

Review and Synthesis: operational prediction of ocean biogeochemistry in the Copernicus Marine Service. Main achievements and perspectives

Dear Editor,

We thank the three reviewers for their detailed and constructive comments, which have led to a substantially revised manuscript. The reviewers converged on several points: the manuscript read too much like a technical report, its introduction and tables were overloaded, several acronyms and citations were missing or inaccurate, the SWOT framing was inappropriate for a scientific journal, and the future directions were not laid out consistently across the forecasting centres. We addressed each of these points as follows.

The introduction has been rewritten and shortened. Section 2 now presents the six models first and explains the modelling concepts in plain language, before describing what converged across the systems over the decade. The data assimilation section opens with a general definition, describes the algorithmic evolution of the operational systems, credits the assimilation software with the appropriate references and acknowledges the contribution of the SEAMLESS project. All tables have been redesigned: two remain in the main text, and the per-centre details have been moved to seven thematic supplementary tables, including a new table outlining the developments planned in each centre for 2025–2028. The SWOT section has been replaced by a discussion of achievements, limitations, prospects and risks, with an expanded treatment of artificial intelligence and of the algorithmic perspectives for data assimilation, and a Conclusions section has been added. The term "green ocean" has been removed and all acronyms are defined at first use and gathered in an appendix.

On two points we respectfully maintain our position and explain why in the responses: the review deliberately covers the first decade of the Service (2015–2024), with the subsequent developments summarised in a dedicated table (S7) and we consider that the Copernicus Marine Service collectively defines the state of the art of operational biogeochemical forecasting.

Our point-by-point responses to each reviewer is submitted and the revised version of our work takes into account all the comments raised by the three reviewers.

With kind regards, on behalf of all co-authors,

Marilaure Grégoire

Answer to Reviewer 1 (in bold our answer point by point).

The authors provide a review of the history of CMEMS along with a description of the biogeochemical models and the regions (monitoring and forecasting centers) where they are being deployed. They also present some example model results and evidence for improvements in biogeochemical modeling and data assimilation. The manuscript is not difficult to read, but the text could be improved in many places to make it more accessible and useful for a wider variety of readers.

General comments

I enjoyed reading about the history of CMEMS and bits about the more general history of operational oceanography and data assimilation. Yet, the introductory text sometimes feels repetitive and not very informative. For example, the description of the Global Ocean Data Assimilation Experiment (GODAE) contains 3 mentions of its time frame in the same paragraph: "1998-2008" (l 43), "GODAE was a 10-year international initiative" (l 44), and "GODAE ended in 2008" (l 51). Its international nature is mentioned twice and so are its achievements: "GODAE demonstrated the feasibility and value of a long-term global ocean observing system supporting real-time ocean forecasting and (re)analysis" (l 47) and "GODAE ended in 2008 and has allowed to achieve significant progress in our forecasting capabilities of ocean physics". Here, the text could be tightened and more information could be added, making it a better and more informative read without using up more space. Similarly, some of the introduction reads like a list of projects (project X was followed by project Y) without providing much, sometimes any (e.g., GMES), information about the projects. Overall, the introductory texts in sections 1 and 2 could be improved structurally in many places to make them more informative and less repetitive for the reader.

Answer: The introduction has been substantially reworked and shortened, focusing on the evolution towards operational biogeochemistry (see also our response to comment 7 of Reviewer 3, whose requests converge with this comment). The redundancies noted by the reviewer have been removed: GODAE's time frame, international character and achievements are now each stated once, in a single condensed paragraph. The "list of projects" character has been reduced by stating, for each step of the programme lineage, the capability it added: GMES is now defined together with its objective; MERSEA introduced the first global coupled physical–biogeochemical assimilation prototype (Brasseur et al., 2009); the MyOcean projects (2009–2015) developed the pre-operational marine core services; and the Copernicus Marine Service made them fully operational in 2015. An explicit definition of the NRT and MY product lines has been added at the end of the introduction. Sect. 2 now opens directly with the description of the modelling systems, the historical and contextual material having been consolidated in the introduction.

As I was reading through the manuscript, there were a few instances where I thought the level of detail provided was not very helpful to a typical reader. Readers familiar with biogeochemical ocean models were given statements that they knew by heart, while not enough detail was given for readers unfamiliar with the subject. A good example of this pattern appears in line 101: "All these processes are mathematically formulated. These models are NPZD-type models encompassing a wide range of complexities. The models differ by the levels of details in the description of the inorganic and organic (living and dead) components and interactions." These sentences state quite basic facts about biogeochemical ocean models and thus aren't really useful to readers who work with them. Yet, I agree that there is clearly a benefit to describing biogeochemical models to other readers. But what does "these processes are mathematically formulated" mean, what are "NPZD-type models" and how does that relate to "inorganic and organic (living and dead) components". The readers who would benefit from learning more about biogeochemical ocean models are not given enough information and provided with an inadequate description here and in other places. I recommend that the authors go through the technical descriptions included in the manuscript and improve them.

Answer: We agree with the reviewer. Section 2.1 has been rewritten with the non-specialist reader in mind. The empty formulations ("NPZD-type models", "these processes are mathematically formulated") are gone. The section now actually explains how these models are built: ocean

material is separated into inorganic and organic compartments, the living part is aggregated into plankton functional types (the PFTs represented in each model are listed and compared), and we describe what is gained and lost when elemental ratios are fixed rather than variable, how the dead organic pools are treated, and which specific processes (denitrification, anammox, nitrogen fixation) are included. Sect. 2.2 gives the mass-balance equation governing any biogeochemical tracer (Eq. 1), and Sect. 2.1 states explicitly that the process formulations are largely empirical, derived from laboratory experiments and extrapolated to the real ocean. Table 1 compares the six models and targets a more expert user. Following the reviewer's recommendation, we applied the same treatment to the other technical descriptions: the data assimilation section now opens with a short plain-language definition of the background/analysis concepts before entering the specifics of each system.

The manuscript text includes many abbreviations, some of which are not explained, even though that would be useful to the reader. I have tried to highlight a subset of those in my specific comments below, but I would recommend that the authors go through the text again with an eye on the abbreviations that are being introduced.

Answer: We have gone through the whole manuscript (text, tables and figure captions) specifically for abbreviations. Acronyms that appeared only once or twice have been spelled out and removed; those that are used throughout the manuscript are now defined at their first occurrence and gathered in an abbreviation list at the end of the manuscript (Appendix A). The specific cases highlighted by the reviewer in the comments below have each been checked and are addressed point by point there. We renamed or clarified some service-specific jargon.

The manuscript makes a brief mention of SOCAT. Overall, there is now a variety of capable statistical models aimed at estimating carbonate system variables but also others, such as nitrate. These include ESPER (Carter et al., 2021, DOI: 10.1002/lom3.10461) and CANYON-B (Bittig et al., 2018, DOI: 10.3389/fmars.2018.00328), and also region-specific versions like CANYON-MED for the Mediterranean (Fourrier et al., 2020, DOI: 10.3389/fmars.2020.00620). These statistical models provide novel ways to assess or improve biogeochemical models and deserve a mention in the "Opportunities and perspectives" section.

Answer: We agree with the reviewer that these methods deserve to be explicitly referred to. We have added a sentence citing the three references as follows: "*Data-driven estimation methods such as ESPER (Carter et al., 2021), CANYON-B (Bittig et al., 2018) and its regional variant CANYON-MED (Fourrier et al., 2020) infer carbonate-system variables, inorganic nutrients and oxygen from standard hydrographic observations. Applied for instance to Argo profiles, they considerably extend the set of variables available for model evaluation, and potentially for assimilation, following the same logic as the PPCn nitrate reconstructions already assimilated operationally in the Mediterranean system (Sect. 2.3)*".

Specific comments

Fig. 1 caption: "used in the CMEMS MFCs in 2024 in the seven MFCs": Double-mention of MFCs.

Answer: Corrected. The caption now reads: "Figure 1: Biogeochemical models used in the seven regions covered by CMEMS: The Global, Arctic, Baltic, Black and Mediterranean Seas, the Iberia-Biscay-Ireland area and the North-Western European Shelf "

L 28: Mention what "SWOT" stands for.

Answer: "SWOT" is no longer used in the manuscript. Following a similar comment of Reviewer 3, the former SWOT framing has been abandoned: Sect. 5 has been renamed "Discussion: achievements, limitations and perspectives", the SWOT table (former Table 3) has been removed.

L 37: Here the tense used switches between past and present: "The 90's marks [...] In this decade, observing systems had developed sufficiently [...] The ocean surface is observed [...] GODAE was a 10-year international initiative".

Answer: The paragraph has been entirely rewritten and now uses the past tense.

L 48: The abbreviation "CLIVAR" is not explained, and neither is "WOCE" in the following sentence.

Answer: CLIVAR is no longer mentioned in the reworked introduction. WOCE has also been removed, including from the caption of Fig. 6, where "repeated sections (e.g. WOCE)" now reads "repeated hydrographic sections".

L 60: GMES started and ended; what happened in between?

Answer: This section has been rewritten as: *" In parallel, in 1998, the European Commission, European Space Agency and national space agencies launched the Global Monitoring for Environment and Security (GMES) program to provide an operational observation capability combining space and in-situ data with models to deliver pre-operational services for environmental monitoring and security. During GMES, the European Marine Environment and Security for the European Area (MERSEA, 2004-2008) project extended the forecasting of physics to biogeochemistry and developed forecasting systems for the global and regional oceans. During MERSEA, a prototype of a coupled physical-biological assimilation system based on the Pelagic Interactions Scheme for Carbon and Ecosystem Studies (PISCES) model (Aumont et al., 2003) was developed to routinely forecast biogeochemical variables over the globe with weekly delivery of biogeochemical products (Brasseur et al., 2009). MERSEA was followed by the European MyOcean project (2009–2012), MyOcean2 (2012-2014) and MyOcean Follow-on (2014-2015) that provided in a pre-operational context marine core services and capabilities. GODAE transitioned to GODAE OceanView (GOV) in 2009 to further mature the forecasting systems including new data streams and assimilation methods, sea-ice and biogeochemical modelling, and routinely providing an enhanced set of products of increased quality to support new user applications. In 2019, GOV was renamed OceanPredict, an international research and development network to accelerate, strengthen and increase the impact of ocean prediction (<https://oceanpredict.org/>). OceanPredict operates six task teams, among which is the Marine Ecosystem Analysis and Prediction Task Team (MEAP-TT). MEAP-TT aims to improve biogeochemical and biological operational systems (for reanalysis, forecast and projections) in terms of model, data integration via data assimilation methods and product delivery to support user needs. OceanPredict has initiated several programs and projects focused on ocean prediction endorsed by the UN Ocean decade. In 2012, GMES was renamed Copernicus, the Earth-observation component of the EU space programme, and its marine service became fully operational in May 2015".*

L 67: "GODAE transitioned to GODAE OceanView (GOV)": It would be useful to provide a year here.

Answer: GODAE OceanView succeeded GODAE in 2009 and became OceanPredict in 2019. This has been clarified in the revised version.

L 75: "Biogeochemical and biological ocean variables are more difficult to observe routinely using sensors on board satellite and in-situ autonomous platforms.": This sentence is not clear, in that it does not mention what the difficulty is: Is it more difficult to observe biogeochemical and biological ocean variables routinely compared to non-routinely? Is it more difficult to use the sensors on board of satellites and in-situ autonomous platforms to observe biogeochemical and biological ocean variables? I assume the authors mean to compare biogeochemical and biological observations to physical observations; this should be made more explicit and explained better. L 76: "The situation is particularly critical for biological data that still require field sampling and laboratory analyses.": Well indeed, because these variables cannot be observed at all using remote sensing or autonomous platforms. I would suggest rephrasing to something like, "In fact, some biogeochemical and biological data such as X still require field sampling and laboratory analyses."

Answer: The sentence has been removed from the introduction. The comparison biogeochemical versus physical observations is now made in the Discussion section (i.e. Sect. 5) highlighting the point raised by the reviewer about biological data: "*The abundance of biogeochemical and, even more, biological observations still lags far behind that of physical observations: from space, only ocean colour gives an indirect access to biogeochemistry, and only in the surface layer under cloud-free conditions, while in-situ biogeochemical sensors on autonomous platforms cover fewer variables and remain scarce, more costly and less stable (sensor drift, biofouling) than their physical counterparts. Because they largely require ship-based sampling and laboratory analysis, biological variables (e.g. zooplankton, benthic biomass, fish biomass) are still extremely scarce, limiting model development and the delivery of an exhaustive quality assessment of all biogeochemical and biological products to fit users' purposes.*"

L 77: This is not a good use of "on the other hand", because it mentions yet another reason why observing and modeling the green ocean is more difficult than the blue ocean. "Furthermore" would be more suitable, and "on the other hand" or "however" could be used for the next sentence, which describes an advancement despite the difficulties described here. It might also make sense to use "physical circulation model" in this sentence to better make the distinction between physical and biogeochemical modeling.

Answer: The reviewer is right about the use of "on the other hand"; the sentence has however been removed altogether in the shortened introduction.

L 94: "2.1 Model structure": This section title is very short and nondescript and makes the reader expect the description of the structure of a single model. "Structure of the CMEMS biogeochemical models" would be more informative and useful to the reader. A similar remark applies to the following section titled "2.1.1. Description" -- what is being described here?

Answer: We agree with this suggestion. The section is now titled "*2.1 The structure of the CMEMS biogeochemical models*", and the uninformative sub-heading "*2.1.1 Description*" has been removed.

L 103 and following: The text here is a good example of information spread around and sometimes repeated that is not helpful to the reader: Paragraph 1 in Section 2.1.1 mentions "all the CMEMS

models", provides a general description of BGC models and introduces the two most complex CMEMS models (ERSEM and BFM) without citations. Paragraph 2 broadly describes the models' applications, including regions of application, without providing specifics. Paragraph 3 then finally mentions that there are 6 CMEMS models with citations and gives a location for each. This is the information that the reader could have used at the start. I would suggest starting out with the six models, mentioning what they have in common, what makes them distinct, and why the large range of marine environments requires these different model formulations.

Answer: This is indeed an excellent suggestion that we adopted. Section 2.1 now starts with the six models, their citations and their regions of application (former paragraph 3 is now the first one); it then describes what the models have in common (the compartment structure, the elements cycled, the PFT approach) and what distinguishes them (number of PFTs, stoichiometry, explicit bacteria, organic pools, benthic treatment, all summarized in Table 1). A closing statement explains why the range of marine environments covered by the Service motivates these different formulations, and why the diversity of complexity is a deliberate choice rather than a hierarchy of quality (Raick et al., 2006; Friedrichs et al., 2007; Ward et al., 2010). See lines 99-102.

L 118: "Over the past decade, two MFCs changed their model, for a more suitable model or a change of partner. The ARC-MFC...": Could this information be moved to Section 2.1.2 "Evolution of CMEMS biogeochemical models over 2015-2024"?

Answer: This has been moved to the paragraph describing the evolution of model structure over 2015-2024.

L 125 and following: Another example of descriptions that are spread out and could be connected and perhaps shortened. Paragraph 1 in Section 2.1.1 briefly describes and lists all elements in CMEMS models; it then also describes how compartments/variables are used in the model. It mentions biogeochemical reactions/dynamics transfer elements from one compartment to another; it mentions that "these models are NPZD-type models" (l 101). This information is then expanded on and partly mentioned again in paragraphs 4 and 5, which describe the division of phytoplankton into groups and the elemental stoichiometry. A more structured approach could be to introduce the concept of NPZD-type models, including compartments, elements and dynamics, how phytoplankton compartments are representing PFTs, which elements are used, etc.

Answer: This section has been significantly reorganized and rewritten to be read more smoothly. Please see our response to the comment on L 103, which details the new structure of the section and also the revised manuscript and section 2.

L 172: "To obtain the complete radiance distribution in time, spatial and spectral space requires solving a full radiative transfer model, which is computationally expensive...": Perhaps mention here that PAR is typically still treated as a single spectral band in many applications. That is, describe the simple approach, the spectral decomposition, and where the CMEMS models fall on the spectrum.

Answer: A sentence now states that most CMEMS models still treat PAR with one or a few spectral bands, before introducing the spectrally resolved schemes recently adopted by BAMHBI and BFM; the "Light" row of Table 1 clarifies the scheme adopted by each model as suggested by the reviewer.

L 193: Explain what "MY" stands for.

Answer: Done in the introduction, in the new paragraph defining the NRT and MY product lines, and in Appendix A.

Eq 1: Consider calling the "sedimentation" term "sinking and sedimentation".

Answer: We rename sedimentation to sinking.

L 234: "2.4 Spatial resolution": It would be useful to include some numbers -- which resolutions are used by the models?

Answer: Typical values are now given in the text in section 2.5 *"The modelling systems are eddy-permitting in the global ocean (i.e. horizontal resolution of ~27.5 km) and eddy-resolving to submesoscale-permitting (horizontal resolution of 2-25 km) in the regional seas. The number of vertical levels increased by a factor of 1.7 to 3.3 in four of the seven NRT systems and in three of the MY systems (ARC, BLK, MED), while it remained unchanged in the PISCES-based GLO and IBI systems"*, the full per-MFC detail remaining in Table S3 for avoiding an overload of technical details in the main text.

L 262: "2.6 Data Assimilation": Here it would be useful to many readers to briefly describe data assimilation and its goals.

Answer: A short definition of data assimilation and why it is used are now provided as an introduction to the Data Assimilation section.

L 264: "(Ensemble) Kalman filters and smoothers and 3Dvar are the DA methods of choice.": If not too complicated, add which model is using which DA technique.

Answer: We have dedicated a specific table, Table S4, to provide information about the DA technique with appropriate references as requested by reviewer 3.

Fig. 2: Change x-axis labels to dates like in Fig. 3e.

Answer: The x-axis of Fig. 2 now shows dates, as in Fig. 3e.

Fig. 2 caption: The use of "synthetic chl a profile assimilation" and "The nudging of the synthetic profiles" is not helpful, because readers may not understand that assimilation and nudging refer to the same process.

Answer: *the legend has been rewritten as: "Evolution of the Root Mean Square Deviation (RMSD) computed, over the Nordic Seas, between Chl-a concentration from model results and BGC-Argo observation for 5 depth ranges in the top 100m in 2015-2019. After January 2017, the ARC-MFC NRT system has assimilated synthetic vertical Chl-a profiles reconstructed from ocean colour data extended at depths. The subsequent decrease of the RMSD is consistent with the expected benefit of the assimilation. Bar plots are number of BGC-Argo profiles data used for calculating the RMSD. "*

Fig. 2 caption: "over the first 100m and 2015-2019 and for 5 depth ranges": I would suggest changing to "for 5 depth ranges in the top 100m in 2015-2019".

Answer: the legend has been rewritten, see above.

L 318: "Four of the seven CMEMS biogeochemical models": I presume these should be the seven MFCs.

Answer: *Five of the MFCs assimilate both physical and biogeochemical variables though the physical data assimilation does not correct the biogeochemical variables and vice-versa. In these weakly coupled data assimilation systems, the assimilation of physical variables may cause spurious physics causing a degradation of the quality of predicted biogeochemical variables. This is the case, for instance, in the global ocean where the assimilation of the physics creates spurious upwelling of nutrients and excessive primary production in the equatorial region (Ford et al., 2018; Gasparin et al., 2021). This problem is managed by activating a relaxation towards three-dimensional climatological fields of biogeochemical data. Due to nonlinear processes, strongly coupled assimilation (e.g. the assimilation of physical variables corrects the biogeochemical ones) has proven challenging and is not applied in any of the operational systems today. In the IBI system, only physical variables are assimilated; biogeochemical variables are not directly corrected but respond dynamically to the assimilated physical state through the online coupling, and their response is used to improve the assimilation methodology.*

Fig. 4: Why are observations shown using different markers (x's and o's)?

Answer: The revised figure uses a single marker and the caption has been clarified (please note that Fig 4 is now Fig. 5).

Fig. 5: Include "nitrate difference" in the 3rd row colorbar labels, just like the first and second rows also state what is shown. It is not helpful that the caption calls it "free run", but the labels say "no DA run" (or just "no DA").

Answer: The colorbar of the third row is now labelled "nitrate difference", and the run naming has been harmonized between the caption and the panel labels ("no DA" throughout) (this figure is now Fig. 4)

Fig. 6: The colors are nice, but it would be useful to also include numbers in the center of each square where entries are non-zero.

Answer: Numbers have been added at the centre of the non-zero cells. We thank the reviewer for the suggestion.

L 394: It is interesting to see all RMSD values aggregated together into a single distribution. Which data products are mainly contributing to this ratio? Why not divide it up by observation type (as described in the lines above)? Later, I see that some of this is done in the following Fig. 8. I would suggest combining the two figures.

Answer: The two figures are now merged into Fig. 7, highlighting the data products used to estimate the RMSD ratio.

L 482: "carbonates": Does this include pH and pCO₂? It might make sense to mention them explicitly.

Answer: The carbonate variables are listed explicitly when they are first mentioned in Sect. 2.1 (pH, pCO₂, dissolved inorganic carbon, alkalinity, air-sea CO₂ flux); the generic term is kept afterwards to avoid repetition.

L 495: "sound quality assessment": This makes it sound like "sound quality" is assessed; I would suggest rephrasing.

Answer: This has been reformulated as: *"Because they largely require ship-based sampling and laboratory analysis, biological variables (e.g. zooplankton, benthic biomass, fish biomass) are still extremely scarce, limiting model development and the delivery of an exhaustive quality assessment of all biogeochemical and biological products to fit users' purposes."*

L 505: "A coordinated predictability analysis as such done in Leroux et al., (2022) would allow to set a limit to the minimum length scales and the time horizon that are predictable considering the different sources of error, with among them, some that cannot be reduced, at least currently." What exactly does this mean? That a predictability analysis could provide better forecast time windows and resolutions at which the model stays close to observations? Or indicate the key sources of model error? Some more explanation would be useful here -- and breaking up the long sentence, so it becomes easier to understand.

Answer: This has been reformulated as :*" A coordinated predictability analysis such as done in Leroux et al. (2022) would allow to set a limit to the minimum length scales and the time horizon that are predictable; i.e. to estimate, for each variable and region, the smallest scales and longest lead times at which the forecast remains more skilful than climatology, given the irreducible uncertainties in forcings and parameters."*