Role of wind stress and heat fluxes in interannual-to-decadal variability of air-sea CO_2 and O_2 fluxes in the North Atlantic

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[1] A coupled ecosystem-circulation model of the North Atlantic is used to examine the individual contributions by wind stress and surface heat fluxes to naturally driven interannual-to-decadal variability of air-sea fluxes of CO_2 and O_2 during 1948–2002. The model results indicate that variations in O_2 fluxes are mainly driven by variations in surface heat fluxes in the extratropics (15°N to 70°N), and by wind stress in the tropics (10°S to 15°N). Conversely, variations in simulated CO_2 fluxes are predominantly wind-stress driven over the entire model domain (18°S to 70°N); while variability in piston velocity and surface heat fluxes is less important. The simulated uptake of O_2 by the North Atlantic amounts to 70 ± 11 Tmol yr^{-1} to which the subpolar region (45°N to 70°N) contributes by 62 ± 10 Tmol yr^{-1}. Whereas the subpolar North Atlantic takes up more than 2/3 of the total carbon absorbed by the North Atlantic in our model (about 0.3 Pg C yr^{-1}), interannual variability of air-sea CO_2 fluxes reaches similar values (about 0.01 Pg C yr^{-1} each) in the subpolar (45°N to 70°N), the subtropical (15°N to 45°N) and the equatorial (10°S to 15°N) Atlantic. **Citation:** Friedrich, T., A. Oschlies, and C. Eden (2006), Role of wind stress and heat fluxes in interannual-to-decadal variability of air-sea CO_2 and O_2 fluxes in the North Atlantic, *Geophys. Res. Lett.*, *33*, L21S04, doi:10.1029/2006GL026538.

1. Introduction

[2] Reliable estimates of air-sea fluxes of CO_2 are needed not only for a better understanding of the global carbon cycle and the long-term fate of anthropogenic CO_2, but also to better constrain inverse models that help to monitor sources and sinks of anthropogenic CO_2 on politically and economically more relevant shorter ($\sim$ annual) time scales. Time-series data [*Bates et al.*, 1999; *Gruber et al.*, 2002] and model studies [*Le Quéré et al.*, 2000; *Bopp et al.*, 2002; *McKinley et al.*, 2003, 2004a; *Wetzel et al.*, 2005], have revealed substantial interannual to decadal fluctuations in air-sea fluxes of CO_2 and also of O_2. Air-sea O_2 fluxes are relevant for methods that attempt to separate terrestrial and marine sinks of anthropogenic CO_2 by employing the atmospheric mixing ratio of O_2/N_2 [*Keeling and Shertz*, 1992]. To better understand the mechanisms that drive these fluctuations in air-sea fluxes of CO_2 and O_2, we made a number of sensitivity studies with different combinations of climatological and interannually varying forcing fields applied to a prognostic, 4-component ecosystem-circulation model of the North Atlantic. This complements earlier model studies [*Wetzel et al.*, 2005] including applications of interannually varying atmospheric forcing fields to one-component [*McKinley et al.*, 2000, 2004a], or multi-component off-line biogeochemical models [*Bopp et al.*, 2002] and to models restored to climatological temperature and salinity values beneath the surface mixed layer [*Le Quéré et al.*, 2000]. While the simulated variability in air-sea fluxes of CO_2 and O_2 is of similar magnitude in all these models, our sensitivity studies aim to elucidate the processes that cause the temporal fluctuations.

2. Model and Forcing

[3] The numerical model consists of an NPZD-type (nitrate, phytoplankton, zooplankton, detritus) ecosystem model [*Oschlies and Garçon*, 1999] embedded into a $\frac{4}{3} \times \frac{4}{3}$ cos(latitude) resolution circulation model with 45 vertical levels based on the Modular Ocean Model version 2.1 [*Pacanowski*, 1995] (the numerical code together with all configurations used in this study can be accessed at http://www.ifm.uni-kiel.de/fb/fb1/tm/data/pers/ceden/spflame/index.html). The model domain spans the Atlantic Ocean from 70°N to 18°S and is the same as that used by [*Eden and Willebrand*, 2001], except that northern and southern boundaries as well as the Straits of Gibraltar are closed with restoring zones for temperature, salinity and biogeochemical tracers. Advection is modelled using the QUICKER scheme [*Leonard*, 1992] with an additional flux correction [*Lafore et al.*, 1998] to ensure positive biogeochemical tracer concentrations. The nitrogen-based ecosystem model is coupled to the oxygen and carbon cycles via the respective Redfield ratios. Particulate inorganic carbon is not modelled explicitly, and surface alkalinity is computed from an observational fit to surface salinities [*Eden and Oschlies*, 2006]. The formulation of air-sea gas exchange follows *Wanninkhof* [1992]. For computational and conceptional simplicity, the atmospheric CO_2 concentrations were set to a preindustrial value of 278 ppm. Given the apparent absence of, up to now, strong non-linear responses of the ocean to the steady rise of atmospheric CO_2 our conclusions about mechanisms of interannual variability should also apply for a run that includes anthropogenic CO_2. Initial conditions for nitrate and oxygen are taken from *Boyer and Levitus* [1997], for DIC from the observational estimate of preindustrial DIC from GLODAP [*Sabine et al.*, 2004]. Initial conditions for phytoplankton, zooplankton and detritus are set to small values [*Oschlies and Garçon*, 1999]. During a 30-year physical spin-up followed by a 20-year biogeochemical spin-up, the model

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Table 1. Model Runs and Forcing Used for Wind-Stress, Surface Heat Flux and Piston Velocity[a]

Name of Model Run	Wind-Stress	Surface Heat Flux	Wind for Piston Velocity
Full forcing	ECMWF clim. + NCEP anom.	ECMWF clim. + NCEP anom.	ECMWF clim. + NCEP anom.
WIND	ECMWF clim. + NCEP anom.	ECMWF clim.	ECMWF clim.
HFLX	ECMWF clim.	ECMWF clim. + NCEP anom.	ECMWF clim.
PISTON	ECMWF clim. + NCEP anom.	ECMWF clim. + NCEP anom.	ECMWF clim.

[a]Note that full "ECMWF clim. + NCEP anom." forcing for wind was used in the heat flux formulation in full forcing, PISTON and HFLX run.

was forced with climatological monthly wind-stress and heat-flux fields computed from ECMWF analysis data [*Barnier et al.*, 1995]. Subsequently, a number of sensitivity experiments were run over a 54-year period (simulating the period 1948 to 2002) using different combinations of climatological and interannually varying monthly wind-stress and heat-flux anomaly fields (Table 1). To be consistent with the model's spin up we have added anomaly fields taken from the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] to the climatological ECMWF data as used during the spinup. Interannual fluctuations in the model results are calculated by subtracting a control simulation with climatological forcing to differentiate between forced signal and model drift, although the latter is small, i.e., an annual increase of CO_2 uptake by 0.0015 Pg C yr^{-2}.

3. Results and Discussion

[4] The general patterns of observational estimates of pre-industrial surface concentrations of dissolved inorganic carbon (DIC) [*Sabine et al.*, 2004] are generally reproduced by the model (Figure 1). However there are systematically lower values in simulated surface DIC concentrations (< 1800 mmol m^{-3}) in the eastern equatorial Atlantic and in the Amazon river plume. At Bermuda the mean annual cycle of pCO_2 agrees closely with Takahashi's compilation of pCO_2 measurements [*Takahashi et al.*, 1997] as does simulated O_2 with observed O_2 from the World Ocean Atlas (WOA) [*Conkright et al.*, 2002] (Figures 2a and 2b). Similar to previous ocean model simulations compiled by *Raynaud et al.* [2005], the amplitude of interannual variations of surface pCO_2 at Bermuda is underestimated by approximately a factor of two (Figure 2c). We speculate that this might be caused by the lack of meso- and submesoscale variability in the model simulations.

3.1. Oxygen

[5] Interannual to decadal fluctuations in simulated air-sea O_2 fluxes are largest in the subpolar North Atlantic (45°N to 70°N, Figure 3). In the zonal integral, anomalies reach up to ± 25 Mmol O_2 m^{-1} yr^{-1} which results in basin-scale fluctuations of ± 20 Tmol O_2 yr^{-1} about the basin-wide uptake of 70 Tmol O_2 yr^{-1} (0°N to 70°N). A comparison of the full forcing run with the HFLX run and the WIND run reveals that variations in wind stress explain only 35% of the variability in air-sea O_2 fluxes generated by the full forcing run, while variations in surface heat fluxes are the driving force of variability of O_2 fluxes everywhere north of 15°N. Oxygen uptake between 15°N and 70°N in the HFLX-run is highly correlated (r = 0.94) with the uptake simulated by the full forcing run.

[6] In agreement with the results presented by *McKinley et al.* [2004a] and *Körtzinger et al.* [2004] this variability is largely driven by interannual variations in wintertime convection and the associated entrainment of oxygen-depleted waters into the surface mixed layer. Patterns of the first empirical orthogonal functions (EOF) based on annual mean properties are almost identical for the simulated air-sea fluxes of O_2 and of heat and they show similar temporal behaviour (r = 0.88). They reveal the typical tripole pattern for the North Atlantic Oscillation (NAO) and explain 28.4% of the interannual variability in simulated air-sea O_2 fluxes (17% for simulated heat fluxes). Regressing air-sea fluxes of O_2 to annual mean NAO-Index [*Hurrell*, 1995] clearly reflects this tripole pattern. During the years of a high NAO-Index O_2 uptake increases in the western subpolar

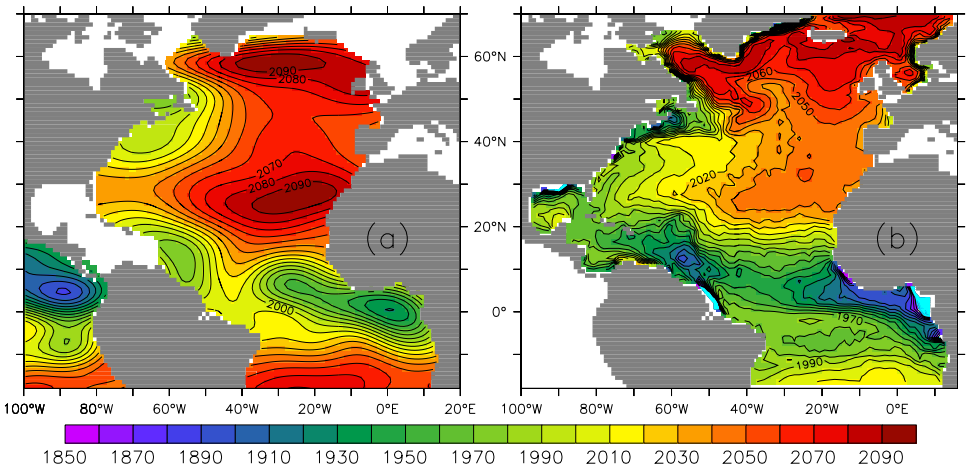

Figure 1. (a) Estimated [*Sabine et al.*, 2004] preindustrial and (b) mean surface DIC simulated by the full forcing run, in mmol/m^3.

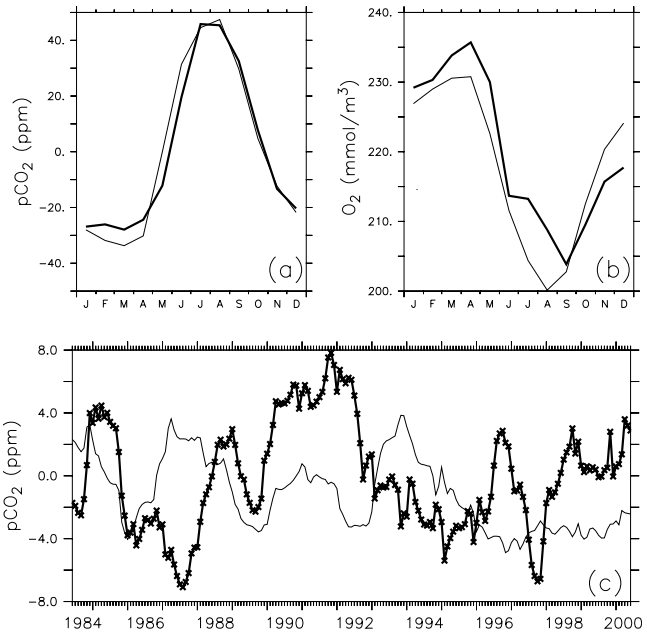

Figure 2. (a) Mean seasonal cycle of oceanic pCO_2 [ppm] (annual mean removed): observed [*Takahashi et al.*, 1997] (bold), simulated by the full forcing run (thin), (b) mean seasonal cycle of surface O_2 [mmol/m^3]: WOA [*Conkright et al.*, 2002] (bold); simulated by the full forcing run (thin) at Bermuda (32°N, 64°W). (c) Comparison of simulated (thin) to observed (bold, crosses) oceanic pCO_2 at Bermuda Hydrostation S. Mean seasonal cycles (and anthropogenic trend for the observations) were removed. A 12-month running mean was applied. Bermuda pCO_2 data were kindly provided by Niki Gruber.

North Atlantic due to increased deep convection, while in the eastern subtropics O_2 fluxes also increase due to the strengthening of the Azores high pressure area, which leads to intensified cooling by enhanced trade winds. In contrast, the tropics (10°S to 15°N) show almost identical air-sea O_2 fluxes in the WIND and full forcing runs (r = 0.97 for outgassing of O_2). At the equatorial divergence water upwelled to the surface is warmed and becomes oversaturated with respect to O_2 and CO_2, which leads to permanent outgassing of both gases. Since the equatorial divergence is wind-stress driven, changes in outgassing of O_2 are strongly related to wind-stress variability.

3.2. Carbon

[7] Simulated total uptake of pre-industrial carbon by the North Atlantic amounts to 0.3 Pg C yr^{-1} during our 54-year integration, with a temporal standard deviation of annual mean fluxes of ± 0.02 Pg C yr^{-1} (Figure 4a). This variability in oceanic carbon uptake is about ten times smaller than estimates from atmospheric inversions of *Bousquet et al.* [2000] but consistent with ocean model results of *McKinley et al.* [2004a], *Le Quéré et al.* [2000], *Wetzel et al.* [2005] and *Raynaud et al.* [2005] and novel atmospheric inversions [*Rödenbeck et al.*, 2003; *McKinley et al.*, 2004b]. Our model results indicate that no single part of the model domain dominates the interannual variability of the North Atlantic carbon uptake. Generally smaller fluctuations of subtropical and equatorial CO_2 fluxes compared to those in the subpolar basin are compensated by the larger low latitude area. While the mean pre-industrial carbon uptake simulated by the model is located mainly in the subpolar North Atlantic (0.22 ± 0.01 Pg C yr^{-1}), standard deviations of the annual air-sea fluxes are of the same magnitude (0.10 ± 0.01 Pg C yr^{-1}) over the subtropical and the equatorial Atlantic.

[8] Overall, the different model runs reveal a pronounced dominance of wind stress in driving the interannual variability of CO_2 fluxes in the entire Atlantic covered by our model (Figures 4e–4g). In the subtropical and subpolar North Atlantic (north of 15°N), the magnitude of the variability of carbon uptake in the WIND run is about 70% of the full forcing run. Temporal changes in carbon uptake simulated by the WIND and the full forcing runs are correlated with r = 0.81. In the equatorial Atlantic, the relatively shallow mixed layers lead to faster equilibration times of CO_2. Thus, CO_2 fluxes can still respond to DIC changes on seasonal to annual time scales and accordingly

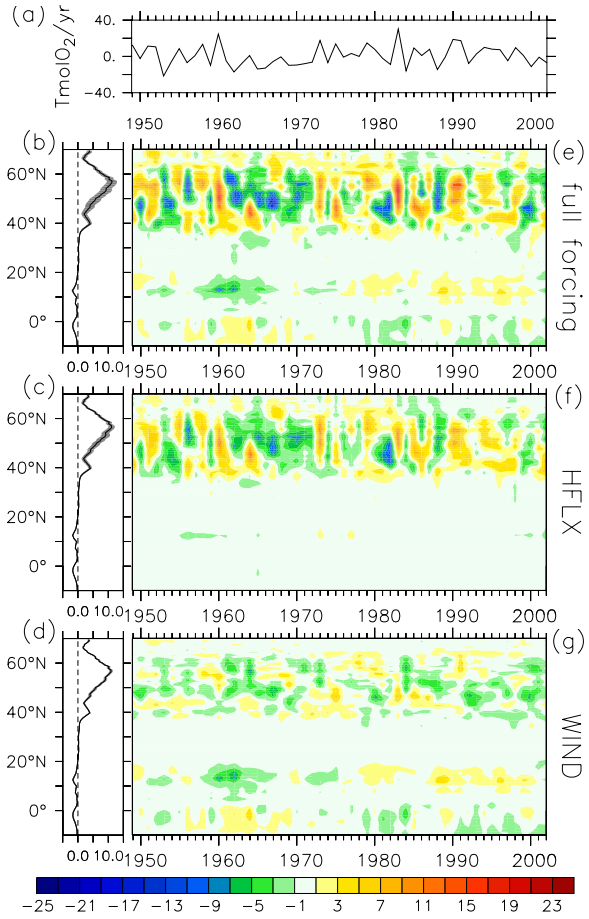

Figure 3. (a) Variability of detrended annual mean values of simulated O_2 uptake 0°N to 70°N in Tmol O_2 yr^{-1}. (b–d) Zonally averaged, annual mean, air-to-sea O_2 flux and standard deviation (shaded) of the interannual variability (mol m^{-2} yr^{-1}) for each of the full forcing, HFLX, and WIND simulations. (e–g) The corresponding zonally integrated, detrended anomalies in Mmol O_2 m^{-1} yr^{-1}. Positive values denote fluxes into the ocean.

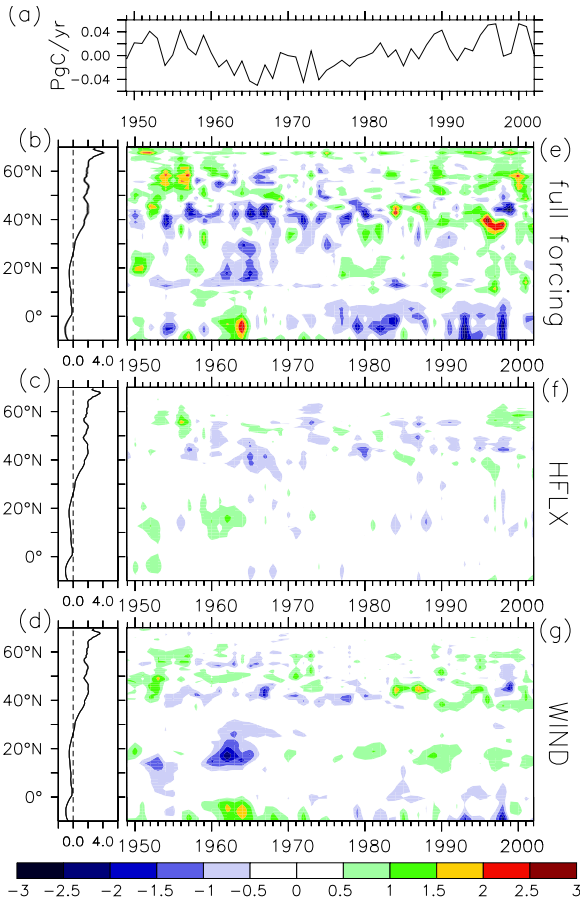

Figure 4. (a) Variability of detrended annual mean values of simulated CO_2 uptake 0°N to 70°N in Pg C yr^{-1}. (b–d) Zonally averaged, annual mean, air-to-sea O_2 flux and standard deviation (shaded) of the interannual variability (mol m^{-2} yr^{-1}) for each of the full forcing, HFLX, and WIND simulations. (e–g) The corresponding zonally integrated, detrended anomalies in Mmol C m^{-1} yr^{-1}. Positive values denote fluxes into the ocean.

show a response to forcing mechanisms similar to the O_2 fluxes discussed above. Consequently, interannual changes in air-sea fluxes of CO_2 and O_2 are closely correlated (r = 0.72) near the equator (5°S to 5°N average) in the wind-stress driven equatorial upwelling. The temporal evolution of equatorial outgassing of CO_2 in the WIND run shows the same high correlation with the full forcing run (r = 0.81) as in the area north of 15°N.

[9] Further sensitivity studies show that the dominant impact of variations in wind stress on variations in air-sea CO_2 exchange cannot only be explained by the wind-speed dependence of the piston velocity in the gas exchange formulation. An additional run with climatological piston velocity (run PISTON of Table 1) still yields 75% of the basin-wide CO_2 flux variance of the full forcing run. In comparison, the WIND and HFLX runs explain 45% and 27% of the basin-wide CO_2 flux variance, respectively.

[10] Chemical buffering of changes in CO_2 concentrations by the large pools of carbonate and bicarbonate ions implies that the CO_2 equilibration time is about ten-times longer than for O_2. Thus rapid changes in DIC concentrations or in surface heat fluxes cannot be balanced by air-sea CO_2 fluxes on seasonal time scales in regions of deep wintertime mixed layers [*Broecker and Peng*, 1974]. This is consistent with our model results showing that simulated variability in the subpolar mixed layer's carbon inventory due to entrainment of DIC-rich waters by convection is more than ten times as important as are the variations due to air-sea CO_2 fluxes. In consequence, a geographical separation into heat-flux and wind-stress driven regions similar to those for O_2 cannot readily be established for the air-sea exchange of CO_2 over the North Atlantic. In the subtropical gyre our model results show a temporal correlation of 0.87 between $\frac{\partial pCO_2}{\partial SST}\frac{dSST}{dt}$ and $\frac{dpCO_2}{dt}$. This indicates an increased CO_2 uptake in this region by intensified cooling, e.g., associated with a negative NAO-phase and driven by changes in both enhanced wind stirring and reduced surface heat input. Our results confirm earlier findings of *McKinley et al.* [2004a] and *Le Quéré et al.* [2003] suggesting that SST is the primary control of interannual variability of pCO_2 in the subtropical gyre.

4. Summary

[11] Sensitivity tests with a coupled physical-biogeochemical model have allowed us to discern the major atmospheric driving mechanisms of interannual variability of air-sea O_2 exchange in the North and equatorial Atlantic. In the model simulations, the subpolar basin contributes most of the North Atlantic O_2 uptake and most of its interannual variability. The latter is driven by changes in wintertime convection controlled predominantly by the NAO through fluctuations in surface heat fluxes. On the other hand, outgassing of O_2 is strongly related to changes in wind stress in the equatorial Atlantic.

[12] Interannual variability of CO_2 fluxes is driven mainly by wind stress variability over the entire model domain; only minor changes derive from variability in piston velocity and heat fluxes. Although the simulated mean carbon uptake is mostly located in the subpolar region, year-to-year fluctuations of the oceanic carbon uptake are of the same magnitude in the subpolar region, the subtropics and the equatorial Atlantic.

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