Glacial Deep Ocean Deoxygenation Driven By Biologically Mediated Air-Sea Disequilibrium

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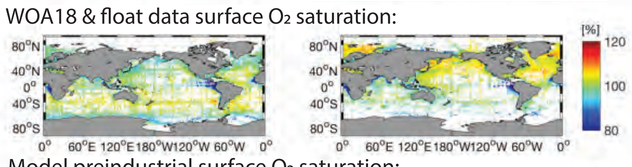
Motivation and methods

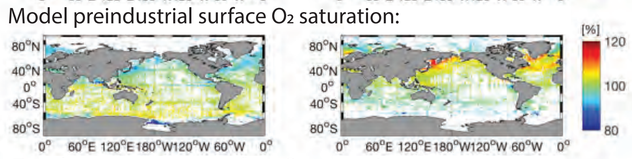
- World Ocean Atlas 2018 and float observations show widespread O_2 disequilibrium
- The model used - Model of Biogeochemistry and Isotopes coupled to Transport Matrix Method driven by UVic ESCM physics[1] - agrees well with these observations

DJF - northern winter | JJA - northern summer

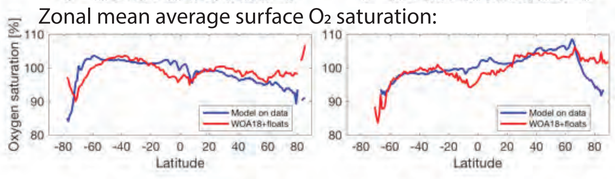
WOA18 & float data surface O_2 saturation:



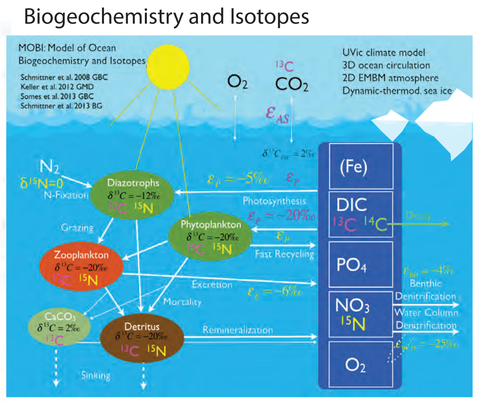
Model preindustrial surface O_2 saturation:



Zonal mean average surface O_2 saturation:



Schematic overview of MOBI - Model of Ocean Biogeochemistry and Isotopes



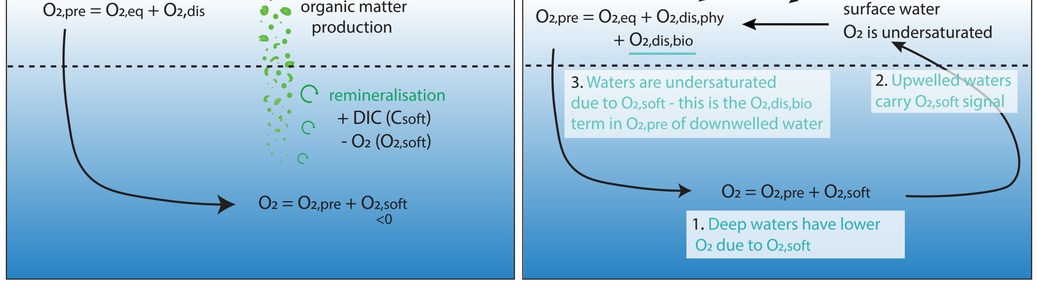
- Preformed O_2 ($O_{2,pre}$) is decomposed into equilibrium ($O_{2,eq}$) and disequilibrium ($O_{2,dis}$) components[2]
- Model is run with full physics and biology, and physics only - the difference between the runs gives the biological contribution to equilibrium and disequilibrium $O_{2,pre}$

$$O_{2,pre} = \underbrace{[O_{2eq,phy}}_{>0} + \underbrace{O_{2,eq,bio}]}_{=0} + \underbrace{[O_{2,dis,phy}}_{<0} + \underbrace{O_{2,dis,bio}]}_{<0}$$

- Interior O_2 is the sum of preformed O_2 and O_2 removed by consumption of organic matter ($O_{2,soft}$) (see schematic below)
- Biological contribution to O_2 ($O_{2,bio}$) is the sum of disequilibrium $O_{2,pre}$ due to biology ($O_{2,dis,bio}$) and O_2 consumed during organic matter regeneration ($O_{2,soft}$)

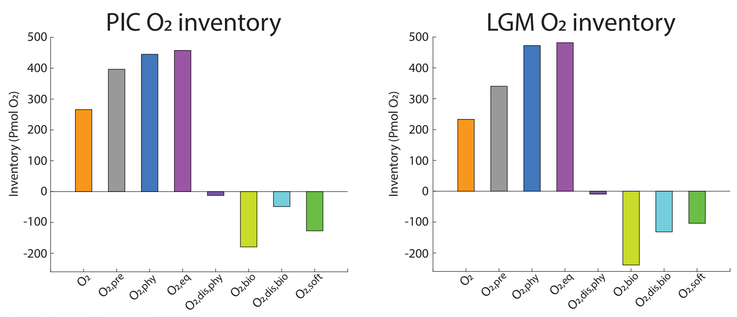
$$O_2 = O_{2,eq,phy} + \overbrace{O_{2,dis,phy}}^{O_{2,phy}} + \overbrace{O_{2,dis,bio}}^{O_{2,bio}} + O_{2,soft}$$

Schematic showing components of $O_{2,bio}$



Preindustrial and LGM control experiments

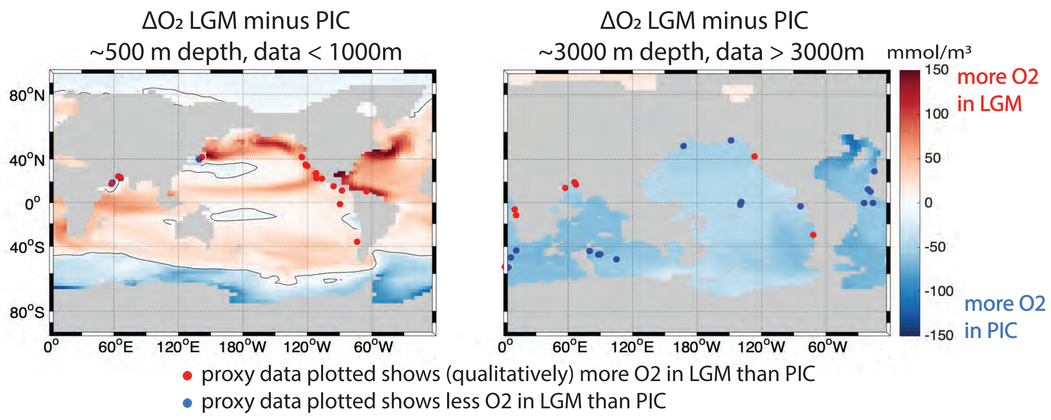
- Our decomposition method is used to investigate changes in O_2 between model runs of preindustrial control (PIC) and last glacial maximum (LGM) conditions, which are tuned to a wide range of proxy data[3]



- Changes in O_2 inventory: LGM minus PIC

ΔO_2: -33 Pmol = [$\Delta O_{2,eq}$: +24 Pmol; $\Delta O_{2,dis,phy}$: +3 Pmol; $\Delta O_{2,phy}$: +27 Pmol] + [$\Delta O_{2,dis,bio}$: -83 Pmol; $\Delta O_{2,soft}$: +23 Pmol; $\Delta O_{2,bio}$: -60 Pmol] $\Longrightarrow$ Changes in O_2 inventory between PIC and LGM are dominated by $O_{2,dis,bio}$

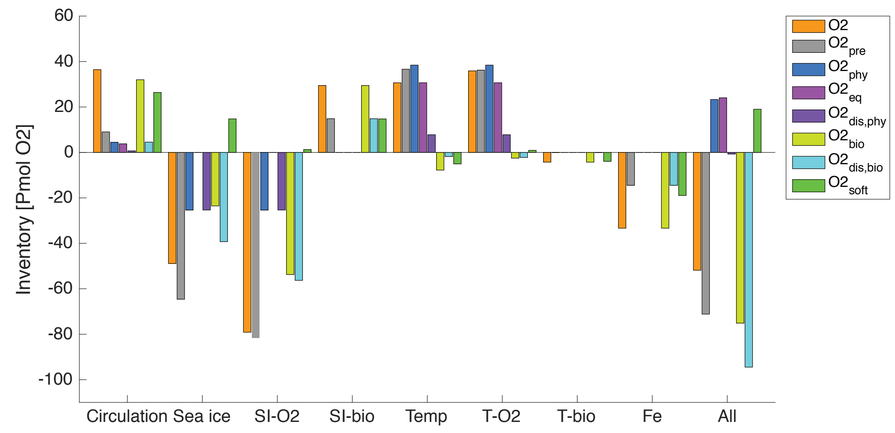
- Comparison of LGM to PIC O_2 changes with qualitative O_2 proxy data at different depths shows good agreement[4]:



Perturbation experiments

- Perturbation experiments allow a single variable from LGM conditions to be imposed on the preindustrial state, keeping all other variables fixed at their PIC value, to determine the effect on different components of the O_2 system

PIC conditions with LGM perturbations

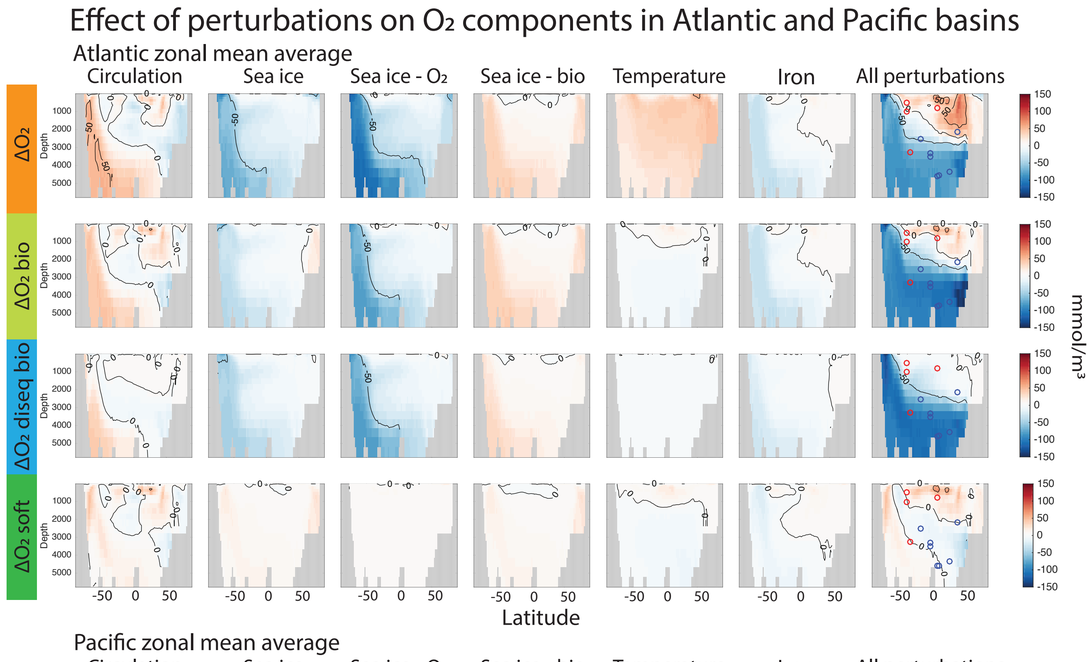


LGM perturbations explained:

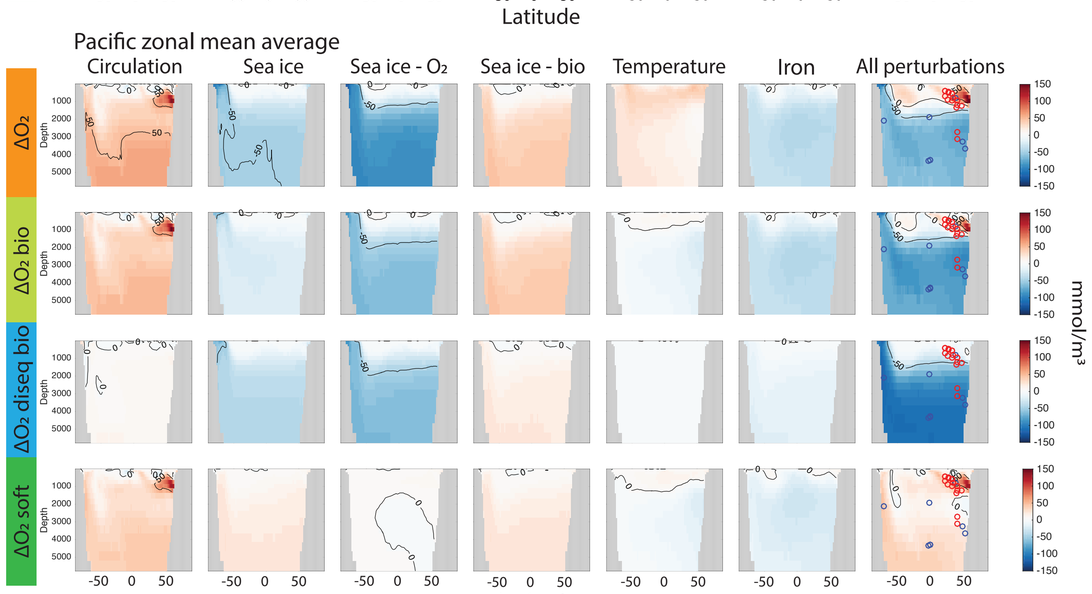
- Circulation - shallower and weaker AMOC
- Sea ice - increased extent. Separate experiments show individual effect of:
  - O_2 gas exchange (SI-O2), and
  - light limitation on biology (SI-bio)
- Temperature - decrease. Separate experiments show individual effect of:
  - increased O_2 solubility (T-O2), and
  - changes to biological productivity and regeneration (T-bio)
- Iron (Fe) - enhanced iron inputs for LGM
- All perturbations: circulation, sea ice, temperature, iron and salinity (not shown)

Effect of perturbations on O_2 components in Atlantic and Pacific basins

Atlantic zonal mean average



Pacific zonal mean average



- proxy data plotted shows more O2 in LGM than PIC
- proxy data plotted shows less O2 in LGM than PIC

Conclusions

- The glacial ocean is deoxygenated relative to the preindustrial ocean

Major factors increasing LGM O_2

- Circulation
  - biological export ↓: less O_2 consumption at depth
- Sea ice (light limitation)
  - biological productivity ↓
  - biological disequilibrium O_2 ↓: less O_2 consumption at depth
- Temperature
  - O_2 solubility ↑

Major factors decreasing LGM O_2

- Sea ice
  - O_2 gas exchange ↓: enhances negative physical disequilibrium
  - O_2 gas exchange ↓: prevents ventilation of O_2 poor deep waters - enhances biologically mediated disequilibrium
- Iron (Fe)
  - biological productivity ↑
  - biological disequilibrium
  - O_2 ↑: enhances oxygen depletion in deep ocean

- Lower biological productivity due to sea ice and circulation, and lower temperatures tend to increase O_2 in the glacial ocean
- However this was more than compensated by biologically mediated disequilibrium O_2 enhanced by sea ice and iron fertilisation leading to global deep ocean deoxygenation in the glacial ocean

References: **1.** Khatiwala, S., Schmittner, A., and Muglia, J. 2019. Science Advances, 5 (6); TMM Github: https://github.com/samarkhatiwala/tmm **2.** Ito, T., Follows, M.J., and Boyle, E.A. 2004. Geophysical Research Letters, 31 (17) **3.** Muglia, J., Schmittner, A., and Skinner, L.C. 2018. Earth and Planetary Science Letters, 496 **4.** Galbraith, E. D. and Jaccard, S. L. 2015. Quartnery Science Reviews, 109; Anderson, R. F. et al. 2019. Global Biogeochemical Cycles, 33 (3).

Transport Matrix Method TMM

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