# Final Report: Biological Pump and Carbon Exchange Process (BICEP)

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## Summary

This proposal aimed to exploit the latest research on the global ocean biological carbon pump (OBCP) to:

1. improve our understanding of how it functions and varies in time and space; and
2. to investigate how it interfaces with the cycling of carbon in other domains of the Earth system.

Building on recommendations made in a series of recent meetings and reports; on ESA-led initiatives and projects; and on other relevant international programmes, the BICEP project synthesised the current state of knowledge in the field and produced a consolidated set of scientific requirements to guide the generation of BICEP products and to evaluate them. A major emphasis was placed on developing unified products to ensure that the carbon budgets made in the project are consistent with each other. Considerable effort was also invested in quantifying uncertainties in the derived products. Concurrently, a large *in situ* dataset of ocean carbon pools and fluxes was established and used to evaluate and select the algorithms, which were then used to generate an enhanced BICEP dataset, consisting of a 20-year time series of data built through application of the selected algorithms to the ESA OC-CCI time series, a merged, bias-corrected ocean-colour data record explicitly designed for long-term analysis. The dataset was used as input to satellite-based characterisation of the ocean biological carbon pump below the mixed layer, and to quantify the biological pools and fluxes in the mixed layer, how they vary in time and space, and how they compare with previous estimates (Figure 1).

The satellite-based ocean biological carbon pump analysis was placed in the context of carbon cycling in other domains of the Earth System, through engagement with Earth System modellers and climate scientists, especially through a workshop, Ocean Carbon from Space, that was used as a vehicle to engage the international community in a discussion on how the work on ocean carbon from space could be advanced further, and how they might be integrated with results from other components of the ocean carbon cycle (e.g. $CO_2$ air-flux and ocean acidification) not covered in our project, and how we could improve the representation of satellite-based ocean carbon work in the context of large international Earth System analyses.

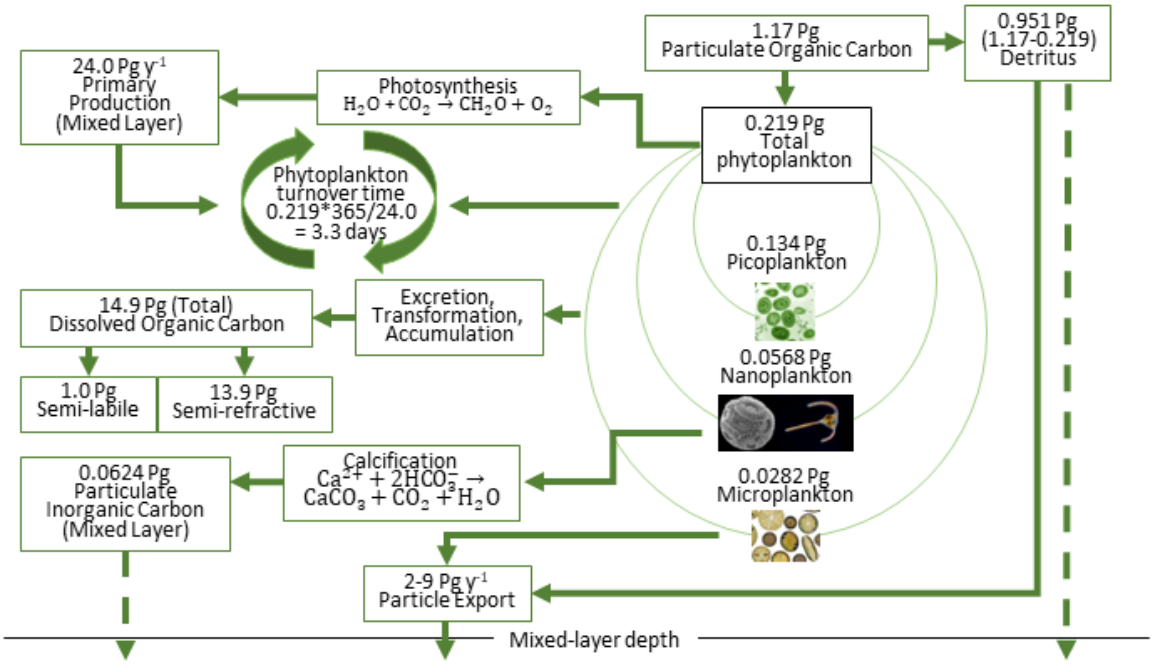


*Figure 1. The biological carbon budget of the ocean mixed layer. The various pools and fluxes are computed using the OC-CCI Version4.2 products and the algorithms developed in the BICEP project. Given values for each carbon pool and flux are the mean over the 1998-2020 period.*

## BICEP Data products and publications

The major deliverable from the project is a series of data products relating to the various components of the biological carbon pump. They are summarised in Table 1.

*Table 1 List of biological pools and fluxes of carbon in the ocean, generated through the BICEP project.*

| Product | Lead | Version | Resolution | | Time | Location | | | Publication |
|---|---|---|---|---|---|---|---|---|---|
| | | | Spatial | Temporal | | PML | CEDA | Link | |
| POC | Kong | 4.2 | 4 km | Monthly | 1997-2020 | ✓ | ✓ | CEDA | Yes |
| | | 4.2 | 9 km | Monthly | 1997-2020 | ✓ | | PML | |
| | | 5 | 4 km | Monthly | 1997-2020 | ✓ | ✓ | CEDA | |
| PC | Sathyendranath | 4.2 | 9 km | Monthly | 1998-2020 | ✓ | | PML | Yes |
| | | 5 | 9 km | Monthly | 1998-2020 | ✓ | ✓ | CEDA | |
| PIC | Kong | 4.2 | 9 km | Monthly | 1998-2020 | ✓ | | PML | MS |
| | | 5 | 9 km | Monthly | 1998-2020 | ✓ | ✓ | CEDA | |
| DOC | Laine | 4.2 | 9 km | Monthly | 2010-2018 | ✓ | ✓ | CEDA | Yes |
| PP | Kulk | 4.2 | 9 km | Monthly | 2010-2018 | ✓ | ✓ | CEDA | Yes |
| | | 5 | 9 km | Monthly | 2010-2018 | ✓ | | PML internal | |
| | | 6 | 9 km | Monthly | 2010-2018 | ✓ | | PML Internal | |
| EP | Jonsson | 4.2 | 9 km | Monthly | 1998-2019 | ✓ | ✓ | CEDA | Yes |

The corresponding peer-reviewed publications that emerged from the project are listed below.


Brewin RJW et al. (2021). Sensing the ocean biological carbon pump from space: A review of capabilities, concepts, research gaps and future developments. Earth-Science Reviews 217:103604. https://doi.org/10.1016/j.earscirev.2021.103604

Brewin RJW et al (2022). A conceptual approach to partitioning a vertical profile of phytoplankton biomass into contributions from two communities. Journal of Geophysical Research: Oceans 127:e2021JC018195. https://doi.org/10.1029/2021JC018195

Brewin RJW et al. (2023). Ocean carbon from space: Current status and priorities for the next decade. Earth-Science Reviews 240:104386. https://doi.org/10.1016/j.earscirev.2023.104386

Gittings J et al. (2021). Links between phenology of large phytoplankton and fisheries in the Northern and Central Red Sea. Remote Sensing, 13(2):231. https://doi.org/10.3390/rs13020231
Jönsson BF et al. (2020). Trends in winter light environment over the Arctic Ocean: A perspective from two decades of ocean color data. 2020. Geophysical Research Letters 47:e2020GL089037. https://doi.org/10.1029/2020GL089037
Jönsson BF et al. (2023). Review of algorithms estimating export production from satellite derived properties. Frontiers in Marine Science 10:1149938. https://doi.org/10.3389/fmars.2023.1149938
Kheireddine M et al. (2021). Particulate scattering and backscattering in relation to the nature of particles in the Red Sea. Journal of Geophysical Research: Oceans 126:e2020JC016610. https://doi.org/10.1029/2020JC016610
Kong C et al. (2024). Comparison of ocean-colour algorithms for particulate organic carbon in global ocean. Frontiers in Marine Science 11:1309050. https://doi.org/10.3389/fmars.2024.1309050
Kostadinov TS et al. (2023). Ocean color algorithm for the retrieval of the particle size distribution and carbon-based phytoplankton size classes using a two-component coated-sphere backscattering model. Ocean Science 19:703-727. https://doi.org/10.5194/os-19-703-2023
Kovač Ž and Sathyendranath S (2022). Fragility of marine photosynthesis. Frontiers in Marine Science 9:963395. https://doi.org/10.3389/fmars.2022.963395
Kulk G et al. (2020). Primary Production, an Index of Climate Change in the Ocean: Satellite-Based Estimates over Two Decades. Remote Sensing 12(5):826. https://doi.org/10.3390/rs12050826
Laine M et al. (2024). A machine learning model-based satellite data record of dissolved organic carbon concentration in surface waters of the global open ocean. Frontiers in Mariene Science 11:1305050. https://doi.org/10.3389/fmars.2024.1305050
Maniaci G et al. (2022). Concentration and distribution of phytoplankton nitrogen and carbon in the Northwest Atlantic and Indian Ocean: A simple model with applications in satellite remote sensing. 2022. Frontiers in Marine Science 9:1035399. https://doi.org/10.3389/fmars.2022.1035399
Psarra S et al. (2022). Phytoplankton dynamics in the Aegean Sea. In: The Handbook of Environmental Chemistry. Springer, Berlin. https://doi.org/10.1007/698_2022_903
Sathyendranath S et al. (2020). Reconciling models of primary production and photoacclimation [Invited]. Applied Optics 59:C100-C114. https://doi.org/10.1364/AO.386252
Sathyendranath S et al. (2023). Ocean biology studied from Space. Surveys in Geophysics 44:1287-1308. https://doi.org/10.1007/s10712-023-09805-9
Shu C et al. (2022). Biogeochemical Model Optimization by Using Satellite-Derived Phytoplankton Functional Type Data and BGC-Argo Observations in the Northern South China Sea. Remote Sensing 14:1297. https://doi.org/10.3390/rs14051297

**Colour and Light in the ocean from Earth Observations CLEO-2: Ocean Carbon from Space Workshop**

This workshop, which was organised in the context of BICEP, jointly with ESA and NASA, was also seen as one of the activities of IOCCG within the context of the CEOS virtual constellation on Ocean Colour.The fully online workshop attracted some 434 registered participants, with global distribution as shown in Figure 2.

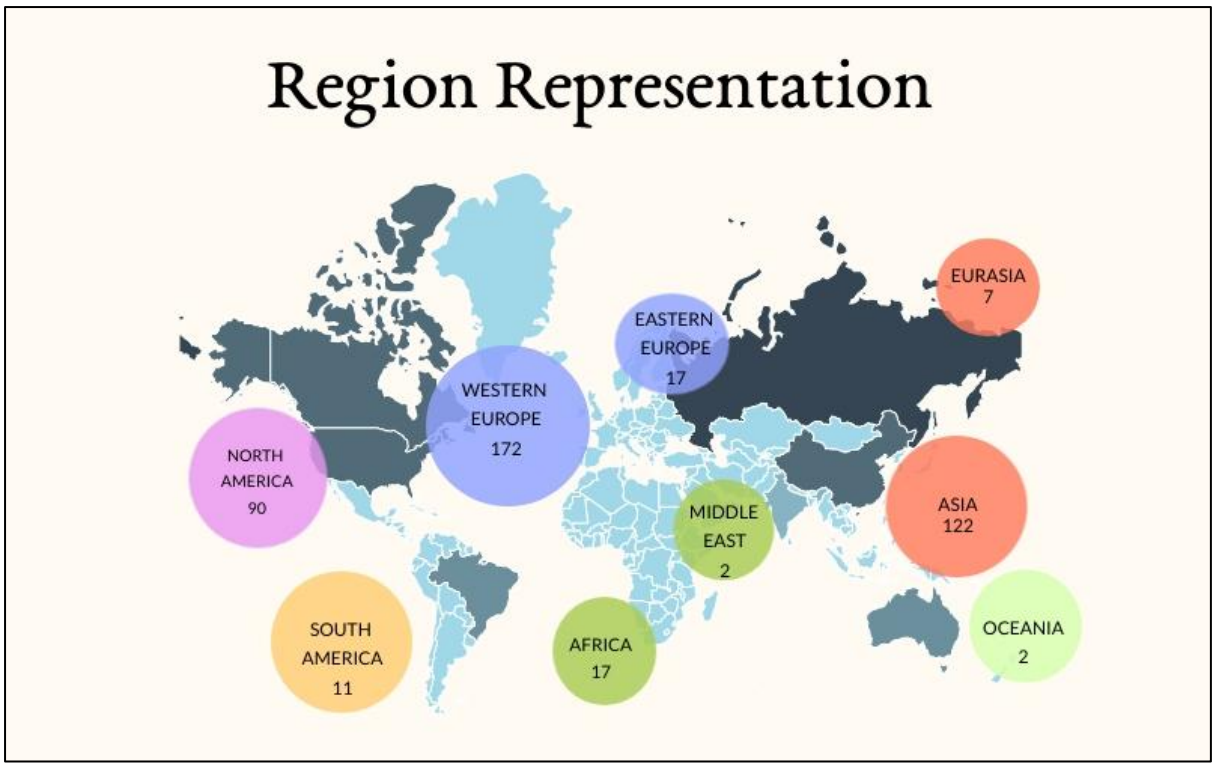


*Figure 2. Geographic distribution of participants at the Ocean Carbon from Space Workshop. Prepared by Javier Alonso Concha and Sabrina Lodadio.*

The follow-up to the workshop led to a community white paper (Brewin et al. 2023) that summarised the major findings of the workshop. Another major outcome was a special issue in Frontiers in Marine Science. The special issue will be a lasting legacy of the project and associated activities, with 31 papers submitted; 19 papers accepted; 7 papers rejected; 5 under review, with some 85/105 authors contributing to the special issue. Some additional papers are yet expected to be submitted.

**Outreach activities**

*BICEP website and other online activities*
A project website was established as part of the BICEP activities (an example is given in Figure 3). Updates for the eo4society webpage were also provided.

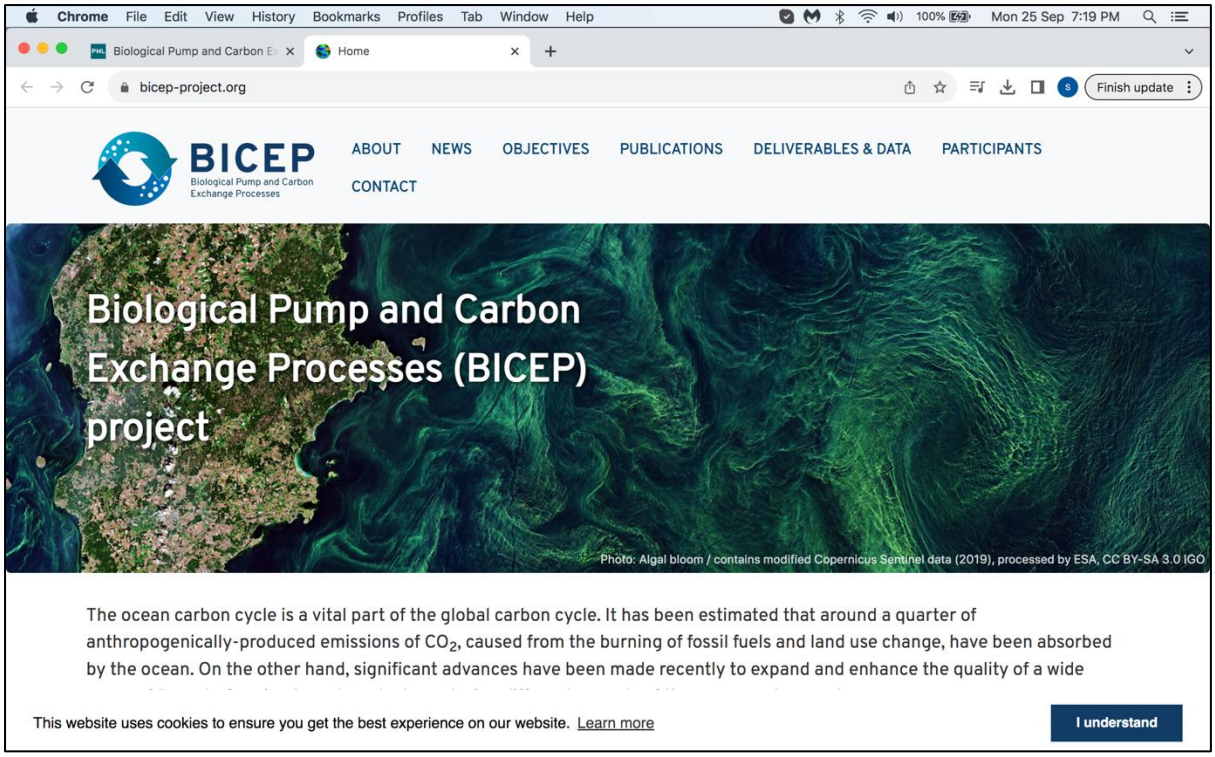

*Figure 3. Home page of the BICEP website, created by Jonathan White, PML.*

The BICEP team was also involved in the development of ESA animations and web stories, one on primary production and one on the datasets generated in the project.

*Training and Education*
Jointly with the Trevor Platt Science Foundation and other partners, including the ESA WIDGEON project, a two-part training course and symposium were organised, for broader engagement with the scientific community.

The online training course consisted of four modules: introduction to satellite-based observations of the oceans, data repositories and access; introduction to processing software tools; the role of the environment in water-borne diseases; and ecosystem monitoring. The online course was delivered through 17 lectures (~2 hours each, including Q&A) over 17 weeks (from April to July, 2023). Around 300-400 participants attended the general lectures, while some 115 participated in more than 80% of the entire course. Total 'live watching time' for the webinars was close to 8,000 hours. Recordings of the online course are available through TPSF YouTube channel.

The in-person training course followed the online component, and 42 participants from around the world attended the 2-day training course held at the Plymouth Marine Lab in August 2023. They then attended the Trevor Platt Science Symposium, contributing oral or poster presentations at the symposium. Some of the trainees were invited to co-chair sessions, and all participated actively in the discussion sessions. The symposium, which was attended by some 120 participants, gave the trainees an opportunity to meet and engage with leading scientists from around the world.

*Royal Society Summer Science exhibition*
The team participated in the Royal Society Summer Science exhibition in July 2021, which was a fully online event. The science exhibitions organised by the Royal Society in the UK are large events that engage general public and schools at both primary and secondary level. Our team's exhibition in July 2021 was focused on observations of carbon from space, with the BICEP team developing online content, including web stories and videos, for the

event. Activities also included an engagement event with fellows of the Royal Society, 'Meet the Scientist' Q&A sessions and a 'Lightning Lecture' with Q&A sessions. Around 60,000 users spend 10 minutes on the Royal Society Summer Science exhibition online hub, with our team's exhibition attracting around 9,000 visitors. The programme was rated as Good/Excellent by 96% of viewers. The carbon from space exhibition attracted further attention, and was follow-up by a radio interview and podcast for BBC radio Cambridgeshire with Naked Scientists.

*Representation at UNFCCC COP*

The BICEP engaged with high-level policy activities as part of the UNFCCC COP. At COP26, BICEP publications were referenced in a UK Universities Network Briefing, team members featured in videos developed by PML and ESA and participated in a Q&A sessions in the Green Zone through the Royal Society. At COP27, BICEP team members acted as invited speakers in a session on Net Zero, presented a poster on the Ocean Carbon Cycle from Space during Earth Information Day and acted as a host in the Ocean Pavilion in the Blue Zone. At COP28, the datasets generated in BICEP featured on a spherical display (PufferTouch) at the Space Pavilion.

Approved by ESA on July 18th 2024
Marie-Helene RIO