Supplemental material for: Interannual variability in the North Atlantic Ocean carbon sink

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Materials and Methods

Model description

The diagnostic model calculates the contributions of the five processes that govern the observed variability of DIC and δ^{13}C in the surface mixed layer: (1) air-sea gas exchange, (2) vertical diffusion, (3) vertical entrainment, (4) horizontal transport, and (5) net community production. To demonstrate the technique here, we start with the conservation equation for the DIC (^{12}C + ^{13}C) in the mixed layer:

$$
\begin{aligned}
\frac{dC}{dt} &= \frac{1}{h} kL \cdot \left(pCO_2^{\mathrm{atm}} - pCO_2^{\mathrm{oc}}\right) \\
&\quad + \frac{1}{h} K_z \left.\frac{dC}{dz}\right|_{\mathrm{tc}} + \frac{1}{h}\,\Theta\left(\frac{dh}{dt}\right) \cdot (C_{\mathrm{tc}} - C) \\
&\quad + J_{\mathrm{trsp}} + J_{\mathrm{ncp}},
\end{aligned}
\tag{1}
$$

where the three expressions on the right hand side represent, respectively, the contribution from (1) air-sea gas exchange, (2) from vertical diffusion, and (3) from vertical entrainment. The term J_{trsp} denotes the source term due to horizontal transport, J_{ncp} the source term due to net community production, h the variable mixed layer depth (defined positively downwards), k the gas exchange velocity, L the solubility of CO_2 in seawater, pCO_2^{atm} the $p\mathrm{CO}_2$ in the atmosphere, K_z the vertical diffusivity at the base of the mixed layer, $dC/dz|_{\mathrm{tc}}$ the vertical DIC gradient at the base of the mixed layer, and C_{tc} the DIC concentration in the thermocline below the mixed layer. $\Theta(dh/dt)$ denotes the Heaviside function, which states that shoaling of the mixed layer (when $dh/dt < 0$) does not introduce new water into the mixed layer and, therefore, does not alter the concentration of the tracers in the mixed layer. Only the deepening of the mixed layer (when $dh/dt > 0$) induces mixing with the underlying waters of the thermocline to produce changes in the tracer concentrations. A similar conservation equation is written for DIC of only the rare isotope, $\mathrm{DI}^{13}\mathrm{C}$. For more details see Gruber et al. [pp 680-683] (1).

Related to the source term for net community production, J_{ncp}, is a corresponding term for the rare isotope (${}^{13}J_{ncp}$), i.e. ${}^{13}J_{ncp} = {}^{13}r_{org}J_{ncp}$, where ${}^{13}r_{org}$ denotes the ${}^{13}\mathrm{C}/{}^{12}\mathrm{C}$ ratio of organic matter. Similarly we write: ${}^{13}J_{trsp} = {}^{13}r_{trsp}J_{trsp}$. We thus end up with 2 conservation equations, 2 equations relating DIC and $\mathrm{DI}^{13}\mathrm{C}$ source terms, and 4 unknowns (J_{ncp}, ${}^{13}J_{ncp}$, J_{trsp}, and ${}^{13}J_{trsp}$), which are solved for, at each time step of the diagnostic model. (Note: This solution scheme differs from that used by Gruber et al. (1) in that they estimated J_{trsp} and ${}^{13}J_{trsp}$ and then solved for dC/dt). The concept of this model is analogous to a procedure called "double deconvolution" (2).

Inputs to the diagnostic model consist of the observed DIC and $\delta^{13}\mathrm{C}$ variations as well as of hydrographic and meteorological observations, mostly obtained from the BATS and Station 'S" hydrographic programs, available from http://www.bbsr.edu. Derived input data, such as the gas exchange coefficient, k, the vertical diffusivity, K_z, the mixed layer, h, and the ${}^{13}\mathrm{C}/{}^{12}\mathrm{C}$ ratio of organic matter, ${}^{13}r_{org}$, have been estimated in a manner identical to that used by Gruber et al. (1), except that the data used here are based on observations from 1983 to 2001. The mean values and seasonal cycles of these quantities are therefore very similar to those reported (1).

Rates of change and fluxes

The model considers the contribution of the five processes on a control volume of 1 m^{-2} surface area extending from the surface (z=0) down to the base of the mixed layer (z=h). Fluxes (F_i) across the boundaries and interior rates of changes ($dC/dt|_i$) are therefore related by

$$F_i = \int_{z=h}^{z=0} \left.\frac{dC}{dt}\right|_i dz = h \cdot \left.\frac{dC}{dt}\right|_i . \tag{2}$$

While air-sea exchange, vertical entrainment, and vertical diffusion represent fluxes across the top and bottom of the control volume, the flux by net community production represents the vertically integrated rate of change induced by this process and the flux by horizontal transport represents the net flux of DIC across the lateral boundaries of the control volume.

Co-variance flux term

The changes in the volume of the mixed layer box give raise to a co-variance flux term that occurs in the absence of concentration changes. This co-variance term can be illustrated by considering the mass balance of carbon in the mixed layer over the annual cycle ($t_1 - t_o$ = 1yr):

$$\int_{t_o}^{t_1} \frac{d(Ch)}{dt} dt' = \int_{t_o}^{t_1} C\frac{dh}{dt} dt' + \int_{t_o}^{t_1} h\frac{dC}{dt} dt' = \int_{t_o}^{t_1} C\frac{dh}{dt} dt' + \sum_{i=1}^{n} \int_{t_o}^{t_1} F_i dt', \tag{3}$$

where the sum is over all the fluxes, F_i, considered. If h were constant, or if there were no correlation between C and dh/dt, the first integral on the most right hand side of the equation would vanish. For the case near Bermuda, this integral, however, contributes significantly to the mass balance of the mixed layer.

Supplemental Table 1. Linear Correlation Coefficients for the Period 1983 to 2001[a].

	SST[b]	h[b]	NAO[b]	sDIC[b]	$\delta^{13}C$[b]	pCO_2[b]	F_{as}[c]	F_{ent}[c]	F_{ncp}[c]	F_{trsp}[c]
SST	1.00	-0.78/-0.56	0.63/0.37	-0.89/-0.76	0.72/0.34	0.15*/ 0.40	-0.62	-0.48	0.59	-0.59
h		1.00	-0.49/-0.38	0.65/ 0.56	-0.30*/-0.19*	-0.25*/-0.19*	0.58	0.46	-0.28	0.50
NAO			1.00	-0.67/-0.47	0.40*/ 0.26*	-0.14*/-0.09*	-0.39	-0.02*	0.31*	-0.65
sDIC				1.00	-0.76/-0.56	0.23*/ 0.16*	0.43	0.46	-0.57	0.63
$\delta^{13}C$					1.00	-0.06*/-0.23*	-0.17*	-0.34	0.29	-0.32
pCO_2						1.00	-0.42	-0.13*	0.17*	-0.03*
F_{as}[c]							1.00	0.62	-0.76	0.78
F_{ent}[c]								1.00	-0.61	0.54
F_{ncp}[c]									1.00	-0.76
F_{trsp}[c]										1.00

[a]: linear correlation coefficients were computed from data averaged over 4 months periods (December-March,April-July,August-November). The symbol h denotes the mixed layer depth, F_{as} is the air-sea gas exchange flux, F_{ent} is the entrainment flux, F_{ncp} is vertically integrated net community production, and F_{trsp} is the flux induced by horizontal transport.

[b]: first number: December-March (DJFM) correlation; second number: correlation for all periods.

[c]: correlations for 12 months running averages and all seasons, except for h where only the DJFM anomalies for h were used.

*: correlations not significant at the 95% confidence level (Student t-test).

References and Notes

1. N. Gruber, C. D. Keeling, T. F. Stocker, Deep Sea Res. I 45, 673 (1998).

2. C. D. Keeling, et al., Aspects of Climate Variability in the Pacific and the Western Americas, D. H. Peterson, ed., Geophys. Monogr. Ser., 55 (AGU, Washington, D.C., 1989), pp. 165–237.