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CARIMED (CARbon, tracers, and ancillary data In the MEDiterranean Sea): A ship-based data synthesis product – overview and quality control procedures

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Abstract. The Mediterranean Sea (MedSea) is highly sensitive to climate-driven changes in temperature, oxygen, and pH, among other variables. To better assess these long-term trends, we developed CARIMED (CARbon, tracers, and ancillary data In the MEDiterranean Sea), the first comprehensive, harmonised data synthesis product for the MedSea. CARIMED integrates hydrographic, inorganic carbon, transient tracer, and ancillary measurements from 46 research cruises spanning the period from 1976 to 2018, containing observations for the entire water column across all MedSea sub-basins. A substantial component of the data was retrieved from fragmented or locally archived historical records, thus consolidating previously inaccessible

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measurements. Following global synthesis approaches, CARIMED applies a quality-controlled, and bias-adjusted framework. A key adaptation was the secondary quality control (2QC) procedure, specifically tailored to the MedSea's unique hydrography, utilising sub-basin divisions and supplementary checks (including statistical consistency assessments) to resolve complex, often contradictory, inter-cruise offsets. This rigorous process minimised systematic biases, yielding a dataset with improved consistency, and highlights the urgent need for adapted standard operating procedures and reference materials to address the MedSea biogeochemical particularities. CARIMED delivers two complementary, freely available products: the aggregated original cruise data product (https://doi.org/10.20350/digitalCSIC/17785; García-Ibáñez et al., 2025) and the final bias-adjusted data synthesis product (https://doi.org/10.25921/cp5b-zq67; Álvarez et al., 2025). This essential resource establishes a new benchmark for assessing long-term biogeochemical trends, validating regional ocean models, and supporting climate-change mitigation and adaptation strategies in this rapidly changing semi-enclosed basin.

1 Introduction

The global ocean currently absorbs close to 30% of anthropogenic CO_2 emissions and nearly 90% of excess heat, driving rapid alterations in its physical, chemical, and biological state (e.g., IPCC, 2022; Friedlingstein et al., 2025). These changes manifest as warming, ocean acidification (OA), and ocean deoxygenation—three major stressors that often act synergistically (Cooley et al., 2022), frequently referred to as the 'triple thread' (e.g., Gruber, 2011). Quantifying these impacts remains hampered by the limited availability, consistency, and quality of observational data.

Long-term assessments of ocean physics and biogeochemistry require sustained and complementary observations. Autonomous platforms and time-series stations resolve short-term variability (e.g., Henson, 2014; Chai et al., 2020), whereas repeat hydrography programmes provide the highest-quality, full-depth measurements (see Talley et al., 2016 and references therein) needed to evaluate long-term trends and, providing reference data sets to calibrate sensor-based measurements usually through interpolation methods (e.g., Bittig et al., 2018; Carter et al., 2021). Ensuring that these diverse observations adhere to the FAIR (Findability, Accessibility, Interoperability, and Reusability) principles (Wilkinson et al., 2016) remains an ongoing effort, supported by international programmes (e.g., UNESCO IOC, ICES, GOOS), specific projects (e.g., the EU SeaDataNet, EMODnet, CORIOLIS, EuroSea, BioGeoSea, ObsSea4Clim, and BioEcoOcean), and major repositories (e.g., NCEI–OCADS, CCHDO, PANGAEA, SEANOE). For biogeochemical datasets, internal consistency additionally requires detailed documentation and calibration, and the identification and adjustment of analytical biases.

Global and regional data synthesis efforts have established community standards for assembling quality-controlled biogeochemical datasets. These include GLODAPv1.1 (Global Ocean Data Analysis Product Global Ocean Data Analysis Product; Key et al., 2004), CARINA (Carbon In the Atlantic; Pierrot et al., 2010; Key et al., 2010), and PACIFICA (PACIFic ocean Interior CArbon; Suzuki et al., 2013), later merged and recalibrated into GLODAPv2 (Olsen et al., 2016; Lauvset et al., 2024). More targeted initiatives—such as SPOTS (Synthesis Product for Ocean Time Series; Lange et al., 2024), SNAPO-CO2 (Metzl et al., 2024, 2025), and CODAP-NA (Coastal Ocean Data Analysis Product in North America; Jiang et al., 2021)—

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demonstrate the community's increasing willingness and capacity to assemble high-quality water-column observational data (Jiang et al., accepted for publication). Complementary regional effort, include DIN-WMED for dissolved inorganic nutrient (Belgacem et al., 2019, 2021) and CTDO2-WMED for dissolved oxygen in the Western Mediterranean Sea (Belgacem et al., 2025a, b), further highlight the value of basin-specific synthesis products tailored to regions with strong temporal and spatial variability. Collectively, these initiatives not only comply with FAIR principles but also aim to streamline workflows to enable efficient and interoperable use of ocean data (Tanhua et al., 2019, 2021), in line with the Framework of Ocean Observing (FOO) readiness-level (RL) concept (Lindstrom et al., 2012; Lange et al., 2023).

Despite their ecological and climatic importance, marginal seas remain underrepresented in these data synthesis products (Lee et al., 2011). In the Mediterranean Sea (MedSea), long-term OA and carbon-cycle assessments are constrained by the sparse seawater CO_2 system measurements (Álvarez et al., 2014; Hassoun et al., 2022) as well as by the lack of public, consistently formatted, and quality-controlled datasets (Malanotte-Rizzoli et al., 2014). The MedSea's semi-enclosed nature, strong evaporative forcing, and short overturning timescales amplify climate-driven changes, making it a natural laboratory for detecting anthropogenic signals (e.g., Robinson and Golnaraghi, 1994; Tanhua et al., 2013b; MedECC, 2020; Ali et al., 2022; Álvarez et al., 2023, and references therein). Yet, historical measurements often remain dispersed across archives, in heterogeneous formats, and are frequently lacking standardised quality control (QC). Shifts in analytical techniques since the 1970s and the introduction of reference materials in the 1990s further complicate the integration of historical data with modern observations and with global synthesis products.

These challenges underscore the need for a basin-wide, harmonised, and bias-adjusted data synthesis product for the MedSea. CARIMED (CARbon, tracers, and ancillary data In the MEDiterranean Sea) addresses this gap. Building on experience from CARINA and GLODAP, CARIMED was motivated by key community efforts, including CIESM (Mediterranean Science Commission) workshops—such as those held in Menton, which focused on OA impacts (CIESM, 2008), and Supetar, which aimed at designing the Med-SHIP repeat hydrography programme (CIESM, 2012; Schroeder et al., 2015, 2024)—and the EU MedSeA and EuroGO-SHIP projects, which sought to compile full-depth water-column seawater CO_2 system measurements (Cossarini et al., 2015; Gemayel et al., 2015; Hassoun et al., 2015; Lovato and Vichi, 2015) and sustain regional, Mediterranean and Black Sea, hydrographic observations, respectively. Previous MedSea compilations, however, were neither FAIR-compliant nor systematically bias-adjusted.

The present CARIMED release includes 46 cruises (1976–2018) that measured 'carbon-relevant variables', combining historical and modern measurements of seawater CO_2 system variables, dissolved oxygen, dissolved inorganic nutrients, transient tracers, and physical parameters from all major MedSea sub-basins. CARIMED does not intend to include data from all available cruises, but focuses on those with carbon-relevant data. Through the application of both primary and secondary QC, CARIMED delivers a FAIR-compliant, bias-adjusted data synthesis product that enables assessments of long-term carbon-cycle changes, OA progression, water mass ventilation, and supports validation of regional biogeochemical models in this climatically sensitive basin.

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2 CARIMED workflow: Overview and data synthesis products

The CARIMED workflow (Fig. 1) comprises a sequence of steps aimed at recovering, standardising, QCing, and harmonising hydrographic and biogeochemical observations collected during research cruises across the MedSea. The individual components of the workflow are described in detail in the following sections: (i) discovery and retrieval of cruise data (Section 3.1); (ii) standardisation and merging of retrieved files into cruise-level files (Section 3.2); (iii) production of merged cruise files including primary (first-level) QC (1QC) flags and cruise-level metadata (Section 3.3); and (iv) identification and adjustment of systematic offsets through a secondary QC (2QC) procedure (Section 5). An overview of the cruises contained in CARIMED is provided in Section 4, while Section 6 presents the CARIMED data synthesis products.

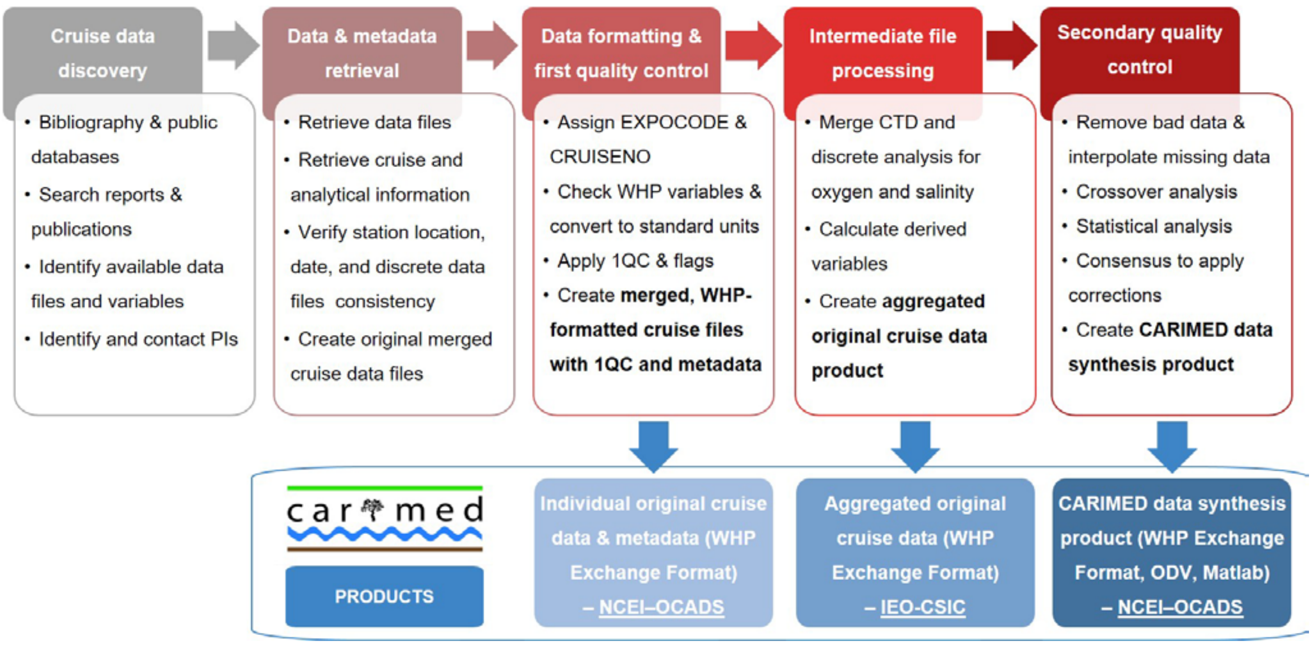

Figure 1: Summary of the CARIMED workflow, from cruise data discovery to the generation of the final data synthesis products. The workflow includes five main stages (shaded blocks) and results in three complementary outputs: individual cruise files with primary (first-level) quality control (1QC), an aggregated original data product (before bias adjustment), and the final CARIMED bias-adjusted data synthesis product (bias-adjusted after secondary quality control). All files are available in WHP (World Ocean Circulation Experiment, WOCE, Hydrographic Program) Exchange format.

The workflow results in two complementary and FAIR-compliant data synthesis products (Section 6). The first is the aggregated original cruise data product, comprising all merged and 1QC'd measurements together with derived variables. The second is the final CARIMED bias-adjusted data synthesis product, which applies the harmonised secondary QC (2QC) adjustments to correct systematic biases in aggregated original cruise dataset, thereby reducing inter-cruise and inter-variable inconsistencies.

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3 Data recovery, formatting, and primary (first-level) quality control (1QC)

The recovery of historical and recent cruise data across the MedSea exposed substantial fragmentation in archival and documentation. Files were retrieved from a variety of sources—data portals, institutional repositories, project archives, and personal communications—frequently differing in format, naming conventions, and documentation level. This heterogeneity, stemming from decades of evolving measurement protocols and data-management practices, as well as the involvement of diverse teams from various countries, necessitated a systematic effort to identify, retrieve, merge and consolidate all relevant material prior to QC and harmonisation.

3.1 Cruise discovery and data retrieval

Cruises included in CARIMED were located through a comprehensive bibliographic review and an extensive search across public repositories and catalogues. Because no single repository provides complete coverage of historical and recent measurements, data discovery and retrieval relied on multiple complementary sources, including cruise reports, scientific publications, conference and workshop proceedings, publicly accessible databases, and direct communication with principal investigators (PIs) or data providers.

The initial compilation efforts were guided by the CIESM (2012) workshop No. 43 and preliminary work conducted within the EU MedSeA project (Gemayel et al., 2015; Lovato and Vichi, 2015). Cruises were selected if they provided water-column data for at least two variables of the seawater CO_2 system and/or transient tracers. Cruises providing seawater CO_2 system data were also required to include dissolved oxygen (O_2) and dissolved inorganic nutrients (NUT) data, with the exception of the earliest cruise in 1976 (MILLERO_76). Some cruises containing transient tracers' data were included even without O_2, NUT, or seawater CO_2 system data (Section 4, Table 1), as transient tracers can be used to estimate the concentration of anthropogenic carbon. Ancillary variables—including spatial and temporal coordinates and thermohaline properties—were required for all cruises.

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Table 1. CARIMED cruise summary table containing basic information on each cruise and measured variables. This table, including additional metadata, is hosted on the CARIMED OCADS site. Note that the cruises in this table are listed in chronological order, whereas in OCADS, the assigned cruise number follows the alphabetical ordering of EXPOCODEs.

Cruise #	Year	EXPOCODE	SECT_ID	Dates	Ship	Chief Scientist(s)	Carbon PI(s)	Tracers PI(s)	O_2	NUT	pH	TA	DIC	TRACERS
17	1976	31GI19760901	MILLERO_76	SEP 1976	GILLISS	Millero	Millero	-	-	-	x	x	-	-
16	1977	318M19771204	GEOSECS_LEG3	7–9 DEC 1977	MELVILLE	Brainbridge	Brainbridge, Keeling, et al	-	x	x	-	x	x	-
23	1981	35JC19811020	MEDIPROD_IV	20 OCT–15 NOV 1981	JEAN CHARCOT	Coste, Minas	Poisson	-	x	x	-	x	x	-
13	1983	29GD19830629	PEP83	29 JUN–15 JUL 1983	GARCIA DEL CID	Estrada	Pérez	-	x	x	x	x	-	-
33	1983	47SK19831005	MC24IS	5–12 NOV 1983	SHIKMONA	Unknown	Unknown	-	x	x	x	x	-	-
34	1984	47SK19840522	MC26IS	22–30 MAY 1984	SHIKMONA	Unknown	Unknown	-	x	x	x	x	-	-
35	1984	47SK19841204	MC30IS	4–12 DEC 1984	SHIKMONA	Unknown	Unknown	-	x	x	x	x	-	-
2	1987	06MT19870818	METEOR_5_6	18 AUG–24 SEP 1987	METEOR	Roether	-	Bader, Fraas, et al.	x	x	-	-	-	x
36	1987	47SK19870824	POEM05IS	24 AUG–11 SEP 1987	SHIKMONA	Unknown	Unknown	-	x	x	x	x	-	-
37	1988	47SK19880807	POEM06IS	7–22 AUG 1988	SHIKMONA	Unknown	Unknown	-	x	-	x	x	-	-
18	1991	35A319910424	ALMOFRONT_LEG1	24 APR–12 MAY 1991	L'ATALANTE	Prieur	Copin	-	x	x	x	x	-	-
3	1994	06MT19941230	METEOR_31_1	30 DEC 1994–5 FEB 1995	METEOR	Roether	-	Beitzel, Bruns, et al.	x	x	-	-	-	x
29	1995	36AE19950209	OTRANTO_5	9–10 FEB 1995	AEGAEO	Krasakopoulou	Krasakopoulou, Souvermezoglou	-	x	x	-	x	x	-
7	1996	06PO19960522	POSEIDON_1996	22–31 MAY 1996	POSEIDON	Unknown	-	Rhein	-	-	-	-	-	x
8	1997	06PO19971023	POSEIDON_234	23 OCT–10 NOV 1997	POSEIDON	Unknown	-	Rhein	-	-	-	-	-	x
40	1997	48UR19970830	URANIA_MAI2	30 AUG–8 SEP 1997	URANIA	Unknown	-	Roether	-	-	-	-	-	x
30	1998	36AE19981014	AEGAEO_M4WF	14–19 OCT 1998	AEGAEO	Roether	-	Roether	x	-	-	-	-	x
4	1999	06MT19990410	METEOR_44_4	10 APR–16 MAY 1999	METEOR	Weikert	-	Bulsiwiecz, Kämper, et al.	x	x	-	-	-	x
22	1999	35HT19990904	PROSOPE	4 SEP–4 OCT 1999	THALASSA	Claustre	Begovic, Copin	-	x	x	x	x	-	-
41	1999	48UR19990211	URANIA_MAI7	11–17 FEB 1999	URANIA	Unknown	-	Roether	-	-	-	-	-	x
5	2001	06MT20011018	METEOR_51_2	18 OCT–11 NOV 2001	METEOR	Roether	Schneider	Klein	x	x	-	x	x	x
39	2007	48UN20070613	TRANSMED_LEGIII	13–27 JUN 2007	UNIVERSITATIS	Fonda	Ibello	-	x	x	x	x	-	-

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42	2007	48UR20070528	TRANSMED_LEGII	28 MAY–12 JUN 2007	URANIA	Azzaro	Cozzi	-	x	x	x	x	-	-
14	2008	29GD20080919	SESAME_SPII	19–28 SEP 2008	GARCIA DEL CID	Navarro	Flecha,Huertas	-	x	x	x	x	-	-
15	2008	29RZ20080406	SESAME_SPI	6–14 APR 2008	REGINA MARIS	Navarro	Flecha, Huertas	-	x	x	x	x	-	-
19	2008	35A320080616	BOUM	16 JUN–20 JUL 2008	L'ATALANTE	Moutin	Goyet, Touratier	-	x	x	-	x	x	-
43	2008	48UR20080215	SESAME_IT01	15–26 FEB 2008	URANIA	Catalano	Cantoni, Luchetta	-	x	x	x	x	-	-
44	2008	48UR20080301	SESAME_IT02	1–9 MAR 2008	URANIA	Azzaro	Cantoni, Luchetta	-	x	x	x	x	-	-
45	2008	48UR20080318	SESAME_IT04	18 MAR–5 APR 2008	URANIA	Santinelli	Goyet	-	x	x	-	x	x	-
46	2008	48UR20081007	SESAME_IT07	7 16 OCT 2008	URANIA	Catalano	Catalano	-	x	x	x	x	-	-
9	2009	29AH20090310	FAMOSO	10–22 MAR, 29 APR–13 MAY, 14–20 SEP 2009	SARMIENTO DE GAMBOA	Latasa	Vidal	-	x	x	x	x	-	-
27	2010	35TT20100525	MOOSE_GE_2010	25 MAY–29 JUN 2010	TETHYS II	Testor	Coppola	-	x	x	-	x	x	-
6	2011	06MT20110405	METEOR_84_3	5–28 APR 2011	METEOR	Tanhua	Álvarez, Mintrop	Tanhua	x	x	x	x	x	x
20	2011	35A320110301	CASCADE	1–23 MAR 2011	L'ATALANTE	de Madron	Touratier	-	x	x	-	x	x	-
24	2012	35LU20120723	MOOSE_GE_2012	23 JUL–9 AUG 2012	LE SUROÎT	Testor	Coppola	-	x	x	-	x	x	-
11	2013	29AJ20130502	MEDSEA_2013	2 MAY–2 JUN 2013	ÁNGELES ALVARIÑO	Ziveri	Goyet, Hassoun	-	x	x	-	x	x	-
25	2013	35LU20130201	DEWEX	01–22 FEB & 3–26 APR 2013	LE SUROÎT	Testor (Leg 1) & Conan (Leg 2)	Coppola, Touratier	-	x	x	-	x	x	-
31	2013	36AE20131004	PERSEUS_2013	4–9 OCT 2013	AEGAEO	Karageorgis	Krasakopoulou, Souvermezoglou	-	x	x	-	x	x	-
10	2014	29AH20140426	HOTMIX	26 APR–31 MAY 2014	SARMIENTO DE GAMBOA	Aristegui	Álvarez, Tanhua	Tanhua	x	x	x	x	x	x
26	2014	35LU20140704	MOOSE_GE_2014	4–22 JUL 2014	LE SUROÎT	Testor	Coppola	-	x	x	-	x	x	-
28	2014	35TT20140814	SOMBA	14 AUG–10 SEP 2014	TETHYS II	Mortier	Keraghel, Louanchi	-	x	x	-	x	x	-
38	2015	48QL20150804	OC_2015	4–18 & 18–31 AUG 2015	MINERVA UNO	Schroeder (Leg 1) & Chiggiato (Leg 2)	Cantoni	-	x	x	x	x	-	-
12	2016	29AJ20160818	TALPRO_2016	18–29 AUG 2016	ÁNGELES ALVARIÑO	Jullion	Álvarez	Tanhua	x	x	x	x	x	x
21	2016	35A320160519	MOOSE_GE_2016	19 MAY–9 JUN 2016	L'ATALANTE	Coppola	Coppola	-	x	x	-	x	x	-
32	2016	36AE20160602	CRELEV	2–10 JUN 2016	AEGAEO	Civitarese	Giani, Urbini, Gianouidi, et al.	Tanhua	x	x	x	x	x	x
1	2018	06M220180302	MSM72	2 MAR–3 APR 2018	MARIA S. MERIAN	Hainbucher	Álvarez, Fajar, Guallart	Tanhua	x	x	x	x	x	x

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Metadata fields, including cruise name, research vessel, sampling dates, chief scientist, and PIs responsible for each variable, were compiled. When available, additional information on analytical methods and measurement QC was collected, with comprehensive cruise reports proving particularly valuable. For many cruises, several independent files were obtained, typically corresponding to different subsets of variables (e.g., CTD, discrete bottle data). Each file was carefully checked for consistency in station, cast, and Niskin bottle identifiers, as well as station coordinates, sampling dates, and pressure/depth records, ensuring agreement with associated reports and/or publications.

All files were catalogued and assigned standardised names and metadata descriptors to facilitate subsequent merging, QC, and integration into the data synthesis product. The compiled set of individual source files for each cruise and variable is available upon request.

3.2 File merging and formatting

A unified and formatted data file was generated for each cruise, containing all retrieved hydrographic and biogeochemical data. Merging was based on reference ancillary information such as station and cast identifiers (when available), sampling dates, bottle numbers (when available), and pressure/depth values, to ensure correspondence among files containing discrete bottle data. Pressure was established as the primary vertical coordinate; depth values were converted to pressure where necessary. Information on each retrieved file—including data source, variable units, formats, analytical techniques, and QC procedures—was incorporated into the file metadata (Section 3.3).

The merging process depended on cruise characteristics (Section 4), a merged cruise data file was created for each case. Following merging, each cruise file containing ancillary, thermohaline, and biogeochemical data was formatted according to the WHP (World Ocean Circulation Experiment, WOCE, Hydrographic Program) Exchange format (Swift and Diggs, 2008), with headers and units as listed in Table S1.

Formatting involved two main steps:

(i) Assignment and creation of standardised identifiers and auxiliary variables:

- Cruise Identification (ID): Each cruise was assigned a cruise number and alias (SECT_ID) (Table 1).
- EXPOCODE: When not already assigned, an EXPOCODE (expedition code) was generated to uniquely identify each cruise, following international oceanographic data-management practices. The EXPOCODE consists of the four-digit ICES (International Council for the Exploration of the Sea) research vessel code (https://vocab.ices.dk/) and the date of departure from port (UTC) in ISO8601 format (YYYYMMDD), if not known, the first sampling station date.
- Stations: Assigned numerical identifiers; original station identifiers using letters or words were replaced by numbers and documented in the cruise metadata.
- Casts: Cast numbers were assigned as 1 when unavailable.
- Bottles: Niskin bottle numbers were assigned sequentially, starting from 1 for the deepest sample, when unavailable.
- Dates: When station dates were missing, at least month and year were retrieved from publications or cruise reports.

- Times: Default time of 0000 UTC was assigned when station times were missing.
- CTD variables: Temperature, salinity, and pressure data were usually obtained from CTD (Conductivity, Temperature, and Depth) sensors; when unavailable (e.g., MILLERO_76), this was noted in the metadata, and the same variable headers (CTDTMP, CTDSAL, CTDPRS; see Table S1) were retained for consistency.

(ii) Conversion of variables to internationally accepted units:

- In situ temperature: Expressed in degrees Celsius (°C) on the International Temperature Scale of 1990 (ITS-90). Values originally reported on the International Practical Temperature Scale of 1968 (IPTS-68) were converted using ITS-90 = IPTS-68 × 0.99976 (Saunders, 1990).
- Salinity: Reported on the Practical Salinity Scale of 1978 (PSS-78).
- Dissolved oxygen (O_2): Expressed in µmol kg^{-1}; data originally in mL L^{-1} were converted using the factor 44.66 mL $µmol^{-1}$ and seawater density derived from salinity and potential temperature.
- Dissolved inorganic nutrient concentrations (NUT): Concentrations (nitrate, nitrite, phosphate, and silicate) were standardised to µmol kg^{-1}. Data originally in µmol L^{-1} were converted using seawater density at corresponding salinity and an assumed measurement temperature of 20ºC, as is the most common practice. Nitrite and nitrate were summed to obtain total oxidised nitrogen ($NO_2^- + NO_3^-$), and listed as nitrate.
- Seawater CO_2 system variables: pH values were converted to the total hydrogen ion scale (pH_T) at 25°C. Conversion from other scales or temperatures was performed using the MATLAB version of CO2SYSv3 (Orr et al., 2018) with the carbonic acid dissociation constants of Mehrbach et al. (1973) reformulated on the total hydrogen scale by Lueker et al. (2000), the bisulfate dissociation constant of Dickson (1990), and the total boron to salinity ratio of Lee et al. (2010). Total alkalinity (TA) and total dissolved inorganic carbon (DIC) were expressed in µmol kg^{-1} (as usually retrieved).
- Transient tracers: Expressed in their standard units (as retrieved).
- Missing data: Coded as -999. Samples lacking temperature, pressure/depth, or salinity were removed from the dataset.

The merged cruise data files, derived from the retrieved data files and formatted according to the WHP standard, subsequently underwent a 1QC process (Section 3.3).

3.3 WHP-formatting, 1QC, and metadata

Each cruise data file underwent a rigorous 1QC following the procedures described by Tanhua et al. (2010) and implemented via the Velo et al. (2023) software tool. The flagging scheme followed WOCE standards, as adopted by GLODAP, using only the flags: 0 (interpolated data), 2 (good data), 3 (questionable data), and 9 (not sampled, measured, or reported). Variables were examined for range variability and property–property relationships to detect anomalous values. Regional context was considered to minimise incorrect flagging. For instance, the typical positive TA-salinity relationship is invalid in the Adriatic Basin due to high TA from low-salinity riverine inputs.

Sensor-based O_2 (CTDOXY) data were cross-checked against discrete O_2 (OXYGEN) data when available, following GO-SHIP (Global Ocean Ship-based Hydrographic Investigations Program) Hydro Manual guidelines (Hood et al., 2010). Recalibration of sensor-based O_2 (CTDOXY) against Winkler O_2 titrations (OXYGEN) was required for several cruises, including PROSOPE, TRANSMED, SESAME legs, BOUM, METEOR_84_3, MEDSEA, SOMBA, TALPRO, CRELEV, and MSM72. For SESAME_IT07, the O_2 data source could not be clearly identified and was assumed to represent uncalibrated CTDOXY. CTDOXY recalibrations, when needed, were documented in the metadata and communicated to the variable PI and the cruise Chief Scientist. Recalibrations were performed as a function of pressure and cruise (Figs. S1a and S1b). After the recalibration process, the residuals between CTDOXY and OXYGEN were centred around zero and exhibited reduced standard deviations than the original retrieved CTDOXY values (Figs. S1c and S1d). A few cruises (MILLERO_76, GEOSECS_Leg3, PROSOPE, MEDIPROD_IV, OTRANTO_5, CRELEV) reported discrete salinity (SALNTY) data contributing less than 28% of corresponding sensor-based salinity (CTDSAL) data. Retrieved CTDSAL values were assumed calibrated against SALNTY, but limited availability of SALNTY data prevented formal verification. Other issues identified during 1QC were, wherever possible, discussed with the respective PIs.

Upon completion of 1QC, standardised metadata were compiled for each cruise, including basic information (ship name, dates, cruise alias, EXPOCODE, Chief Scientist, and station numbering) and variable-specific details (unit conversion methods, analytical techniques, and quality assurance and control procedures, particularly the use of reference materials). Metadata were incorporated as a readme-style header in the WHP Exchange Format files—a comma-delimited ASCII (CSV) structure. Each cruise file begins with a line specifying the data type (in this case, BOTTLE data, i.e., bottle data and CTD data at the discrete bottle depths), followed by a timestamp and a CARIMED reference. The subsequent section contains metadata, including references to the initial retrieved files, citation information, and associated publications, reports, or data repositories. Finally, the 1QC-flagged (Table S1) and formatted data are presented, with the file concluding with the END_DATA line.

These merged 1QC files per cruise, including cruise-level metadata, are available through the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) Ocean Carbon and Acidification Data System (OCADS), with file identifiers (DOI) listed in Table S2.

4 Cruises included in CARIMED

4.1 Cruise information and original data

Individual cruise data and metadata are centrally accessible via the CARIMED summary cruise table hosted within the NCEI–OCADS (Jiang et al., 2023), with file identifiers (DOI) listed in Table S2. This repository provides: (i) the WHP-compliant CSV files containing the merged cruise data, verified by the 1QC process, along with their associated metadata; (ii) corresponding cruise reports, where available; and (iii) a map illustrating the station locations for each dataset. For each cruise, a dedicated NCEI–OCADS metadata landing page is available, summarising key metadata such as identifiers, temporal and spatial coverage, measurement methods, PIs and institutions, and station map.

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4.2 General overview of cruises included in CARIMED

The CARIMED data synthesis products integrate 46 hydrographic cruises conducted between 1976 and 2018 (Fig. 2, Table 1). These cruises provide full-depth water-column data across all major MedSea sub-basins. Spatial gaps remain evident, particularly in the Libyan-Tunisian, Egyptian, Greek, and Turkish exclusive economic zones of the Eastern Mediterranean Basin, while the Western Mediterranean Basin shows the highest density of both cruise coverage and sampling (Fig. 2c, d).

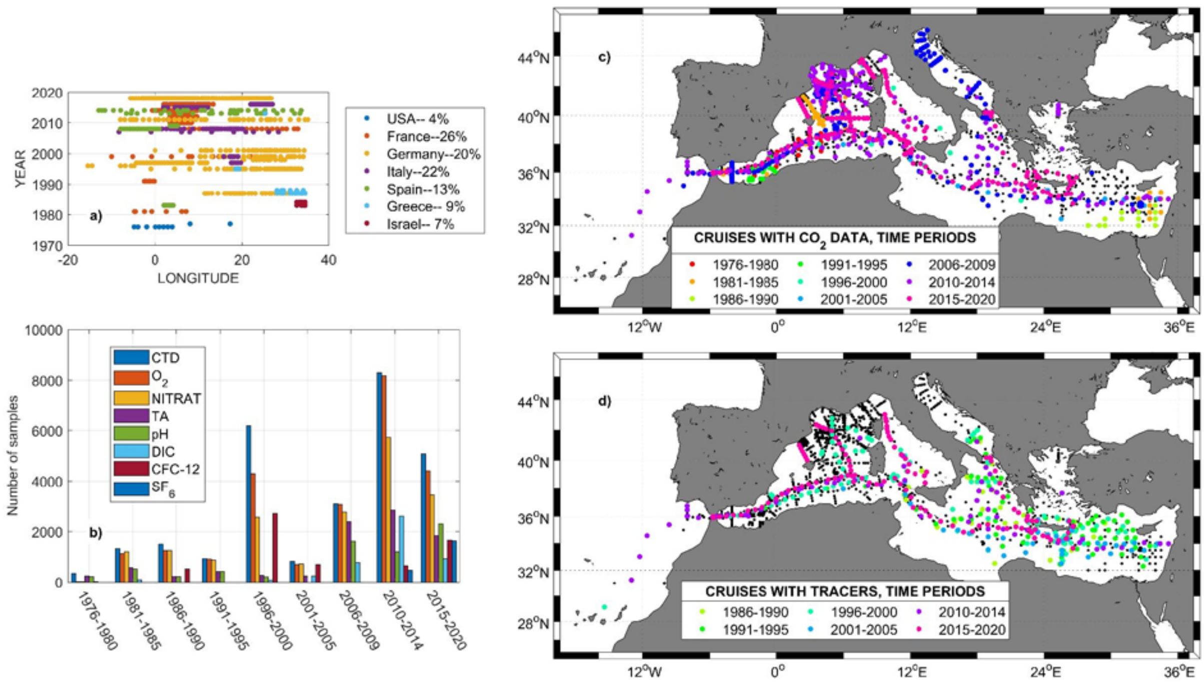

Figure 2: Overview of the cruises included in the CARIMED data synthesis products: (a) spatiotemporal distribution of stations (year *vs.* longitude), coloured by Chief Scientist country, with the legend indicating the percentage of cruises per country; (b) histogram of the number of samples per variable, grouped into five-year periods, with variables categorised as CTD (thermohaline variables), dissolved oxygen (O_2), dissolved inorganic nutrients represented with nitrate (NITRAT), total alkalinity (TA), pH, total dissolved inorganic carbon (DIC), and transient tracers (CFC-12, and SF_6); and (c-d) maps showing the cruise stations included in CARIMED grouped by five year-periods with measurements of (c) the seawater CO_2 system variables, or (d) transient tracers, with black dots showing all stations included in CARIMED, providing a reference baseline.

Cruises on RV's from France, Germany, and Italy account for 68% of the entire dataset (Fig. 2a). Sampling density increased significantly during the 2000s (Fig. 2b) due to international collaborations enabled by Research Infrastructure initiatives (e.g., EUROFLEETS) and projects (e.g., METEOR_84_3, MSM72, MEDSEA_2013; and the SESAME cruises: SESAME_SPI, SESAME_SPII, SESAME_IT01, SESAME_IT02, SESAME_IT04, and SESAME_IT07). A notable imbalance persists in Chief Scientists from North African and Eastern Mediterranean countries, which likely reflects limited access to research vessels and/or specialised expertise in seawater CO_2 system and transient tracer measurements, as previously noted by Hassoun et al. (2022). Nevertheless, successful regional efforts, such as the SOMBA (Système d'Observations à la mer dans le Bassin Algérien) 2014 cruise (Keraghel et al., 2020), demonstrate fruitful collaboration and growing regional capacity.

The high data density in the Gulf of Lion stems from the French MOOSE (Mediterranean Ocean Observing System for the Environment) programme (Coppola et al., 2019), which conducts cruises approximately every two years. More recently, the Med-SHIP programme has promoted repetition every the 5–6 years of North–South hydrographic lines in each MedSea sub-basin, with TALPRO and CRELEV cruises in 2016 (Schroeder et al., 2024) serving as reference occupations. The decadal reoccupation of the MED01 GO-SHIP line is represented by METEOR_84_3 in 2011 (Tanhua et al., 2013b) and MSM72 in 2018 (Hainbucher et al., 2020).

Figure 2b summarises the sample availability by variable across five-year periods. CTD temperature and salinity consistently form the backbone of the hydrographic component. O_2 is the most frequently measured biogeochemical variable, with nitrate being the most abundant among NUT. TA is the most abundant seawater CO_2 system variable, followed by pH and DIC. CFC-12 is the most frequent transient tracer, with SF_6 measurements appearing in the most recent period. Figures 2c and 2d depict the spatial distributions of stations with measurements of seawater CO_2 system variables and transient tracers, respectively, against the backdrop of all CARIMED stations (black points).

4.3 Particular issues with cruises and variables included in CARIMED

This section provides necessary context on particular issues encountered during the recovery, formatting, and 1QC of specific cruises and variables included in CARIMED. Further detailed information on the measurement techniques and associated references for each cruise is available within the metadata accompanying the NCEI–OCADS summary cruise table for CARIMED (Table 1; see Section 6; Table S2).

4.3.1 Cruises from 1976 to 1988

Early oceanographic studies in the MedSea (e.g., Schmidt, 1912; Wüst, 1961) primarily focused on circulation. Seawater CO_2 chemistry investigations in the MedSea began in the 1970s (Alekin, 1972; Chernyakova, 1976; Millero et al., 1979). The CARIMED dataset recovered data from Prof. F. Millero's cruise (1976), retrieved through technical report digitisation (D. Pierrot, AOML, NOAA), and GEOSECS (Geochemical Ocean Sections Study) Leg 3 (1977) (Weiss et al., 1983). The French MEDIPROD_IV (1981) cruise (Groupe MEDIPROD, 1984) focused on the West Mediterranean Basin (Packard et al., 1988) and while its CTD, O_2, and NUT data from this project are publicly available (Minas et al., 2012), its seawater CO_2 system data were recovered by digitising a technical report provided by M. Fichaut (IFREMER).

The Spanish PEP (Producció Estival Profunda) 1983 cruise contributed pH and TA data (Pérez et al., 1986). Additional pH and TA datasets were recovered from the MEDAR/MEDATLAS 2002 initiative (MEDAR Group, 2002; Fichaut et al., 2003) and five RV Shikmona cruises from the Levantine Basin, retrieved from the Israel Marine Data Center (ISRAMAR) and PANGAEA (MC24IS, MC26IS, and MC30IS cruises; MEDAR Group, 2012a, b, c). Two additional RV Shikmona cruises, POEM05IS and POEM06IS, were likely conducted under the framework of the Physical Oceanography of the Eastern Mediterranean (POEM) project (Malanotte-Rizzoli and Robinson, 1988). None of these cruises included transient tracer

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measurements; only the METEOR_5_6 cruise in 1987 measured CFC-11, CFC-12, Helium, Tritium, and Neon (Roether and Schlitzer, 1991; Schlitzer et al., 1991; Roether et al., 1998; Roether et al., 1999).

During 1976–1988, TA and pH were the most frequently measured seawater CO_2 system variables, both measured potentiometrically. DIC was measured in only two cruises, also by potentiometric titration. Reference materials for biogeochemical measurements, particularly those related to seawater CO_2 system variables, were not available in this early period.

4.3.2 Cruises from 1991 to 1999

Of the ten cruises compiled for CARIMED for this decade, only three (ALMOFRONT_LEG1 in 1991; OTRANTO_5 in 1995; and PROSOPE in 1999) included seawater CO_2 system measurements; most cruises measured transient tracers (CFCs, Helium, Tritium), but none measured SF_6. These cruises, along with METEOR_51_2 (2001) and METEOR_84_3 (2011), were key to study MedSea ventilation (Schneider et al., 2014; Li and Tanhua, 2020).

The ALMOFRONT_LEG1 (1991) cruise supported the first MedSea TA and DIC budget estimates (Copin-Montégut, 1993), (French contribution to Frontal-Joint Global Ocean Flux Study, JGOFS, studying the Almeria-Oran frontal area; Prieur and Sournia, 1994). Physical, chemical, and biological data from this project are stored at Laboratoire d'Oceanographie de Villefranche (LOV-CNRS). Potentiometric TA and pH and calculated DIC (not included in CARIMED) were provided by L. Prieur and C. Schmechtig (LOV-CNRS). No CO_2-in-seawater reference materials (CO_2-RM) were used in this cruise.

The OTRANTO_5 (1995) was among the first to use CO_2-RM in the MedSea, measuring DIC and TA potentiometrically, following DOE (1994) (Krasakopoulou et al., 2011). The PROSOPE (1999) cruise (Claustre et al., 2002), which covered the Eastern and West Mediterranean Basins, also used CO_2-RMs to control potentiometric TA following the double end-point technique of Pérez and Fraga (1987) and potentiometric pH (controlled with TRIS following DOE, 1994).

4.3.3 Cruises from 2001 to 2010

This decade saw coordinated sampling in both Western and Eastern Mediterranean Basins under EU projects such as SESAME (Southern European Sea: Assessing and Modelling Ecosystem changes) that sponsored the Italian and Spanish 2008 cruises and the French BOUM (Biogeochemistry from the Oligotrophic to the Ultra oligotrophic Mediterranean Sea) cruise (Moutin et al., 2012). National initiatives also expanded basin coverage, notably the Italian VECTOR (VulnErabilità delle Coste e degli ecosistemi marini italiani ai cambiamenti climaTici e loro ruolO nei cicli del caRbonio mediterraneo; D'Ortenzio and Ribera d'Alcala, 2009) conducted the TRANSMED 2007 cruises (TRANSMED_LEGII in the Western and TRANSMED_LEGIII in the Eastern MedSea; Rivaro et al., 2010). The Eastern MedSea was further sampled by METEOR_51_2 (2001). Convection in the Gulf of Lion was a focus of the Spanish FAMOSO (FAte of the northwestern Mediterranean Open sea Spring blOom) cruise (Mouriño-Carballido et al., 2016) in 2009, and the French MOOSE (Observation Infrastructure Système D'observation Intégré Et Multidisciplinaire En Méditerranée) programme conducted its annual MOOSE_GE cruise in 2010.

Only the METEOR_51_2 (2001) cruise measured transient tracers and represents the first repeat of the eastern part of the MED01 GO-SHIP line. It was the first CARIMED cruise to include coulometric DIC measurements (Johnson et al., 1993) and used CO_2-RM for TA and DIC QC. This cruise was the first MedSea component considered in global data products like CARINA (Pierrot et al., 2010) and GLODAPv2 (Olsen et al., 2016).

The first cruise compiled for CARIMED with spectrophotometric pH measurements (Clayton and Byrne, 1993) was the Spanish SESAME_SPI (Huertas et al., 2012), followed by several additional SESAME legs and FAMOSO. Only the TRANSMED cruises reported potentiometric pH. DIC and TA were measured following DOE (1994) protocols in SESAME_IT04 (2008) and MOOSE_GE (2010) at the SNAPO-CO2 facility (Metzl et al., 2024) at LOCEAN (CNRS, Paris). CO_2-RM were used across all cruises; and BOUM was the only cruise to report using NUT RMs from OSIL (Ocean Scientific International) (Pujo-Pay et al., 2011).

4.3.4 Cruises from 2011 to 2015

This period includes the second repeat of the MED01 GO-SHIP line, METEOR_84_3 in 2011, which was the first CARIMED cruise to deliver an overdetermined seawater CO_2 system (pH, DIC, and TA measured; Álvarez et al., 2014). This cruise, along with MeDSeA in 2013 (Mediterranean Sea Acidification; Ziveri and Grelaud, 2015; Hassoun et al., 2015) and HOTMIX in 2014 (Catalá et al., 2018), spanned the entire MedSea. Regional initiatives complemented these occupations: PERSEUS in 2013 sampled the North Aegean Basin, while other cruises focused on the Gulf of Lion, like CASCADE cruise in 2011 (Cascading, Surge, Convection, Advection and Downwelling Events; Touratier et al., 2016), MOOSE_GE_2012 and MOOSE_GE_2014 (Fourrier et al., 2022), and DEWEX in 2013 (Deep Water Experiment; Conan et al., 2018). Additional coverage of the Western Mediterranean Basin, including the Alboran and Tyrrhenian Basins was provided by SOMBA_2014) and OC_2015; Ocean Certain cruise; Cantoni et al., 2020; Schroeder et al., 2020). All cruises used state-of-the-art methods for pH (spectrophotometry), TA (potentiometry), and DIC (coulometry/potentiometry), utilizing CO_2-RM. Only METEOR_84_3 and HOTMIX provided transient tracer measurements.

4.3.5 Cruises from 2016 to 2018

This short period is notable for the implementation of the two 2016 Med-SHIP cruises: TALPRO and CRELEV (Schroeder et al., 2024). The third repeat of the MED01 GO-SHIP line, MSM72 (2018), also occurred here. pH measurements during CRELEV and MSM72 utilised purified indicator dyes, following modern oceanographic practice (e.g., Liu et al., 2011).

5 Secondary quality control (2QC) framework for the Mediterranean Sea

The CARIMED dataset was subjected to 2QC procedures to evaluate and harmonise data consistency across all the compiled 46 cruises. This process identifies and adjusts systematic biases in measurements, ensuring that the CARIMED data synthesis product achieves higher coherency (Section 5.3).

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Secondary QC focuses on detecting systematic biases that exist beyond measurement random uncertainty. Such biases typically arise when combining datasets collected from different sources, using different instrumentation, analytical protocols, and methodological standards, often spanning several decades, which consequently possess varying degrees of uncertainty. According to the International Vocabulary for Metrology (VIM; JCGM, 2012), measurement uncertainty is a non-negative parameter that characterizes the dispersion of the quantity values attributed to a measurand and is defined as the dispersion of the values attributed to the measurand, usually expressed as a standard deviation or confidence interval. This uncertainty comprises both random and systematic components: random uncertainty is associated with the variability of measurand values under replicate conditions, while systematic uncertainty reflects the deviation from a considered true or reference value.

Technological advances have progressively reduced random uncertainty—improving precision in terms of repeatability (measurements under identical conditions) and reproducibility (measurements under different conditions)— making systematic biases easier to isolate. The first 2QC approach tailored to ship-based hydrographic data was developed by Gouretski and Jancke (1999) to detect, objectively quantify, and correct 'inter-cruise offsets' (systematic differences) between WOCE cruises in the 1990s and historical hydrographic records (see Álvarez et al. (2024) for an overview of hydrographic 2QC procedures). These procedures are designed to reduce uncertainty in compiled datasets, whether from single or multiple sources. The resulting 2QC-synthesis product exhibits increased internal consistency, promoting its usability with a higher degree of confidence in downstream analysis. In the digital era, ocean data products with informed uncertainty are essential components of the ocean-observing value chain, serving as the backbone of scientific assessments required by various stakeholders (Guidi et al., 2020; EMB, 2021).

Amidst an increasing number of data synthesis products for ocean biogeochemistry (e.g., Lange et al., 2023; Jiang et al., accepted for publication), GLODAP updates integrating ship-based biogeochemical observations (Olsen et al., 2016; Lauvset et al., 2024) have established a benchmark for 2QC procedures. These efforts build upon methodological experience gained in the CARINA initiative (Tanhua et al., 2010; Tanhua and Lauvset, 2015). Fundamentally, the 2QC method involves examining potential biases between cruise datasets in geographically overlapping regions (crossover areas) and on vertical spaces (pressure, potential temperature or density surfaces) characterised by very low temporal variability. These biases are quantified against a typical uncertainty threshold defined for each physical or chemical variable, using datasets measured following internationally recognised Standard Operating Procedures (SOP) and reference materials (RM) as reference (the 'true value' in metrological terms). Ideally, ship-based measurements, both sensor and discrete data, should be traceable to the international system of units (SI), with informed uncertainty regarding their precision and accuracy to ensure consistency.

However, recent efforts within projects such as MINKE (Metrology for Integrated marine maNagement and Knowledge-transfer nEtwork, EU INFRAIA-02-2020), SapHTies (Metrology for standardised seawater pH_T measurements in support of international and European climate strategies, EU EMPIR 20NRM06), and EuroGO-SHIP (Developing a Research Infrastructure Concept to Support European Hydrography, HORIZON-INFRA-2022-DEV-01-01) evidence two primary challenges to improve the consistency of ocean observations: the need for standardised, internationally endorsed SOPs and the

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availability of RMs, particularly for biogeochemical variables (e.g., Pearlman et al., 2021; Capitaine et al., 2023; Hartman et al., 2023; Firing et al, 2024; García-Ibáñez and Easley-Vidal, 2025; Woodward et al., in preparation).

Two specific issues render 2QC procedures particularly challenging in the MedSea:

- Rapid temporal variability: Physical and biogeochemical properties in the MedSea evolve on temporal and spatial scales significantly shorter than those in other ocean basins (Chiggiato et al., 2023, and references therein). Consequently, the region lacks a vertical layer with low temporal variability.
- Biogeochemical complexity: MedSea biogeochemical variables are distinct in terms of their cycles and drivers (Álvarez et al., 2023) and challenging in terms of analytical SOPs and RMs. NUT exhibit low concentrations, transitioning from oligotrophic to ultra-oligotrophic regimes from the Western to the Eastern sub-basins. Conversely, DIC and, specially, TA and pH values are high compared to other ocean basins. Furthermore, these properties must be measured within a high-salinity matrix, which challenges both the working range and the background matrix of the available RMs (García-Ibáñez and Easley-Vidal, 2025; and the review chapters in Aoyama et al., 2025).

To overcome these challenges, recent efforts have implemented adapted 2QC procedures to enhance the usability of ship-based NUT (Belgacem et al., 2020) and sensor-based O_2 data (Belgacem et al., 2025a) in the Western Mediterranean Basin. Building upon these initiatives, we propose an adapted 2QC procedure tailored to the specific oceanographic characteristics of the different MedSea sub-basins, integrating both crossover and statistical evaluation techniques.

5.1 CARIMED 2QC framework: crossover analysis adapted to the Mediterranean Sea

The CARIMED 2QC framework employs the established running cluster crossover procedure (cnaX) originally used in CARINA (Tanhua et al., 2010) and consistently applied in recent GLODAPv2 updates (Lauvset et al., 2024). However, for CARIMED, these routines were adapted to account for the distinct hydrography and high spatiotemporal variability of the MedSea.

Unlike GLODAP, which typically relies on deep-water crossovers, the crossover depth intervals in CARIMED were defined individually for each sub-basin. The selected layers correspond to those of minimum temporal variability, as identified in previous reviews (Schneider et al., 2014; Stöven and Tanhua, 2014; Schroeder et al., 2016; Li and Tanhua, 2020, Belgacem et al., 2025a) and corroborated by transient tracer observations compiled within CARIMED. Figure S2 shows the Tracer Minimum Zone (TMZ) for each sub-basin, based on regional mean vertical profiles. Mediterranean sub-basin boundaries follow Manca et al. (2004) (Table S3 and Fig. S3). TMZs are assumed to represent older, slowly renewing water masses, and therefore serve as the vertical domains for crossover inspection. However, some variability is detected even within these layers (Figs. S15 and S16), highlighting the MedSea's sensitivity to climate change and warranting cautious crossover inspection.

The specific crossover depth criteria were applied as follows:

- For the Levantine and Ionian Basins, crossovers were performed at depths between 600 m and 2,000 m.
- For the Adriatic Basin, crossovers were performed for water depths greater than 800 m (Cardin et al., 2015).

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- For the Tyrrhenian Basin, 2QC was based on crossovers between 1,900 m and 3,000 m.
- For the Western Mediterranean Basin, crossovers were performed for waters were performed at depths between 600 m and 2,000 m.

These criteria were applied consistently across all cruise years, even where major water-mass changes occurred, such as the Eastern Mediterranean Transient (EMT) at the end of the 1980s that induced a dramatic change in the deep and bottom layers of the Eastern Mediterranean Sea where saltier and warmer waters from the Aegean Sea replace the resident deep water with an Adriatic Sea origin (see Malanotte-Rizzoli et al., 1999; Lascaratos et al., 1999; Klein et al., 1999), and the Western Mediterranean Transient (WMT), a major deep water formation event in 2004/05 (López-Jurado et al. 2005), introducing warmer and saltier bottom waters in the Gulf of Lion, that propagate into the Alboran and the Tyrrhenian Sea after 2010 (e.g., Schroeder et al., 2016). Crossover analyses were conducted for salinity and all biogeochemical variables.
The adapted cnaX routine objectively quantifies systematic differences between a target cruise and nearby cruises conducted within a ~250 km radius across different vertical coordinates (potential temperature, pressure, and density), yielding a weighted cruise-by-cruise mean offset and standard deviation for each crossover pair (e.g., Figs. S4 and S5). The quality of these results is objectively quantified by considering the amount of data per station and the number of stations per cruise, which together influence the weighted standard deviation of the offset and the overall confidence of the crossover pair. Where sufficient crossover pairs exist for a given target cruise and variable, the adapted routine calculates a final cruise-level weighted mean offset and standard deviation considering all cruise pairs (e.g., Figs. S6 and S7), indicating the required correction. These offsets are variable-dependent: additive adjustments are evaluated for salinity, DIC, TA, and pH, while multiplicative factors are evaluated for O_2 and NUT.
Ideally, final adjustments would be determined via the weighted least-squares inversion procedure proposed by Johnson et al. (2001), as utilised in GLODAP, which minimises offsets for a given cruise and variable across all crossover pairs. However, strict application of this procedure in CARIMED would inadvertently remove genuine temporal trends and regime shifts in the deep MedSea water masses. Ongoing work within the GLODAP reference group is currently developing a new 2QC method tailored to retain temporal trends while quantifying systematic biases (N. Lange and S. Lauvset, personal communication).
The crossover routine could not be applied to SESAME_SPI (2008) because sampling only extended to 600 m. It was also not feasible for PEP83 (1983) and GEOSECS_LEG3 (1977) due to the very limited number of crossover pairs with enough quality, the latter cruise contains only two stations.
A curated subset of crossover results is included in the CARIMED adjustments workbench (hosted at GEOMAR; https://carimed.geomar.de/), documenting the evidence supporting the adjustments applied (Section 5.3). In several cases, crossover analyses remained inconclusive for specific cruises or variables, due to one or more limiting factors: insufficient vertical or horizontal sampling density; sparse temporal overlap (crossover pairs separated by long intervals), high variability relative to analytical precision, and difficulty distinguishing systematic biases from true temporal variability. In some instances,

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crossovers even yielded contradictory adjustment directions for the same cruise when evaluated in different sub-basin (NUT for the MEDSEA 2013 cruise).

5.2 Supplemental statistical information: adjustment limits and crossover support

A supplemental statistical consistency assessment was conducted by inspecting the average, standard deviation (STD), and mean absolute deviation (MAD) within the minimum temporal variability depth layers (Section 5.1), following Belgacem et al. (2025a). These statistical values were calculated for every cruise and grouped according to the sub-basin classification by Manca et al. (2004) (see Table S3 and Fig. S3). In this scheme, the Western Mediterranean Basin comprises regions DF1 (Algero-Provençal) and DS1 (Alboran Sea), the Tyrrhenian Basin comprises regions DT1 (Tyrrhenian North) and DT3 (Tyrrhenian South), the Ionian Basin comprises regions DJ5, DJ7, and DJ8 (Ionian South, Ionian Middle West, and Ionian Middle East, respectively), the Cretan Passage comprises region DH3 (Cretan Passage), and the Levantine Basin comprises regions DL1, DL2, DL3, and DL4 (Levantine North, Levantine North-East, Levantine South, and Levantine South-East, respectively).

To guide the required adjustments, minimum adjustments limits were prescribed for each variable. Consistent with 2QC procedures, these limits represent the minimum systematic bias that can be confidently identified relative to the measurement uncertainty, typically approximated by measurement precision. While GLODAP established highly restrictive limits based on consistently high-quality hydrographic data, the CARIMED synthesis comprises historical and recent cruises collected using evolving methodologies, SOPs, and quality assurance procedures. Many early cruises were conducted before the availability of RMs for biogeochemical variables.

Figure S8 presents a preliminary inspection of the intra-cruise homogeneity (precision) for physical and biogeochemical variables. Heatmaps of STD values per cruise (Tables 1 and S2) and sub-basin show the inter-cruise variability by region, with biogeochemical variables, particularly for NUT and TA, which display higher STD values.

The overall mean STD values for each variable were therefore adopted as the minimum adjustment limits. For NUT and O_2, STD values were converted to a percentage of the mean, providing the relative adjustment limit (Table 2). The high STD value obtained for salinity clearly reflects the significant temporal shifts characteristic of the MedSea over the CARIMED temporal coverage. The O_2 adjustment limit aligns with the value obtained by Belgacem et al. (2025). Importantly, the derived limit for NUT clearly exceeds the stringent GLODAP convention of 2%, also used by Belgacem et al. (2020) in the Western basin (values of about 5% would be obtained using Western Basin CARIMED cruises). Conversely, the adjustment limits for TA, DIC, and pH derived from the CARIMED cruises are comparable to GLODAP values.

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Table 2. Adjustment limits for CARIMED calculated from the average standard deviation (STD) of the measured variables in layers with minimum temporal variability across all Mediterranean Sea sub-basins using CARIMED cruises. Absolute STD values are transformed to a percentage using the corresponding mean values for O_2 and NUT.

Variable	Average STD	Limit of adjustment
Salinity	~0.034	~0.005
Oxygen	~6 µmol kg^{-1}	~3%
Silicate	~0.5 µmol kg^{-1}	~5%
Nitrate	~0.4 µmol kg^{-1}	~5%
Phosphate	~0.02 µmol kg^{-1}	~5%
DIC	~4.6 µmol kg^{-1}	~4 µmol kg^{-1}
TA	~4.3 µmol kg^{-1}	~4 µmol kg^{-1}
pH	~0.005	~0.01

As noted in Section 5.1, the crossover analysis results proved challenging due to the dynamic nature of the MedSea. To provide robust confidence in the suggested adjustments, the crossover results were therefore supplemented with a statistical evaluation of the mean and STD values of each property per cruise and region within the minimum temporal variability depth layers.

The outcomes of this statistical assessment are presented in the Supplementary Information, separating the Western MedSea regions (Alboran Sea, Algero-Provençal Basin, Gulf of Lion, and Tyrrhenian Basin) (Figs. S9 to S11) from the Eastern MedSea regions (Adriatic Basin, Ionian Basin, Cretan Passage, and Levantine Basin) (Figs. S12 to S14). These evaluations were used to either validate or override the crossover-derived adjustments, effectively compensating for the spatial and temporal limitations of data availability. In several cases, statistical evidence was essential. For example, the anomalously low DIC concentrations observed during the MEDIPROD_IV (1981) cruise across the Alboran, Algero-Provençal, Western, and Gulf of Lion regions. Similarly, the low NUT values reported for the MEDSEA (2013) cruise were confirmed across both the Western and Eastern sub-basins.

5.3 Applied adjustments and final consistency assessment

Careful analysis of both the crossover results and the statistical information within the minimum temporal variability layers enabled the detection of systematic biases in salinity and biogeochemical variables that exceeded the predefined adjustment limits (Table 2). Lacking a completely objective quantitative approach (as the standard inversion procedure was not suitable

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for the MedSea's dynamic deep water), the CARIMED group relied on expert judgement-driven analysis to determine the magnitude and applicability of corrections.

Cruises that followed modern GO-SHIP best practices and utilized RMs were selected as primary benchmarks for comparison. For cruises crossing multiple sub-basins, determining the final adjustment was challenging, as crossover analysis sometimes proposed contradictory adjustments for the same cruise when applied separately in different sub-basins. Adjustment limits were surpassed only when the bias was exceptionally clear, particularly when comparing recent high-precision cruises. All corrections were rigorously inspected to ensure they did not remove true temporal trends or natural variability before being applied. The specific adjustments for each cruise and variable are listed in Table S4, and additional graphical justifications are provided in the CARIMED adjustment workbench hosted in GEOMAR (https://carimed.geomar.de/). Variables corrected through the 2QC process are denoted by the _2QC suffix in the final CARIMED bias-adjusted data synthesis product headers (e.g., OXYGEN_2QC; Table 3). The proposed corrections are the following:

- Salinity: Four cruises needed an adjustment in CTDSAL, suggesting issues related to CTD calibration, even for recent cruises. Corrections included:
    - A downward adjustment of 0.015 units for MC24IS,
    - A downward adjustment of 0.007 units for POSEIDON_234,
    - An upward adjustment of 0.010 units for MEDSEA_2013,
    - A downward adjustment of 0.010 units for OC_2015.
- Oxygen: OXYGEN required adjustment in seven cruises:
    - METEOR_5_6 and POEM05IS needed an upward adjustment of 2%,
    - METEOR_31_1 needed a downward adjustment of 5%,
    - METEOR_44_4 needed an upward adjustment of 3%,
    - MC24IS and MC30IS needed a downward adjustment of 4%,
    - MC26IS and SESAME_IT01 needed a downward adjustment of 2%.
- Nutrients: NUT required the most significant adjustments both in number and magnitude. Approximately 30% of the cruises needed adjustments, particularly for phosphate and silicate. This issue strongly underscores the ongoing need for adapted SOPs and RMs.
- Carbonate system: For the seawater CO_2 system variables, no adjustments were applied to pH. Despite the change in methodologies, transitioning from potentiometric to spectrophotometric measurements, the overall agreement for pH was comparatively better, which may be related to a better agreement of pH at the higher MedSea pH values (Álvarez et al., accepted). However, adjustments for TA and DIC were particularly high, sometimes exceeding the adjustment limit by an order of magnitude, even for cruises that reported using CO_2-RMs. Findings from an inter-laboratory comparison exercise based on high DIC, TA, and pH mid-depth water from the Levantine Basin (Ibello et al., 2026) will also help to devise a strategy to improve the consistency of these climate-relevant biogeochemical variables.

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The statistical consistency of the dataset was investigated before and after applying the 2QC adjustments (Fig. 3a, b). Specifically, we quantified MAD values for ‘good’ data (flag 2) within the minimum temporal variability layers (Section 5.1) across different MedSea regions, arranged from west to east, using the entire CARIMED dataset. High MAD values, indicating higher data dispersion around the regional mean, are evident for all variables in the Adriatic Basin, even after adjustments were applied. This behaviour reflects the pronounced temporal variability of this region. Conversely, regions showing lower MAD values are generally located in the Eastern MedSea (Ionian Basin, Cretan Passage, and Levantine Basin). Overall, the 2QC procedures successfully improved the internal consistency of the CARIMED dataset, as evidenced by the reduction in MAD after applying the CARIMED 2QC framework (Fig. 3c). Mean reductions were 14% for OXYGEN, 8% for NITRATE, 9% for PHOSPHATE, 13% for SILICATE, 16% for TA, and 26% for DIC. As no 2QC adjustments were applied to pH, no change in pH MAD was expected. A few exceptions were noted, including a slight increase in MAD for NUT in the Adriatic Basin and for CTDSAL, which likely points to the regime shifts in the MedSea. The overall decrease in MAD confirms that the CARIMED 2QC framework successfully minimised systematic biases and produced an internally consistent CARIMED dataset suitable for robust regional biogeochemical studies.

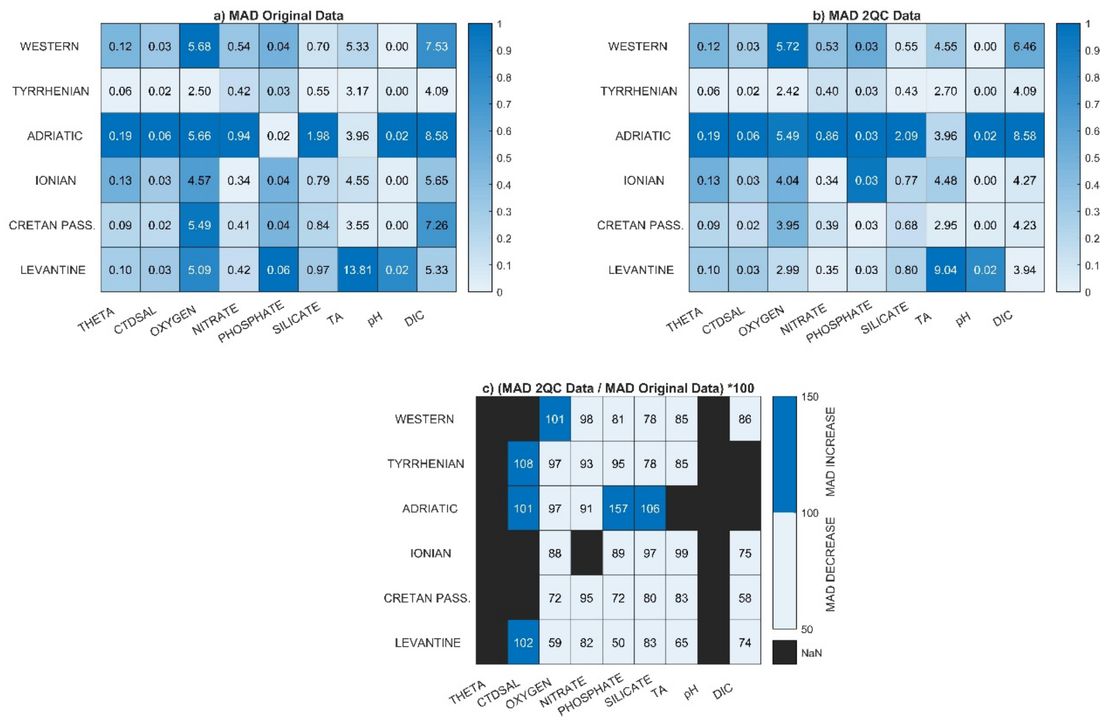

Figure 3: Overall Mean Absolute Deviation (MAD) (a) before and (b) after applying the 2QC adjustments to the CARIMED cruise collection. MAD are calculated for different Mediterranean Sea regions defined after Manca et al. (2004) and within the depth layers of minimum temporal variability (Section 5.1). Regions are shown in the y-axis and physical and biogeochemical variables in the x-axis: potential temperature (THETA, in ºC), salinity (CTDSAL), dissolved oxygen (OXYGEN, in µmol kg^{-1}), dissolved inorganic nutrients (NITRATE, PHOSPHATE, and SILICATE, all in µmol kg^{-1}), total alkalinity (TA, in µmol kg^{-1}), pH on the total hydrogen

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ion scale at 25ºC (pH), and total dissolved inorganic carbon (DIC, in µmol kg^{-1}). The Western Basin comprises regions DF1 and DS4 (Algero-Provençal and Algerian East); the Tyrrhenian Basin comprises regions DT1 and DT3 (Tyrrhenian Sea North and Tyrrhenian Sea South); the Adriatic Basin comprises region DJ3 (Adriatic South); the Ionian Basin comprises regions DJ5, DJ7, and DJ8 (Ionian South, Middle East, and West, respectively); the Cretan Passage region comprises region DH3 (Cretan Passage), and the Levantine Basin comprises regions DL1, DL2, DL3, and DL4 (Levantine North, North East, South and South East, respectively) (see Fig. S3 and Table S3 for more information).

6 CARIMED synthesis data products availability

The CARIMED data synthesis products consist of two complementary components: (i) the aggregated original data product containing all measurements subjected to 1QC, and (ii) the final CARIMED bias-adjusted data synthesis product containing both the original data with flag 2 and bias-adjusted (2QC) data, with interpolated ancillary data (O_2 and NUT) if seawater CO_2 data is available (Table 3).

Table 3. Variables, header aliases, units, and flag headers in the CARIMED data synthesis products. The table lists variables included in the aggregated (original cruise data) and final (original and bias-adjusted cruise data) data synthesis products, including derived physical and biogeochemical variables. The final CARIMED bias-adjusted data synthesis product provides secondary quality control (2QC) adjusted variable values.

Variable	Header	Units	Flag Header [a]	Variable 2QC adjusted [b]
Expedition code	EXPOCODE			
Cruise alias	SECT_ID			
Cruise number	CRUISENO			
Date (YYYYMMDD)	DATE			
Hour (HHMM)	TIME			
Latitude	LATITUDE			
Longitude	LONGITUDE			
Station	STNNBR			
Cast	CASTNO			
Niskin Bottle	SAMPNO			
CTD Pressure	CTDPRS	Decibar		
CTD Temperature (ITS-90)	CTDTMP	Degree Celsius		
CTD Salinity (PSS-78)	CTDSAL		CTDSAL_FLAG_W	CTDSAL_2QC
CTD Oxygen	CTDOXY	µmol kg^{-1}	CTDOXY_FLAG_W	
Winkler Oxygen	OXYGEN	µmol kg^{-1}	OXYGEN_FLAG_W	OXYGEN_2QC
Apparent Oxygen Utilization	AOU	µmol kg^{-1}	OXYGEN_FLAG_W	
Silicate	SILCAT	µmol kg^{-1}	SILCAT_FLAG_W	SILCAT_2QC
Nitrate+Nitrite	NITRAT	µmol kg^{-1}	NITRAT_FLAG_W	NITRAT_2QC
Nitrite	NITRIT	µmol kg^{-1}	NITRIT_FLAG_W	
Phosphate	PHSPHT	µmol kg^{-1}	PHSPHT_FLAG_W	PHSPHT_2QC
Total Dissolved Inorganic Carbon	TCARBN	µmol kg^{-1}	TCARBN_FLAG_W	TCARBN_2QC
Total Alkalinity	ALKALI	µmol kg^{-1}	ALKALI_FLAG_W	ALKALI_2QC

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pH on the total hydrogen ion scale at 25°C and 0 dbar of pressure	PH_TOT_25C		PH_TOT_25C_FLAG_W	PH_TOT_25C_2QC
Chlorofluorocarbon 11	CFC-11	pmol kg^{-1}	CFC-11_FLAG_W	
Chlorofluorocarbon 12	CFC-12	pmol kg^{-1}	CFC-12_FLAG_W	
Chlorofluorocarbon 113	CFC113	pmol kg^{-1}	CFC113_FLAG_W	
Sulfur hexafluoride	SF6	fmol kg^{-1}	SF6_FLAG_W	
Carbon tetrachloride	CCL4	pmol kg^{-1}	CCL4_FLAG_W	
Partial pressure of CFC-11	pCFC-11	ppt		
Partial pressure of CFC-12	pCFC-12	ppt		
Partial pressure of CFC113	pCFC113	ppt		
Partial pressure of SF_6	pSF6	ppt		
Partial pressure of CCl_4	pCCL4	ppt		
Tritium (^{3}H)	TRITUM	TU	TRITUM_FLAG_W	
^{3}H counting error	TRITER	TU		
Helium (He)	HELIUM	nmol kg^{-1}	HELIUM_FLAG_W	
He counting error	HELIER	nmol kg^{-1}		
δ^3He	DELHE3	%	DELHE3_FLAG_W	
δ^3He counting error	DELHER	%		
Neon (Ne)	NEON	nmol kg^{-1}	NEON_FLAG_W	
Ne counting error	NEONER	nmol kg^{-1}		
Potential Temperature (ITS-90)	THETA	Degree Celsius		
Potential density anomaly referred to surface	SIGMA0	kg m^{-3}		
Potential density anomaly referred to 1000 dbar	SIGMA1	kg m^{-3}		
Potential density anomaly referred to 2000 dbar	SIGMA2	kg m^{-3}		
Potential density anomaly referred to 3000 dbar	SIGMA3	kg m^{-3}		
Potential density anomaly referred to 4000 dbar	SIGMA4	kg m^{-3}		
Neutral density	GAMMA	kg m^{-3}		
Maximum Sampling Depth	MAXSAMPDEPTH	meters		
Bottom Depth	DEPTH	meters		

a - the aggregated original data product includes data flagged as 3 (probably bad), 2 (good), and 0 (interpolated).
b - the final data synthesis product contains only data flagged as 2 (good) and 0 (interpolated).

6.1 Aggregated original cruise data product

The aggregated original cruise data product is a unified aggregated CARIMED dataset compiling the unadjusted physical, biogeochemical, and tracer measurements from all 46 cruises included in Table 1. This ensemble file includes all variables present in the individual cruise files (Table S1), in addition to several derived variables (see Table 3 for the full variable list). These include:

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(i) cruise identifiers such as SECT_ID and CRUISENO (identifying each cruise according to the NCEI–OCADS system, alphabetically ordered by EXPOCODEs; Table S2), year, and month;

(ii) derived physical and chemical variables, including potential temperature and density anomalies (calculated using the Thermodynamic Equation Of Seawater – 2010, TEOS-10), partial pressures of CFC-11 and CFC-12 (Warner and Weiss, 1985), CCl4 (Bullister and Wisegarver, 1998), CFC-113 (Bu and Warner, 1995), and SF_6 (Bullister et al., 2002), and apparent oxygen utilization (AOU; García et al., 1992).

Metadata such as maximum sampling depth and bottom depth (from the ETOPO Global Relief Model bathymetry; Amante and Eakins, 2009) are also provided. Each variable is expressed in standardized units and accompanied by WOCE-style quality flags (0, 2, 3, and 9). The dataset is organized by cruise, with each cruise identified by its EXPOCODE.

CTD salinity (CTDSAL) is the only salinity variable included, as it is available for nearly all cruises. Both OXYGEN (discrete) and the recalibrated CTDOXY (sensor) are included. Since OXYGEN discrete data are generally more reliable but less abundant, missing OXYGEN values were substituted with corresponding CTDOXY values and assigned a flag value of 0 (interpolated), and vice versa consistent with GLODAP protocols. AOU was calculated using the resulting combined OXYGEN data.

The aggregated original cruise data product is available from DIGITAL.CSIC (https://digital.csic.es/): https://doi.org/10.20350/digitalCSIC/17785 (García-Ibáñez et al., 2025).

6.2 Final CARIMED bias-adjusted data synthesis product

The final CARIMED bias-adjusted (2QC) data synthesis product maintains the same structure and variables as the aggregated original cruise data product. Crucially, it exclusively contains values flagged as ‘good’ (flag 2), and incorporates the adjustments derived from the 2QC analysis to remove systematic offsets, thus establishing an improved consistency.

Where seawater CO_2 system data were available, and ancillary variables such as O_2 and NUT were either missing or deemed unreliable (flagged as 3), these variables were vertically interpolated using a quasi-Hermitian piecewise polynomial, closely following the GLODAP procedure (Olsen et al., 2016).

The final CARIMED bias-adjusted data synthesis product is available from NCEI–OCADS (https://www.ncei.noaa.gov/): https://doi.org/10.25921/cp5b-zq67 (Álvarez et al., 2025) and can also be found within the Ocean Data View Ocean collections and the webODV Explore site.

7 Conclusions, lessons learned, and outlook

The CARIMED data synthesis products represent the first comprehensive, basin-wide compilation of hydrographic, biogeochemical, and tracer measurements for the MedSea from cruises that measured carbon-relevant variables, harmonised under a consistent QC framework. By integrating data from 46 cruises spanning more than four decades, CARIMED provides an unprecedented resource for understanding the long-term evolution of the MedSea’s physical and biogeochemical properties.

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The dataset consolidates previously fragmented or inaccessible observations and ensures their long-term preservation and data accessibility, as well as interoperability with global efforts such as GLODAP (Olsen et al., 2016).

The CARIMED workflow demonstrates that a coordinated, basin-scale synthesis is feasible even in a semi-enclosed, data-limited and conflictive region such as the MedSea. A key lesson learned is the importance of data rescue and standardisation: a substantial fraction of measurements existed only in non-standard formats or were archived locally without public access. Their recovery required collaboration with cruise PIs and national data centres, highlighting the need for systematic archiving practices and clear metadata documentation. When available, additional information on analytical methods and measurement QC was collected, and comprehensive cruise reports were particularly valuable, often providing the context required to correctly apply the adjustments. Ensuring that future datasets follow FAIR principles will greatly enhance their long-term usability.

The experience gained in the MedSea also emphasises that while GLODAP-style crossovers are effective for the global ocean, regional implementations require tailored approaches that account for finer water-mass structures and higher temporal variability. The lessons from CARIMED may thus inform the design of future data synthesis products.

Looking ahead, sustained observational efforts will be essential to extend and maintain CARIMED data synthesis products. The Med-SHIP repeat hydrography program (Schroeder et al., 2015), an Ocean Decade Action endorsed by UNESCO, and large-scale initiatives such as MonGOOS (The Mediterranean Oceanographic Network for the Global Ocean Observing System) are essential in providing new high-precision measurements and ensuring continuity with existing ship-based observations, delivering benchmark environmental information for better implementation of the Ocean Decade Sustainable Goals in the MedSea (Cappelletto et al., 2021). We strongly encourage the scientific community to submit new and legacy cruise data to public repositories such as NCEI–OCADS and to adopt the CARIMED framework when reporting physical, biogeochemical, and tracer observations from the MedSea. Expanding the database with additional cruises and repeated occupations will allow more robust detection and evaluation of OA, deoxygenation, and anthropogenic carbon storage trends across the basin.

The data products presented here are available online and are provided in two files: the aggregated original cruise data product, available from DIGITAL.CSIC (https://doi.org/10.20350/digitalCSIC/17785, García-Ibáñez et al., 2025), and the final CARIMED bias-adjusted data synthesis product, available from NCEI–OCADS (https://doi.org/10.25921/cp5b-zq67; Álvarez et al., 2025).

We recommend that the final CARIMED bias-adjusted data synthesis product be used as the primary source for quantitative scientific analyses, including the evaluation of ocean biogeochemical models, the estimation of anthropogenic carbon storage, or the assessment of long-term OA trends. The aggregated original cruise data product should be used only for specialised applications requiring unadjusted measurements. Users should pay close attention to the QC flags provided for each variable, particularly the interpolated status (flag 0), and should cite the CARIMED data synthesis product DOI as well as the original cruise data DOIs (Table S2) when relevant. We invite users to report any anomalies that may have gone undetected or to suggest potential misclassifications within the present products (e.g., data that are probably good but assigned flag 3, or data that are probably erroneous).

Finally, CARIMED's completion underscores the value of community-driven initiatives in regional ocean data synthesis. Sustained institutional and financial support will be critical for ensuring regular updates, open access, and long-term stewardship of this data synthesis product. Through these collective efforts, CARIMED could continue to provide a cornerstone for observational and modelling studies addressing the impacts of climate change on the MedSea.

Last but not least, CARIMED emphasises the need to support North African countries in Med-SHIP hydrographic cruises to foster collaboration, exchange knowledge and improve sampling coverage within under sampled MedSea regions.

Data availability

The aggregated original cruise data product is made available at DIGITAL.CSIC (https://doi.org/10.20350/digitalCSIC/17785; García-Ibáñez et al., 2025), and the final CARIMED bias-adjusted data synthesis product, available from NCEI–OCADS (https://doi.org/10.25921/cp5b-zq67; Álvarez et al., 2025). Both data products are available in multiple formats to ensure broad accessibility, adhering to FAIR (Findable, Accessible, Interoperable, and Reusable) data principles: (1) WHP-Exchange bottle format following WOCE Hydrographic Program Exchange format standards, (2) NetCDF format, and (3) Apache Parquet format. These merged 1QC files per cruise, including cruise-level metadata, are available through NCEI–OCADS, with file identifiers (DOI) listed in Table S2.

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We strongly encourage potential stakeholders and users to follow the FAIR data use statement (see CARIMED NCEI–OCADS landing page, LINK) and to contact principal investigators to explore collaboration opportunities and co-authorship.

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