THE ROLE OF OCEAN CARBON TRANSPORT IN THE GLOBAL CARBON CYCLE

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The presentation is intended as an introduction to the workshop on carbon transports. It reviews the major concepts, issues and justifications underlying attempts to estimate ocean carbon transport and reviews the observational approaches to carbon transport estimation. There are several "big issues'' in carbon cycle science that can be addressed by studies of ocean transport:

(1) Terrestrial and oceanic sinks of carbon: How big? Where? Why? What are the controls?

This issue addresses the present-day budget for anthropogenic CO_2, and particularly the distribution and controlling factors of net terrestrial sinks for atmospheric CO_2. The latter are of increasing political and economic importance under international CO2 mitigation agreements. Inverse modelling of meridional and zonal atmospheric, data(e.g. CO_2, O_2, ^{13}C), is one way to constrain terrestrial sources and sinks on large spatial and temporal scales. Such modelling benefits from carbon transport estimates because ocean transports create gradients in atmospheric CO_2 which must be diagnosed in order to resolve spatial gradients arising from fossil-fuel emissions and net terrestrial sinks.

CO_2 is taken up from the atmosphere in certain regions (e.g. regions of net heat loss) and returned to the atmosphere at a different location (e.g. regions of net heating). Regional differences in the biological pump also drive carbon transports. These oceanic carbon transports can create significant atmospheric pCO_2 gradients which allow for a return transport of carbon via the atmosphere. In the Atlantic, following the suggestion of Brewer et al. (1989) it has been possible to estimate carbon transports from hydrographic section data. The present-day oceanic transport of carbon is, however, comprised of both a "natural component'' and an "anthropogenic component''. The latter arises because the ocean contains anthropogenic CO_2 (anthropogenic CO_2 is the "extra'' concentration of total dissolved inorganic carbon in seawater that results from exposure of ocean waters to an atmosphere with $pCO_2 > \mu 280$ atm, (i.e. the preindustrial or "natural'' value)).

Using so-called pre-formed CO_2 backcalculation techniques (see review by Wallace, 2001) the section-wide distribution of both anthropogenic and "natural'' components of inorganic carbon can be estimated. This, in turn, allows for estimation of the carbon transport in the preindustrial ocean (assuming circulation has not changed) as well as estimation of the anthropogenic carbon transport. In the Atlantic, this type of analysis indicates that the natural transport of carbon was southwards at all latitudes because predominantly southward-flowing deeper water contains higher TCO_2 levels than the upper-ocean return flow. This "natural" southwards transport is now, however, partially offset by northwards transport of anthropogenic CO_2 (anthropogenic CO_2 concentrations being highest in "younger'' near-surface waters).

Estimation of the "natural'' southwards transport across the equator allows the ocean-driven interhemispheric gradients of atmospheric CO_2 to be estimated. To-date, direct estimates have only been made for the South Atlantic (10-30°S, Holfort et al., 1988) and for 24°N (Rosón et al., 2001). No direct carbon transport estimates have been attempted for the Pacific or Indian Oceans. Hence it is presently impossible to assess the global oceanic interhemispheric transport. A recent global assessment of carbon transport in GCMs has been published by Sarmiento et al. (2000).

(2) Locations of anthropogenic CO_2 uptake by the oceans: where does anthropogenic CO_2 cross the air-sea interface? And why?

This issue relates to the physics (and chemistry) underlying anthropogenic CO_2 uptake, which must be resolved if we are to predict future uptake under a possibly altered circulation. Anthropogenic CO_2 uptake can be thought of as the anthropogenic perturbation of the natural air-sea CO_2 flux. The thermodynamic uptake capacity for anthropogenic CO_2 at the sea-surface is a function of the temperature, alkalinity and pCO_2 of the surface seawater. Due to the dissociation of CO_2 in seawater, the uptake capacity for anthropogenic CO_2 actually increases with increasing temperature and decreases with increasing pCO_2

(Revelle factor changes). The uptake is greatest where this thermodynamic uptake capacity is large and where “old’’, sub-surface waters, which have not seen the atmosphere for decades or centuries, are re-exposed to the (altered) atmosphere. The uptake cannot be measured directly: the present-day air-sea CO_2 flux which can be estimated from pCO_2 measurements in surface-water and air, is a mixture of “natural’’ and anthropogenic components. The distribution of this air-sea flux perturbation can be modelled using carbon-cycle GCMs. However, it is likely that the distribution of uptake in models is critically dependant on the representation of vertical/diapycnal motions, including mixing, which are themselves notoriously difficult to represent.

Holfort et al. (1998) noted that hydrographic section-based carbon transport estimates applied to the problem of anthropogenic CO_2 flux divergence and storage represents perhaps the only way, independent of GCMs, to assess the geographical distribution of anthropogenic CO_2 uptake. In this approach, the transport of anthropogenic CO_2 across different sections is estimated, and when combined with estimates of between-section anthropogenic carbon storage allows coarse estimation of the air-sea flux of anthropogenic CO_2 from mass-balance.

Based on the anthropogenic carbon transport estimates from Holfort et al. (1998) and Roson et al. (2001), such a balance can be attempted for the latitude bands 30°S-10°S, 10°S-24°N and 24°N to Bering Strait. The mass-balance can be represented in several ways. For example the calculated transports and storage terms for the period of measurements can be estimated, and by assuming (for a latitude band bounded by two sections) that:

$$\text{Storage} = (T_s - T_n) + F_{\text{air-sea.}}$$

Where T_S and T_N refer to net transport across sections defining the southern and northern boundaries of the ocean volume respectively, $(T_S - T_N)$ is therefore the horizontal transport convergence and $F_{\text{air-sea}}$ is the net air-to-sea flux within this region. The air-sea flux for the 1990’s can be estimated if the storage term can be measured (by repeat surveys) or otherwise estimated. Alternatively, the transports across each section can be assumed to have increased over time in approximate proportion to the surface water anthropogenic CO_2 increase (which can be estimated). The resulting cumulative convergence or divergence can be estimated and compared with the measured anthropogenic CO_2 inventory between the sections to estimate cumulative uptake from the atmosphere. Taking the latter approach and applying it to these three latitude bands in the Atlantic results in the following pattern:

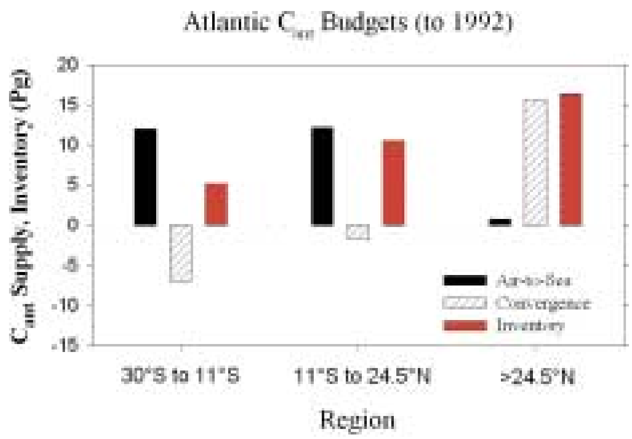

Figure 1. Bar graph depicting the cumulative anthropogenic CO_2 (C_{ant}) budget (1750-1992) of three different regions of the Atlantic Ocean (30°S-11°S, 11°S-24.5°N, and >24.5°N including the Arctic Ocean). For each region, the three bars represent the cumulative magnitude of the transport convergence, air-to-sea flux and storage terms of equation. (From Wallace et al., In prep., 2001)

This figure suggests that horizontal transport is insufficient to supply all the observed inventory of anthropogenic carbon for the mid-latitude South Atlantic and the Tropical Atlantic regions. A net atmosphere-to-ocean flux of anthropogenic carbon is required. The picture for the North Atlantic north of 24°N looks different. It appears from these estimates that the horizontal convergence of anthropogenic carbon is sufficient to explain all of the anthropogenic carbon contained in the Arctic and northern North Atlantic Ocean. This implies negligible air-sea uptake of anthropogenic CO_2 in this region. This is a surprising result which contradicts almost all GCM model results.

What is the reason for this apparent discrepancy?

1. The transport estimates are wrong. According to Rosón et al. (2001), the transport of anthropogenic carbon through the Florida Straits dominates the section budget for 24°N. Inaccurate estimation of the anthropogenic CO_2 concentration in the Florida Straits might therefore alter the overall transport estimate. In addition, there remain difficulties in estimating anthropogenic CO_2 concentrations in deeper water, especially in depth ranges where transient tracers such as CFCs are undetectable. Southward flow of anthropogenic CO_2 in the North Atlantic Deep Water may therefore have been underestimated.
2. The models are wrong. Some current ocean carbon cycle models may not accurately depict the balance between advective supply and air-sea flux due to their having too weak Atlantic overturning combined, possibly, with overly strong vertical mixing. Too weak overturning would cause underestimation of both the northwards heat transport (a common characteristic of many coarse-resolution GCMs) as well underestimate the northwards advective supply of anthropogenic CO_2. On the other hand, unrealistically strong convective activity or "artificial upwelling'' (e.g. in the vicinity of the north wall of the Gulf Stream) would tend to overexpose "older'' deeper water masses to the atmosphere in the model thereby overestimating the local uptake of anthropogenic CO_2 there.

The direct transport calculations, if they are correct, suggest that the warm upper-layer waters which flow into the North Atlantic from the South Atlantic, as the upper limb of the ocean's meridional overturning circulation, have had time to pre-equilibrate with the contemporary atmospheric pCO_2 before entering the northern North Atlantic. In such a case there is little potential for additional anthropogenic CO_2 uptake within the North Atlantic prior to this water sinking and entering the ocean interior on its return flow to the south. At present, it is too early to say which (if any) scenario is closer to reality. It could well be that the transport estimates are in error and that the model-based estimates are more reliable. On the other hand, most GCMs have difficulties representing water mass properties, thermocline structure, heat transport, convection, etc. in the Atlantic: all of these factors have potential significance for anthropogenic CO_2 budgets. At present it is fair to say that the apparent discrepancy is interesting and illustrates one way in which transport-based estimates and model-estimates can be compared in order to test the representation of anthropogenic CO_2 uptake in models. In order to move forward, continued improvements in the methods by which anthropogenic CO2 can be estimated from hydrographic data are required as well as critical analyses of the errors and uncertainties involved in estimating carbon transports.

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