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The formation of the ocean's anthropogenic carbon reservoir

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The shallow overturning circulation of the oceans transports heat from the tropics to the mid-latitudes. This overturning also influences the uptake and storage of anthropogenic carbon (C_{ant}). We demonstrate this by quantifying the relative importance of ocean thermodynamics, circulation and biogeochemistry in a global biochemistry and circulation model. Almost 2/3 of the C_{ant} ocean uptake enters via gas exchange in waters that are lighter than the base of the ventilated thermocline. However, almost 2/3 of the excess C_{ant} is stored below the thermocline. Our analysis shows that subtropical waters are a dominant component in the formation of subpolar waters and that these water masses essentially form a common C_{ant} reservoir. This new method developed and presented here is intrinsically Lagrangian, as it by construction only considers the velocity or transport of waters across isopycnals. More generally, our approach provides an integral framework for linking ocean thermodynamics with biogeochemistry.

High quality measurements demonstrate that the oceans have absorbed about a third of anthropogenic CO_2 (C_{ant}) emissions[1,2]. However our understanding of the mechanisms governing this uptake are quite elementary. The air-sea exchange of C_{ant} should be expected to play a first-order role in determining the rate of exchange of C_{ant} across the base of the ocean's planetary boundary layer or mixed layer. This mainly occurs in the Equatorial region and mid-to-high latitudes[3]. Previous efforts such as model-data synthesis using inverse techniques[3–7] have investigated meridional transport of water and C_{ant} in an Eulerian framework. This work tended to emphasize the role of C_{ant} uptake associated with the Southern Ocean divergence. Recent attention has been devoted to the relationship between anthropogenic heat and carbon uptake by the ocean[8,9]. None of this research to date has articulated a mechanistic framework linking ocean uptake of carbon to thermodynamic processes associated with the ocean overturning. Here we develop such a framework based on previous efforts to understand oceanic carbon uptake pathways[10–13], with special focus on the shallow overturning circulation (SOC).

The SOC includes overturning of tropical waters (TW), subtropical mode waters (STMW) and subpolar mode waters (SPMW), primarily Subantarctic Mode Water (SAMW)[14] (see Fig. 1). Observations indicate that the waters with densities characteristic of the SOC ($\sigma < 27.0$) and intermediate waters (IW; $27.0 \leq \sigma < 27.5$) contain as much as 63–83% of the global C_{ant} inventory, yet occupy only 27.1% of the global ocean volume (Fig. 2 and Supplementary Fig. 1, Table 1). The range depends on the method used to estimate C_{ant} concentrations at the time of WOCE[1,15,16]. To understand the higher efficiency of these water masses in retaining C_{ant} we must first understand the formation mechanism(s) of this reservoir. This exercise is particularly important considering the much shorter times scales of re-emergence into the surface layer (thereby inhibiting further C_{ant} uptake) of these water masses as compared to deeper water masses. In addition, they contribute a much lower fraction to the total C_{ant} inventory relative to what would be expected given their the large surface area of their outcrop regions (94.8%; Fig. 2, Table 1). The apparent mismatch between a large area available for air-sea exchange and a relatively small interior inventory for C_{ant} suggests that (a) air-sea C_{ant} fluxes are small in the tropics relative to high latitudes, (b) C_{ant} is exported from the lighter layers to denser water masses, or both.

We present here a novel suite of analysis tools that aim to deconvolve the roles of gas exchange, ocean interior diapycnal transports, and ocean interior diapycnal diffusive exchanges in prescribing how the ocean interior C_{ant} reservoir is formed. We identify a central role for poleward ocean transport of C_{ant}, related to the poleward transport of heat associated with the SOC. This transport sustains a strong exchange of C_{ant} between

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