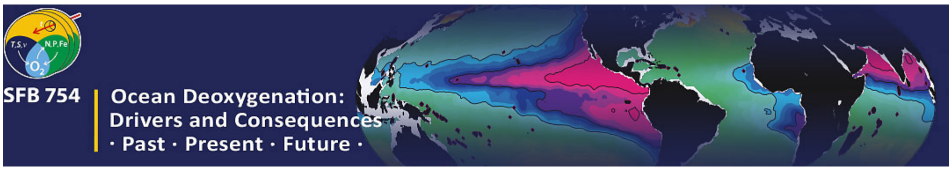

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Symmetric marine biogeochemical responses in warming and cooling worlds

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The marine biological response to atmospheric CO_2 concentration being reduced from a greenhouse to an icehouse climate shows a surprisingly symmetric hysteresis compared to when it is increased from an icehouse to a greenhouse climate. We equilibrate the University of Victoria Earth System Climate Model, at 280 and 1260 ppm atmospheric CO_2, then force it with a 1% per year increase (the "ramp-up") and a 1% per year decrease (the "ramp-down") to compare the 500 year marine biogeochemical response. Both ramp-up and ramp-down simulations start from similar globally-integrated oxygen content due to biological and physical drivers that compensate on thousand-year timescales, though initial ramp-down tropical suboxic volumes are nearly twice those of the ramp-up. In the ramp-up, increasing net primary production (NPP) and enhanced remineralization in the Southern Ocean moves phosphate to deep ocean storage and contributes to a decline in deep ocean oxygen content. NPP in the low latitudes decreases, causing a net gain of oxygen in the subsurface tropical ocean. Global NPP displays a rapid increase after about 3.5 degrees of global mean sea surface temperature warming. In the ramp-down, deep ocean phosphate is mixed back to the surface where the heat content remains relatively high, and high NPP and remineralization rates trap it in the upper ocean despite rapid overturning. This shift in phosphate storage to the near-surface delays the decline in global NPP until about 3.5 degrees of global mean sea surface temperature cooling. High NPP and strong remineralization in the ramp-down decreases subsurface tropical oxygen, despite cooling global mean temperatures. However, deep ocean oxygen increases rapidly due to strong ventilation via Southern Ocean pathways. In both ramp-up and ramp-down the largest oxygen anomalies are held in the abyssal Pacific and Indian Ocean basins, whereas the largest phosphate anomalies are held in the Atlantic and Arctic. Our study has implications for the past, suggesting a combination of physical and biological drivers are responsible for the delayed transition of greenhouse to icehouse climates relative to transitions of icehouse to greenhouse climates. Furthermore we show a distinct difference in greenhouse and icehouse climate phosphate storage, where greenhouse climates store phosphate higher in the water column.

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