concentrations of seven major ions, Cl^-, SO_4^{2-}, NO_3^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, were measured with a Dionex Model 2010i chromatograph, equipped wth AS4A (for anions) and FAST SEP CATION I and II (for cations) columns. Samples of 200 to 250 g were cut from both D-1 and D-3 and pumped through ion-exchange filters to measure total beta radioactivity in a Tennelec LB 1000 series Alpha/Beta Counting System. Total beta radioactivity is routinely used to identify time-stratigraphic horizons associated with known atmospheric thermonuclear tests (*6*).
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Carbon Dioxide Transport by Ocean Currents at 25°N Latitude in the Atlantic Ocean

PETER G. BREWER, CATHERINE GOYET, DAVID DYRSSEN

Measured concentrations of CO_2, O_2, and related chemical species in a section across the Florida Straits and in the open Atlantic Ocean at approximately 25°N, have been combined with estimates of oceanic mass transport to estimate both the gross transport of CO_2 by the ocean at this latitude and the net CO_2 flux from exchange with the atmosphere. The northward flux was 63.9×10^6 moles per second (mol/s); the southward flux was 64.6×10^6 mol/s. These values yield a net CO_2 flux of 0.7×10^6 mol/s (0.26 ± 0.03 gigaton of C per year) southward. The North Atlantic Ocean has been considered to be a strong sink for atmospheric CO_2, yet these results show that the net flux in 1988 across 25°N was small. For O_2 the equivalent signal is 4.89×10^6 mol/s northward and 6.97×10^6 mol/s southward, and the net transport is 2.08×10^6 mol/s or three times the net CO_2 flux. These data suggest that the North Atlantic Ocean is today a relatively small sink for atmospheric CO_2, in spite of its large heat loss, but a larger sink for O_2 because of the additive effects of chemical and thermal pumping on the CO_2 cycle but their near equal and opposite effects on the CO_2 cycle.

THE NORTH ATLANTIC OCEAN HAS been widely regarded as an important CO_2 sink and heat source for the atmosphere. The large-scale circulation consists of both the horizontal wind-driven gyre circulation and the vertically overturning thermohaline-driven circulation. Both act in concert to transport heat and trace greenhouse gases to latitudes where disequilibrium with the atmosphere occurs. Linkage of the heat and gas fluxes is a necessary component of carbon cycle and climate modeling, yet calculations of these fluxes have proceeded along independent paths. We have measured oceanic CO_2 concentrations and related chemical properties (temperature, salinity, O_2 and NO_3 concentrations, and alkalinity) in a section through the Florida Straits at 26.5°N (Hollywood, Florida, to Great Isaacs Rock, Bahamas) and in the open Atlantic Ocean at 25°N (Bahamas to Africa) in order to test an earlier and controversial hypothesis of Brewer and Dyrssen (*1*), based on a few data, that treatment of CO_2 data in a manner identical to that used for heat transport would yield a very small net CO_2 flux.

The section is the same as that used by others for the estimate of heat flux (*2*), and we made specific use of the oceanic transports of water derived from these studies to compute the chemical fluxes. The work was carried out on the Research Vessel *Oceanus* Cruise 205 in November 1988 at five stations across the Florida Straits and four stations in the open Atlantic (Fig. 1). Time did not permit a full oceanic section, and thus interpolation along density surfaces sampled by others (*2–4*) was necessary.

For the North Atlantic, the earlier calculations (*2–4*) have shown that the northward flow of 30 Sverdrups (Sv) (*5*), principally through the Florida Straits, has a mean temperature of 18.8°C, and that the compensating return flow has a mean temperature of 9.7°C. This difference provides the observed net heat flux of $\sim 1.1 \times 10^{15}$ W. Although some uncertainty still surrounds this estimate (*6*), on the basis of atmospheric observations, the oceanic data are compelling.

The equivalent calculation for trace gases is more difficult because of the technical difficulty of obtaining measurements and the enrichment of gases in the cold, deep flows where mass transports are less easily determined. Moreover heat is an internally conserved property of sea water, whereas the biogenic gases are transferred both at the sea surface, because of thermal, partial pressure, and biogenic processes, and internally,

P. G. Brewer and C. Goyet, Department of Chemistry, Woods Hole Oceanographic Institution, Woods Hole, MA 02543.
D. Dyrssen, Department of Analytical and Marine Chemistry, Chalmers University of Technology, S-412 96 Göteborg, Sweden.

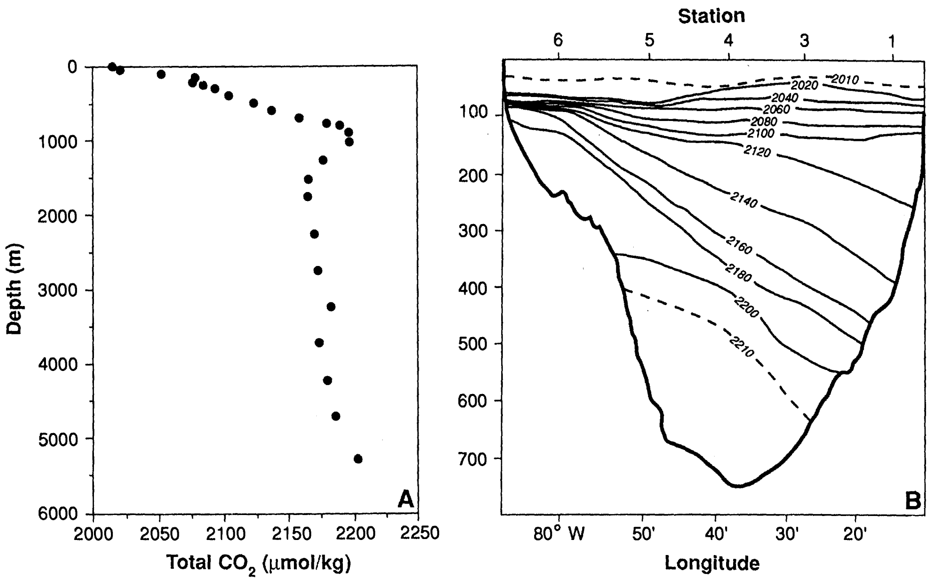

Fig. 1. Oceanic total CO_2 concentrations (**A**) for station 9 in the open Atlantic at 24°38'N, 64°1'W and (**B**) for the Florida Straits section (contours are in micromoles per kilogram).

Table 1. Estimates of oceanic chemical properties in selected depth intervals for the Florida-Bahamas section and for the 25°N section based upon four stations in the western basin. The layer transports are as calculated in (*2*); the negative sign indicates southward flow; Alk, alkalinity.

	Property				Flux		
Depth (m)	O_2 (μmol/liter)	Alk (μeq/liter)	CO_2 (μmol/liter)	Transport (10^6 m^3/s)	O_2 (10^3 mol/s)	Alk (10^3 eq/s)	CO_2 (10^3 mol/s)
			Florida Straits				
0 to 25	190	2423	2047	2.60	494	6300	5322
25 to 75	190	2428	2062	4.80	912	11654	9898
75 to 150	172	2449	2135	5.91	1017	14474	12618
150 to 250	163	2454	2190	5.59	911	13718	12242
250 to 350	156	2423	2242	3.60	562	8723	8071
350 to 450	140	2418	2232	2.56	358	6190	5714
450 to 550	138	2388	2223	2.05	283	4895	4557
550 to 650	145	2377	2262	1.44	208	3423	3257
650 to 750	145	2371	2272	0.87	126	2063	1977
750 to 850	145	2371	2277	0.10	15	237	228
Total flux					4886	71677	63882
			Mid-ocean section				
0 to 25	210	2476	2104	1.36	286	3367	2861
25 to 75	214	2475	2112	−2.43	−520	−6014	−5132
75 to 150	214	2465	2126	−4.17	−892	−10279	−8865
150 to 250	205	2456	2148	−3.34	−685	−8203	−7174
250 to 350	196	2442	2157	−2.21	−433	−5397	−4767
350 to 450	192	2430	2172	−1.29	−248	−3135	−2802
450 to 550	183	2417	2190	−0.48	−88	−1160	−1051
550 to 650	169	2407	2205	0.21	35	505	463
650 to 750	152	2398	2230	0.54	82	1295	1204
750 to 850	147	2393	2243	0.66	97	1579	1480
850 to 950	160	2392	2251	0.61	98	1459	1373
950 to 1050	165	2388	2247	0.28	46	669	629
1050 to 1150	192	2390	2245	0.04	8	96	90
1150 to 1250	201	2392	2241	−0.30	−60	−718	−672
1250 to 1350	223	2388	2236	−0.58	−129	−1385	−1297
1350 to 1450	223	2392	2236	−0.82	−183	−1961	−1834
1450 to 1625	232	2388	2230	−0.88	−204	−2101	−1962
1625 to 1875	241	2388	2232	−1.49	−359	−3558	−3326
1875 to 2250	250	2386	2228	−2.65	−662	−6323	−5904
2250 to 2750	254	2393	2236	−3.75	−952	−8974	−8385
2750 to 3500	254	2396	2240	−5.96	−1514	−14280	−13350
3500 to 4500	259	2402	2245	−9.55	−2473	−22939	−21440
4500 to bottom	263	2407	2254	6.77	1780	16295	15260
Total flux					−6970	−71162	−64601

because of production and consumption effects. Esaias *et al.* (*7*) and Platt and Sathyendranath (*8*) provide examples of the complexity of upper ocean processes that enter into the cycle.

Brewer and Dyrssen (*1*) made use of TTO North Atlantic data (*9*) to estimate roughly the CO_2 flux, but encountered several problems. The nearest TTO station to the Florida Straits was at 28°45'N, 79°46'W, some 120 miles north of the section studied by Roemmich and Wunsch (*4*) and contained only two data points. Furthermore, the TTO CO_2 data set contains errors probably resulting from the effect of dissolved organic matter on the observations (*10*). Our data were obtained both by titration and by coulometry (*11*) and thus we avoided this problem. The analytical accuracy of the procedures was estimated to be ±3 μeq/kg (eq, equivalents) in alkalinity, ±7 μmol/kg in total CO_2 (titration) and ±5 μmol/kg in total CO_2 (coulometry).

We have used our data to provide estimates of concentration in several depth and isopycnal ranges and combined these with published estimates of mass transport (Table 1). The transport estimates are those of Hall and Bryden (*3*); a full inverse analysis of the Roemmich and Wunsch data set (*4*) by Rintoul (*12*) yielded virtually identical results for O_2, but an analysis was not done for CO_2. The principal errors in estimating the flux arise from both the layer velocities and from the coarse section averaging.

The inferred total CO_2 flux (Table 1) is at first surprising; the northward transport of CO_2 by the ocean across this latitude is 63.9 × 10^6 mol/s, the southward transport is 64.6 × 10^6 mol/s and thus the net CO_2 flux is 0.7 × 10^6 mol/s or 0.26 gigaton of C per year (*13*). The flux is small compared to the present annual rate of production of CO_2 from fossil fuels of about 5.5 gigatons of C per year. For O_2 the equivalent transports are 4.89 × 10^6 mol/s northward and 6.97 × 10^6 mol/s southward; these values yield a net flux of 2.08 × 10^6 mol/s, or some three times the net CO_2 flux.

The difference in the net CO_2 and O_2 fluxes results from the strong enrichment of CO_2 (and nutrients) in the deep flow in the Florida Straits (Fig. 1) and the strong depletion of O_2 because of respiratory processes. Advection by the Gulf Stream northward results in strong cooling of surface waters (*14*) and exposure of the CO_2-rich, O_2-poor waters beneath to the atmosphere. [The flow from the Florida Straits contributes some 90% of the CO_2 and nutrient input to the surface layers of the North Atlantic. The clear waters of the Gulf Stream drive the plankton blooms (*7*).] On surface exposure of water with high CO_2 partial pressures, gas is released to the atmosphere; cooling by 9.1°C (*2–4*); gas solubility increases for CO_2 by approximately 3.75%. These effects are of opposite sign, and of apparently almost equal magnitude so that the net flux of CO_2 is quite small. For O_2 the above effects are additive and result in a large net flux: exposure of water with low partial pressures of O_2 results in atmospheric O_2 invasion, and cooling further enhances the solubility. These data confirm that both biological and physical cycles of the ocean are important in planetary CO_2 balance. We predict that surface evasion of CO_2 from the North Atlantic will occur in winter. Although a larger net residual southward transport cannot be absolutely ruled out, we believe that the picture we paint of opposing effects must intuitively be the case and will yield a small net signal.

The calculation of the alkalinity balance shows transports of 71.7×10^6 eq/s northward, and 71.2×10^6 eq/s southward. The difference of 0.5×10^6 eq/s northward is again indistinguishable from zero but suggests that the North Atlantic is a small alkalinity sink. The balance however reflects the interaction of processes quite different than for CO_2; transfer at the air-sea interface does not apply for alkalinity but depends on processes involving $CaCO_3$ uptake and dissolution and changes in N metabolism (*15*).

Our calculation, most emphatically, does not mean that oceanic uptake of the fossil fuel signal is small. Transport of fossil fuel CO_2 is taking place in the surface flows and is extractable from the CO_2 flux signal (*16*). Deep waters in the North Atlantic that have radiochemical and fossil fuel burdens (*17*) have yet to reach 25°N in other than the deep western boundary current, and thus the present-day balance is artificially poised in time. Interconversion of CO_2 between gaseous and dissolved organic C (*18*) also occurs, and the magnitude of this cycle is currently controversial (*19*).

Our estimates of CO_2 transport for a single ocean basin are consistent with the global exchanges between sea and air provided by Pearman *et al.* (*20*). These exchanges are calculated to have changed by a factor of 2 in the last 40 years. Unraveling signals such as these is essential for knowledge of the planetary C cycle and will be a principal focus of the Joint Global Ocean Flux Study (JGOFS) (*21*) in the decade ahead. The large absolute fluxes and the small net signal present enormous challenges to scientists in this field.

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A Devonian Spinneret: Early Evidence of Spiders and Silk Use

WILLIAM A. SHEAR, JACQUELINE M. PALMER, JONATHAN A. CODDINGTON, PATRICIA M. BONAMO

A nearly complete spider spinneret was found in Middle Devonian rocks (about 385 to 380 million years old) near Gilboa, New York. This is the earliest evidence yet discovered for silk production from opisthosomal spigots, and therefore for spiders. Two previously known Devonian fossils described as spiders lack any apomorphies of the order Araneae and are probably not spiders. The spigots of the Devonian spinneret resemble those of members of the living suborder Mesothelae, but the number of spigots and their distribution are like those of members of the suborder Opisthothelae, infraorder Mygalomorphae. The Devonian spider belonged to a clade that may be the sister group of all other spiders, of Mesothelae, or of Opisthothelae.

SPIDERS (ARTHROPODA: CHELICERata: Araneae) are among the most important terrestrial predatory animals. Among the arachnids, they alone produce silk from opisthosomal (abdominal) glands that open through modified setae called spigots, which in turn are located on reduced abdominal appendages, the spinnerets. This character complex is the most diagnostic apomorphy of spiders. We report here on the earliest evidence yet discovered in the fossil record of spinnerets, of spiders themselves, and of silk production by animals.

Although two spider fossils have been reported from the Devonian Period, in neither of these cases can any apomorphies of the order Araneae be demonstrated. *Paleocteniza crassipes* (*1*), from the Lower Devonian (404 million years old?) Rhynie Chert, is a minute, crumpled exoskeleton that is undoubtedly arachnid, but is more likely from one of the trigonotarbids that are the most abundant animals in that deposit. Spinnerets, characteristic patterns of leg jointing, eye arrangement, and other spider apomorphies that are potentially present even in very small, immature animals cannot be detected in this fossil or are certainly not there (*2*). *Archaeometa devonica* (*3*), from the slightly later Alken-an-der-Mosel, West Ger-

W. A. Shear, Department of Biology, Hampden-Sydney College, Hampden-Sydney, VA 23943, and American Museum of Natural History, New York, NY 10024.
J. M. Palmer, Museum of Comparative Zoology, Harvard University, Cambridge, MA 02138.
J. A. Coddington, Department of Entomology, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560.
P. M. Bonamo, Center for Evolution and the Paleoenvironment, State University of New York, Binghamton, NY 13901.