing data, spikes, and sensor drift, thereby substantially enhancing
 289 overall data quality. Since deep ocean data is often collected over extended periods, delayed mode QC
 290 plays a crucial role in identifying and correcting inconsistencies caused by sensor degradation or
 291 calibration drift. This is especially important for long-term environmental studies, where maintaining
 292 consistency across datasets is essential for reliable trend analysis and meaningful comparisons.
 293 All datasets here described, whether collected through stand-alone or cabled system, have been processed
 294 in delayed mode with the aim of archiving the dataset for long-term use and sharing high-quality data
 295 with the scientific community.
 296 Following QUARTOD (QA/QC for Real-Time Oceanographic Data) recommendations (*Pouliquen et al.*
 297 *2011*), a QC protocol was customized for each sensor type and designed to be as automated as possible.
 298 Data that failed one or more tests were either flagged or removed according to the test rules. Missing or
 299 bad (removed) data were substituted with NaNs, while preserving their corresponding timestamps to
 300 maintain a regular temporal grid in the dataset. Custom thresholds were defined for regional and seasonal
 301 variability based on climatological data from the Mediterranean Sea (Table 3).

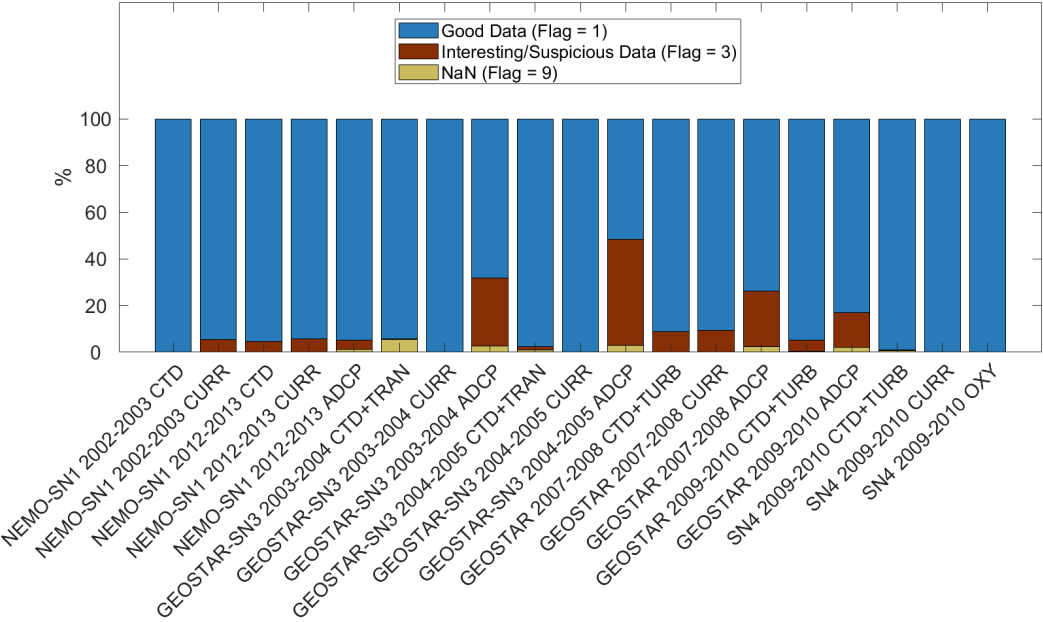
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Table 3: Example of regional thresholds used in quality control tests for the Mediterranean Sea,
 including seasonal and climatological variability.

SITE	VARIABLE	RANGE
Ionian Sea and Tyrrhenian Sea	Temperature	13-14° C
	Conductivity	4-5 S/m
	Current Speed	0-20 cm s ⁻¹
Marmara Sea	Temperature	14-16° C
	Conductivity	4-5 S/m
	Current Speed	0-40 cm s ⁻¹
Cadiz Gulf	Temperature	2-3° C
	Conductivity	2-4 S/m
	Current Speed	0-20 cm s ⁻¹

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310 These measures ensured that flagged data reflected real anomalies rather than environmental variability.
 311 Figure 4 provides an overview of the quality of the seafloor observatory data after applying the post-
 312 processing and the QC procedure using flags defined in Table 2.
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 315 **Figure 4: Data quality distribution across observatories and sensors after QC. Data quality flags as percentages for all processed**
 316 **datasets. Bars indicate observatory name, campaign years, and sensor type. Flag codes: Good Data (Flag = 1); Interesting/Suspicious**
 317 **Data (Flag = 3); NaN (Flag = 9);**

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 319
 320 The QC procedure was carried out through a stepwise sequence of tests, such as:
 321 **Time check** - The test concerns missing timestamps requires that the observation date and time are
 322 reliable and cover the whole campaign duration with the frequency of the instrument. Missing data are
 323 typically detected and flagged. In some cases, the acquisition system automatically inserts a standard out-
 324 of-range value (e.g., ‘999’) in the raw data to indicate a malfunction; these values are identified and
 325 replaced with NaNs.
 326 **Out of range test** - Removing any measurements that exceed the output-range thresholds assigned
 327 individually to each sensor

328 **Gross Range test** - The global range test evaluates each observed value against the full spectrum of
329 physically plausible measurements, encompassing both the extreme conditions expected in the oceans
330 and the operational limits of the sensors. Any value that falls outside this predefined range is automatically
331 flagged or removed, ensuring that clearly erroneous measurements are excluded from subsequent
332 analyses.

333 **Percent Good** (ADCP only) - This test uses the percent good of the beams, which indicates what fraction
334 of the pings were accepted for a given ensemble. The percent good test determines whether the data that
335 are being returned are sufficient to provide the required data quality. For Teledyne RDI ADCPs, when
336 the coordinate frame is not set to beam coordinates, the Percent Good test refers to the percentage of valid
337 three- and four-beam solutions, i.e., the proportion of data for which no beams or only one beam has been
338 rejected by the sensor.

339 **Error velocity test** (ADCP only) - Uses error velocity, which derives from the four-beam geometry of
340 an ADCP, each pair of opposing beams providing two independent measurements of velocity. The error
341 velocity can be treated as an indicator of errors for each depth bin. Threshold specification from the sensor
342 manufacturer.

343 **Regional/Seasonal range test** - This is a variation on the gross range test, where the thresholds are
344 adjusted to seasonal averages (e.g., climatological ranges, expected variability from the measured region).
345 Table 3 provides an example of specific ranges for observations from the Mediterranean Sea.

346 **Spike test** - This test checks for single value spikes usually due to an electrical signal from the sensor,
347 relative to adjacent data points. Spikes consisting of more than one data point are difficult to capture, but
348 their onset may be flagged by the following Rate of change test.

349 **Rate of change** – This test inspects the time series for for changes between consecutive observations that
350 exceed a defined threshold. The observed quantities can change substantially over short periods in some
351 locations, hindering the value of this test, so the thresholds have been chosen carefully and tailored based
352 on the sensor’s operational limits and location. The threshold is defined using the local variability of the
353 signal (e.g., a multiple of the standard deviation computed over a moving time window). Unlike classical
354 outlier detection methods based on deviation from a mean value, this test evaluates the temporal
355 consistency of the measurements and flags, rather than removes, suspect data In the case of dissolved
356 oxygen measurements, because of its dynamic nature (*Fusi et al.2023*), this test does not involve outliers’
357 removal but flagging.

358 **Flat line** - A common sensor failure mode can provide a data series that is nearly a flat line suggesting
359 sensor failure. This test checks for a continuously repeated observation of the same value. Since in the
360 deep sea there is generally little variability, this kind of test is performed for flagging suspicious data
361 which it cannot be considered necessarily bad in this specific case.

362 **Sensor Tilt** (for current meter and ADCP) - Current sensors must be aligned within an expected range of
363 tilt angles to properly measure horizontal and vertical currents. For fixed-mounted sensors, as in the case
364 of seafloor observatories, significant variations in tilt are not expected, and the applicability of this test is
365 therefore limited. In this context, we examined the vertical consistency of ADCP velocity profiles (i.e.,
366 gradients along depth), which can help identify non-physical variations potentially associated with
367 instrumental issues or platform disturbances, although this approach does not represent a direct substitute
368 for tilt measurements.

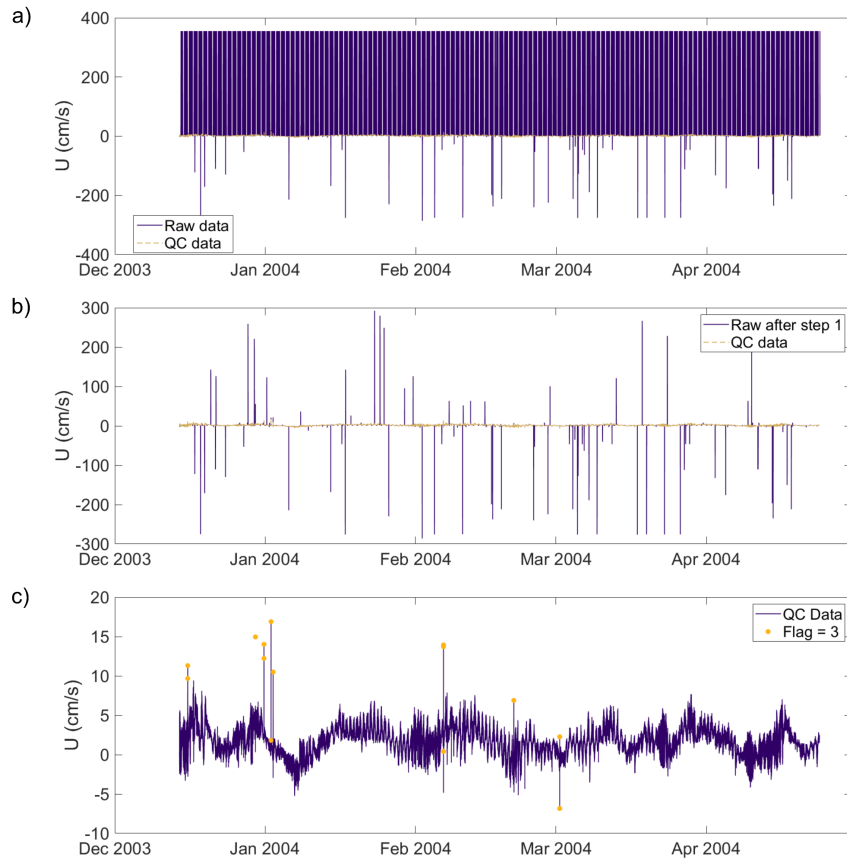
369 **Echo Intensity** (ADCP only) - If a beam reflects off a boundary, then the echo intensity increases from
370 the previous bin. The test checks for echo intensities that may indicate interaction with the surface,
371 bottom, or in-water structures.

372 **Current gradient** (ADCP only) - The current speed is expected to change at a gradual rate with depth.
373 This test checks for excessive current speed/direction changes in the vertical profile.

374 An example of the QC procedure is shown in Fig. 5, using the eastward velocity component measured by
375 the punctual current meter on GEOSTAR-SN3 during the 2003–2004 mission. The raw data initially
376 contained numerous spikes, out-of-range values, and outliers, making interpretation difficult (Fig. 5a).
377 Applying only the out-of-range test significantly improved data clarity (Fig. 5b) and completing the full
378 QC process resulted in a clean and accurate representation of the eastward velocity component (Fig. 5c).
379 All tests were conducted within the valid measurement range for the instrument, as specified in Table 4.
380 These QC procedures, excluding the tilt test, were also applied to CTD probes, turbidimeters, and
381 transmissometers. For CTD data, derived quantities were calculated using the international TEOS-10
382 (*Thermodynamic Equation of SeaWater, 2010*) subroutines (McDougall and Barker, 2011), including in-
383 situ salinity (S, PSU), absolute salinity (SA, g/kg), conservative temperature (CT, °C), potential
384 temperature (θ , °C), and in-situ density (ρ , kg/m³).

385 For dissolved oxygen measurements, the same QC procedures were used, with a modified rate-of-change
386 test to account for the dynamic nature of oxygen in the marine environment (Fusi et al.2023).

387 The ADCP measurements required a slightly different approach compared to the other sensors due to
388 their operational differences. Figure 6 shows an example of the QC steps applied to the velocity magnitude
389 measured by the ADCP mounted on SN3 observatory during the 2003-2004 acquisition campaign.



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Figure 5: Quality control procedure applied to the eastward velocity component measured by the punctual current meter at GEOSTAR-SN3 (2003–2004). (a) Raw data showing outliers; (b) intermediate results after range and spike tests; (c) final cleaned dataset after applying full QC protocol.

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This sensor measures indirectly current time series across various depth ranges, up to ~ 20 m from the top of the observatory. Consequently, visual inspection of the raw dataset is more difficult to interpret, as can be seen in Fig. 6(a), noisy data is not immediately evident in the raw data. The two panels of Fig. 6(a) have been limited to a single month to better highlight the differences between the raw and the quality checked data, particularly in the upper ranges where the measurements are noisier due to greater signal dispersion. Figure 6(b) displays detailed data extracted from two different depths at 5.33 and 20.33 m above the sensor, highlighting more clearly the effects of the QC procedures. Each depth range is tested for ranges, spikes, outliers, flat lines, and tilt, like the other sensors. Additionally, the rate of change in the vertical direction, the percentage of data acquired using three or more beams, echo intensities to account for spurious ping interactions, and the velocity error range are also evaluated.

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Table 4: Statistical parameters computed for time series from all observatories, including sensor type and campaign details.

Observatory name	Acquisition campaign	Sensor	Variable	Minimum	Maximum	Mean	Standard deviation
NEMO-SN1	2002-2003	CTD	T (°C)	13,71	13,77	13,75	0,01
			C (S/m)	4,648	4,656	4,652	0,001
			Depth (dbar)	2102,8	2110,7	2109,7	1,8
		Current meter	U (cm/s)	-17,7	10,8	-2	1,9
			V (cm/s)	-5,2	24	7,8	3
			W (cm/s)	-12,5	20,2	-0,6	1
	2012-2013	CTD	T (°C)	13,74	13,82	13,76	0,02
			C (S/m)	4,656	4,665	4,658	0,002
			Depth (dbar)	2060,1	2060,8	2060,5	0,1
		Current meter	U (cm/s)	-12,1	8,9	-1,4	1,4
			V (cm/s)	-15,9	7,1	-3	1,9
			W (cm/s)	-7,4	7,8	0,5	0,6
		ADCP	U (cm/s)	-19,9	20	-2	3
			V (cm/s)	-19,9	20	-4,1	3,4
			W (cm/s)	-19,7	17,9	-0,3	1,1
			Echo average (cnt)	43	130,4	51,6	3,1
GEOSTAR-SN3	2003-2004	CTD	T (°C)	13,52	13,61	13,54	0
			C (S/m)	4,631	4,697	4,681	0,007
			Depth (dbar)	3401,2	3401,9	3401,6	0,1
		Transmissometer	Beam attenuation (m ⁻¹)	0,344	0,398	0,363	0,015
		Current meter	U (cm/s)	-6,8	16,9	1,7	1,6
			V (cm/s)	-13,2	14,4	2,3	1,8
			W (cm/s)	-18,3	15,8	-0,9	1,3
		ADCP	U (cm/s)	-27,4	28,6	-1,6	4,6
			V (cm/s)	-29,9	23,3	0,1	2,5
			W (cm/s)	-23,4	7,4	-0,7	0,7
			Echo average (cnt)	43,2	59,8	44,1	0,6
	2004-2005	CTD	T (°C)	13,53	13,55	13,54	0,01
			C (S/m)	4,661	4,671	4,666	0,003
			Depth (dbar)	3401,2	3401,9	3401,6	0,1
		Transmissometer	Beam attenuation (m ⁻¹)	-0,072	0,008	-0,051	0,02
		Current meter	U (cm/s)	-15,9	16,4	1,2	1,4
			V (cm/s)	-15,9	19,8	2,3	1,7
			W (cm/s)	-17,2	15,4	-1,3	1
		ADCP	U (cm/s)	-19,4	19,9	0,4	3,2
			V (cm/s)	-19,5	20	-0,8	0,6
			W (cm/s)	-8,7	9,1	-0,7	0,6
			Echo average (cnt)	42,6	45,3	43,5	0,3

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Observatory name	Acquisition campaign	Sensor	Variable	Minimum	Maximum	Mean	Standard deviation
GEOSTAR	2007-2008	CTD	T (°C)	2,44	2,68	2,58	0,04
			C (S/m)	3,244	3,267	3,258	0,004
			Depth (dbar)	3254,3	3257,8	3256	0,8
		Turbidimeter	Turbidity (NTU)	-0,095	0,631	-0,017	0,037
		Current meter	U (cm/s)	-18,3	10,2	-0,3	2,2
			V (cm/s)	-15,7	17,3	-2	2,6
			W (cm/s)	-9,1	14,9	-0,6	0,7
		ADCP	U (cm/s)	-29,1	28,1	-0,7	3,7
			V (cm/s)	-29,2	28,9	-1,7	3,6
			W (cm/s)	-9,1	10,6	-0,4	0,5
			Echo average (cnt)	44,6	49,1	46,3	1
	2009-2010	CTD	T (°C)	2,48	2,67	2,61	0,03
			C (S/m)	3,246	3,264	3,258	0,003
			Depth (dbar)	3227,6	3231,3	3229,4	0,8
		Turbidimeter	Turbidity (NTU)	-0,076	0,543	-0,023	0,039
		Current meter	U (cm/s)	-9	11,3	0,1	0,6
			V (cm/s)	-11,3	10	-0,6	0,5
			W (cm/s)	-12,4	19,1	0	0,2
		ADCP	U (cm/s)	-29,6	28,5	-0,8	4,1
			V (cm/s)	-29	29,8	0,1	3,7
			W (cm/s)	-8,1	11,7	-0,5	0,5
			Echo average (cnt)	44,7	52,3	47,1	1,6
SN4	2009-2010	CTD	T (°C)	14,42	15,83	14,66	0,15
			C (S/m)	4,637	4,798	4,665	0,017
			Depth (dbar)	166,5	167,2	166,9	0,1
		Turbidimeter	Turbidity (NTU)	0,923	48,398	3,719	4,083
		Current meter	U (cm/s)	-39,4	26,6	-1,5	4,4
			V (cm/s)	-29,1	25,3	-0,4	2,3
			W (cm/s)	-29	11,9	-0,4	1,3
		Oxygen	DO (μmol/l)	5,1	103,1	39,1	9,2
	2013-2014	CTD	T (°C)	14,49	15,76	14,81	0,16
			C (S/m)	4,647	4,791	4,685	0,018
			Depth (dbar)	167,1	167,6	167,3	0,1
		Turbidimeter	Turbidity (NTU)	0,712	82,346	4,447	7,433
		Current meter	U (cm/s)	-30,9	6,2	-1,4	3,7
			V (cm/s)	-15,7	9,4	0,2	2,1
			W (cm/s)	-1,6	4,9	0,3	0,6

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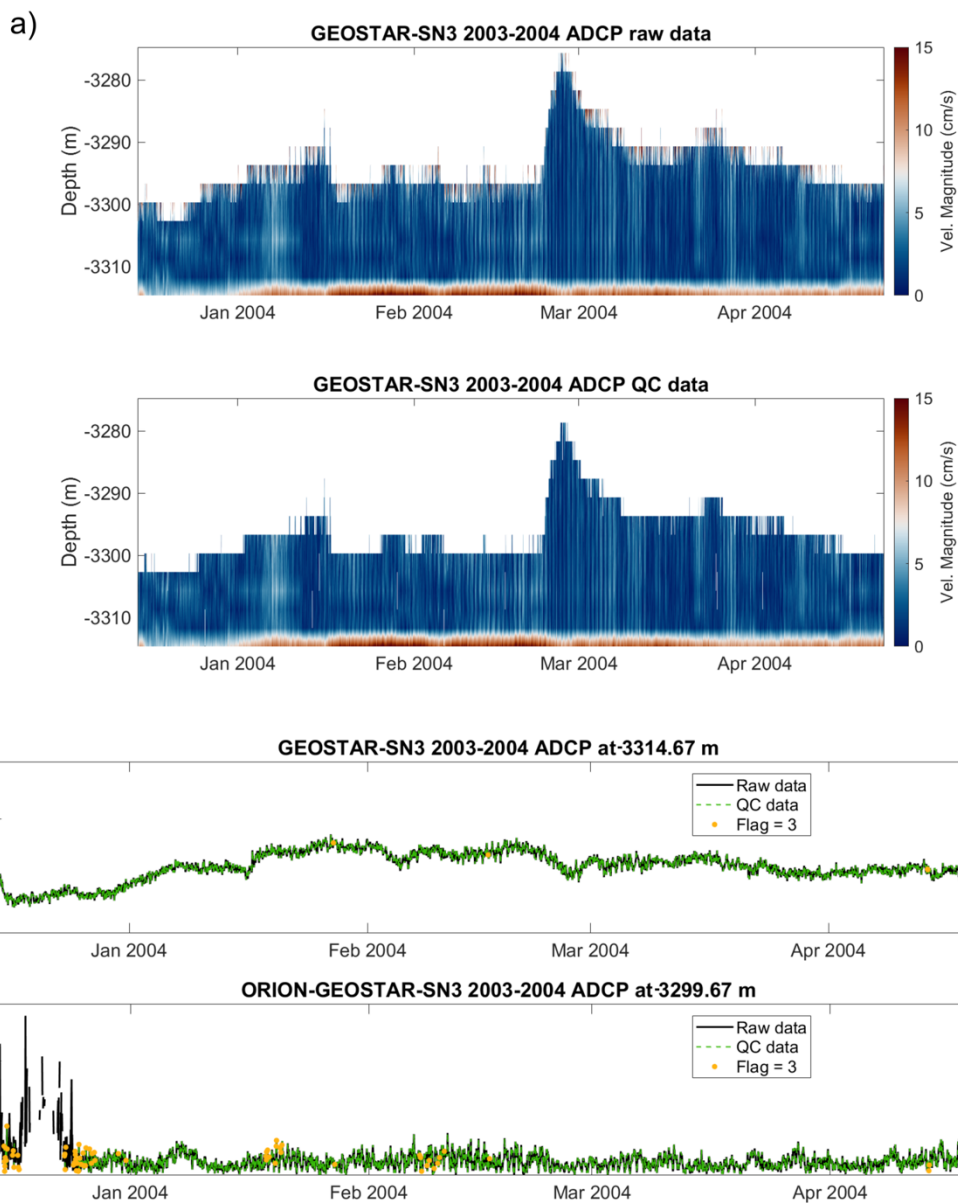


Figure 6: Quality control of ADCP velocity magnitude data at GEOSTAR-SN3 (2003–2004). (a) Color map of current magnitude across depth: top panel = raw data; bottom = QC-checked. (b) Time series from two depth bins: range 5.33 m corresponding to -3314.67 m depth (on the top panel), and range 20.33 m corresponding to -3299.67 m (bottom panel). Black = raw data, green = quality-checked data, yellow = flagged.

4 Results

Although the acquired datasets pertain to several EOVs, the results reported here primarily concern temperature data, intending to provide some benchmarks of the deep layer state over the last decade across the Mediterranean Sea, from the Sea of Marmara to the Cádiz area. After post-processing a QC validation routine has been performed, potential temperature (θ) and density anomaly (σ_{2000} , calculated with reference pressure of 2000 dbar) data derived following TEOS-10 international standards (<https://teos-10.org/>), exhibit interesting variability at all sea-bottom sites monitored during these years (Fig. 7).

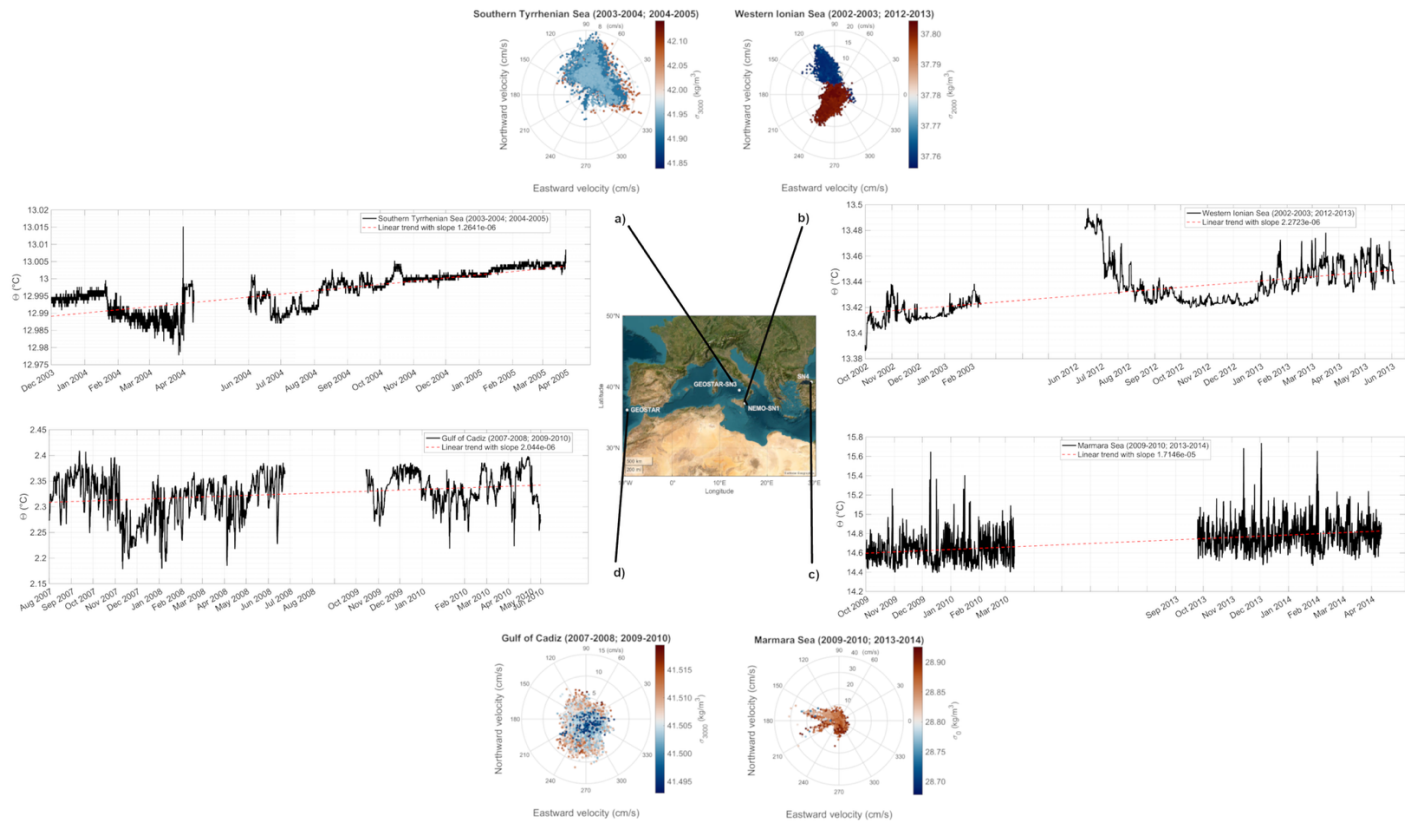


Figure 7: Potential temperature time series and corresponding current hodographs, along with potential density anomalies (calculated relative to in situ pressure), reveal a warming trend and variability observed between 2001 and 2013 in the Tyrrhenian Sea (a), the Ionian Sea (b), the Marmara Sea (c), and the Gulf of Cádiz (d) across the Mediterranean region (map at the center created with Google Earth).

While the available time series are relatively short for each site and might therefore reflect regional or decadal variability, all temperature trends measured between 2001 and 2013 at all deep layers are coherently positive and broadly consistent with the warming patterns reported in the literature (IPCC, 2013). Although the statistical weight varies among sites depending on the length of the observation period, the annual rate of temperature increase, calculated for all datasets using least-squares linear fits to hourly measurements, remains within the same order of magnitude, ranging from $+0.011\text{ }^{\circ}\text{C year}^{-1}$ in the Tyrrhenian Sea to $+0.018\text{ }^{\circ}\text{C year}^{-1}$ in the Gulf of Cadiz and $+0.047\text{ }^{\circ}\text{C year}^{-1}$ in the Ionian Sea. The higher value observed in the Ionian Sea reflects the fact that it was derived from two time series collected a decade apart, providing a coherent and reliable estimate of a decadal-scale warming process. The only exception is the Marmara Sea, where the rate is an order of magnitude higher ($+0.15\text{ }^{\circ}\text{C year}^{-1}$), likely due to its shallower depth (166 m).

At all sites, temperature data reveal notable internal variability, but the recorded variations are not directly comparable as they result from differences in monitoring periods and local characteristics; therefore, they have to be assessed on a case-by-case basis. In the NEMO-SN1 case in the Ionian Sea, the variability observed over one decade does not represent a simple warming signal but rather a real change in deep water masses. (*Malanotte-Rizzoli et al., 1999; Hainbucher et al., 2006; Artale et al. 2018*). This is evident looking at the current hodograph, also showing potential density anomaly (σ_{2000}), where velocities are found to be oriented toward NW with a mean potential density anomaly of 37.86 kg/m^3 on the period 2001-2002, while they are oriented toward SW with a mean potential density anomaly of 37.9 kg/m^3 for the other period 2012-2013 (Fig. 7b). In ten years, it reveals a change of $\Delta\sigma^2 = 0.05\text{ kg/m}^3$, which is four times bigger than the usual range of inter-annual variability expected at these depths in the Ionian bottom water (*Hainbucher et al., 2006; Artale et al. 2018*). Along with changes in thermohaline properties, the current hodograph for the Ionian Sea also reveals a clear shift in the direction of prevailing currents (*Giambenedetti et al., 2024*), offering a rare snapshot of water mass redistribution. This shift may be attributed to the alternating advection of dense water masses that the Ionian basin receives from the Adriatic or Aegean Sea, which could sustain the better-known decadal reversals (BIOS) occurring in the upper-layer circulation (*Gacic et al., 2010*). This is an example of how the variability of the deep layer, generally assumed to be a stationary state environment, can instead feed internal processes impacting properties of the water masses and circulation dynamics.

Despite their scientific importance, deep-ocean time series remain sparse in both time and space. Therefore, developing techniques to handle data gaps and maximize the information content of existing records is essential. All time series here reported contain missing data, with gap lengths varying according to maintenance needs, technological refurbishments, or ship availability. To address these discontinuities, a combination of Singular Spectrum Analysis (SSA) and Optimal Interpolation (OI) was applied to

selected time-series (Fig. 8). Given the relatively short duration of the records and the presence of substantial gaps, a rigorous assessment of reconstruction accuracy is not feasible. The SSA/OI approach was therefore not intended to provide a quantitatively validated reconstruction, but rather to obtain a continuous time series suitable for estimating large-scale, low-frequency variability and associated trends. SSA is a fully data-driven, nonparametric method particularly suitable for time series with relatively long and continuous gaps. It does not require a priori assumptions on a predefined model that might introduce artificial oscillations in the variability, although it still requires methodological choices (*Ghil et al., 2002; Kondrashov and Ghil, 2006; Beckers and Rixen, 2003*). The approach involves two main steps: (i) SSA extracts the dominant deterministic components, such as trends, seasonal and tidal oscillations, and low-frequency variability, providing a continuous background estimate across missing intervals; and (ii) OI is then applied to the detrended and SSA-backgrounded residuals, optimally merging observed data with the reconstructed background field based on their covariance structure.

This SSA–OI approach combines the signal reconstruction capability of SSA with the statistical optimality of OI, effectively filling both short and long gaps while preserving the realistic variance and autocorrelation structure of the original record. Missing segments were reconstructed by identifying and interpolating the dominant modes (6 mode) selected based on the fraction of explained variance, retaining the leading components that capture the associated physical oceanographic variability (*Marullo et al., 2011*). This approach aims to maintain the temporal coherence and dynamical consistency of the reconstructed time series. Beyond data reconstruction, this approach enhances the performance of subsequent analyses, such as Power Spectral Density (PSD) estimation.

Figure 8 presents the reconstructed temperature time series (left part), and their corresponding power spectra (right part). The comparison between the time-domain and frequency-domain representations helps to interpret the nature of the observed variability.

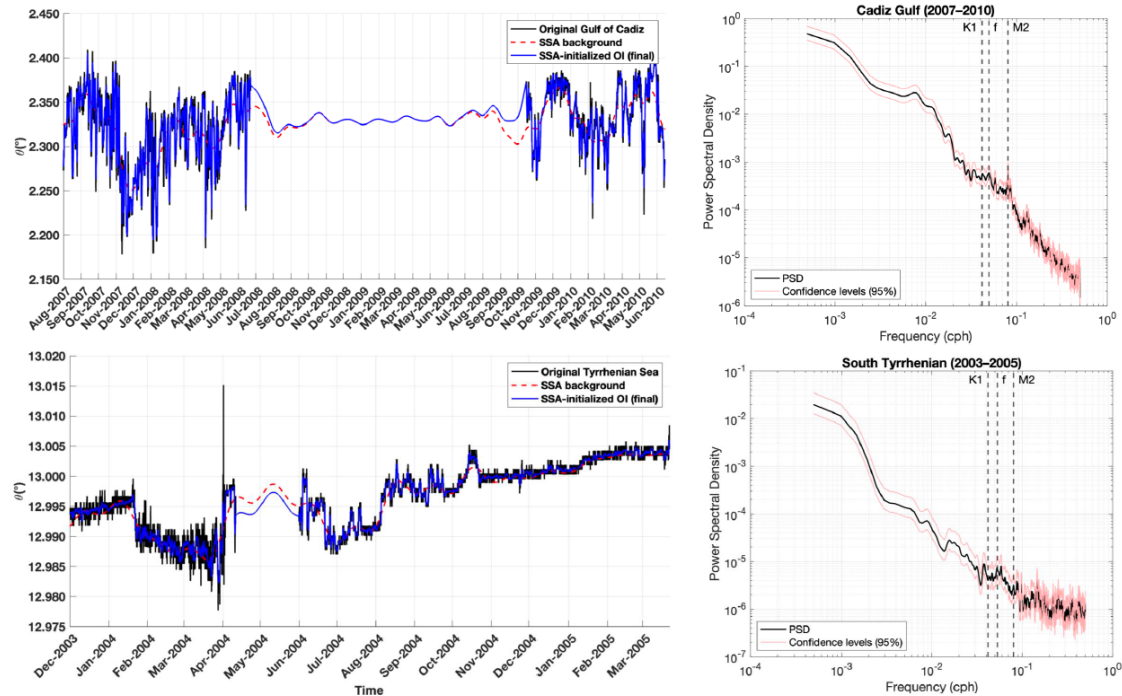


Figure 8. Time series from the Gulf of Cádiz (upper left) and the Tyrrhenian Sea (lower left) showing original data with gaps (black), SSA-based background estimation (red dashed line), and the reconstructed signal (blue line). Corresponding spectra (upper and lower right) highlight dominant low-frequency energy, indicating slow, persistent variability associated with long-term warming recorded.

In both sites, the reconstructed series exhibit a gradual low-frequency warming signal, which is reflected in the spectra by the concentration of variance at low frequencies, consistent with slow and persistent deep-water changes. The spectral estimates are further supported by the 95% confidence limits, within which the main spectral features are contained. In addition, peaks are visible near the K1 (lunisolar diurnal) and M2 (lunar semidiurnal) tidal frequencies, and near the local inertial frequency f , generated by the Coriolis effect. These higher-frequency components, although weaker than the low-frequency signal, indicate that tidal and inertial dynamics remain active in the deep ocean and may influence the redistribution of heat.

5 Data availability

The datasets described in this study can be accessed through the Multidisciplinary Oceanic Information SysTem (MOIST, <https://doi.org/10.13127/MD/MOIST>, Azzarone *et al.*, 2010) and via the INGV

ERDDAP server (<http://oceano.bo.ingv.it/erddap/index.html>), (Table 5 in Appendix A provides the complete references for each dataset.). Data and metadata have been formatted into NetCDF (Network Common Data Form) and comply with Climate and Forecasting (CF) metadata conventions. These specifications are also aligned with OceanSITES and SeaDataNet vocabularies, ensuring semantic clarity, long-term interoperability, and machine-readability. Domain-specific metadata attributes are harmonized using the NERC Vocabulary Server (NVS), which provides authoritative controlled vocabularies for parameter descriptions, units, and semantic consistency across datasets. Organizational identifiers follow the European Directory of Marine Organisations (EDMO) and the Research Organization Registry (ROR), and SPDX is used for licensing. In line with the INGV Data Policy, all datasets are released under a Creative Commons Attribution 4.0 International License (CC BY 4.0), allowing free use with appropriate citation. To be fully compliant with FAIR principles, each dataset is registered and assigned a Digital Object Identifier (DOI) through the INGV Data Registry (<https://data.ingv.it/>), acknowledging the efforts of those who contributed to generating the data and products and assuring data availability in further scientific publications. Multiple datasets are available, each corresponding to a specific observatory and mission. A comprehensive summary, including DOIs and citation formats, is available on the MOIST portal for each dataset.

6 Conclusions and Perspectives

The implementation of harmonized post-processing and quality control (QC) procedures for deep-sea data is a key step toward expanding the availability of reliable, high-quality oceanographic observations from the least sampled regions of the global ocean. Standardizing these methods ensures data accuracy and consistency while enabling the effective use and sharing of information essential to understanding deep-sea variability, still among the most poorly characterized components of the climate system. Beyond data collection, the application of advanced analytical methods proposed in this study minimizes spectral leakage and enhances the reliability of frequency-domain diagnostics, enabling a more accurate characterization of dominant variability modes and periodic signals. Furthermore, the reconstruction of longer and more continuous records increases the resolution and robustness of spectral estimates, allowing a deeper and more comprehensive interpretation of the frequencies associated with the observed oceanographic processes.

Strengthening and extending the deep-ocean observational network, particularly in under-sampled regions, remains essential to improve both regional process understanding and global climate modeling. By promoting open access and adherence to FAIR data principles, this effort contributes to the goals of

542 the UN Decade of Ocean Science, supporting the development of a more integrated, sustainable, and
543 climate-relevant deep-ocean observing framework.

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569 **Appendix A**

570 **Table 5: Summary of all datasets discussed in the paper, including their DOIs and corresponding citations**

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Observatory Name and acquisition period	Sensor type	Citation to add in the references
NEMO-SN1 (2002-2003)	CTD	Favali P., Beranzoli L., Etiope G., Marinaro G., Giambenedetti B., Lo Bue N.. CTD dataset with Quality Control (SBE 37-SM @ 1 sample / 12 min) from INGV/NEMO-SN1 seafloor platform during GNDT-SN1 project in Western Ionian Sea site (East Sicily), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/wis-sn1-2002-ctd-qc , 2024
	Current meter	Favali P., Beranzoli L., Etiope G., Marinaro G., Lo Bue N., Giambenedetti B.. Current meter dataset with Quality Control (FSI 3D-ACM @ 2 Hz) from INGV/SN1 seafloor platform during GNDT-SN1 project in Western Ionian Sea site (East Sicily), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/wis-sn1-2002-curr-qc , 2024
NEMO-SN1 (2012-2013)	CTD	Embricco D., Marinaro G., Giovanetti G., Lo Bue N., Giambenedetti B.. CTD dataset with Quality Control (SBE 37-SM @ 1 sample / hour) from INGV/NEMO-SN1 seafloor platform during SMO project in Western Ionian Sea site (East Sicily), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/wis-sn1-2012-ctd-qc , 2023
	Current meter	Giovanetti G., Marinaro G., Embricco D., Lo Bue N., Giambenedetti B.. Current meter dataset with Quality Control (Nobska MAVS-3 @ 2 Hz) from INGV/NEMO-SN1 seafloor platform during SMO project in Western Ionian Sea site (East Sicily), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/wis-sn1-2012-current_meter-qc , 2023
	ADCP	Giovanetti G., Marinaro G., Embricco D., Lo Bue N., Giambenedetti B.. ADCP dataset with Quality Control (RDI WorkHorse 600 KHz @ 2 profile / hour) from INGV/NEMO-SN1 seafloor platform during SMO project in Western Ionian Sea site (East Sicily), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/wis-sn1-2012-adcp-qc , 2023
GEOSTAR SN3 (2003-2004)	CTD	Favali P., Beranzoli L., Etiope G., Marinaro G., Lo Bue N., Giambenedetti B. (2024). CTD dataset with Quality Control (SBE 16 @ 1 sample / hour) from INGV/GEOSTAR - SN-3 seafloor platform during ORION-GEOSTAR3 project in Southern Tyrrhenian Sea site (Marsili Basin), ORION1 campaign. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/sts-geostar-2003-ctd-qc , 2024
	Transmissometer	Favali P., Beranzoli L., Etiope G., Marinaro G., Lo Bue N., Giambenedetti B.. Transmissometer dataset with Quality Control (Ctg Alphatracka II @ 1 sample / hour) from INGV/GEOSTAR - SN-3 seafloor platform during ORION-GEOSTAR3 project in Southern Tyrrhenian Sea site (Marsili Basin), part of ORION network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/sts-geostar-2003-transm-qc
	Current meter	Favali P., Beranzoli L., Etiope G., Marinaro G., Lo Bue N., Giambenedetti B.. Current meter dataset with Quality Control (FSI 3D-ACM @ 2 Hz) from INGV/GEOSTAR - SN-3 seafloor platform during ORION-GEOSTAR3 project in Southern Tyrrhenian Sea site (Marsili Basin), part of ORION network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/sts-geostar-2003-curr-qc , 2024
	ADCP	Favali P., Beranzoli L., Etiope G., Marinaro G., Lo Bue N., Giambenedetti B.. ADCP dataset with Quality Control (RDI WorkHorse 300 kHz @ 1 sample / hour) from INGV/GEOSTAR - SN-3 seafloor platform during ORION-GEOSTAR3 project in Southern Tyrrhenian Sea site (Marsili Basin), part of ORION network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/sts-geostar-2003-adcp-qc , 2024
GEOSTAR SN3 (2004-2005)	CTD	Favali P., Beranzoli L., Etiope G., Marinaro G., Lo Bue N., Giambenedetti B.. CTD dataset with Quality Control (SBE 16 @ 1 sample / hour) from INGV/GEOSTAR - SN-3 seafloor platform during ORION-GEOSTAR3 project in Southern Tyrrhenian Sea site (Marsili Basin), ORION2 campaign. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/sts-geostar-2004-ctd-qc , 2024
	Transmissometer	Favali P., Beranzoli L., Etiope G., Marinaro G., Lo Bue N., Giambenedetti B.. Transmissometer dataset (alphatracka II @ 1 sample / hour) from INGV/GEOSTAR - SN-3 seafloor platform during ORION-GEOSTAR3 project in Southern Tyrrhenian Sea site (Marsili Basin), part of ORION network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/sts-geostar-2004-transm-qc , 2024
	Current meter	Favali P., Beranzoli L., Etiope G., Marinaro G., Lo Bue N., Giambenedetti B.. Current meter dataset with Quality Control (FSI 3D-ACM @ 2 Hz) from INGV/GEOSTAR - SN-3 seafloor platform during ORION-GEOSTAR3 project in Southern Tyrrhenian Sea site (Marsili Basin), part of ORION network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/sts-geostar-2004-curr-qc , 2024
	ADCP	Favali P., Beranzoli L., Etiope G., Marinaro G., Lo Bue N., Giambenedetti B.. ADCP dataset with Quality Control (RDI WorkHorse 300 KHz @ 1 profile / hour) from INGV/GEOSTAR - SN-3 seafloor platform during ORION-GEOSTAR3 project in Southern Tyrrhenian Sea site (Marsili Basin), part of ORION network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/sts-geostar-2004-adcp , 2024

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GEOSTAR (2007-2008)	CTD	Lo Bue N., Giambenedetti B.. CTD dataset with Quality Control (SBE 16plus @ 1 sample / hour) from INGV/GEOSTAR seafloor platform during NEAREST project in Iberian Margin site (Gulf of Cadiz), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/im-geostar-2007-ctd-qc , 2023
	Turbidity meter	Marinaro G., Embriaco D., Lo Bue N., Giambenedetti B.. Turbidity meter dataset with Quality Control (ECO-BB(RT)D 6000m @ 1 sample / hour) from INGV/GEOSTAR seafloor platform during NEAREST project in Iberian Margin site (Gulf of Cadiz), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/im-geostar-2007-turb-qc , 2023
	Current meter	Marinaro G., Embriaco D., Lo Bue N., Giambenedetti B.. Current meter dataset with Quality Control (Nobska MAVS-3 @ 5 Hz) from INGV/GEOSTAR seafloor platform during NEAREST project in Iberian Margin site (Gulf of Cadiz), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/im-geostar-2007-curr-qc , 2023
	ADCP	Marinaro G., Embriaco D., Lo Bue N., Giambenedetti B.. ADCP dataset with Quality Control (RDI WorkHorse 300 kHz @ 1 profile / hour) from INGV/GEOSTAR seafloor platform during NEAREST project in Iberian Margin site (Gulf of Cadiz), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/im-geostar-2007-adcp-qc , 2023
GEOSTAR (2009-2010)	CTD	Embriaco D., Marinaro G., Lo Bue N., Giambenedetti B.. CTD dataset with Quality Control (SBE 16plus @ 1 sample / hour) from INGV/GEOSTAR seafloor platform during Esonet NoE project in Iberian Margin site (Gulf of Cadiz), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/im-geostar-2009-ctd-qc , 2023
	Turbidity meter	Embriaco D., Marinaro G., Lo Bue N., Giambenedetti B.. CTD dataset with Quality Control (SBE 16plus @ 1 sample / hour) from INGV/GEOSTAR seafloor platform during Esonet NoE project in Iberian Margin site (Gulf of Cadiz), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/im-geostar-2009-ctd-qc , 2023
	Current meter	Embriaco D., Marinaro G., Lo Bue N., Giambenedetti B.. Current meter dataset with Quality Control (Nobska MAVS-3 @ 5 Hz) from INGV/GEOSTAR seafloor platform during Esonet NoE project in Iberian Margin site (Gulf of Cadiz), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/im-geostar-2009-curr-qc , 2023
	ADCP	Embriaco D., Marinaro G., Lo Bue N., Giambenedetti B.. ADCP dataset with Quality Control (RDI WorkHorse 300 kHz @ 1 sample / hour) from INGV/GEOSTAR seafloor platform during ESONET-NOE-LIDO project in Iberian Margin site (Gulf of Cadiz), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/im-geostar-2009-adcp-qc , 2023
SN4 (2009-2010)	CTD	Marinaro G., Embriaco D., Lo Bue N., Giambenedetti B.. CTD dataset with Quality Control (SBE 16plus @ 1 sample / 10 min) from INGV/SN-4 seafloor platform during ESONET-MARMARA-DM project in Mamara Sea site (Mamara Sea), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/mar-sn4-2009-ctd-qc , 2024
	Turbidity meter	Marinaro G., Embriaco D., Lo Bue N., Giambenedetti B.. Turbidity meter dataset with Quality Control (ECO-NTU(RT)D 6000m @ 1 sample / 10 min) from INGV/SN-4 seafloor platform during ESONET-MARMARA-DM project in Mamara Sea site (Mamara Sea), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/mar-sn4-2009-turb-qc , 2024
	Current meter	Marinaro G., Embriaco D., Lo Bue N., Giambenedetti B.. Current meter dataset with Quality Control (Nobska MAVS-3 @ 5 Hz) from INGV/SN-4 seafloor platform during ESONET-MARMARA-DM project in Mamara Sea site (Mamara Sea), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/mar-sn4-2009-curr-qc , 2024
	Oxygen	Marinaro G., Lo Bue N., Giambenedetti B.. Oxygen meter dataset with Quality Control (AADI Optode 3830 @ 1 Hz) from INGV/SN-4 seafloor platform during ESONET-MARMARA-DM project in Mamara Sea site (Mamara Sea), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/ms-sn4-2009-oxygen_meter-qc , 2024
SN4 (2013-2014)	CTD	Marinaro G., Embriaco D., Lo Bue N., Giambenedetti B.. CTD dataset with Quality Control (SBE 16plus @ 1 sample / hour) from INGV/SN-4 seafloor platform during MARSITE 1 project in Mamara Sea site (Mamara Sea), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/mar-sn4-2013-ctd-qc , 2024
	Turbidity meter	Marinaro G., Embriaco D., Lo Bue N., Giambenedetti B.. Turbidity meter dataset with Quality Control (ECO-NTU(RT)D 6000m @ 1 sample / 10 min) from INGV/SN-4 seafloor platform during MARSITE 1 project in Mamara Sea site (Mamara Sea), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/mar-sn4-2013-turb-qc , 2024
	Current meter	Marinaro G., Embriaco D., Lo Bue N., Giambenedetti B.. Current meter dataset with Quality Control (Nobska MAVS-3 @ 5 Hz) from INGV/SN-4 seafloor platform during MARSITE 1 project in Mamara Sea site (Mamara Sea), part of EMSO network. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/md/mar-sn4-2013-curr-qc , 2024

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References

1. **Alves, J. M. R., Carton, X., and Ambar, I.** (2011): Hydrological structure, circulation and water mass transport in the Gulf of Cadiz, *Int. J. Geosci.*, **2**, 432–456, <https://doi.org/10.4236/ijg.2011.24047>.
2. **Artale, V., et al.** (2018): Linking mixing processes and climate variability to the heat content distribution of the Eastern Mediterranean abyss, *Sci. Rep.*, **8**, 11317, <https://doi.org/10.1038/s41598-018-29343-4>.
3. **Azzarone, A., Marcucci, N. M., & Marinaro, G.** (2010). Multidisciplinary Oceanic Information SysTem (MOIST). Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/MD/MOIST>
4. **Beckers, J. M. and Rixen, M.** (2003): EOF calculations and data filling from incomplete oceanographic datasets, *J. Atmos. Oceanic Technol.*, **20**, 1839–1856, [https://doi.org/10.1175/1520-0426\(2003\)020<1839:ECADFF>2.0.CO;2](https://doi.org/10.1175/1520-0426(2003)020<1839:ECADFF>2.0.CO;2).
5. **Beranzoli, L., De Santis, A., Etiope, G., Favali, P., Frugoni, F., Smriglio, G., Gasparoni, F., and Marigo, A.** (1998): GEOSTAR: a geophysical and oceanographic station for abyssal research, *Phys. Earth Planet. Inter.*, **108**, 175–183, [https://doi.org/10.1016/S0031-9201\(98\)00094-6](https://doi.org/10.1016/S0031-9201(98)00094-6).
6. **Beranzoli, L., De Santis, A., Calcara, M., Cifardini, A., et al.** (2009): Multiparametric seafloor exploration: the Marsili Basin and volcanic seamount case (Tyrrhenian Sea, Italy), in: *Proc. 3rd IASME/WSEAS Int. Conf. Geology and Seismology (GES'09)*, WSEAS Press.
7. **Budillon, G., Lo Bue, N., Siena, G., and Spezie, G.** (2010): Hydrographic characteristics of water masses and circulation in the Northern Ionian Sea, *Deep Sea Res. II*, **57**, 441–457, <https://doi.org/10.1016/j.dsr2.2009.08.017>.
8. **Bushnell, M., Waldmann, C., Seitz, S., Buckley, E., Tamburri, M., Hermes, J., et al.** (2019): Quality assurance of oceanographic observations: standards and guidance adopted by an international partnership, *Front. Mar. Sci.*, **6**, 706, <https://doi.org/10.3389/fmars.2019.00706>.
9. **Chiggiato J., V. Artale, X. Durrieu de Madron, K. Schroeder, I. Taupier-Letage, D. Velaoras, M. Vargas-Yáñez** (2023) Chapter 9 – Recent changes in the Mediterranean Sea, Editor(s): Katrin Schroeder, Jacopo Chiggiato,

- Oceanography of the Mediterranean Sea, Elsevier, 2023, Pages 289-334, ISBN 9780128236925, <https://doi.org/10.1016/B978-0-12-823692-5.00008-X>
10. **de Lavergne, C., Madec, G., Capet, X., et al.** (2016): Getting to the bottom of the ocean, *Nat. Geosci.*, **9**, 857–858, <https://doi.org/10.1038/ngeo2850>.
 11. **Desbruyères, D. G., Purkey, S. G., McDonagh, E. L., Johnson, G. C., and King, B. A.** (2016): Deep and abyssal ocean warming from 35 years of repeat hydrography, *Geophys. Res. Lett.*, **43**, 10356–10365, <https://doi.org/10.1002/2016GL070413>.
 12. **Embriaco, D., Marinaro, G., Frugoni, F., Monna, S., et al.** (2014): Monitoring of gas and seismic energy release along the North Anatolian Fault (Sea of Marmara, NW Turkey), *Geophys. J. Int.*, **196**, 850–866.
 13. **Favali, P., Beranzoli, L., D’Anna, G., Gasparoni, F., et al.** (2006): NEMO-SN-1: the first real-time seafloor observatory of ESONET, *Nucl. Instrum. Methods Phys. Res. A*, **567**, 462–467.
 14. **Favali, P., Beranzoli, L., D’Anna, G., Gasparoni, F., et al.** (2009): A fleet of multiparameter observatories for geophysical and environmental monitoring at seafloor, *Ann. Geophys.*, **49**.
 15. **Favali, P., Beranzoli, L., Italiano, F., Migneco, E., et al.** (2011): NEMO-SN1 developments in view of the EMSO and KM3Net infrastructures, *Nucl. Instrum. Methods Phys. Res. A*, **626–627**, S53–S56.
 16. **Favali, P., Chierici, F., Marinaro, G., Giovanetti, G., et al.** (2013): NEMO-SN1 cabled observatory in the Western Ionian Sea, *IEEE J. Oceanic Eng.*, **38**, 358–374.
 17. **Ferrari, R., Mashayek, A., McDougall, T. J., Nikurashin, M., et al.** (2016): Turning ocean mixing upside down, *J. Phys. Oceanogr.*, **46**, 23.
 18. **Fuda J.-L., Font J., García Lafuente J., Gasparini G.P., Millot C. and Others** (2007). Hydrochanges: first results and perspectives. *Rapp. Comm. Int. Médit.* **38**, p. 27
 19. **Gačić, M., Borzelli, G. E., Civitarese, G., Cardin, V., et al.** (2010): Can internal processes sustain reversals of ocean upper circulation? The Ionian Sea example, *Geophys. Res. Lett.*, **37**, L09608, <https://doi.org/10.1029/2010GL043216>.
 20. **García-Lafuente, J., Delgado, J., Criado-Aldeanueva, F., Bruno, M., et al.** (2006): Water mass circulation on the continental shelf of the Gulf of Cádiz, *Deep Sea Res. II*, **53**, 1182–1197, <https://doi.org/10.1016/j.dsr2.2006.04.011>.
 21. **Giambenedetti, B., Lo Bue, N., and Artale, V.** (2024): Role of abyssal ocean stratification in potential vorticity redistribution through the water column, *Ocean Sci.*, **20**, 1209–1228, <https://doi.org/10.5194/os-20-1209-2024>.
 22. **Giovanetti, G., Monna, S., Lo Bue, N., Embriaco, D., et al.** (2016): Observing volcanoes from the seafloor in the central Mediterranean area, *Remote Sens.*, **8**, 298, <https://doi.org/10.3390/rs8040298>.
 23. **Hainbucher, D., Rubino, A., and Klein, B.** (2006): Water mass characteristics in the deep layers of the western Ionian Basin, *Geophys. Res. Lett.*, **33**, L05608, <https://doi.org/10.1029/2005GL025318>.
 24. **Heuzé, C., Purkey, S. G., and Johnson, G. C.** (2022): It is high time we monitor the deep ocean, *Environ. Res. Lett.*, **17**, 121002.
 25. **Howell, K. L., Hilário, A., Allcock, A. L., et al.** (2021): A decade to study deep-sea life, *Nat. Ecol. Evol.*, **5**, 265–267, <https://doi.org/10.1038/s41559-020-01352-5>.
 26. **IOC, SCOR, and IAPSO** (2010): The international thermodynamic equation of seawater – 2010, *Manuals and Guides*, **56**, 196 pp.
 27. **IPCC** (2013): Climate Change 2013: The Physical Science Basis, Cambridge University Press.
 28. **Kondrashov, D. and Ghil, M.** (2006): Spatio-temporal filling of missing points in geophysical data sets, *Nonlin. Processes Geophys.*, **13**, 151–159, <https://doi.org/10.5194/npg-13-151-2006>.
 29. **Lascaratos, A., Roether, W., Nittis, K., and Klein, B.** (1999): Recent changes in deep water formation and spreading in the eastern Mediterranean Sea, *Prog. Oceanogr.*, **44**, 5–36, [https://doi.org/10.1016/S0079-6611\(99\)00019-1](https://doi.org/10.1016/S0079-6611(99)00019-1).
 30. **Levin, L. A., Bett, B. J., Gates, A. R., Heimbach, P., et al.** (2019): Global observing needs in the deep ocean, *Front. Mar. Sci.*, **6**, 241, <https://doi.org/10.3389/fmars.2019.00241>.

31. **Lo Bue, N., Artale, V., and Schroeder, K.** (2021): Impact of deep oceanic processes on circulation and climate variability, *Front. Mar. Sci.*, **8**, 801479, <https://doi.org/10.3389/fmars.2021.801479>.
32. **MacDougall, T. J. and Barker, P. M.** (2011): Getting started with TEOS-10 and the GSW Oceanographic Toolbox, SCOR/IAPSO WG127, 28 pp.
33. **MacKinnon, J. A., Zhao, Z., Whalen, C. B., Waterhouse, A. F., et al.** (2017): Climate Process Team on internal wave–driven ocean mixing, *Bull. Am. Meteorol. Soc.*, **98**, 2429–2454.
34. **Malanotte-Rizzoli, P., Manca, B. B., d’Alcalà, M. R., Theocharis, A., et al.** (1997): Hydrography and circulation in the Ionian Sea during POEM-Phase I, *Prog. Oceanogr.*, **39**, 153–204.
35. **Malanotte-Rizzoli, P., Manca, B. B., d’Alcalà, M. R., Theocharis, A., et al.** (1999): The Eastern Mediterranean in the 80s and 90s: transition of intermediate and deep circulations, *Dyn. Atmos. Oceans*, **29**, 365–395.
36. **Marinaro, G., Etiope, G., Lo Bue, N., Favali, P., et al.** (2006): Monitoring of a methane-seeping pockmark by cabled benthic observatory, *Geo-Mar. Lett.*, **26**, 297–302.
37. **Munk, W.** (1966): Abyssal recipes, *Deep Sea Res.*, **13**, 707–730.
38. **Ochoa, J. and Bray, N.** (1991): Water mass exchange in the Gulf of Cádiz, *Deep Sea Res. A*, **38**, S465–S503.
39. **Polzin, K. L. and McDougall, T.** (2021): Mixing at the ocean’s bottom boundary, in: *Drivers, Mechanisms and Impacts*, Elsevier.
40. **Pouliquen, S., et al.** (2011): Recommendations for in-situ data real-time quality control.
41. **Rhein, M., Rintoul, S., Aoki, S., Campos, E., Chambers, D., Feely, R., and Wang, F.** (2013): Observations: Ocean, in *Climate Change 2013: The Physical Science Basis*, IPCC.
42. **Schroeder, K., T. Tanhua, H.L. Bryden, M. Álvarez, J. Chiggiato, and S. Aracri** (2015). Mediterranean Sea Ship-based Hydrographic Investigations Program (Med-SHIP). *Oceanography* 28(3), <http://dx.doi.org/10.5670/oceanog.2015.71>.
43. **Stommel, H. and Arons, A. B.** (1960): On the abyssal circulation of the world ocean–II, *Deep Sea Res.*, **6**, 217–233.
44. **Talley, L. D., Pickard, G. L., and Emery, W. J.** (2011): *Descriptive Physical Oceanography*, 6th ed., Academic Press.
45. **Visbeck, M.** (2018): Ocean science research is key for a sustainable future, *Nat. Commun.*, **9**, 690, <https://doi.org/10.1038/s41467-018-03158-3>.