The Impact of the North Atlantic Oscillation on the Uptake and Accumulation of Anthropogenic CO₂ by North Atlantic Ocean Mode Waters

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Supplementary Material

S1 MODEL – OBSERVATION COMPARISON

We compare the model to observations along the CLIVAR/CO₂ north-south Atlantic Ocean hydrographic section (A16). As discussed in section 2.3, the model is in agreement with observations of anthropogenic inventories along the A16 transect (Figure 2). There is also
reasonable agreement between the observed and modeled vertical structure of anthropogenic carbon concentrations, temperature, salinity, DIC, and alkalinity along the A16 transect (Figure S1 and S2). While the model shows the same overall vertical structure as the observations, model gradients tend to be sharper. In particular, temperature, salinity, alkalinity, and anthropogenic carbon decrease more rapidly with depth in the model than in the observations. In addition, subsurface DIC and anthropogenic carbon concentrations tend to be lower in the model than in the observations. Further analysis, including a full synthesis of \( C_{anthro} \) observations, is needed in order to understand the differences between the model and observations.

**S2 MODEL BIAS**

The impact of changing physics on anthropogenic carbon (\( C_{anthro} \)) in the North Atlantic Ocean is evaluated using two separate model simulation, ‘Repeat Annual Cycle’ (RAC) and ‘Variable Physics’ (VP), described in section 2.1. This analysis assumes an identical mean state for the two models, such that the mean rate of \( C_{anthro} \) uptake for the two models is equivalent. While this appears to be the case for some regions (e.g. Figure S3a), in others there is a clear offset between the two model simulations (e.g. Figure S3b) resulting from different forcing. In the subtropical and subpolar mode waters, different isopycnal bands show different biases with \( \sigma_{26.25-26.75} \), \( \sigma_{27.55-27.6} \) and \( \sigma_{27.65-27.675} \) showing a negative bias and \( \sigma_{27.675-27.7} \) showing a positive bias (Figure S4).

The RAC forcing in Large and Yaeger [2004] was constructed to have balanced global heat and freshwater fluxes while retaining cross-correlations in surface forcing terms on the synoptic or storm time-scale. It is not surprising that the mean ocean circulation state of RAC differs somewhat from the mean circulation in the VP integration given all of the potential non-
linearities that can rectify variability in surface forcing into mixed layer depths, surface currents, etc. It is difficult to accurately correct for this bias, especially in regions of significant non-linear increases in $C_{anthro}$ and with substantial interdecadal variability. However, as this analysis focuses on interannual variability in the ocean system and not on long-term trends, differences in model mean state do not strongly impact our findings. A positive bias (when the mean $C_{anthro}$ accumulation of the VP simulation is greater than that of the RAC simulation) will result in a positive shift in $C_{anthro}^{\Delta physics}$ values. However, correlations based on changes in interannual variability between the model simulations will not be impacted. Specifically, the impact of model bias on $\Delta I_{anthro}^{\Delta physics}$ will be minimal due to the short time-scales of integration (one year).

S3 SUBPOLAR MODE WATER $\sigma_{27.675-27.7}$

For this study, we identify seven Subpolar Mode Water (SPMW) isopycnal bands, defined as: $27.3 \leq \sigma_0 < 27.4$, $27.4 \leq \sigma_0 < 27.5$, $27.5 \leq \sigma_0 < 27.55$, $27.55 \leq \sigma_0 < 27.6$, $27.6 \leq \sigma_0 < 27.65$, $27.65 \leq \sigma_0 < 27.675$, and $27.675 \leq \sigma_0 < 27.7$. We focus our analysis on the densest SPMW in the eastern basin, $\sigma_0$ values between 27.6 and 27.7, as these waters have a longer residence time than lighter SPMW and are the precursor to Labrador Sea Water (LSW) [Brambilla and Talley, 2008]. However, the anthropogenic carbon inventory ($I_{anthro}^{\Delta physics}$) for several of the densest SPMW isopycnal bands appears to be impacted by model bias (see section S2), with $\sigma_{27.55-27.6}$ and $\sigma_{27.65-27.675}$ showing a negative bias and $\sigma_{27.675-27.7}$ showing a positive bias. We assume that this bias results from a difference in mean model state and so all interannual variability (changes in $\Delta I_{anthro}^{\Delta physics}$) is directly attributable to changes in model physics. However, due to the potential for different biases along different SPMW surfaces, it is necessary to evaluate the density bands
individually rather than as a cumulative inventory. Therefore, to deconvolve the mechanisms
driving interannual variability in the SPMW $I_{anthro}$, we focus on a single SPMW isopycnal band.
We use the following selection criteria for selecting the band: significant impact of variable
physics on the anthropogenic carbon inventory, significant interannual variability in
anthropogenic carbon accumulation rate ($dC_{anthro}/dt$), and potential to impact $C_{anthro}$ content of
LSW.

Variable ocean physics results in significant changes to the anthropogenic carbon
inventory along both the $\sigma_{27.5-27.6}$ and $\sigma_{27.675-27.7}$ bands (Figure S5). The $\sigma_{27.675-27.7}$ isopycnal band
shows the largest interannual variability in $dC_{anthro}/dt$ (Figure S6, mean absolute variability of
10.1 Tg C/yr). In addition, $\sigma_{27.675-27.7}$ is one of the densest SPMW in the model simulation and so
is likely to be an important precursor to LSW. Therefore, we conduct the SPMW analysis along
the $\sigma_{27.675-27.7}$ isopycnal band.

**S4 DOMINANT TERMS CONTROLLING DIC**

To deconvolve the dominant terms controlling changes in $\Delta I_{anthro}^{physics}$ (equation 3), we
partition the change in DIC into 5 components following Doney et al. [2007; 2009]:

$$dI_{DIC}' \approx \int (F'_{CO2} + A'_{DIC} + E'_{DIC} + B'_{DIC} + V'_{DIC}) dt$$

(S1)

where $dI_{DIC}'$ is the monthly change in DIC inventory anomaly in mol $C/m^2/month$, $F'_{CO2}$ is the
change in air-sea CO2 flux, $A'_{DIC}$ is the change in the vertical integral of the convergence of the
resolved advective DIC transport, $E'_{DIC}$ is the change in the vertical integral of the convergence
of the eddy-parameterized DIC transport, $B'_{DIC}$ is the change in the vertical integral of net
biological release of inorganic carbon, and $V'_{\text{DIC}}$ is the change in the surface virtual flux of DIC due to freshwater fluxes. $F'_{\text{CO2}}$, $A'_{\text{CO2}}$, $E'_{\text{CO2}}$, $C'_{\text{CO2}}$, and $V'_{\text{CO2}}$ are integrated over a month such that the units for these terms are mol C/m²/month. $A_{\text{DIC}}$ is defined as:

$$A_{\text{DIC}} = - \int_{0}^{1280} \nabla \cdot (\bar{v}_{\text{resDIC}}) \, dz$$  \hspace{1cm} (S2)

where $\bar{v}_{\text{res}}$ is the resolved model velocity. The physical convergence terms and net biological release terms are integrated over the main thermocline (1280m based on the model vertical grid), and all terms are defined such that positive values result in an increase in DIC inventory.

To determine the terms responsible for changes in $I_{\text{anthro}}$, we define $dI'_{\text{anthro}}$ as:

$$dI'_{\text{anthro}} = dI'_{\text{DIC Transient}} - dI'_{\text{DIC Pre_industrial}}$$  \hspace{1cm} (S3)

where $dI'_{\text{DIC Transient}}$ and $dI'_{\text{DIC Pre_industrial}}$ are the monthly change in DIC inventory anomaly for the model pair with increasing atmospheric CO₂ and constant atmospheric CO₂, respectively. Equation (S3) can be expanded using equation (S1) to express $dI'_{\text{anthro}}$ in terms of the 5 convergence and flux terms, hereafter collectively referred to as the terms of equation (S1). Finally, we calculate $dI'_{\text{anthro}}$ using equations (2), (S1) and (S3) in order to investigate the impact of changing ocean physics on the carbon terms. Following Doney et al. [2007; 2009], we determine the dominant terms responsible for changes in $dI'_{\text{anthro}}$ by comparing the slopes of the 5 terms linearly regressed against $dI'_{\text{anthro}}$. The dominant term will result in a regression slope close to 1. Slopes greater than one indicate that the term is producing a larger anomaly than that observed in $dI'_{\text{anthro}}$. This anomaly is therefore being compensated by one (or more) of the other terms. Negative slopes indicate terms acting to dampen the impact of the dominant term(s).

Using equations (S1)-(S3), we evaluate the primary terms responsible for changes in $I'_{\text{anthro}}$ in the subtropical and subpolar gyre. Interannual variability in anthropogenic carbon in
the subtropical gyre is highly correlated with changes in advective convergence, in particular
with the horizontal convergence of carbon (Figure S7). This is consistent with previous work,
which showed that interannual changes in DIC and temperature in the subtropics are dominated
by advective transport [Doney et al., 2007; Doney et al., 2009]. This analysis suggests that most
of the changes in $I_{\text{anthro}}$ observed in the gyre interior are due to $C_{\text{anthro}}$ anomalies and changes in
isopycnal thickness advected from outcrop regions where large scale mixing events and CO$_2$ air-
sea fluxes occur.

Similarly, an analysis of the primary budget terms responsible for changes in subpolar

$\Delta I_{\text{physics}}^\text{anthro}$ is conducted. As in the subtropics, the majority of $dI_{\text{anthro}}^\text{physics}$ variability is due to changes in
advective DIC convergence (Figure S8). However, in the subpolar gyre, this relationship is
driven by large changes in the horizontal advective carbon convergence that is compensated by
similarly large, but inversely related, changes in the vertical advective carbon convergence. Part
of this relationship may be explained by net mass convergence that is compensated by
downwelling.

REFERENCES

Averaged properties and mean circulation, *Journal of Geophysical Research-Oceans*,
113(C4).

Doney, S. C., et al. (2007), Mechanisms governing interannual variability of upper-ocean
temperature in a global ocean hindcast simulation, *Journal of Physical Oceanography*,
37(7), 1918-1938.

Doney, S. C., et al. (2009), Mechanisms governing interannual variability in upper-ocean
inorganic carbon system and air-sea CO$_2$ fluxes: Physical climate and atmospheric dust,

Large, W. G., and S. G. Yeager (2004), Diurnal to decadal global forcing for ocean and sea-ice
models: The data sets and flux climatologies, NCAR Technical Note NCAR/TN-
460+STR.