

INCREASE OF NORDIC SEAS ANTHROPOGENIC CO₂ INVENTORY OVER THE LAST TWO DECADES AS OBSERVED FROM OCEAN MEASUREMENTS

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ABSTRACT

This paper presents estimates of the ¹³C Suess effect and anthropogenic carbon concentration increase in the Nordic Seas since 1981.

The increase of the atmospheric CO₂ concentration caused by fossil fuel combustion, cement production and land use changes is significantly dampened by ocean CO₂ uptake. The current magnitude of this uptake can be inferred on a global scale by estimating the global air-sea CO₂ flux [Takahashi *et al.*, 2002] and the magnitude of the ocean inventory can be estimated by combining ocean carbon system data with information on water mass ages [Gruber *et al.*, 1996]. These techniques have substantially advanced our knowledge of the role of the ocean as a CO₂ sink and we now know that the current global ocean carbon uptake corresponds to approximately 25% of the industrial emissions, while the accumulated ocean uptake since the start of the industrial revolution has been inferred to correspond to approximately 50% of the emitted CO₂ [Sabine *et al.*, 2004].

Still, our understanding of where and when anthropogenic CO₂ (C_{ant}) is taken up by the oceans and how it is transported within is limited. This is due to the fact that the air-sea flux estimates gives the combined pre-industrial and anthropogenic carbon flux so the flux of C_{ant} can only be determined on a global scale, and the ocean C_{ant} concentration estimates provided by the inventory approach reflect the combined effects of ocean uptake and redistribution.

The behavior of the northern North Atlantic as a sink for C_{ant} has received some attention in recent years. Simple model calculations have shown that the air-sea CO₂ flux in this region may have decreased since pre-industrial times [Wallace, 2001, Anderson and Olsen, 2002]. This effect results from the region being fed with warm water from the south via the Gulf Stream-North Atlantic Current-North Atlantic Drift-Norwegian Atlantic Current system. As the water moves northwards it is cooled and the increased solubility induces a transfer of CO₂ from the atmosphere to the ocean. This cooling-induced uptake is part of the natural pre-industrial exchange of CO₂ between ocean and atmosphere. As a result of the uptake of C_{ant}, the total inorganic carbon (C_t) content of the source water from the Gulf Stream system has increased.

Now, when C_t increase the pCO₂ response for a given increase in C_t becomes larger; i.e. its buffer capacity decreases. Assume that the pCO₂ of the warm source waters increases at the same rate as the atmosphere – this implies a given change in C_t. As the water moves northwards and carbon concentrations increase as a consequence of cooling-induced uptake, the buffer capacity is reduced, and as this happens the effect on pCO₂ of the given change in C_t increases. Thus the increase in the south – tracking the atmospheric increase – may bring about changes greater than the atmospheric increase further north. As long as the system is undersaturated with respect to the atmosphere, surface ocean pCO₂ may increase at a greater rate than the atmosphere.

Recent observations from the sub-polar North Atlantic have indeed revealed that surface ocean $p\text{CO}_2$ has increased at a greater rate than the atmosphere over the last twenty years [Lefèvre *et al.*, 2004, Friis *et al.*, 2005], and anthropogenic carbon transport estimates do show a large northward C_{ant} transport in the North Atlantic [Rosón *et al.*, 2003, Macdonald *et al.*, 2003, Álvarez *et al.*, 2003].

This study evaluates the anthropogenic changes of CO_2 and $\delta^{13}\text{C}$ in the Nordic Seas -the northern limb of the Atlantic Meridional Overturning Circulation- that took place between 1981 and 2002/2003. The changes have been determined by comparing data obtained during the TTO-NAS study with data obtained during the Nordic Seas surveys of R/V *Knorr* in 2002 and R/V *G.O. Sars* in 2003 using a Multi Linear Regression approach.

The results reveal a large decrease of $\delta^{13}\text{C}$ in the Atlantic domain of the Nordic Seas; the oceanic Suess effect here is of similar magnitude to the atmospheric Suess effect. The time it takes to establish isotopic equilibrium between ocean and atmosphere (~10 yrs) is longer than the residence time of the Atlantic Water in the Nordic Seas, so we conclude that this water is equilibrated with respect to the anthropogenic changes of the atmosphere as it enters the region. Moreover, we see that the $p\text{CO}_2$ increase required to sustain the observed C_t increase in the Atlantic domain is larger than the atmospheric increase, i.e. the surface ocean $p\text{CO}_2$ increases at a greater rate than the atmosphere. With the carbon chemistry that prevails off the coast of Florida, however, the C_t increase corresponds to a $p\text{CO}_2$ increase similar to the atmospheric increase. Our observations thus support the proposed theories regarding the behavior of the North Atlantic anthropogenic CO_2 sink; uptake from the atmosphere takes place in the southern regions with the C_{ant} carried northwards and sequestered by the overturning circulation.

The excessive $p\text{CO}_2$ increases were only seen in the Atlantic domains of the Nordic Seas. We believe that this is due to their dilution with Polar Water (PW) that exits from under the Arctic ice cover. As the PW exits it is undersaturated with respect to present day atmospheric CO_2 levels. This water will represent a local C_{ant} sink in the Nordic Seas. Additionally, deep mixing will bring deep water with capacity for C_{ant} uptake up to the surface. Our results indicate that this process is limited to the Greenland Sea region.

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