Assessment of gap-filling techniques applied to satellite phytoplankton composition products for the Atlantic Ocean

Ehsan Mehdipour[1,2], Hongyan Xi[1], Alexander Barth[3], Aida Alvera-Azcárate[3], Adalbert Wilhelm[2], Astrid Bracher[1,4]

[1]Alfred Wegener Institute (AWI), Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
[2]School of Business, Social & Decision Sciences, Constructor University, Bremen, Germany
[3]GeoHydrodynamics and Environment Research (GHER), University of Liège, Liège, Belgium
[4]Institute of Environmental Physics, University of Bremen, Bremen, Germany

Correspondence to: Ehsan Mehdipour (ehsan.mehdipour@awi.de)

Author Comments in response to Referee #1

This manuscript presents a timely and relevant study that assesses the performance of two gap-filling methods, DINEOF and DINCAE, applied to satellite-derived chlorophyll-a and phytoplankton functional type products in the Atlantic Ocean. The study is well-motivated, and the methodological rigor is commendable. The work contributes meaningfully to the ocean color remote sensing community and addresses a practical challenge in producing spatially continuous biogeochemical products. Therefore, I recommend this paper for publication. However, there are several aspects of the manuscript that would benefit from revision to improve clarity, structure, and academic presentation.

- We sincerely thank the reviewer for the constructive and detailed comments and suggestions, which have greatly helped us to improve the quality and clarity of the manuscript. We have carefully addressed each point in our responses below and will revise the manuscript accordingly, as indicated in the respective replies.

1. The manuscript is generally well-written, but there are a few areas where sentence structure and clarity could be improved. The introduction section is overly long and contains redundant background descriptions, which compromise the logical flow. It is recommended that the authors streamline this section by first clearly identifying the problem posed by data gaps in phytoplankton functional type products, followed by a focused overview of existing gap-filling methods, and then a concise rationale for selecting and comparing DINEOF and DINCAE in this study. A clearer structure will help readers better grasp the novelty and objectives of the work.

- We have restructured the Introduction section to improve clarity and logical flow. The revised version follows a three-step structure as suggested: (1) a clear identification of the problem related to data gaps in PFT products, (2) a concise overview of existing gap-filling approaches, and (3) a focused rationale for selecting and comparing DINEOF and DINCAE in this study. Redundant background information has been removed. The changes can be found on pages 2–4 of the revised manuscript.

2. The detailed explanation of the DINEOF and DINCAE methods is commendable, providing insight into their respective advantages and limitations. While the methods section is detailed and provides useful information for reproducibility, the level

of granularity is at times excessive, resembling a technical report rather than a scientific manuscript. Several parts describe operational or troubleshooting procedures in a narrative style that could be significantly condensed. For instance, the explanation regarding the use of the holdout method for generating the test dataset includes unnecessary implementation details that do not directly contribute to the scientific understanding. It is suggested to summarize such content more concisely, focusing on methodological rationale rather than process narration. Similarly, generic background statements—such as those explaining what hyperparameters are and why they matter—can be omitted or substantially shortened, with emphasis placed instead on the specific choices made in this study and their justification.

- We have carefully revised the Methods section to remove or condense narrative descriptions and operational details that were not essential for scientific understanding. Specifically, we shortened the explanation of the holdout method and eliminated generic background information (e.g., on hyperparameters) to focus more on the methodological rationale and the specific choices made in this study. As a result, the section is now more concise and maintains a clearer focus on reproducibility and relevance. The revisions can be found in Sections 2.2.3 and 2.3.3 of the revised manuscript.

3. The results are well-presented, particularly the comparisons between DINEOF and DINCAE gap-filling methods. However, some of the claims about the relative advantages of DINCAE over DINEOF, especially in complex regions, could be better substantiated with more detailed statistical analysis. For instance, the statement that DINCAE outperforms DINEOF in specific regions (e.g., coastal areas) could benefit from a deeper analysis of the underlying causes for these discrepancies. While the manuscript effectively outlines the strengths and limitations of both gap-filling methods, it could further benefit from a more detailed discussion on the future improvements or modifications required for both techniques. Potential solutions to optimize computational efficiency could be discussed.

- The claim that DINCAE had better results in the complex region was thoroughly justified in section 3.2 (Performance evaluation) by showing lower errors in Figures 5 and 6, particularly in these regions. Section 3.3.1 (Gradient field) also showed the better reconstruction of gradients in the dataset. This claim does not mean that the DINCAE model has a thoroughly better performance than DINEOF, as validation with in situ measurements shows better results for DINEOF. We have toned down the statement of comparison between DINCAE and DINEOF to make sure that the transferred message is compatible with the statistics (see lines 24, 408, 578, 588, 645, 755, 765 of the revised manuscript).
- The following text was added in Section 3.2 to explain the underlying causes for the discrepancies between DINEOF and DINCAE in dynamic regions (see lines 471–477 of the revised manuscript).
    - "The discrepancy between the two models in dynamic regions may arise from their fundamental methodological differences. DINEOF reconstructs missing data by extracting dominant spatiotemporal modes from the entire temporal domain, with an additional emphasis on the local spatiotemporal structure through a Laplacian filter. This EOF-based reconstruction can underrepresent transient or localized features. In contrast, DINCAE employs a U-Net-style architecture that interpolates missing values based on nearby spatiotemporal information, allowing it to more effectively capture localized or transient variability in the data by preserving fine-scale details through skip connections."
- The future improvements or modifications required for both techniques are explained extensively in Section 3.5 (Novelty and Limitations). The following recommendation was added to state the potential solutions to optimize computational efficiency (see lines 694–700 of the revised manuscript).

- “The computational efficiency of both models can be enhanced by introducing an internal data segmentation step prior to pattern extraction, which would allow parallelized computations across multiple clusters or nodes. For DINEOF, this approach could reduce the cost of iterative EOF decomposition by processing spatial segments independently and later merging the reconstructed fields. For DINCAE, parallelization can be achieved by distributing training and inference over spatial subsets or by adopting model architectures optimized for distributed GPU computation. Additionally, implementing chunked data handling and memory-efficient input/output could further optimize large-scale processing for both methods.”

4. The study provides an important contribution to gap-filling in marine remote sensing, but the broader environmental implications of the findings could be more thoroughly explored. Specifically, how might these improved gap-filling techniques contribute to more accurate global phytoplankton monitoring, climate change studies, or marine conservation efforts?

- To better highlight the broader environmental implications of our findings, we included the following statements in Section 4 (Conclusion and outlook) of the revised manuscript (see lines 732–740 and 778–781):
  - “Missing data in satellite-derived biogeochemical observations can lead to underrepresentation of important spatiotemporal dynamics, especially in regions characterized by high variability or ecological sensitivity, such as coastal zones and upwelling areas. Missing data in these regions can obscure critical information about transient biological events and environmental responses. The application of robust gap-filling techniques enables the reconstruction of these dynamic patterns, providing more complete datasets that can be exploited for improved modelling, targeted field campaigns, and continuous environmental monitoring. For example, enhanced reconstructions of Chla concentration can support fisheries management by linking biological productivity with fish distribution, assist in the early detection and prediction of harmful algal blooms, and improve estimates of net primary production. These downstream applications ultimately contribute to the development of more sustainable marine and climate management strategies.”
  - “Although the current methods are best suited for regional monitoring, scaling them to global applications would require additional optimization. Nevertheless, constructing a globally gap-filled Chla dataset, even at a reduced spatiotemporal resolution, could provide invaluable input for long-term climate assessments, global biogeochemical modelling, and validation of Earth system models.”