

# 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.** **TSI** 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 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; hosted at <https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/oceans/CARIMED/>, last access: 26 June 2026). 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<sub>2</sub> emissions and nearly 90 % of excess heat, driving rapid alterations in its physical, chemical, and biological state (e.g., 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 threat” (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, McDonagh et al., 2026 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 – United Nations Educational, Scientific and Cultural Organization Intergovernmental Oceanographic Commission, ICES – International Council for the Exploration of the Sea, GOOS – Global Ocean Observing System), specific European Union projects (e.g., the SeaDataNet – Pan-European infrastructure for marine and ocean data management, EMODnet – European Marine Observation and Data Network, Copernicus Marine Environ-

ment Monitoring Service, EuroSea – Improving and integrating the European Ocean Observing and Forecasting System, BioGeoSea – Biogeochemical observation to better understand and protect our ocean, ObsSea4Clim – Ocean observations and indicators for climate and assessments, and BioEcoOcean – Co-Creating Transformative Pathways to Biological and Ecosystem Ocean Observation), and major repositories (e.g., NOAA NCEI-OCADS – National Oceanic and Atmospheric Administration – National Center for Environmental Information – Ocean Carbon and Acidification Data System, CCHDO – CLIVAR and Carbon Hydrographic Data Office, PANGAEA, SEANO). 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; 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-CO<sub>2</sub> (Metzl et al., 2024, 2025), and CODAP-NA (Coastal Ocean Data Analysis Product in North America; Jiang et al., 2021) – demonstrate the community's increasing willingness and capacity to assemble high-quality water-column observational data (Jiang et al., 2026). Complementary regional efforts include the aggregated data regarding eutrophication (dissolved inorganic nutrients, dissolved oxygen, chlorophyll and acidity accomplished by EMODnet Chemistry (HCMR/HNODC, 2025) with specific quality control procedures tailored for

the Mediterranean Sea (Lipizer et al., 2026) but no specific bias detection and correction procedures. In contrast, the data products DIN-WMED for dissolved inorganic nutrients (Belgacem et al., 2019, 2021) and CTDO2-WMED for dissolved oxygen in the western Mediterranean Sea (Belgacem et al., 2025a, b), developed procedures to detect and apply adjustments to the aggregated data, and further highlight the value of basin-specific data 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<sub>2</sub> system measurements (Álvarez et al., 2014; Hassoun et al., 2022) as well as by the lack of publicly available, consistently formatted, and quality-controlled datasets (Malanotte-Rizzoli et al., 2014). The MedSea is not simply a reduced-scale analogue of the global ocean but a dynamically distinct system, characterized by strong evaporative forcing, important air-sea interactions, and relatively rapid overturning circulation. Ventilation timescales in the MedSea are relatively short compared to the global ocean, facilitating the rapid propagation of surface-driven perturbations to intermediate and deep layers. As a result, changes in dense water formation, stratification, and circulation can be transmitted through the water column on relatively short timescales, directly impacting the oxygen, carbon, and nutrient distribution. Recent studies suggest potential weakening of dense water formation under warming scenarios, while deoxygenation and acidification signals are projected to intensify across the basin (e.g., Robinson and Golnaraghi, 1994; Tanhua et al., 2013a; MedECC, 2020; Ali et al., 2022; Álvarez et al., 2023, and references therein). In such a rapidly responding system, detecting and attributing long-term changes critically depends on consistent, high-quality observations capable of resolving both ventilation-driven variability and biogeochemical trends.

Yet, historical measurements in the MedSea remain dispersed across multiple archives, stored in heterogeneous formats, and often lack standardised quality control (QC). Shifts in analytical techniques since the 1970s, along with the introduction of reference materials in the 1990s further complicate the integration of historical data with modern observations and their consistency with global data 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. Build-

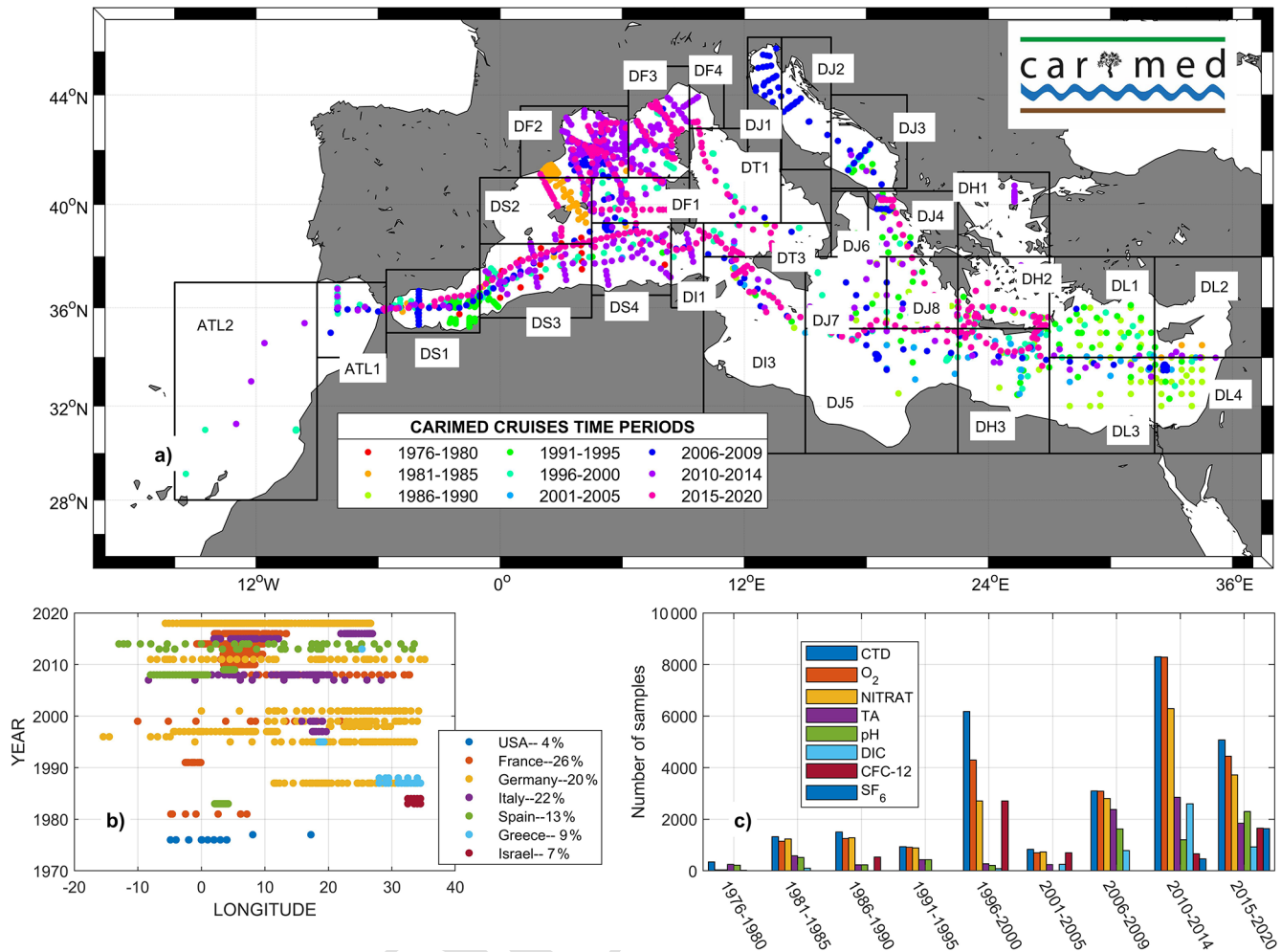
ing on experience from CARINA and GLODAP, CARIMED was motivated by key community efforts, including CIESM (Mediterranean Science Commission) workshops – such as those held in Menton, which focused on OA impacts (CIESM, 2008), and Supetar, which aimed at designing the Med-SHIP repeat hydrography programme (CIESM, 2012; Schroeder et al., 2015, 2024b) – and the EU MedSeA and EuroGO-SHIP projects, which sought to compile full-depth water-column seawater CO<sub>2</sub> system measurements (Cosarini et al., 2015; Gemayel et al., 2015; Hassoun et al., 2015; Lovato and Vichi, 2015; Schroeder et al., 2024a) and sustain regional, Mediterranean, and Black Sea hydrographic observations, respectively. Previous MedSea data compilations, however, were neither FAIR-compliant nor systematically bias-adjusted.

The present CARIMED release includes 46 cruises (1976–2018) (Fig. 1) that measured carbon-relevant variables, combining historical and modern measurements of seawater CO<sub>2</sub> system variables, dissolved oxygen, dissolved inorganic nutrients, transient tracers, and physical variables from all major MedSea sub-basins. 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.

## 2 CARIMED workflow: Overview and data synthesis products

The CARIMED workflow (Fig. 2) 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 (Sect. 3.1); (ii) standardisation and merging of retrieved files into cruise-level files (Sect. 3.2); (iii) production of merged cruise files including primary (first-level) QC (1QC) flags and cruise-level metadata (Sect. 3.3); and (iv) identification and adjustment of systematic offsets through a secondary QC (2QC) procedure (Sect. 5). An overview of the cruises contained in CARIMED is provided in Sect. 4, while Sect. 6 presents the CARIMED data synthesis products.

The workflow results in two complementary and FAIR-compliant data synthesis products (Sect. 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 2QC adjustments to correct systematic biases in the aggregated original cruise dataset, thereby reducing inter-cruise and inter-variable inconsistencies.



**Figure 1.** Overview of the cruises included in the CARIMED data synthesis products: (a) map showing the cruise stations included in CARIMED grouped by five year-periods; (b) spatiotemporal distribution of stations (year vs. longitude), coloured by Chief Scientist country, with the legend indicating the percentage of cruises per country; (c) histogram of the number of samples per variable, grouped into five-year periods, with variables categorised as CTD (thermohaline variables), dissolved oxygen (O<sub>2</sub>), dissolved inorganic nutrients represented with nitrate (NITRAT), total alkalinity (TA), pH, total dissolved inorganic carbon (DIC), and transient tracers (CFC-12, and SF<sub>6</sub>). Regional areas according to Manca et al. (2004) are depicted in Fig. 1a. See Table 2 for more information.

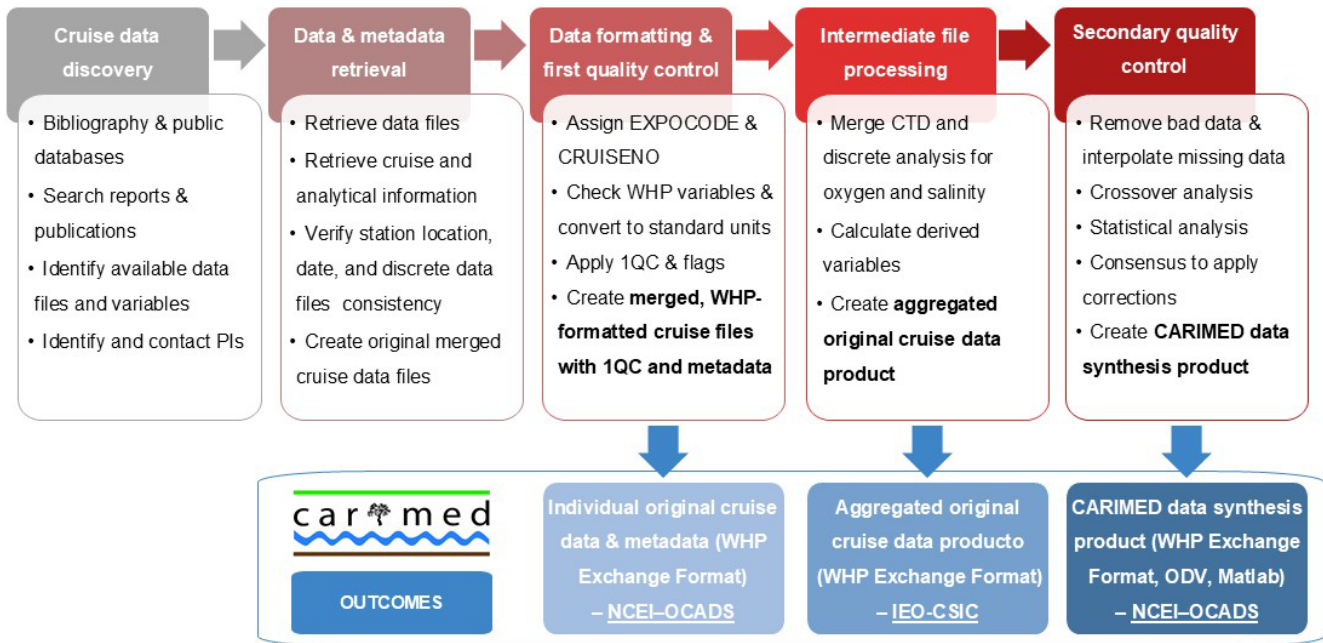
### 3 Data recovery, formatting, and primary (first-level) quality control (1QC)

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



**Figure 2.** 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. NCEI-OCADS and IEO-CSIC correspond to the National Oceanic and Atmospheric Administration National Center for Environmental Information – Ocean Carbon and Acidification Data System and the Spanish Institute of Oceanography-Agencia Consejo Superior de Investigaciones Científicas data repositories.

seawater CO<sub>2</sub> system and/or transient tracers. Cruises providing seawater CO<sub>2</sub> system data were also required to include dissolved oxygen (O<sub>2</sub>) and dissolved inorganic nutrient data, with the exception of the earliest cruise in 1976 (MILLERO\_76). Some cruises containing transient tracers' data were included even without O<sub>2</sub>, dissolved inorganic nutrients, or seawater CO<sub>2</sub> system data (Sect. 4, Table 1), as transient tracers can be used to estimate the amount of content of anthropogenic carbon. Ancillary variables – including spatial and temporal coordinates and thermohaline properties – were required for all cruises.

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 information. 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 (Sect. 3.3).

The merging process depended on cruise characteristics (Sect. 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

**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      | ALIAS           | Dates                                  | Ship               | Chief Scientist(s)                     | Carbon PII(s)                   | Tracers PII(s)            | O <sub>2</sub> | Nutrients | pH | TA | DIC | TRACERS |
|----------|------|---------------|-----------------|----------------------------------------|--------------------|----------------------------------------|---------------------------------|---------------------------|----------------|-----------|----|----|-----|---------|
| 17       | 1976 | 31G119760901  | MILLERO_76      | SEP 1976                               | GILLISS            | Millero                                | Millero                         | –                         | –              | –         | –  | –  | –   | –       |
| 16       | 1977 | 318M19771204  | GEOSECS_LEG3    | 7-9 DEC 1977                           | MELVILLE           | Brainbridge                            | Brainbridge, Keeling, et al.    | –                         | –              | –         | –  | –  | –   | –       |
| 23       | 1981 | 351C19811020  | MEDIPROD_IV     | 20 OCT–15 NOV 1981                     | JEAN CHARCOT       | Coste, Minas                           | Poisson                         | –                         | –              | –         | –  | –  | –   | –       |
| 13       | 1983 | 29GDI19830629 | PER83           | 29 JUN–15 JUL 1983                     | GARCIA DEL CID     | Estrada                                | Pérez                           | –                         | –              | –         | –  | –  | –   | –       |
| 33       | 1983 | 47SK19831005  | MC24IS          | 5–12 NOV 1983                          | SHIKONA            | Unknown                                | Unknown                         | –                         | –              | –         | –  | –  | –   | –       |
| 34       | 1984 | 47SK19840522  | MC26IS          | 22–30 MAY 1984                         | SHIKONA            | Unknown                                | Unknown                         | –                         | –              | –         | –  | –  | –   | –       |
| 35       | 1984 | 47SK19841204  | MC30IS          | 4–12 DEC 1984                          | SHIKONA            | Unknown                                | Unknown                         | –                         | –              | –         | –  | –  | –   | –       |
| 2        | 1987 | 06MT19870818  | METEOR_5_6      | 18 AUG–24 SEP 1987                     | METEOR             | Roeber                                 | Unknown                         | –                         | –              | –         | –  | –  | –   | –       |
| 36       | 1987 | 47SK19870824  | POEMOIS         | 24 AUG–11 SEP 1987                     | SHIKONA            | Unknown                                | Unknown                         | –                         | –              | –         | –  | –  | –   | –       |
| 37       | 1988 | 47SK19880807  | POEMOIS         | 7–22 AUG 1988                          | SHIKONA            | Unknown                                | Unknown                         | –                         | –              | –         | –  | –  | –   | –       |
| 18       | 1991 | 35A319910424  | ALMORONT_LEG1   | 24 APR–12 MAY 1991                     | L'ATALANTE         | Prieur                                 | Copin                           | –                         | –              | –         | –  | –  | –   | –       |
| 3        | 1994 | 06MT19941230  | METEOR_31_1     | 30 DEC 1994–5 FEB 1995                 | METEOR             | Roeber                                 | –                               | Beizel, Bruns, et al.     | –              | –         | –  | –  | –   | –       |
| 29       | 1995 | 36AE19950209  | OTRANTO_5       | 9–10 FEB 1995                          | MEGALO             | Kraskopoulou                           | Kraskopoulou, Souvermezoglou    | –                         | –              | –         | –  | –  | –   | –       |
| 7        | 1996 | 06PO19960522  | POSEIDON_1996   | 22–31 MAY 1996                         | POSEIDON           | Unknown                                | –                               | Rhein                     | –              | –         | –  | –  | –   | –       |
| 8        | 1997 | 06PO19971023  | POSEIDON_234    | 23 OCT–10 NOV 1997                     | POSEIDON           | Unknown                                | –                               | Rhein                     | –              | –         | –  | –  | –   | –       |
| 40       | 1997 | 48UR19970830  | URANIA_MAI2     | 30 AUG–8 SEP 1997                      | URANIA             | Unknown                                | –                               | Roeber                    | –              | –         | –  | –  | –   | –       |
| 30       | 1998 | 36AE19981014  | MEGALO_M4WF     | 14–19 OCT 1998                         | MEGALO             | Roeber                                 | –                               | Roeber                    | –              | –         | –  | –  | –   | –       |
| 4        | 1999 | 06MT19990410  | METEOR_44_4     | 10 APR–16 MAY 1999                     | METEOR             | Weikert                                | –                               | Bulswicz, Kämpfer, et al. | –              | –         | –  | –  | –   | –       |
| 22       | 1999 | 35HT19990904  | PROCOPE         | 4 SEP–4 OCT 1999                       | THALASSA           | Claire                                 | Begovic, Copin                  | –                         | –              | –         | –  | –  | –   | –       |
| 41       | 1999 | 48UR19990211  | URANIA_MAI7     | 11–17 FEB 1999                         | URANIA             | Unknown                                | –                               | –                         | –              | –         | –  | –  | –   | –       |
| 5        | 2001 | 06MT20011018  | METEOR_51_2     | 18 OCT–11 NOV 2001                     | METEOR             | Roeber                                 | Schneider                       | Roeber                    | –              | –         | –  | –  | –   | –       |
| 39       | 2007 | 48UR20070613  | TRANSMED_LEGIII | 13–27 JUN 2007                         | UNIVERSITATIS      | Fonda                                  | Ibello                          | Klein                     | –              | –         | –  | –  | –   | –       |
| 42       | 2007 | 48UR20070528  | TRANSMED_LEGII  | 28 MAY–12 JUN 2007                     | URANIA             | Azzaro                                 | Cozzi                           | –                         | –              | –         | –  | –  | –   | –       |
| 14       | 2008 | 29GDI20080919 | SENAME_SPII     | 19–28 SEP 2008                         | GARCIA DEL CID     | Navarro                                | Fiecha, Huertas                 | –                         | –              | –         | –  | –  | –   | –       |
| 19       | 2008 | 35A320080616  | SENAME_SPII     | 6–14 APR 2008                          | REGINA MARIS       | Navarro                                | Fiecha, Huertas                 | –                         | –              | –         | –  | –  | –   | –       |
| 15       | 2008 | 29KZ20080606  | BOUM            | 16 JUN–20 JUL 2008                     | L'ATALANTE         | Goyet, Touratier                       | Goyet, Touratier                | –                         | –              | –         | –  | –  | –   | –       |
| 43       | 2008 | 48UR20080215  | SENAME_IT01     | 15–26 FEB 2008                         | URANIA             | Catalano                               | Catalano, Luchetta              | –                         | –              | –         | –  | –  | –   | –       |
| 44       | 2008 | 48UR20080301  | SENAME_IT02     | 1–9 MAR 2008                           | URANIA             | Azzaro                                 | Catalano, Luchetta              | –                         | –              | –         | –  | –  | –   | –       |
| 45       | 2008 | 48UR20080318  | SENAME_IT04     | 18 MAR–5 APR 2008                      | URANIA             | Santelli                               | Goyet                           | –                         | –              | –         | –  | –  | –   | –       |
| 46       | 2008 | 48UR20081007  | SENAME_IT07     | 7 16 OCT 2008                          | URANIA             | Catalano                               | Goyet                           | –                         | –              | –         | –  | –  | –   | –       |
| 9        | 2009 | 29AH20090310  | FAMOSO          | 10–22 MAR 29 APR–13 MAY 14–20 SEP 2009 | SARMENTO DE GAMBIA | Lalasa                                 | Vidal                           | –                         | –              | –         | –  | –  | –   | –       |
| 27       | 2010 | 35TT20100525  | MOOSE_GE_2010   | 25 MAY–29 JUN 2010                     | TETHYS II          | Testor                                 | Coppola                         | –                         | –              | –         | –  | –  | –   | –       |
| 6        | 2011 | 06MT20110405  | METEOR_84_3     | 5–28 APR 2011                          | METEOR             | Tanhua                                 | Alvarez, Mintrop                | Tanhua                    | –              | –         | –  | –  | –   | –       |
| 20       | 2011 | 35A320110301  | CASCADE         | 1–23 MAR 2011                          | L'ATALANTE         | de Madron                              | Touratier                       | –                         | –              | –         | –  | –  | –   | –       |
| 24       | 2012 | 35LU20120723  | MOOSE_GE_2012   | 23 JUL–9 AUG 2012                      | LE SUROIT          | Testor                                 | Coppola                         | –                         | –              | –         | –  | –  | –   | –       |
| 11       | 2013 | 29AJ20130502  | MEDSEA_2013     | 2 MAY–2 JUN 2013                       | ANGELES ALVARO     | Zivert                                 | Goyet, Hassoun                  | –                         | –              | –         | –  | –  | –   | –       |
| 25       | 2013 | 35LU20130201  | DEWEX           | 01–22 FEB & 3–26 APR 2013              | LE SUROIT          | Testor (Leg 1) & Conan (Leg 2)         | Coppola, Touratier              | –                         | –              | –         | –  | –  | –   | –       |
| 31       | 2013 | 36AE20131004  | PENSEUS_2013    | 4–9 OCT 2013                           | MEGALO             | Karageorgis                            | Kraskopoulou, Souvermezoglou    | –                         | –              | –         | –  | –  | –   | –       |
| 10       | 2014 | 29AH20140426  | HOTMIX          | 26 APR–31 MAY 2014                     | SARMENTO DE GAMBIA | Aristegui                              | Alvarez, Tanhua                 | Tanhua                    | –              | –         | –  | –  | –   | –       |
| 26       | 2014 | 35LU20140704  | MOOSE_GE_2014   | 4–22 JUL 2014                          | LE SUROIT          | Testor                                 | Coppola                         | –                         | –              | –         | –  | –  | –   | –       |
| 28       | 2014 | 35TT20140814  | SOMBA           | 14 AUG–10 SEP 2014                     | TETHYS II          | Mortier                                | Kerangiel, Louanchi             | –                         | –              | –         | –  | –  | –   | –       |
| 38       | 2015 | 48QI20150804  | OC_2015         | 4–18 & 18–31 AUG 2015                  | MINERVA UNO        | Schroeder (Leg 1) & Chigellato (Leg 2) | Cantoni                         | –                         | –              | –         | –  | –  | –   | –       |
| 12       | 2016 | 29AJ20160818  | TALPRO_2016     | 18–29 AUG 2016                         | ANGELES ALVARO     | Jullien                                | Alvarez                         | Tanhua                    | –              | –         | –  | –  | –   | –       |
| 21       | 2016 | 35A320160519  | MOOSE_GE_2016   | 19 MAY–9 JUN 2016                      | L'ATALANTE         | Coppola                                | Coppola                         | –                         | –              | –         | –  | –  | –   | –       |
| 32       | 2016 | 36AE20160602  | CRELEV          | 2–10 JUN 2016                          | MEGALO             | Civilares                              | Giant, Urbini, Gianouli, et al. | Tanhua                    | –              | –         | –  | –  | –   | –       |
| 1        | 2018 | 06MT20180302  | MISM72          | 2 MAR–3 APR 2018                       | MARIA S. MERIAN    | Hainbucher                             | Alvarez, Fajar, Gualart         | Tanhua                    | –              | –         | –  | –  | –   | –       |

(Swift and Diggs, 2008), with headers and units as listed in Table S1 in the Supplement.

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 (ALIAS) (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/>, last access: 26 June 2026) 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 00:00 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 ( $^{\circ}\text{C}$ ) 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  $\text{ITS-90} = \text{IPTS-68} \times 0.99976$  (Saunders, 1990).
- *Salinity*. Reported on the Practical Salinity Scale of 1978 (PSS-78).

- *Dissolved oxygen ( $\text{O}_2$ )*. Expressed in  $\mu\text{mol kg}^{-1}$ ; data originally in  $\text{mL L}^{-1}$  were converted using the factor  $44.66 \text{ mL } \mu\text{mol}^{-1}$  and seawater density derived from salinity and potential temperature.
- *Dissolved inorganic nutrient contents*. Amounts of content (nitrate, nitrite, phosphate, and silicate) were standardised to  $\mu\text{mol kg}^{-1}$ . Data originally in  $\mu\text{mol L}^{-1}$  were converted using seawater density at corresponding salinity and an assumed measurement temperature of  $20^{\circ}\text{C}$ , as is the most common practice. Nitrite and nitrate are measured together as total oxidised nitrogen ( $\text{NO}_2^- + \text{NO}_3^-$ ), given the low nitrite content in open ocean and specially in the MedSea, total oxidised nitrogen is listed as nitrate.
- *Seawater  $\text{CO}_2$  system variables*. pH values were converted to the total hydrogen ion scale ( $\text{pH}_\text{T}$ ) at  $25^{\circ}\text{C}$ . 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  $\mu\text{mol kg}^{-1}$  (as usually retrieved).
- *Transient tracers*. Expressed in their standard units (see Table 4) (as retrieved, see Table S1).
- *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 (Sect. 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  $\text{O}_2$  (CTDOXY) data were cross-checked against discrete  $\text{O}_2$  (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<sub>2</sub> (CTDOXY) against Winkler O<sub>2</sub> 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<sub>2</sub> 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 (Fig. S1a and b in the Supplement). After the recalibration process, the residuals between CTDOXY and OXYGEN were centred around zero and exhibited lower standard deviations than the original retrieved CTDOXY values (Fig. S1c and d). 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 and CTDSAL paired data (only 315 samples from the MEDIPROD\_IV, PROSOPE and CRELEV cruises, out of the compiled 27 590 total samples) prevented formal verification. Other issues (wrong latitude and longitude coordinates, non-existent stations and/or depths, weird or badly reported units, for example) 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 in the Supplement) 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 NOAA-NCEI-OCADS repository, 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 repository (Jiang et al., 2023), with Digi-

tal Object Identifiers (DOI) listed in Table S2. This repository provides: (i) the WHP-compliant CSV files containing the merged individual 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 a station map.

### 4.2 General overview of cruises included in CARIMED

The CARIMED data synthesis products integrate 46 hydrographic cruises conducted between 1976 and 2018 (Fig. 1, 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. 1a).

Cruises on research vessels' from France, Germany, and Italy account for 68 % of the entire dataset (Fig. 1b). Sampling density increased significantly during the 2000s (Fig. 1c) due to international collaborations enabled by Research Infrastructure initiatives (e.g., EUROFLEETS) and particular 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<sub>2</sub> 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 program has promoted repetition every 5–6 years of North–South hydrographic lines in each MedSea sub-basin, with TALPRO and CRELEV cruises in 2016 (Schroeder et al., 2024b) 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 1c summarises the sample availability by variable across five-year periods. CTD temperature and salinity consistently form the backbone of the hydrographic component. O<sub>2</sub> is the most frequently measured biogeochemical variable,

with nitrate being the most abundant among the dissolved inorganic nutrients. TA is the most abundant seawater CO<sub>2</sub> system variable, followed by pH and DIC. CFC-12 is the most frequent transient tracer, with SF<sub>6</sub> measurements appearing in the most recent period.

### 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 IQC 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 (Tables 1 and S2 and Sect. 6).

#### 4.3.1 Cruises from 1976 to 1988

Early oceanographic studies in the MedSea (e.g., Schmidt, 1912; Wüst, 1961) primarily focused on assessing circulation. Seawater CO<sub>2</sub> 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<sub>2</sub>, and dissolved inorganic nutrients data from this project are publicly available (Minas and MEDAR Group, 2012), its seawater CO<sub>2</sub> system data were recovered by digitising a technical report provided by M. Fichaut (IFREMER).

The Spanish PEP (Producción 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 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<sub>2</sub> system variables, both measured potentiometrically. DIC was measured in only two cruises, also by potentiometric titration. Reference materials for biogeo-

chemical measurements, particularly those related to seawater CO<sub>2</sub> 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<sub>2</sub> system measurements; most cruises measured transient tracers (CFCs, helium, tritium), but none measured SF<sub>6</sub>. These cruises, along with the more recent ones 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'Océanographie 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<sub>2</sub>-in-seawater reference materials were used in this cruise.

The OTRANTO\_5 (1995) was among the first to use CO<sub>2</sub> reference materials 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 western Mediterranean Basins, also used CO<sub>2</sub> reference materials 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 2008 (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'Alcalà, 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<sub>2</sub> reference materials for TA and DIC QC. This cruise was the first MedSea component considered in global data synthesis products like CARINA (Pierrot et al., 2010) and GLODAPv2 (Olsen et al., 2016). Please note that CARIMED cruises also contained in GLODAPv2 (METEOR\_51\_2 and 84\_3, see next section) were retrieved and treated using uncorrected data.

The first cruise compiled for CARIMED with spectrophotometric pH measurements (Clayton and Byrne, 1993) was the Spanish SESAME\_SPI in 2008 (Huertas et al., 2012), followed by several additional SESAME legs and FAMOSO cruises. 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-CO<sub>2</sub> facility (Metzl et al., 2024) at LOCEAN (CNRS, Paris). CO<sub>2</sub> reference materials were used across all cruises; and BOUM was the only cruise to report using reference materials for dissolved inorganic nutrients 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<sub>2</sub> 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<sub>2</sub> reference materials. 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., 2024b). 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 (Sect. 5.3).

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 characterises 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 measured 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-data 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., 2026), 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; Lauvset and Tanhua, 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 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<sub>T</sub> 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 availability of reference materials, 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).

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 analytically challenging. Dissolved inorganic nutrients 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 reference materials (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 dissolved inorganic nutrients (Belgacem et al., 2020) and sensor-based O<sub>2</sub> data (Belgacem et al., 2025a) in the western Mediterranean Basin. Building upon these initiatives, we use 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 2 and Figs. 1 and 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 and 2000 m.
- For the Adriatic Basin, crossovers were performed for water depths greater than 800 m (Cardin et al., 2015).
- For the Tyrrhenian Basin, 2QC was based on crossovers between 1900 and 3000 m.
- For the western Mediterranean Basin, crossovers were performed for waters at depths between 600 and 2000 m.

**Table 2.** Code names and regional areas defined by Manca et al. (2004), illustrated in Figs. 1 and S3. Unique and grouped areas are used to elaborate the 2QC framework analysis in the CARIMED cruises.

| Unique and grouped areas used in the 2QC framework | CODE | AREA                |
|----------------------------------------------------|------|---------------------|
| Gulf of Lion                                       | DF2  | Gulf of Lion        |
|                                                    | DF3  | Liguro Provençal    |
|                                                    | DF4  | Ligurian East       |
|                                                    | DS2  | Balearic Sea        |
| Alboran Sea                                        | DS1  | Alboran Sea         |
| Algerian Basin                                     | DS3  | Algerian West       |
| Western Basin                                      | DS4  | Algerian East       |
|                                                    | DF1  | Algero Provençal    |
| Tyrrhenian Basin                                   | DT1  | Tyrrhenian North    |
|                                                    | DT2  | Tyrrhenian East     |
|                                                    | DT3  | Tyrrhenian South    |
|                                                    | DI1  | Sardinia Channel    |
|                                                    | DI3  | Sicily Strait       |
|                                                    | DJ1  | Adriatic North      |
|                                                    | DJ2  | Adriatic Middle     |
| Adriatic Basin                                     | DJ3  | Adriatic South      |
|                                                    | DJ6  | Ionian NorthWest    |
|                                                    | DJ4  | Ionian NorthEast    |
| Ionian Basin                                       | DJ7  | Ionian MiddleWest   |
|                                                    | DJ8  | Ionian MiddleEast   |
|                                                    | DJ5  | Ionian South        |
|                                                    | DH1  | Aegean North        |
|                                                    | DH2  | Aegean South        |
| Cretan Passage                                     | DH3  | Cretan Passage      |
| Levantine Basin                                    | DL1  | Levantine North     |
|                                                    | DL2  | Levantine NorthEast |
|                                                    | DL3  | Levantine South     |
|                                                    | DL4  | Levantine SouthEast |
|                                                    | ATL1 | Gulf of Cadiz       |
|                                                    | ATL2 | Atlantic            |

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 replaced 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  $\sim 250$  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<sub>2</sub> and dissolved inorganic nutrients.

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 affecting the whole water column (Béthoux et al., 1998; Ozer et al., 2017; Schroeder et al., 2017; Kubin et al., 2023) and regime shifts (Roether et al., 1996; Rubino and Hainbucher, 2007; Schroeder et al., 2016) 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, 2025). 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/>, last access: 26 June 2026), documenting the evidence supporting the adjustments applied (Sect. 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, crossovers even yielded contradictory adjustment directions for the same cruise when evaluated in different sub-basins (e.g. dissolved inorganic nutrients 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 (SD), and mean absolute deviation (MAD) within the minimum temporal variability depth layers (Sect. 5.1), following Belgacem et al. (2025a). These statistical values were calculated for every cruise and grouped according to the sub-basins classification by Manca et al. (2004) (see Table 2, Fig. 1 with the areas and Fig. S3 with the areas and stations compiling with the depth criteria for crossover analysis presented in Sect. 5.1). In this scheme, we inspected in the western Mediterranean Basin: area DS1 (Alboran Sea), area DS3 (Algerian Basin), areas DS4 and DF1 (Western Basin), area DF2 (Gulf of Lion), and areas DT1 and DT2 (Tyrrhenian Basin); in the eastern Mediterranean we inspected: area DJ3 (Adri-

atic Basin), areas DJ5, DJ7, and DJ8 (Ionian Basin), are DH3 (Cretan Passage), and areas DL1, DL2, DL3, and DL4 (Levantine Basin). See Table 2 for more details.

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. 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 reference materials for biogeochemical variables, and on top the long-term temporal variability in the MedSea is evident. Therefore, the adjustment limits are the same order of magnitude as GLODAP but less restrictive (Table 3).

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

The overall mean SD values for each variable were therefore adopted as the minimum adjustment limits. For dissolved inorganic nutrients and O<sub>2</sub>, SD values were converted to a percentage of the mean, providing the relative adjustment limit (Table 3). The high SD value obtained for salinity clearly reflects the significant temporal shifts characteristic of the MedSea over the CARIMED temporal coverage. The O<sub>2</sub> adjustment limit aligns with the value obtained by Belgacem et al. (2025a). Importantly, the derived limit for dissolved inorganic nutrients 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). In contrast, the adjustment limits for TA, DIC, and pH derived from the CARIMED cruises are comparable to GLODAP values.

As noted in Sect. 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 SD 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 Supplement, separating the western MedSea regions (Alboran Sea, Algerian Basin, Western 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, for the

**Table 3.** Adjustment limits for CARIMED calculated from the average standard deviation (SD) of the measured variables in layers with minimum temporal variability across all Mediterranean Sea sub-basins using CARIMED cruises. Absolute SD values are transformed to a percentage using the corresponding mean values for O<sub>2</sub> and dissolved inorganic nutrients.

| Variable  | Average SD<br>Limit of adjustment                            |
|-----------|--------------------------------------------------------------|
| Salinity  | ~ 0.034<br>~ 0.005                                           |
| Oxygen    | ~ 6 $\mu\text{mol kg}^{-1}$<br>~ 3 %                         |
| Silicate  | ~ 0.5 $\mu\text{mol kg}^{-1}$<br>~ 5 %                       |
| Nitrate   | ~ 0.4 $\mu\text{mol kg}^{-1}$<br>~ 5 %                       |
| Phosphate | ~ 0.02 $\mu\text{mol kg}^{-1}$<br>~ 5 %                      |
| DIC       | ~ 4.6 $\mu\text{mol kg}^{-1}$<br>~ 4 $\mu\text{mol kg}^{-1}$ |
| TA        | ~ 4.3 $\mu\text{mol kg}^{-1}$<br>~ 4 $\mu\text{mol kg}^{-1}$ |
| pH        | ~ 0.005<br>~ 0.01                                            |

anomalously low DIC concentrations observed during the MEDIPROD\_IV (1981) cruise across the Alboran, Algerian, Western, and Gulf of Lion regions. Similarly, the low dissolved inorganic nutrient 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 3). Lacking a completely objective quantitative approach (as the standard inversion procedure was not suitable 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 reference materials 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 sepa-

rately 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 S3, and additional graphical justifications are provided in the CARIMED adjustment workbench hosted in GEOMAR (<https://carimed.geomar.de/>, last access: 26 June 2026). 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 4). The proposed corrections are the following:

- *Salinity.* Four cruises needed an adjustment in CTD-SAL, suggesting issues related to CTD calibration, even for recent cruises. Corrections included:
  - A downward adjustment of 0.015 for MC24IS,
  - A downward adjustment of 0.007 for POSEIDON\_234,
  - An upward adjustment of 0.010 for MEDSEA\_2013,
  - A downward adjustment of 0.010 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.* Dissolved inorganic nutrients 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 reference materials.
- *Carbonate system.* For the seawater CO<sub>2</sub> 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., 2025). 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<sub>2</sub> reference materials. A clear example is the OTRANTO\_5 cruise where DIC and TA profiles have a coherent vertical distribution, a good precision, but bad accuracy. The METEOR\_51\_2 TA was corrected both in CARIMED (+5 µmol kg<sup>-1</sup>) and GLODAPv2 (+9 µmol kg<sup>-1</sup>) while no corrections were applied for biogeochemical variables in the METEOR\_84\_3 cruise in both data products. Preliminary 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.

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 (Sect. 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 dissolved inorganic nutrients 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.

## 6 CARIMED data synthesis products availability

Along with the individual original cruise data files, CARIMED outcomes consist of two data synthesis products: (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<sub>2</sub> and dissolved inorganic nutrients)

if seawater CO<sub>2</sub> data is available. See Table 4 for the variables information and Table S4 regarding the corresponding flags.

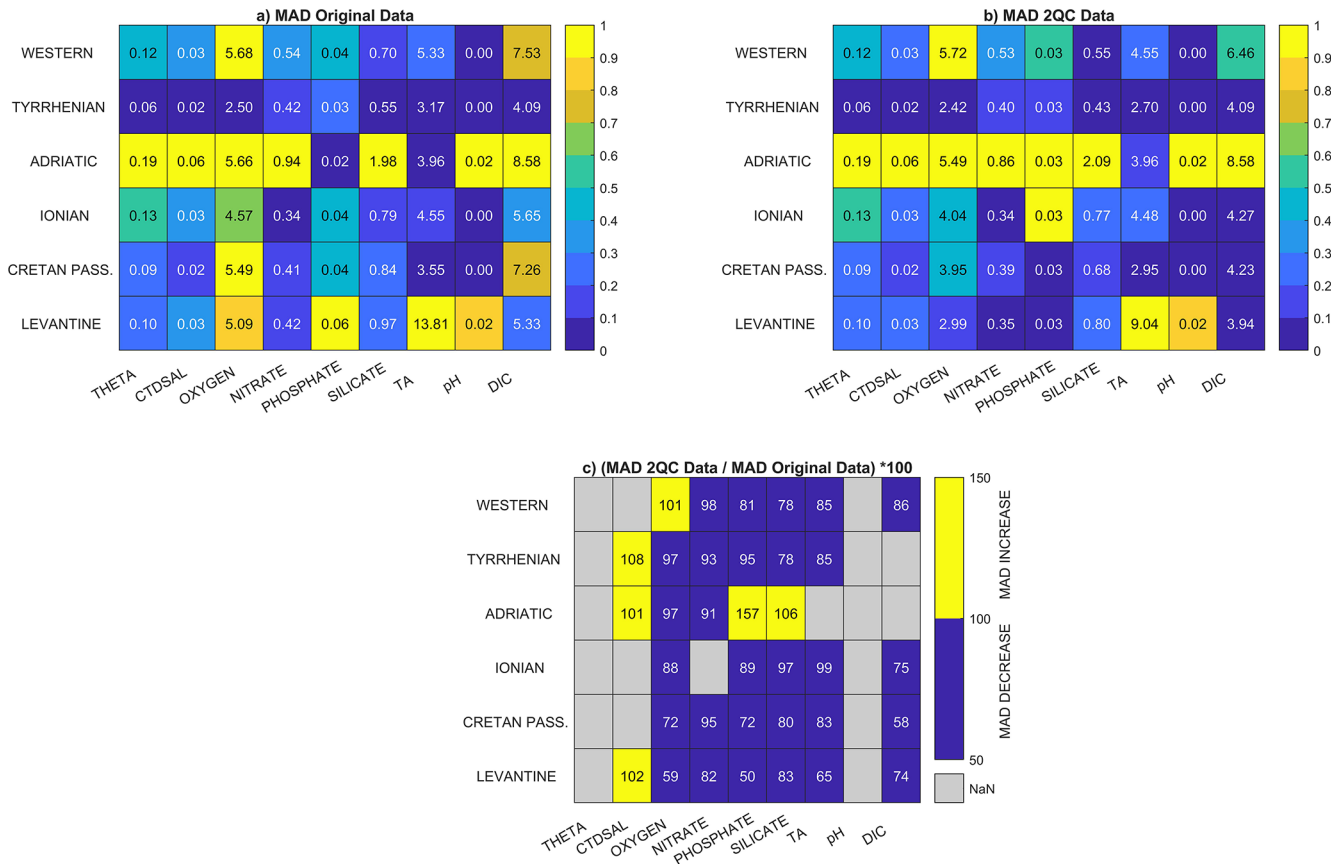
### 6.1 Aggregated original cruise data synthesis product

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 4 for the full variable list). These include:

- cruise identifiers such as ALIAS and CRUISENO (identifying each cruise according to the NCEI-OCADS system, alphabetically ordered by EXPCODEs; Table S2), year, and month;
- derived physical and chemical variables, including potential temperature and density anomalies (calculated using the Thermodynamic Equation Of Seawater – 2010, TEOS-10; IOC, SCOR and IAPSO, 2010), partial pressures of CFC-11 and CFC-12 (Warner and Weiss, 1985), CCl<sub>4</sub> (Bullister and Wisegarver, 1998), CFC-113 (Bu and Warner, 1995), and SF<sub>6</sub> (Bullister et al., 2002), and apparent oxygen utilization (AOU; García and Gordon, 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) (see Table S4). The dataset is organized by cruise, with each cruise identified by its EXPCODE.

CTD salinity (CTDSAL) is the only salinity variable included, as it is available for nearly all cruises. Salinometer data from the following cruises: MILLERO\_76, GEOSECS\_Leg3 and OTRANTO\_5, were assigned to the CTDSAL variable with flag 0 (interpolated values) (432 samples vs a total of 27590, Table S4). 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 (see Table S4) 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/>, last access: 26 June 2026); <https://doi.org/10.20350/digitalCSIC/17785> (García-Ibáñez et al., 2025).



**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 (Sect. 5.1). Regions are shown in the y-axis and physical and biogeochemical variables in the x-axis: potential temperature (THETA, in °C), salinity (CTDSAL), dissolved oxygen (OXYGEN, in  $\mu\text{mol kg}^{-1}$ ), dissolved inorganic nutrients (NITRATE, PHOSPHATE, and SILICATE, all in  $\mu\text{mol kg}^{-1}$ ), total alkalinity (TA, in  $\mu\text{mol kg}^{-1}$ ), pH on the total hydrogen ion scale at 25 °C (pH), and total dissolved inorganic carbon (DIC, in  $\mu\text{mol kg}^{-1}$ ). The Western Basin comprises areas DF1 and DS4 (Algero-Provençal and Algerian East); the Tyrrhenian Basin comprises areas DT1 and DT3 (Tyrrhenian Sea North and Tyrrhenian Sea South); the Adriatic Basin comprises area DJ3 (Adriatic South); the Ionian Basin comprises areas DJ5, DJ7, and DJ8 (Ionian South, Middle East, and West, respectively); the Cretan Passage region comprises area DH3 (Cretan Passage), and the Levantine Basin comprises areas DL1, DL2, DL3, and DL4 (Levantine North, North East, South and South East, respectively) (see Figs. 1 and S3 and Table 2 for more information).

## 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, with two exceptions: dissolved oxygen is only provided as the combined variable OXYGEN with mainly discrete Winkler data and calibrated sensor-based oxygen data (see Sect. 6.1 and Table S4), pH is also provided at in situ temperature and pressure conditions from bias-adjusted data. In situ pH was calculated with the CO2SYS package for Matlab® (van Heuven et al., 2011) with option 10 for the CO<sub>2</sub> constants (Lueker et al., 2000) and option 1 for the total boron to chlorinity ratio (Üppstrom, 1974) and bisulphate constant (Dickson, 1990) as agreed by the GLODAPv2 team (Olsen et al., 2016; Velo et al., 2010).

Please note that in situ pH was mostly calculated from measured TA and pH (5929 samples from a total of 6726), when TA was unavailable from measured DIC and pH (212 samples from a total of 6726) and finally, if no DIC or TA was available, a constant value of  $2500 \mu\text{mol kg}^{-1}$  was assumed for TA (584 samples from a total of 6726). Crucially, it exclusively contains values flagged as “good” (flag 2) and interpolated (flag 0), sensor-based or vertically as following. The bias-adjusted data product incorporates the adjustments derived from the 2QC analysis to remove systematic offsets, thus establishing an improved consistency.

Where seawater CO<sub>2</sub> system data were available, and ancillary variables such as O<sub>2</sub> and dissolved inorganic nutrients were either missing or deemed unreliable (flagged as 3), these variables were vertically interpolated using a

**Table 4.** 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 <sup>a</sup> | Variable 2QC adjusted <sup>b</sup> |
|------------------------------------------------------------------------------------------------|------------|-------------------------|--------------------------|------------------------------------|
| Expedition code                                                                                | EXPCODE    |                         |                          |                                    |
| Cruise alias                                                                                   | ALIAS      |                         |                          |                                    |
| Cruise number                                                                                  | CRUISENO   |                         |                          |                                    |
| Date (YYYYMMDD)                                                                                | DATE       |                         |                          |                                    |
| Time (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 <sup>c</sup>                                                                        | CTDOXY     | $\mu\text{mol kg}^{-1}$ | CTDOXY_FLAG_W            |                                    |
| Winkler Oxygen                                                                                 | OXYGEN     | $\mu\text{mol kg}^{-1}$ | OXYGEN_FLAG_W            | OXYGEN_2QC                         |
| Apparent Oxygen Utilization                                                                    | AOU        | $\mu\text{mol kg}^{-1}$ | OXYGEN_FLAG_W            |                                    |
| Silicate                                                                                       | SILCAT     | $\mu\text{mol kg}^{-1}$ | SILCAT_FLAG_W            | SILCAT_2QC                         |
| Nitrate+Nitrite                                                                                | NITRAT     | $\mu\text{mol kg}^{-1}$ | NITRAT_FLAG_W            | NITRAT_2QC                         |
| Nitrite                                                                                        | NITRIT     | $\mu\text{mol kg}^{-1}$ | NITRIT_FLAG_W            |                                    |
| Phosphate                                                                                      | PHSPHT     | $\mu\text{mol kg}^{-1}$ | PHSPHT_FLAG_W            | PHSPHT_2QC                         |
| Total Dissolved Inorganic Carbon                                                               | TCARBN     | $\mu\text{mol kg}^{-1}$ | TCARBN_FLAG_W            | TCARBN_2QC                         |
| Total Alkalinity                                                                               | ALKALI     | $\mu\text{mol kg}^{-1}$ | ALKALI_FLAG_W            | ALKALI_2QC                         |
| 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                     |
| pH on the total hydrogen ion scale at in situ temperature and pressure conditions <sup>d</sup> |            |                         | PH_TOT_25C_FLAG_W        | PH_TOT_IS_2QC                      |
| Chlorofluorocarbon 11                                                                          | CFC-11     | $\text{pmol kg}^{-1}$   | CFC-11_FLAG_W            |                                    |
| Chlorofluorocarbon 12                                                                          | CFC-12     | $\text{pmol kg}^{-1}$   | CFC-12_FLAG_W            |                                    |
| Chlorofluorocarbon 113                                                                         | CFC113     | $\text{pmol kg}^{-1}$   | CFC113_FLAG_W            |                                    |
| Sulfur hexafluoride                                                                            | SF6        | $\text{fmol kg}^{-1}$   | SF6_FLAG_W               |                                    |
| Carbon tetrachloride                                                                           | CCL4       | $\text{pmol kg}^{-1}$   | 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 <sub>6</sub>                                                            | pSF6       | ppt                     |                          |                                    |
| Partial pressure of CCL <sub>4</sub>                                                           | pCCL4      | ppt                     |                          |                                    |
| Tritium ( <sup>3</sup> H)                                                                      | TRITUM     | TU                      | TRITUM_FLAG_W            |                                    |
| <sup>3</sup> H counting error                                                                  | TRITER     | TU                      |                          |                                    |
| Helium (He)                                                                                    | HELIUM     | $\text{nmol kg}^{-1}$   | HELIUM_FLAG_W            |                                    |
| He counting error                                                                              | HELIER     | $\text{nmol kg}^{-1}$   |                          |                                    |
| $\delta^3\text{He}$                                                                            | DELHE3     | %                       | DELHE3_FLAG_W            |                                    |
| $\delta^3\text{He}$ counting error                                                             | DELHER     | %                       |                          |                                    |
| Neon (Ne)                                                                                      | NEON       | $\text{nmol kg}^{-1}$   | NEON_FLAG_W              |                                    |
| Ne counting error                                                                              | NEONER     | $\text{nmol kg}^{-1}$   |                          |                                    |
| Potential Temperature (ITS-90)                                                                 | THETA      | Degree Celsius          |                          |                                    |
| Potential density anomaly referred to surface                                                  | SIGMA0     | $\text{kg m}^{-3}$      |                          |                                    |

Table 4. Continued.

| Variable                                        | Header       | Units              | Flag Header <sup>a</sup> | Variable 2QC adjusted <sup>b</sup> |
|-------------------------------------------------|--------------|--------------------|--------------------------|------------------------------------|
| Potential density anomaly referred to 1000 dbar | SIGMA1       | kg m <sup>-3</sup> |                          |                                    |
| Potential density anomaly referred to 2000 dbar | SIGMA2       | kg m <sup>-3</sup> |                          |                                    |
| Potential density anomaly referred to 3000 dbar | SIGMA3       | kg m <sup>-3</sup> |                          |                                    |
| Potential density anomaly referred to 4000 dbar | SIGMA4       | kg m <sup>-3</sup> |                          |                                    |
| Neutral density                                 | GAMMA        | kg m <sup>-3</sup> |                          |                                    |
| Maximum Sampling Depth                          | MAXSAMPDEPTH | meters             |                          |                                    |
| Bottom Depth                                    | DEPTH        | meters             |                          |                                    |

<sup>a</sup> the aggregated original data product includes data flagged as 3 (probably bad), 2 (good), and 0 (interpolated). <sup>b</sup> the bias adjusted data product contains only data flagged as 2 (good) and 0 (interpolated). <sup>c</sup> the bias adjusted data product contains no CTDOXY but the merged OXYGEN variable with measured Winkler and calibrated CTDOXY data. <sup>d</sup> just the bias adjusted data product contains pH on the total hydrogen ion scale at in situ temperature and pressure conditions, calculated from bias-adjusted data.

quasi-Hermitian piecewise polynomial, closely following the GLODAP procedure (Olsen et al., 2016) (see Table S4).

The final CARIMED bias-adjusted data synthesis product is available from NCEI-OCADS (https://www.ncei.noaa.gov/, last access: 26 June 2026); 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 Data availability

CARIMED information is hosted at NCEI-OCADS, https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/oceans/CARIMED/ (CARIMED, 2026) with links to relevant information, the original cruise summary table and the data products. 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.

## 8 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 integrat-

ing 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. 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 frame-  
 5 work 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.

10 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  
 20 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 proba-  
 25 bly 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  
 30 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  
 35 support North African countries in Med-SHIP hydrographic cruises to foster collaboration, exchange knowledge and improve sampling coverage within under sampled MedSea regions.

**Supplement.** The supplement related to this article is available  
 40 online at [the link will be implemented upon publication].

**Author contributions.** MA, MIGI and TT designed the study, conceptualization, methodology, validation and formal analysis. The manuscript was written by MA and MIGI, with contributions from all authors. NL and AV conducted the crossover analysis for  
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 75

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 80

We strongly encourage potential stakeholders and users to follow FAIR data use practices and to contact principal investigators to explore collaboration opportunities and co-authorship.

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