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The North Atlantic Carbon Cycle: New Perspectives from JGOFS and WOCE

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Abstract

The rationale for studying the North Atlantic CO_2 system revolves around the high latitude formation of deep and intermediate water masses and the subsequent important role of the North Atlantic in the natural carbon cycle and uptake of anthropocentric CO_2. Both the vitality of the debate and present level of uncertainty are highlighted by a series of papers presented at the Royal Society North Atlantic Carbon Cycle meeting in the Fall of 1994. The major terms for a North Atlantic carbon budget include the net CO_2 air-sea flux, the meridional fluxes of dissolved inorganic and organic (DIC and DOC) associated with the overturning circulation, vertical redistribution through particle and DOC export and subsequent remineralization, riverine input and sediment burial, and temporal changes in the DIC inventory. We review current model and observational estimates, including potential errors, for each component both for the modern and pre-industrial ocean. At present, the carbon budget for the North Atlantic cannot be closed to within 0.2-0.3 Gt C/yr, and significant disagreements exist over the major term balances. Future research directions for addressing the North Atlantic carbon budget are also discussed.

A central objective of the Joint Global Ocean Flux Study (JGOFS) is to improve our estimates and understanding of the flux of carbon both within the ocean and across the ocean-atmosphere and ocean-sediment interfaces. One rationale for studying the North Atlantic CO_2 system revolves around the high latitude formation of deep and intermediate water masses and the subsequent important role of the North Atlantic in the natural carbon cycle and uptake of anthropocentric CO_2 (Sarmiento et al., 1995). A second, equally compelling, argument rests on using the diverse range of biogeographical and hydrographic regimes (Longhurst, 1995) across the basin to explore the interaction among air-sea exchange, circulation and biological processes that determine the surface distribution of dissolved inorganic carbon.

The first major JGOFS field effort focused on the spring bloom in the eastern North Atlantic (North Atlantic Bloom Experiment, NABE; Ducklow and Harris, 1993), while a long-term biogeochemical time-series was initiated in the Sargasso Sea in 1988 (Bermuda Atlantic Time-Series Study,

BATS; Michaels and Knap, 1996). The large-scale distribution of ocean carbon parameters for the basin are also being reevaluated as part of the JGOFS global CO_2 survey in conjunction with the World Ocean Circulation Experiment (WOCE) hydrographic programme. Together with a wealth of historical datasets (e.g. TTO; Brewer et al., 1985; Takahashi et al., 1995), the data collected over the last decade in the North Atlantic provide perhaps our best opportunity to constrain the carbon budget for an ocean basin.

The marine carbon system is a challenging subject, requiring a detailed knowledge of the interplay between ocean biogeochemistry and physics. The ocean carbon cycle is also perturbed by climate variability on timescales ranging from the interannual ENSO and North Atlantic Oscillation to millenia and glacial/interglacial transitions. The oceanic uptake of anthropogenic CO_2 adds further complications. Traditional time-series data or oceanographic cruise data are limited in spatial and temporal extent, and a variety of approaches incorporating ship of opportunity, moorings and satellite data, data-assimilation models, and novel measurement systems are needed to address such issues on the regional or basin scale.

Preliminary efforts for a basin-wide synthesis of the North Atlantic carbon budget are underway, and both the vitality of the debate and the present level of uncertainty are highlighted by a series of papers presented at the Royal Society North Atlantic Carbon Cycle meeting in the Fall of 1994 (Eglinton et al., 1995). Here, we present one view of the problem, in particular stressing the components of the carbon budget that require further work.

The major terms of a North Atlantic carbon budget, shown schematically in Figure 1, include: the net air-sea CO_2 flux, the meridional fluxes of dissolved inorganic and organic (DIC and DOC) at the northern and southern boundaries, vertical redistribution through particle and DOC export and subsequent remineralization, riverine input and sediment burial, and temporal changes in the DIC inventory related to uptake of anthropogenic CO_2. The magnitudes of these fluxes can be estimated to varying levels of certainty.

Two quantities are needed to compute the air-sea CO_2 flux—the ocean-atmosphere partial pressure difference (Δ pCO_2) and the gas exchange rate, which is generally parameterized as a function of wind speed. Surface water pCO_2 increases with DIC and temperature and decreases with alkalinity and less strongly with salinity. Biological DIC uptake for the production of organic matter typically dominates over biological calcification, and the so-called "biological" and "solubility" pumps (Volk and Hoffert, 1985) often are out of phase over the seasonal cycle, with temperature domintated, summer outgassing (positive Δ pCO_2s) in oligotrophic regions (e.g. Bates et al., 1996), and biology dominated, summer drawdown (negative pCO_2s) at the more productive, higher latitudes (Chipman et al., 1993; Takahashi et al., 1993).

Although a fairly extensive historical surface pCO_2 data set exists for the North Atlantic (e.g. Takahashi et al., 1995), the coverage is insufficient to adequately represent the large seasonal and spatial variability in the surface water ΔpCO2 (-120 uatm to +100 uatm), and some form of space-time extrapolation must be applied to the data (e.g. Takahashi et al., 1995; Lefevre, 1995). Advances have also been made in constraining gas exchange rates using dual-tracer release experiments, but questions remain regarding how to scale such results to CO_2 (Wanninkhof, 1992; Watson et al., 1995); at present, air-sea gas exchange rates are known to no better than a factor of two.

Based on a historical reconstruction of the seasonal pCO2 field, Takahashi et al. (1995) estimate that annual mean, pCO2 difference with the atmosphere is about -8.6 uatm over the North Atlantic basin (18S-78N). This results in a net ocean CO2 uptake of between 0.2 to 0.5 Gt C/yr, depending on the choice of gas exchange parameterization. Most of the uptake occurs in the subpolar gyre

north of 42N, with a moderate net subtropical sink nearly balanced by a tropical Atlantic source.

Further refinement of the net North Atlantic air-sea flux is difficult considering the spatial and temporal data requirements and size of the signal in pCO_2. A 2.5 uatm change in mean pCO_2 accounts for a flux of about 0.1 Gt C/yr over the basin compared with current measurement uncertainties at about 1.0 uatm. Barring a dramatic increase in the amount of available pCO_2 data, one approach for improving basin-scale pCO_2 maps would be take advantage of correlations pCO_2 with properties such as SST, nutrients and ocean color (Watson et al., 1991; Takahashi et al., 1993; Stephens et al., 1995) that can be measured either by remote sensing or estimated from the broader hydrographic databases.

On the basin scale, the net meridional transports of DIC due to thermohaline overturning, wind-driven gyres, and surface Ekman flow become increasingly important. The northward inflow of warm surface water and export of cold deep water sets up a natural CO_2 solubility pump with net air-sea uptake at high latitudes and southward DIC outflow at depth. The thermohaline component is closely linked to the overturning transport ($10\text{-}20\times10^6$ m^3 s^{-1}) and northward ocean heat transport, and a number of diagnostic calculations give a range of preindustrial carbon fluxes out of the North Atlantic: 0.6 Gt C/yr (Broecker and Peng, 1992); 0.5±0.1 Gt C/yr (Watson et al., 1995); 0.33±0.15 Gt C/yr (Keeling and Peng, 1995).

Meridional CO_2 transports can alternatively be calculated by combining zonal DIC section data with hydrographic section velocity estimates, preferably derived from an inverse procedure. The resulting CO_2 fluxes include the thermohaline component as well as fluxes due to ageostrophic surface Ekman flow and wind-driven gyre circulation, and the calculations are complicated by the uncertainty in the barotropic velocity field and surface wind stress and by the poor CO_2 coverage in space and time. Computed CO_2 southward net transports for the preindustrial period are 0.4 Gt C/yr (25 N, Brewer et al., 1989), 0.4-0.8 Gt C/yr (20-60 N, Martel and Wunsch, 1993), and 0.6 Gt C/yr (11-30 S, Holfort et al., 1996). The present day flux estimates are lower by about 0.2 Gt C/yr because of the increase from anthropogenic carbon of the DIC in inflowing surface water.

An additional and often neglected component of the meridional CO_2 transport arises because there is a net southward mass flux in the basin required to balance the net atmospheric water vapor flux from the Atlantic to the Pacific (e.g. Wijffles et al., 1992). The mass flux, which can be estimated from flow through the Bering Strait modified by the net freshwater input over the Arctic and North Atlantic, can be thought of as a zonal average barotropic flux and contributes another approximate 0.6 Gt C/yr to the southward transport (Holfort et al., 1996). Some confusion has arisen in the literature because this throughflow is typically not included in all section estimates nor many numerical models.

The strength of the biological carbon pump in the North Atlantic is difficult to access directly from observations due to our limited understanding of the controls of export flux from the surface. Using CZCS ocean color composites and primary production algorithms, Longhurst et al. (1995) estimate that the total primary productivity for the basin is about 6.3 Gt C/yr. Using their suggested basin-wide f-ratio of 0.1, the ratio of export production to total, yields a new production of 0.63 GtC yr-1. For comparison, the Princeton GCM ecosystem model (Sarmiento et al., 1993) produces 0.9-1.3 Gt C/yr of new production for the North Atlantic, with an average f-ratio of 0.42. The model f-ratio is likely too high, related to excessive nutrient upwelling, and a reasonable first order estimate is in the range of 0.6-0.9 Gt C/yr. Based on data from BATS and a few other sites where good DOC data exist, roughly about a 1/3 of this export production may be leaving the euphotic zone as semi-labile DOC rather than particulate matter (Ducklow et al., 1995).

A number of other, smaller components (riverine input, sediment burial, net DOC remineralization) must be included to balance the basin carbon budget at the 0.1–0.2 Gt/yr level. Often the riverine input is taken to approximately balance the sediment carbon flux over the basin. The magnitude and variability of the meridional DOC fluxes and net DOC convergence/divergence for the basin are still almost entirely unknown but may be addressed in the near future with the development of improved DOC analytical techniques (e.g. Ducklow et al., 1995).

Model calculations suggest that the ocean takes up at present about 40% of the fossil fuel carbon released to the atmosphere. The resulting anthropogenic signal in the surface water (50 umol/kg) decreases rapidly with depth and is small relative to the natural variations in background DIC concentrations (1900-2200 umol/kg). The high quality DIC time series collected at Hydrostation S and BATS show an average increase of about 1.7 umol/kg/yr in surface waters for the last decade (Bates et al., 1996), close to the expected equilibrium response.

Measurement errors for DIC have, until the recent introduction of reference DIC standards (Dickson and Goyet, 1994), limited efforts to directly estimate anthropogenic CO_2 uptake by monitoring the change in DIC concentrations over time. A number of more indirect methods have been introduced, each with its own weaknesses, but together they provide a relatively consistent picture for the removal of excess CO_2 by the North Atlantic (Wallace, 1995).

One approach, originally introduced by Brewer (1978) and Chen (1993), involves computing the pre-industrial DIC distribution from preformed nutrients, mixing relationships, and Redfield ratios. Using the GEOSECS and TTO datasets, Gruber et al. (1996) calculate a North Atlantic anthropogenic CO_2 burden of 20±4 GT C in the early 1980's.

Anthropogenic CO_2 uptake is primarily limited by ocean transport, and 3-D general circulation model (GCM) predicted uptake rates for the North Atlantic 18.4 GT C (or about 0.4 GT C/yr in the 1980's; Sarmiento et al., 1995) are similar in magnitude to that found by Gruber et al. (1996) but with a different spatial distribution. The current generation of numerical models contains a number of known deficiencies, particularly with the formation and outflow of North Atlantic Deep Water. Preliminary efforts to use the measured distributions of transient tracers such as tritium and the CFCs to estimate CO2 uptake, particularly in the main thermocline, show good promise.

Although carbon budgets can be constructed for the North Atlantic that balance to about 0.1 Gt C/yr, a closer examination of the terms suggest that our present uncertainties are no better than about 0.2-0.3 Gt C/yr, or about at the edge of saying whether the pre-industrial North Atlantic was an important net carbon sink. For example, Sarmiento et al. (1995) find essentially no net CO_2 uptake in pre-industrial times and a modern anthropogenic carbon storage of 0.4 Gt C/yr balanced by 0.3 Gt C/yr net air-sea flux and a small meridional DOC convergence. For contrast, Holfort et al. (1996) report that nearly all of the excess CO_2 inventory in the North Atlantic actually entered the ocean in the south and was advected northward; they also suggest that the present net air-sea flux (0.5 Gt C/yr in their calculation) has changed little since the pre-industrial.

Solving the question of the North Atlantic CO2 sink will require a variety of new and novel approaches. Three areas that show promise are automated chemical measurement systems, next generation biogeochemical data-assimilation models, and atmospheric inversion techniques.

At the root of much of the present uncertainty in the North Atlantic carbon budget is the sparsity of data, particularly at high latitudes during the winter. The desired temporal and spatial data scales are incompatible with traditional oceanographic shipboard sampling, and alternatives based on the remote measurement of chemical species from volunteer observing ships (VOS), moorings, drifters

and floats are required. For example, Friederich et al. (1995) demonstrated a capability from tests on a mooring in Monterey Bay for measuring the air-sea pCO2 difference with 1–2 uatm accuracy hourly for up to several months.

On-going improvements in three dimensional numerical models offer an alternative and complementary approach, and recent results from the Princeton carbon cycle model (Sarmiento et al., 1995), which includes a complete carbonate system and simple phosphate based biological model, are generally consistent with both the net air-sea and meridional CO_2 flux estimates. Future modeling directions will include more emphasis on data assimilation, with the ability to directly incorporate near real-time, basin-scale satellite datasets such wind speed, sea surface height, SST and ocean color.

Finally, efforts are underway to back-out surface CO_2 flux patterns by inverting atmospheric data from the extensive NOAA/CMDL CO_2 monitor program using atmospheric transport codes (Tans et al., 1996).

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