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The Southern Ocean during the ice ages: A slumped pycnocline from reduced wind-driven upwelling?

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The Southern Ocean is recognized as a potential cause of the lower atmospheric concentration of CO_2 during ice ages, but the mechanism is debated. In the ice age Antarctic Zone, biogeochemical paleoproxy data suggest a reduction in the exchange of nutrients (and thus water and carbon) between the surface and the deep ocean. We report simple calculations with those data indicating that the decline in the supply of nutrients during peak glacials was extreme, >50% of the interglacial rate. Weaker wind-driven upwelling is a prime candidate for such a large decline, and new, complementary aspects of this mechanism are identified here. First, reduced upwelling would have resulted in a "slumping" of the pycnocline into the AZ. Second, it would have allowed diapycnal mixing to "mine" nutrients out of the upper water column, possibly causing an even greater slumping of the vertical nutrient gradient (or "nutricline"). These mechanisms would have reduced shallow subsurface nutrient concentrations, decreasing wintertime resupply of nutrients to the surface mixed layer, beyond the reduction in upwelling alone. They would have complemented two changes previously proposed to accompany a decline in upwelling: (1) halocline strengthening and (2) reduced isopycnal mixing in the deep ocean. Together, the above changes would have encouraged declines in the nutrient content and/or the formation rate of new deep water in the AZ, enhancing CO_2 storage in the deep ocean.