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The role of Southern Ocean mixing and upwelling in glacial-interglacial atmospheric CO_2 change

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Decreased ventilation of the Southern Ocean in glacial time is implicated in most explanations of lower glacial atmospheric CO_2. Today, the deep ($>$ 2000 m) ocean south of the Polar Front is rapidly ventilated from below, with the interaction of deep currents with topography driving high mixing rates well up into the water column. We show from calculations based on the conservation of buoyancy, that mixing rates are high in all the deep waters of the Southern Ocean. Between the surface and $\sim$2000 m depth, water is upwelled by a residual meridional overturning that is directly linked to buoyancy fluxes through the ocean surface. Combined with the rapid deep mixing, this upwelling serves to return deep water to the surface on a short time scale.

We propose two new mechanisms by which, in glacial time, the deep sea may have been more isolated from the surface. Firstly, the deep ocean appears to have been more stratified because of the denser bottom water resulting from intense sea ice formation toward the Antarctic continent. The greater stratification would have slowed the deep mixing. Secondly, sub-zero atmospheric temperatures may have decreased the buoyancy flux from the atmosphere to the ocean. This would have reduced or eliminated the upwelling (contrary to commonly-held assumptions, upwelling is not solely a function of the westerly wind stress, but is directly coupled to the buoyancy flux too). If Southern ocean upwelling rates are important in setting atmospheric CO_2, the observed very close link between Antarctic temperatures and atmospheric CO_2 could then be explained as a natural consequence of the connection between the air-sea buoyancy flux and upwelling in the Southern Ocean.

For these mechanisms to be important in the glacial-interglacial CO_2 problem, atmospheric CO_2 must be disproportionately sensitive to conditions in the Southern Ocean.

While there are good theoretical reasons for believing this should be the case, most current general circulation model (GCM) -based carbon cycle simulations do not display such behaviour. Shortcomings in the representation of the high-latitude vertical exchange processes described above are likely the chief reason for this. However, these problems are not easily remedied in models that can be integrated for the length of time required for carbon cycle studies. We show that, in a box model (similar to those of previous authors), that weaker mixing and reduced upwelling in the Southern Ocean can explain the low glacial atmospheric CO_2. It is well known that box models of the oceanic controls of atmospheric CO_2 are more sensitive to high-latitude processes than are existing GCMs, but the real ocean need not necessarily behave more like one of these GCMs than a box model in this regard.