FINAL REPORT PROGRAM LEFE

Two pages to be written in English

Program LEFE/ AO INSU 2020	**Project Title** Hypoxia in the deglacial North Pacific Ocean	**Years 2020 – 2022**

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Context (2-3 lignes)

Ocean ventilation is a key climatic process which controls the exchange of carbon, oxygen, and other gases between the deep ocean and atmosphere. The Pacific constitutes around half the global ocean, making it the largest reservoir of carbon that can readily exchange with the atmosphere on centennial-millennial time scales. Yet, the processes by which it is ventilated today, and how this ventilation has changed under differing climate states, are poorly understood.

Objectives / scientific questions (2-3 lignes)

- reconstruct changes in North Pacific ventilation during the Last Glacial Maximum and over deglaciation using 14C, oxygen isotopes, and clumped isotopes
- understand the link between North Pacific ventilation, climate, and deep ocean oxygen changes over the last deglaciation

Main results

1) Radiocarbon constraints on deglacial ocean ventilation

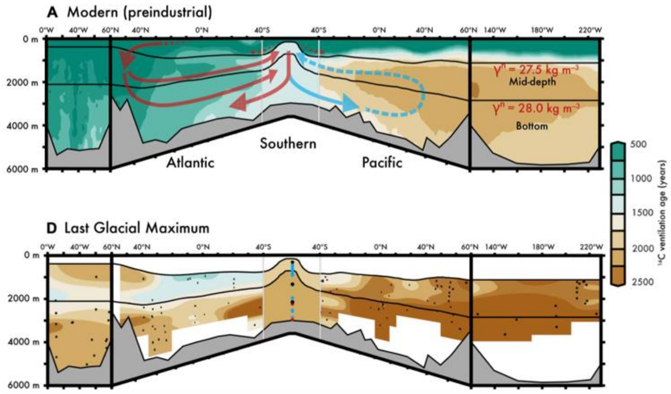
Radiocarbon ($^{14}C/^{12}C$) is a tracer uniquely sensitive to ocean circulation and air-sea gas exchange. We generated new records of benthic-planktic foraminiferal ^{14}C in North Pacific sediment cores, and conducted a global compilation of ^{14}C data. Using these new and published marine fossil radiocarbon measurements, we established several benchmarks for deep-ocean circulation and ventilation since the last ice age. We find the most ^{14}C-depleted water in glacial Pacific bottom depths, rather than the mid-depths as they are today, which is best explained by a slowdown in glacial deep-sea overturning in addition to a "flipped" glacial Pacific overturning configuration. These observations cannot be produced by changes in air-sea gas exchange alone, and they underscore the major role of changes in the overturning circulation for glacial deep-sea carbon storage in the vast Pacific abyss and the concomitant drawdown of atmospheric CO_2. Published in Rafter et al. (2022).

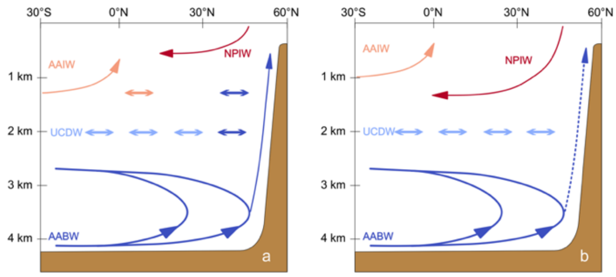
2) Oxygen isotope constraints on North Pacific circulation

There are currently two contrasting views of the circulation of the modern Pacific; the classical view sees southern sourced abyssal waters upwelling to about 1.5 km depth before flowing southward, whereas the bathymetrically constrained view sees the mid-depths (1–2.5 km) largely isolated from the global overturning circulation and predominantly ventilated by diffusion. Through both a modern and a Last Glacial Maximum (LGM) analysis focusing on oxygen isotopes in seawater and benthic foraminifera as conservative tracers, we show that isopycnal diffusion strongly influences the mid-depths of the Pacific. Diapycnal diffusion is most prominent in the subarctic Pacific, where an important return path of abyssal tracers to the surface is identified in the modern state. At the LGM we infer an expansion of North Pacific Intermediate Water, as well as increased layering of the deeper North Pacific which would weaken the return path of abyssal tracers. These proposed changes imply a likely increase in ocean carbon storage within the deep Pacific during the LGM relative to the Holocene. Published in Millet et al. (2023).

3) Clumped isotopes: deglacial temperatures, circulation, and hypoxia in the North Pacific

Clumped isotopes in benthic foraminifera are a novel proxy for deep ocean temperature. The first major part of this study focused on the refinement of the $\delta^{18}O$ and clumped isotope thermometers in foraminifera (published in Daeron and Gray, 2023). We are currently generating the first record of benthic clumped isotope temperatures over the last deglaciation, which will be used to reconstruct Pacific circulation changes over deglaciation and test the cause of previously documented hypoxia in the North Pacific (circulation or warming).





Left: radiocarbon sections through the global ocean during the (A) preindustrial and (D) LGM (Rafter et al., 2022). The black lines represent neutral density (Yn) surfaces of 27.5 and 28 kg m^{-3}.

Right: schematic of Pacific circulation in the (a) preindustrial and (b) LGM based on oxygen isotopes (Millet et al., 2023). Water masses are labeled: Antarctic Bottom Water (AABW), Upper Circumpolar Deep Water (UCDW), Antarctic Intermediate Water (AAIW) and North Pacific Intermediate Water (NPIW).

Future of the project :

This project closely relates to ongoing work using numerical modelling to understand how the Pacific is ventilated (thesis B. Millet).

Number of publications, communications and theses

- Rafter, P., Gray, W.R, Hines, S.K.V., Burke, A., Costa, K.M., Gottschalk, J., Hain, M.P., Rae, J.W.B, Southon, J.R., Walczack, M.H., Yu, J., Adkins, J.F., DeVries, T. (2022) Global reorganization of deep-sea circulation and carbon storage after the last ice age. Science Advances, 8, 46. doi: 10.1126/sciadv.abq5434
- Daeron, M & Gray, W.R. (2023) Revisiting oxygen-18 and clumped isotopes in planktic and benthic foraminifera (2023) Paleoceanography and Paleoclimatology. doi: 10.1029/2023PA004660
- Millet, B., Gray, W.R., de Lavergne, C., Roche, D. (2023) Oxygen isotope constraints on the ventilation of the modern and glacial Pacific. Climate Dynamics. https://doi.org/10.1007/s00382-023-06910-8

Data availablility

https://doi.pangaea.de/10.1594/PANGAEA.946522

https://github.com/mdaeron/isoForam