FINAL REPORT PROGRAM LEFE

Program LEFE/ IMAGO	**Project Title: BIOCOD** (BIOlogical Productivity changes and their leverage on the Carbon and Oxygen cycles during the last Deglaciations)	**Years 2019 – 2021**

PI: Duchamp-Alphonse S. (GEOPS laboratory)
stephanie.duchamp@universite-paris-saclay.fr
Participating Laboratories: GEOPS, LSCE, LMD

Contribution to EPICA
Other funding sources: ANR HUMI 17 (2017-2022)

Context: During glacial terminations of the past 800 000 years (800 ka), atmospheric CO_2 concentrations (pCO_2) rose by 50-100 ppm within a few thousand years. Despite the central role played by CO_2 forcing in climate changes, including recent ones, the synergistic mechanisms leading to these deglacial transitions remain elusive.

Objectives / scientific questions: We aimed to combine several empirical approaches together with results from global climate modeling to better quantify short-term changes in biological productivity and estimate their contribution to the pCO_2 and pO_2 variations during glacial terminations of the past 800 ka, and particularly during Termination V.

Main results: The significant rises in pCO_2 recorded during glacial terminations are associated with important changes in atmospheric and oceanic circulations that are accompanied by deep reorganization of marine and terrestrial productivity patterns. Therefore, they represent perfect candidates to study short-term interactions between the C-cycle and biological productivity.

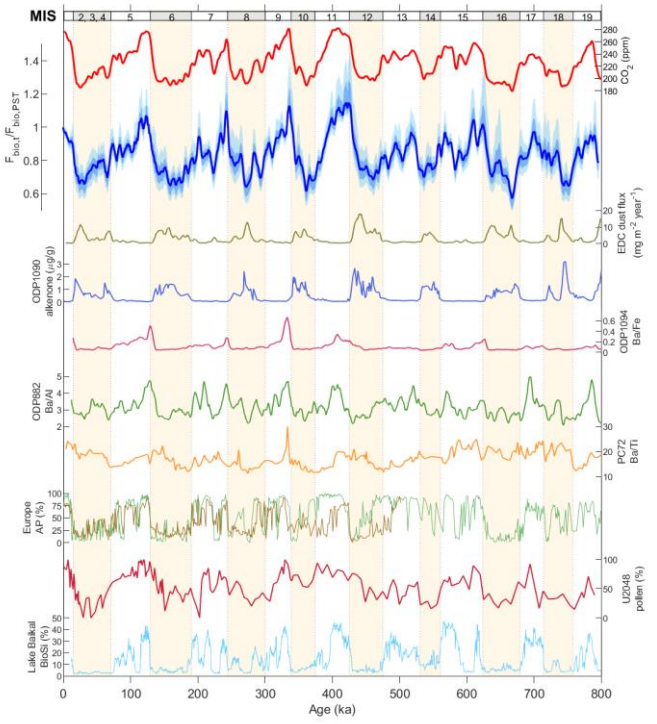

***Illustration 1 (modified from Yang et al., 2022)**: Comparison of the reconstructed GPP-O_2 with global and regional paleoclimate records. From top to bottom: 5-ka moving average CO_2 (ppmv) (Lüthi et al., 2008; Bereiter et al., 2015); 5-ka moving average reconstructed GPP-O_2 (Brandon et al., 2020; Yang et al., 2022; **this study**), the dark and light blue shadings represent 68 and 95% ranges of Monte-Carlo sensitivity solutions, respectively. 5-ka moving average EDC dust flux (Lambert et al., 2012). Alkenone concentration from the ODP 1090 core (Martinez-Garcia et al., 2009). 5-ka moving average Ba/Fe ratio from the ODP 1094 core (Boering et al., 2004. 5-ka moving average Ba/Al ratio at the ODP 882 site (Jaccard et al., 2010). Ba/Ti ratio from the TT013-PC72 core (Murray et al., 2000). Arboreal pollen (AP) fraction from Lake Ohrid (brown) (Sadori et al., 2016) and Tenaghi Philippon (dark green) (Tzedakis et al., 2006). Fractional abundances of the pollen end-members at the MD96-2048 core, southeastern Africa (Dupont et al., 2019). Biogenic silica from Lake Baikal (Prokopenko et al., 2006).*

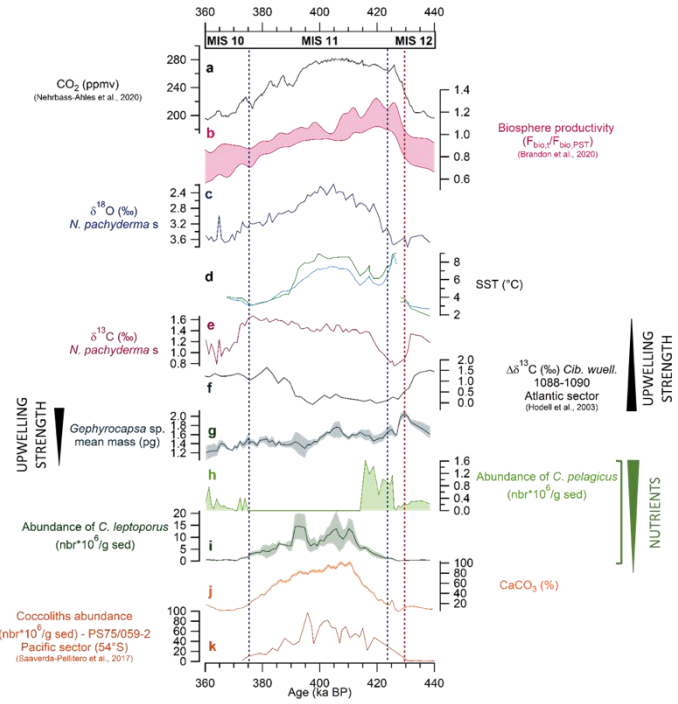

***Illustration 2 (Brandon et al., 2022)**: Records of CCP and upwelling strengths in the SO and relation with variation of pCO_2. **This study:** b) Biosphere productivity (Fbio,t/Fbio,PST) (Brandon et al., 2020); from MD04-2718 (Brandon et al., 2022): c) $\delta^{18}O_{N.\ pachyderma}$; d) summer SST reconstructed using % N. pachyderma s. percentages (blue curve) and Modern Analog Technique method (green curve); e) $\delta^{13}C_{N.\ pachyderma}$; g) Gephyrocapsa sp. mean mass (pg); h) Coccolithus pelagicus abundance (*10^6/g sed); i) Calcidiscus leptoporus abundance (*10^6/g sed); j) $CaCO_3$ (%) derived from Ca_{XR}.; **Results from literature**: a) CO_2 (ppmv) (Nehrbass-Ahles et al., 2020); f) $\Delta\delta^{13}C_{C.\ wuellerstorfi}$ from ODP Site 1088- ODP Site 1090 (Hodell et al., 2003); k) PS75/059-2 Coccoliths abundance (10^9coccoliths/g of sediment, Saavedra-Pellitero et al., 2017b).*

Illustration 1: Using the ancient air enclosed in polar ice cores, we've obtained the first 800 ka record of triple isotopic ratios of atmospheric oxygen, which reflects past global primary productivity (GPP, blue curve, *Brandon et al., 2020; Yang et al., 2022*). We've shown that global biosphere productivity usually increases millennia before glacial terminations. These increases use to occur concomitantly with CO_2 changes (red curve in the top) and imply a dominant control of CO_2 on global biosphere productivity (*Yang et al., 2022*), supporting the hypothesis of a negative

feedback under glacial climate, by which global photosynthesis becomes limited by low pCO_2 and prohibits further CO_2 drawdown. Our data also show that biosphere productivity at the end of Termination V and during Marine Isotope Stage (MIS) 11 was 10 to 30 % higher than during other terminations. Comparisons with local marine and terrestrial productivity data (curves from ODP, PC72, Europe, U2048 sites as well as Lake Baikal) suggest that terrestrial productivity might have a more significant impact on GPP compared to marine productivity. Particularly, a strong terrestrial productivity in a context of low eccentricity might explain the GPP pattern recorded during TV and MIS 11. We propose that higher biosphere productivity could have maintained low pCO_2 at the beginning of MIS 11, thus highlighting its control on the global climate as well (*Brandon et al., 2020*).

Illustration 2: While numerous studies have highlighted the central role of Southern Ocean (SO) dynamics in modulating rapid increases in pCO_2 during deglaciations, fewer studies focused on the impact of the Biological Carbon Pump - and more specifically the Carbonate Counter Pump (CCP) - in contributing to increase pCO_2 in oceanic surface waters and thus, in the atmosphere. We obtained micropaleontological (coccolith, planktonic foraminifera) and geochemical ($CaCO_3$, Ca_{XRF}, $\delta^{13}C_{N.\ pachyderma}$) analyses from sediment core MD04-2718 retrieved in the Indian sector of the SO, covering MIS 12 to MIS 10 (440,000 - 360,000 years) (*Brandon et al., 2022*). We compared our results with published records from the SO to reconstruct past changes in CCP and upwelling dynamics and understand their leverage on the ocean-atmosphere portioning of CO_2. We demonstrated that the sharp increase in pCO_2 during Termination V was likely associated with enhanced deep-water ventilation in the SO, that promoted the release of previously sequestered CO_2 to the ocean surface. Enhanced CCP is observed later, during MIS 11, and is likely the consequence of higher sea surface temperature and higher nutrient availability due to the reinvigoration of SO upwelling leading to increased coccolith production and export (*Brandon et al., 2022*). The low eccentricity signal recorded during MIS 11 might have additionally strengthened the CCP, exerting a specific control on *Gephyrocapsa* morphotypes. In addition to the strong global biological productivity (*Brandon et al., 2020*) and higher carbon storage on land, these synergistic mechanisms may have permitted to shape the distinctive 30 ka-long pCO_2 plateau characteristic of MIS 11.

Future of the project:

The INSU-LEFE-IMAGO BIOCOD project has clearly shown the importance of studying variations in biological productivity during glacial-interglacial cycles at global and local scales. It also shows the crucial need for multi-proxy and multi-archive approaches to have a complete overview of the mechanisms involved in pCO_2 variations in the past. The innovative results obtained during this INSU-LEFE-BIOCOD project are the starting point of the BIOCOD project funded by the ANR for the period 2023-2026. This ANR project, coordinated by Stéphanie Duchamp-Alphonse, gathers 4 French laboratories (GEOPS, LSCE, IGE, EPOC) and 6 external collaborations and will make it possible to better understand the relationships between biological productivity and the carbon cycle in the past, for a better understanding of their relationship in the future.

Number of publications, communications and theses

3 publications: i) Brandon, M. et al., 2022. *QSR* 287 (107556). doi:10.1016/j.quascirev.2022.107556 – ii) Yang J.-W et al., 2022. *Science* 375, 1145-1151. doi : 10.1126/science.abj8826 ; iii) Brandon, M. et al., 2020. *Nat. Communications* 11 (2112). doi:10.1038/s41467-020-15739-2.

9 communications in International conferences : Brandon et al., 2023 (INQUA), 2022 (Q13), 2021 (EGU, QUIGS-IFG), 2020 (EGU), 2019 (IUGG) – Yang et al., 2023 (IUGG), 2022 (EGU), 2021 (EGU).

5 press releases : Brandon et al., 2020 (IPSL, INSU, CEA) – Yang et al., 2022 (INSU, Twitter)

1 Postdoc : Ji-Woong Yang (2019-2021, LSCE)

1 PhD : Margaux Brandon (2017-2020, GEOPS-LSCE)

2 Master students (2*4 months): C. Guarnieri (2019) – A. Karsenti (2020).

Data availablility

Yang et al., 2022: https://doi.pangaea.de/10.1594/PANGAEA.941483

Brandon et al., 2022: https://doi.pangaea.de/10.1594/PANGAEA.944858

Brandon et al., 2020: https://doi.pangaea.de/10.1594/PANGAEA.914609