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Interannual variability of the air-sea flux of oxygen in the North Atlantic

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Abstract. In studies using timeseries observations of atmospheric O_2/N_2 to infer the fate of fossil fuel CO_2, it has been assumed that multi-year trends in observed O_2/N_2 are insensitive to interannual variability in air-sea fluxes of oxygen. We begin to address the validity of this assumption by investigating the magnitude and mechanisms of interannual variability in the flux of oxygen across the sea surface using a North Atlantic biogeochemical model. The model, based on the MIT ocean general circulation model, captures the gross patterns and seasonal cycle of nutrients and oxygen within the basin. The air-sea oxygen flux exhibits significant interannual variability in the North Atlantic, with a standard deviation (0.36 mol m^{-2} y^{-1}) that is a large fraction of the mean (0.85 mol m^{-2} y^{-1}). This is primarily a consequence of variability in winter convection in the subpolar gyre.

Introduction

The variability of air-sea O_2 fluxes has recently become of particular interest since observed atmospheric O_2/N_2 trends have been used to estimate the partitioning of the sink of fossil fuel CO_2 between the ocean and terrestrial biosphere [*Keeling et al.*, 1996; *Bender et al.*, 1996]. These studies indicate that approximately one-third of anthropogenically produced CO_2 is taken up by the global land biota (2.0 $\pm$ 0.9 Pg carbon y^{-1} ($PgCy^{-1}$);[*Keeling et al.*, 1996]). *Keeling et al.* [1996] also use the meridional gradient of O_2/N_2 and CO_2 to infer that the sink in the Northern Hemisphere land biota is approximately the same magnitude (1.9 $\pm$ 0.9 $PgCy^{-1}$) as the global sink. Forest inventory studies, however, suggest a smaller global land biota sink (0.5 $\pm$ 0.5 $PgCy^{-1}$, [*Schimel et al.*, 1995]).

A key assumption made by *Keeling et al.* [1996] and *Bender et al.* [1996] is that multi-year trends in observed O_2/N_2 are insensitive to interannual variability in the global, annual mean air-sea oxygen flux. The global atmospheric balance for CO_2 and O_2/N_2 is assumed to be comprised only of the long-term trends imparted by fossil fuel combustion, land biota and ocean CO_2 uptake. However, data suggests that interannual variability may be significant. *Bender et al.* [1996] study atmospheric O_2/N_2 data from two stations at 41° S and interpret a large seasonal cycle with substantial interannual variability (21% of the mean). At a latitude with minimal terrestrial influence, the likely source for O_2 variability is air-sea exchange.

The magnitude of interannual variability in air-sea oxygen fluxes has yet to be estimated either globally or regionally. Although the impact of interannual variability on CO_2 sink estimates will be reduced by forming multi-year averages, the timescale on which interannual variability is negligible also remains an unknown.

In this study we focus on air-sea O_2 flux variability in a model of North Atlantic ocean. Our goals are two-fold. Firstly, to examine the regional interannual variability of air-sea O_2 fluxes. Is there potential for a significant uncertainty in estimates of fossil fuel CO_2 partitioning due to the assumption that interannual variability in air-sea O_2 fluxes can be neglected? Secondly, we elucidate the physical mechanisms underlying the model's variability.

North Atlantic biogeochemical model

We use a North Atlantic biogeochemical model based on the MIT ocean general circulation model (MITgcm) [*Marshall et al.*, 1997a] [*Marshall et al.*, 1997b] integrated globally at one degree horizontal resolution, with 21 vertical levels, and initialized with *Levitus and Boyer* [1994] climatology. It was forced with 12-hourly, reanalyzed wind stress and heat flux fields during the period 1979-1996, and a nine-year segment (1987-1995) of model variables stored for use in offline studies. Geostrophic eddy transfer is parameterized using the *Gent and McWilliams* [1990] scheme and the upper ocean mixed-layer is parameterized by convective adjustment. The MITgcm and offline model are discussed in more detail in *Dutkiewicz et al.* [2000].

The biogeochemical model is based on the cycles of phosphorus and oxygen in the ocean. The governing equations for phosphate, P, and oxygen, O_2 are

$$\frac{\partial P}{\partial t} = -\nabla \cdot (\mathbf{u}P) + \nabla \cdot (\kappa \nabla P) + C_P + S_b + S_r \quad (1)$$

$$\frac{\partial O_2}{\partial t} = -\nabla \cdot (\mathbf{u}O_2) + \nabla \cdot (\kappa \nabla O_2) + C_{O_2} + R_{O_2:P} \cdot (S_b + S_r) + E \quad (2)$$

where $\mathbf{u}$ is the transformed Eulerian mean velocity and $\nabla \cdot (\kappa \nabla P)$ is a tensorial representation of mixing along isentropic surfaces, with transfer coefficient $\kappa = 10^3$ m^2 s^{-1} as in the MITgcm [*Gent and McWilliams*, 1990]. Convective mixing (C) is achieved using statistics of convection in the MITgcm to govern the distribution and frequency of vertical mixing events [*Dutkiewicz et al.*, 2000], and acts on the local gradients of individual tracers. S_b is the loss of P due to formation of sinking particles, and S_r the source from remineralization.

We use a simplified, light and nutrient limited parameterization of particulate export: $S_b = -\epsilon(\frac{\partial \Phi}{\partial z})\frac{P}{P+P_{max}}$. Light limitation is implemented to ensure that the rate of export cannot exceed the photosynthetic energy supplied by

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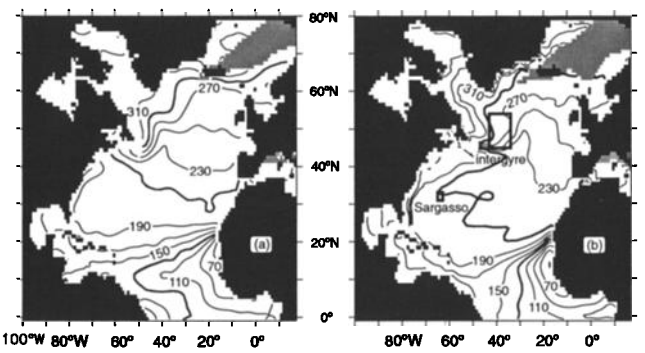

Figure 1. (a) Observed and (b) modeled climatological dissolved O_2 on $\sigma_\theta = 27.5$ density surface (μmol kg^{-1}). Gray areas are north of the isopycnal outcrop. The 130, 210 and 290 isolines are darkened for clarity.

the vertical flux divergence of photosynthetically radiation radiation, $\partial\Phi/\partial z$, assuming a photosynthetic efficiency, ϵ. This is an upper bound where all photosynthetically available photons are assumed used for new production. When light is limiting ($P \gg P_{max}$) the export rate asymptotes to $-\lambda_b P_{max} = \epsilon(\frac{\partial\Phi}{\partial z})$. Here P_{max} is the concentration of nutrients at which light becomes limiting to export production. The characteristic timescale for export of P, $1/\lambda_b$, is chosen such that when light is not limiting it is about 1 week. The monthly mean solar radiation flux at the surface of the ocean (Φ(y,0,t)) is determined using the astronomical formula of *Paltridge and Platt* [1976] and a latitudinally varying albedo according to *North et al.* [1981]. The profile of light in the water column is assumed to follow $\Phi(z) = \Phi(0)e^{-k_w z}$, where k_w, the extinction coefficient, is an empirical function of latitude, based on Secchi depth observations [*Lewis et al.*, 1988; *Parsons et al.*, 1984]. Photosynthetic efficiency, ϵ, is assumed to have a value of 1.35×10^{-5} μmol P per Joule of surface incident radiation when vertically averaged over the euphotic zone, consistent with *Morel* [1978]. Export production is reduced by sea-ice, proportional to the fractional ice cover in each grid cell. The sinking particle flux at all depths is parameterized using an exponential profile with a scale height of 400m [*Dutkiewicz et al.*, 2000], the divergence of which provides the remineralization source of P.

Biological sources and sinks of O_2 are assumed to be in fixed proportion to those of P, where $R_{O_2:P} = -175 : 1$ [*Takahashi et al.*, 1985]. Air-sea gas exchange (E) of O_2 is parameterized as a function of wind speed, sea surface temperature and salinity [*Wanninkhof*, 1992] with solubility properties as determined by *Weiss* [1970]. Air-sea oxygen fluxes are reduced by sea-ice, proportional to the fractional ice cover in each grid cell. A constant atmospheric O_2 concentration of 21 pph is assumed.

At open boundaries, we restore to climatological P and O_2 [*Conkright et al.*, 1994; *Levitus and Boyer*, 1994] with a timescale of 2 months. Since we are primarily interested in upper ocean variability, we restore to P climatology, but not O_2, below 1200m on a 200 month timescale. Tracer fields are initialized from the climatology of *Conkright et al.* [1994] and *Levitus et al.* [1994] and the model is integrated over a repeating 9 year cycle for 10 cycles until an equilibrium solution, exhibiting interannual variability, is obtained.

Model results

The model successfully captures the broad distribution of P and O_2 in the upper ocean and exhibits a strong surface seasonal cycle typical of the North Atlantic. In Figure 1 we compare the 9 year mean modeled O_2 distribution on the mean $\sigma_\theta = 27.5$ isopycnal surface to the observed distribution [*Conkright et al.*, 1994; *Levitus and Boyer*, 1994]. Modeled dissolved O_2 decreases towards the interior of the subtropical gyre, indicative of respiration of exported organic matter, in a manner consistent with the broad features of the climatology. However, it overestimates the magnitude of the oxygen minimum zone on the eastern margin near Africa. In addition, high O_2 isolines extend too far south, suggesting that the model ventilates too quickly or does not export biological matter efficiently enough in other regions of the subtropics and tropics. Model isolines appear displaced to the north in the subpolar gyre in comparison to the data. This discrepancy may be due in part to summer bias in the data. Vertical displacement of the isopycnal in the physical model could also contribute to each of these discrepancies. In another comparison (not shown), we find that seasonal, surface ocean O_2 saturation levels are broadly consistent with the climatology of *Najjar and Keeling* [1997].

Over decadal and longer timescales, large scale circulation and surface heat fluxes lead to a net transfer of O_2 rich waters to the south at depth and a northward flux of warm, O_2 depleted waters near the surface. The model has a net transport of oxygen to the south, balanced by a net annual uptake from the atmosphere. At 24° N and 48° N, the modeled southwards O_2 transport is 2161 and 2057 kmol s^{-1} respectively, very close to the southward estimates of 2069±581 and 1748±475 kmol s^{-1}, respectively, deduced by *Ganachaud* [1999] from observed hydrographic and O_2 data.

Upper ocean convective mixing is particularly significant in determining nutrient supply to the surface ocean and air-sea fluxes of oxygen. The general circulation model captures the mean mixed-layer cycle and its interannual variability, as illustrated in Figure 2 where data from the Bermuda Atlantic Time-Series Station (BATS, 31°40"N, 64°10"W) are compared to area-averaged model results for a small re-

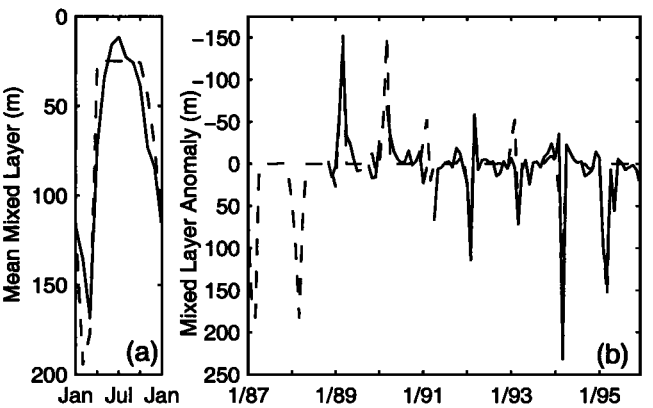

Figure 2. Observed (BATS, solid) and modeled (Sargasso region, dashed) mixed-layers. BATS observations began in October 1988. Mixed-layer depths are determined using a criteria of $\Delta T|_z = 0.5$°C. Both the modeled (a) mean annual cycle for 1989-95 and (b) variability with this cycle removed compare well with observations.

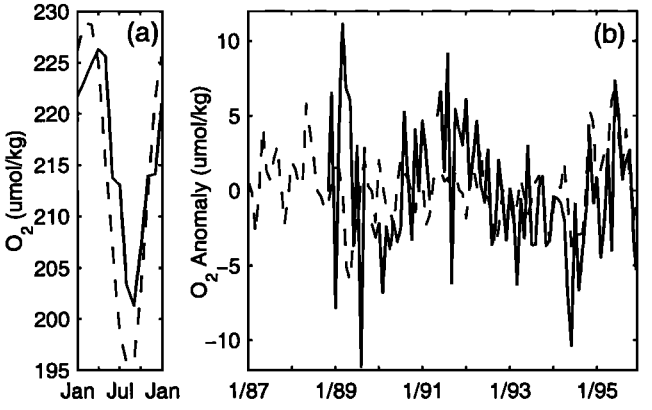

Figure 3. Surface O_2 at BATS / Sargasso: observed (solid) and modeled (dashed) **(a)** mean 1989-95 cycle and **(b)** variability with this cycle removed (μmol kg^{-1})

gion representative of the Sargasso Sea (marked on Figure 1b). We also find that modeled annual cycles of mixed layer depth, surface P and O_2 in the intergyre region (marked on Figure 1b) compare well (not shown) with observed data from Ocean Weather Ship "Charlie" (OWS C, 52°48"N, 35°30"W).

We compare observed and modeled surface O_2 at BATS and in the Sargasso region in Figure 3. The mean amplitude and phase of the surface annual cycle of O_2 in the Sargasso Sea compares well with the observed cycle (3a). The model, however, shows less variability than the observed data on sub-seasonal and interannual timescales (3b). The mean P cycle (not shown) in the model looks unlike the data, exhibiting a regular seasonal cycle that is not observed. Modeled P at BATS does not exhibit the intermittent peaks in concentration that are seen in the data. The lack of sub-seasonal variations may be attributed to the low resolution of the model since mesoscale eddies are not explicitly resolved. Further, monthly mean model results should be less variable than instantaneous monthly observations.

In summary, the physical model works well in the North Atlantic, but the biological model is too simple to capture complex ecosystem dynamics at BATS. Despite this shortcoming, the model exhibits interannual variability in surface O_2 concentrations (and therefore, air-sea fluxes) that is comparable, although smaller in magnitude, to the data at BATS. We conclude that physical processes control surface O_2 concentrations and air-sea O_2 fluxes, and that the simplicity of the biological model is acceptable given the goals of our work.

What is the interannual variability in the integrated, basin-scale oxygen flux in the model? We find a substantial and significant interannual variability in the net air-sea exchange of O_2 over the North Atlantic basin (Figure 4a) which varies by as much as one-half of the mean flux, from year to year. The standard deviation of the timeseries is 0.36 mol m^{-2} y^{-1}, a large fraction of the mean flux into the North Atlantic (0.85 mol m^{-2} y^{-1}). Since the modeled surface O_2 exhibits weaker than observed variability on both short (month) or long (decadal) timescales, we expect that our estimate of variability in basin-averaged modeled air-sea fluxes represents a lower bound. Sensitivity experiments show similar variability over a range of values for the air-sea exchange and export parameterization coefficients.

What is the cause of this variability? The dominant balance on seasonal and interannual timescales in the North Atlantic is a vertical one; net O_2 supply to the surface ocean by wintertime air-sea exchange and net biological production is balanced by transfer of O_2 to the seasonal thermocline by convective overturning. Below, O_2 is consumed by remineralization of particles.

We illustrate the annual-average, basin-scale variations in the individual influences on the surface layer of the model in Figure 4b. Annual air-sea O_2 flux anomalies are largely driven by changes in convective mixing, primarily in the subpolar gyre, and the consequent transport of oxygen away from the surface waters. The dominant factor controlling changes in the air-sea flux is interannual change in entrainment of oxygen-depleted waters from the seasonal thermocline. Anomalies in biological production of oxygen tend to show the opposite influence, since enhanced entrainment also supplies more nutrients which may boost the biological production, but this process is generally of secondary importance to the air-sea O_2 flux anomaly. Advective transport anomalies in the model are generally small.

Conclusions

Using a biogeochemical model of the North Atlantic, we have shown that there may be significant interannual variability in the basin-wide air-sea flux of O_2. We find variations as much as one half of the mean uptake of O_2 by the North Atlantic. The variability, we believe, represents a lower bound, since modeled surface O_2 tends to be less variable than the observed ocean. This significant variability prompts further investigation. We are pursuing a global, multidecadal study which will provide an estimate of the annual global imbalance of air-sea O_2 fluxes.

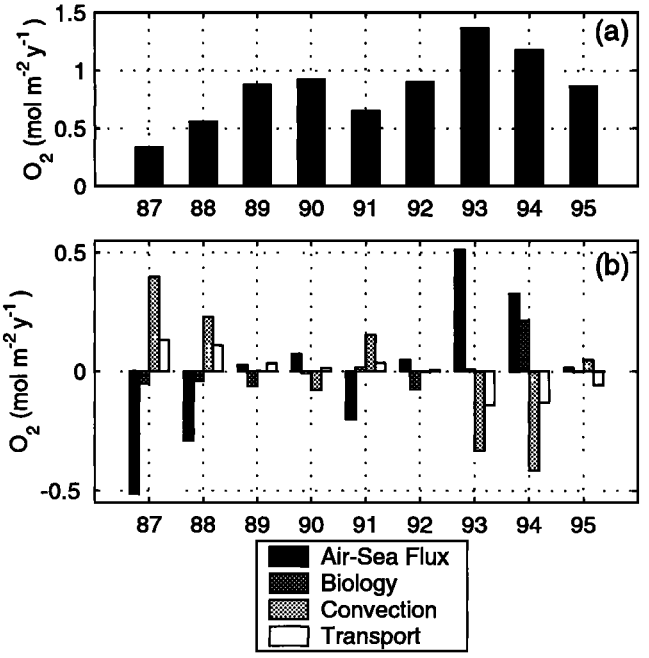

Figure 4. **(a)** Modeled sequence of North Atlantic annual and basin average, air-sea O_2 flux (mol m^{-2} y^{-1}). **(b)** Annual, basin-averaged, anomalies (relative to 9 year mean) of the air-sea flux and the dominant biological and physical influences driving the flux anomalies.

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