Decadal variability of the air-sea CO_2 fluxes in the Subtropical waters of the Eastern North Atlantic based on empirical algorithms

Padin[1], X.A., Molinés[2], de la Paz[1], M., J.-M., Ríos[1], A.F. and Pérez[1], F.F.

1 Grupo de Oceanoloxía. Instituto de Investigacións Mariñas (CSIC), Eduardo Cabello 6, 36208 Vigo (Spain)

2 Laboratoire Ecoulements Geophysiques et Industriels, BP 53X 38041 Grenoble-cedex (France)

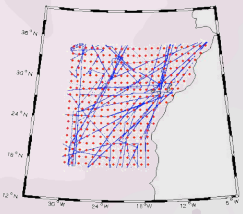

Figure 1.

INTRODUCTION: The best procedure for achieving an accurate estimation of seawater CO_2 fugacity (fCO_2^{sw}) and of the capacity of ocean to absorb CO_2 is from of sampling networks. Furthermore robust empirical algorithms make the most of the information that the *in situ* recordings provide for extending the observed fCO_2^{sw} relationships both in temporal and spatial scale. The purpose of this paper is to construct an empirical algorithm for estimating the long-term trend of the fCO_2^{sw} and FCO_2 over the subtropical waters of the Eastern North Atlantic Ocean.

DATA: Underway measurements of fCO_2^{sw}, sea surface temperature (SST), sea surface salinity (SSS) and other ancillary variables located between 34ºN – 17ºN and 30ºW and the African continent excluding shelf areas around the coast with a depth cut-off of 500 m (Fig. 1) were downloaded from the CarboOcean webpage (www.carboocean.org). This dataset was completed from the co-location of different products of NCEP/NCAR (http://www.cdc.noaa.gov/) and DRAKKAR (http://www.ifremer.fr/lp/drakkar/) projects with the NAO index (Jones et al., 1997). At least the final dataset were averaged on monthly 1º x 1º grid for homogenizing the data in both space and time (Fig. 1).

ALGORITHM ESTIMATION (Escheme 1): Every fCO_2^{sw} value was referenced to their respective months during the year 2000 correcting the CO_2 increase in the atmosphere from the measurement date in the meteorological station of Izaña located at 28ºN (Canary Island, Spain) belonging to NOAA's Earth System Research Laboratory network. Subsequently the thermodynamic influence on fCO_2^{sw} measurements was removed by normalising the fCO_2^{sw} data to 23ºC according to Takahashi et al. (1993). This new variable ('fCO_2^{sw}) was modelled from SST, mixing layer depth (MLD) and the NAO index (Jones et al., 1997) for the first time from a multiple linear regression (MLR) analysis using the statistic program STATISTICA. The thermodynamic and the atmospheric CO_2 correction were undone for computing the modelled fCO_2^{sw} values. The *rms* error and the coefficient of determination (r^2) of the fitting was ±9.5 µatm and 0.87, respectively. The partial contribution to the empirical algorithm pointed out SST as the main forcing explaining 81% of the fCO_2^{sw} variability whereas both MLD and NAO only explained 3%.

FCO_2 FLUXES: The CO_2 exchange between the ocean and the atmosphere (FCO_2; mol m^{-2} yr^{-1}) was calculated according to: $FCO_2 = a\,k\,S\,\Delta fCO_2$ where a is the unit conversion factor, S (mol kg^{-1} atm^{-1}) is the CO_2 solubility in seawater (Weiss et al., 1974), k (cm h^{-1}) is the CO_2 transfer velocity (Wanninkhof, 1992) and ΔfCO_2 (µatm) is the air-sea fCO_2 difference (i.e. $fCO_2^{sw} - fCO_2^{atm}$).

EXTRAPOLATION: The fCO_2^{sw} and FCO_2 variability at long-term trend was analyzed extrapolating the observed relationships from 1980 to 2006. The fCO_2^{sw} reconstruction was based on the robust consistency of the *in situ* SST fitting, main factor explaining the fCO_2^{sw} variability, by the NCEP/NCAR model.

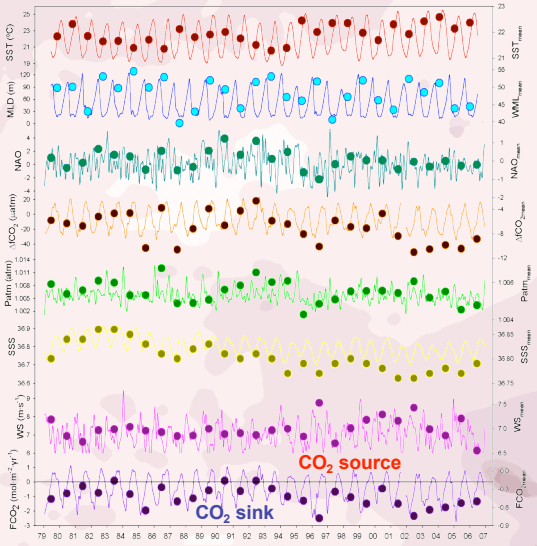

Figure 5.

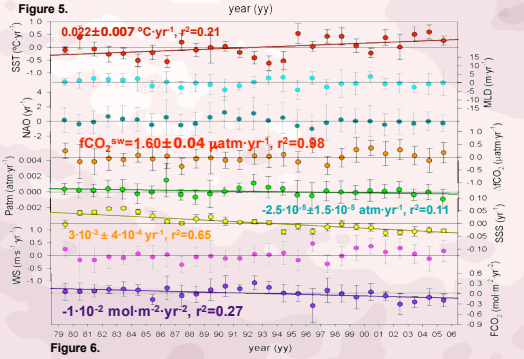

Figure 6.

b±std		air-sea CO_2 gradient (ΔfCO_2)				air-sea CO_2 flux (FCO_2)				
%	r^2	NAO	MLD	SST	r^2	ΔfCO_2	WS	Patm	MLD	SST
year	0.60	*1.69±0.09*	*-0.21±0.02*	*-2.34±0.36*	0.86	*0.051±2·10^{-3}*	*-0.24±0.02*	*43±5*	*-3·10^{-3}±1·10^{-4}*	*-0.03±0.01*
		47	**8**	**5**		**72**	**9**	**3**	**1**	**1**
winter	0.50	*1.30±0.18*	*-0.21±0.04*	*-2.73±0.73*	0.77	*0.051±3·10^{-3}*	*-0.22±0.03*	*48±12*		
		32	**10**	**8**		**64**	**9**	**4**		
spring	0.77	*2.02±0.13*	*-0.16±0.03*	*-2.39±0.65*	0.86	*0.053±3·10^{-3}*	*-0.25±0.03*	*36±10*		
		67	**6**	**4**		**75**	**9**	**2**		
summer	0.84	*2.16±0.10*	*-0.14±0.03*		0.88	*0.041±3·10^{-3}*	*-0.28±0.03*	*66±11*		
		80	**3**			**77**	**6**	**5**		
autumn	0.26	*-0.21±0.05*	*1.04±0.29*		0.84	*0.063±3·10^{-3}*	*-0.28±0.03*	*-0.09±0.03*		
		16	**11**			**69**	**14**	**1**		

Table 1.

RESULTS AND DISCUSSION: The annual averages of every variable from 1980 to 2006 made evident some significant trends at decadal scale. So, SST showed fluctuations with a period of approximately 7 years and an amplitude of 1.5ºC in addition to a unambiguous warming. The NAO index also reproduced the decadal cycles that seems to came early the SST oscillations in 5 years agreeing the delay of 3–5 years of the ocean responses to the NAO changes (Eden and Jung, 2001). The ΔfCO_2 mean throughout the time span showed a slight underaturation of subtropical waters of around -7±14 µatm. Attending to FCO_2, the study region was described as a net soft sink of 0.5±0.8 mol m^{-2} yr^{-1} that was no statistically different of 0.3±0.3 mol m^{-2} yr^{-1} proposed by the recent climatological CO_2 atlas (Takahashi et al., 2009). The annual FCO_2 means were comprised between -0.16±0.78 and -0.74±0.94 mol m^{-2} yr^{-1} computed during the years 1992 and 2002, respectively. So, the ocean uptake in this area of 2.4 10^6 km^2 has taken up from ~0.005 during the first 1990's to a maximum of 0.02 PgC yr^{-1} during 2002 for a total absorption of 0.3 PgC from 1980 to 2006.

The long-term trend was assessed subtracting the seasonal cycle from monthly means. These seasonal residuals were averaged at annual scale and subsequently fitted to a least-squares regression linear (Fig. 6). The subtropical waters were warming over the time span in parallel to a clear freshening. The time series of fCO_2^{sw} constructed from the empirical algorithm showed a year-to-year increase that is statistically lower than the fCO_2^{atm} rise of 1.74±0.02 µatm yr^{-1}. However the ΔfCO_2 showed a no significant trend like the one reported from the time series recorded in the ESTOC site (Santana-Casiano et al., 2007) and in contrast to the increase found in the subpolar waters (Schuster and Watson, 2007). On the other hand, the FCO_2 values pointed out an acceleration of the ocean uptake of -1·10^{-2} mol m^{-2} yr^{-2} (r^2=0.27) that represented an increase of 60% during the study period. This trend to absorb CO_2 that represented a little amount was opposed to the changes observed in the subpolar North Atlantic Ocean although do not contradict the reported reduction of the sink capacity of the North Atlantic Ocean.

As well as the geographical variability, the interannual rates depend much more on season (Padin et al., 2008). As particular feature, a maximum acceleration of the ocean absorption of 0.02±0.01 mol m^{-2} yr^{-2} that was also shown during the summer was highlighted in December coinciding with a notable rise of wind speed and a relaxation of the atmospheric pressure.

The contribution of the three inputs in the interannual ΔfCO_2 variability was analyzed from their seasonal residuals (Tabla 1). The NAO index that is significantly linked to biological and physical processes was clearly the main driver of the interannual ΔfCO_2 variability explaining a 47%, especially during spring and summer. Contrary, MLD was more relevant during autumn and winter although showed opposite correlations. So, negative correlations as winter pointed out the relationship between the fertilization associated to the mixing processes and the biological CO_2 drawdown whereas the direct correlation was reached during the breakdown of the summer stratification and the entrance of CO_2-enriched subsurface waters.

The ocean uptake whose interannual fluctuations were explained in 86% was strongly controlled by the ΔfCO_2 and so, by the NAO index. This close link clearly demonstrated the direct correlation between the NAO index and the FCO_2 variability. Attending to the observed in the northern latitudes, these results confirm that the ocean uptake is not in phase throughout the North Atlantic Ocean under the same NAO scenario (Wetzel et al., 2005).

in situ fCO_2^{sw}

normalization to year 2000

normalization to 23ºC (Takahashi et al., 2003)

in situ 'fCO_2^{sw}

'fCO_2^{sw} = 362.8±*0.4* -11.3±*0.2*(SST-23) -0.15±*0.01*·MLD+2.0±*0.2*·NAO JONES

modelled 'fCO_2^{sw}

normalization to 23ºC (Takahashi et al., 2003)

normalization to year 2000

modelled fCO_2^{sw}

Escheme 1.

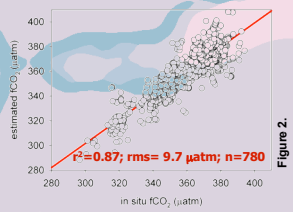

Figure 2.

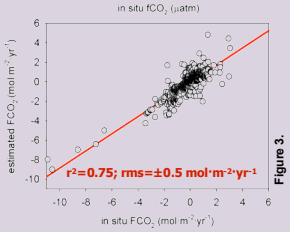

Figure 3.

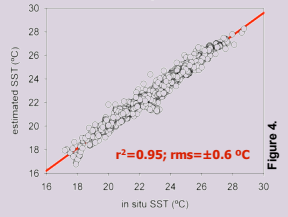

Figure 4.

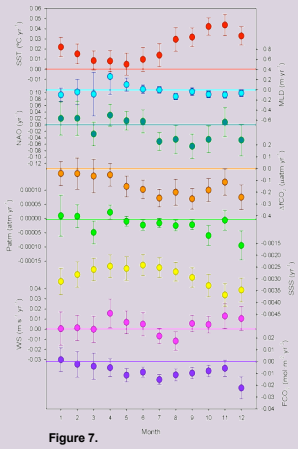

Figure 7.

REFERENCES

Eden, C. and Jung, T. 2001. North Atlantic interdecadal variability: Oceanic response to the North Atlantic Oscillation (1865-1997). J. Climate 14, (5) 676-691.

Jones, P.D., Johnson, T. and Wheeler, D., 1997: Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. Int. J. Climatol. 17, 1433-1450.

Schuster, U. and Watson, A.J., 2007. A variable and decreasing sink for atmospheric CO2 in the North Atlantic. Journal of Geophysical Research, 112, C11006, doi:10.1029/2006JC003941.

Padin, X.A., Navarro, G., Gilcoto, M., Ríos, A.F., Pérez, F.F. 2008. Estimation of air-sea CO2 fluxes in the Bay of Biscay based on empirical relationships and remotely sensed observations

Santana-Casiano, J.M., González-Dávila, M., Rueda, M.J., Llinás, O. and González-Dávila, E.F. 2007. The interannual variability of oceanic CO2 parameters in the northeast Atlantic subtropical gyre at the ESTOC site. Global Biogeochemical Cycles, 21, GB1015, doi:10.1029/2006GV002788.

Wanninkhof, R., 1992. Relationship between wind speed and gas exchange over the ocean. Journal of Geophysical Research, 97:7373-7382.

Weiss, R. F. 1974. Carbon dioxide in water and seawater: The solubility of a nonideal gas. Marine Chemical, 2:201–215.

Wetzel, R., Winguth, A., Maier-Reimer, E., 2005. Sea-to-air CO2 flux from 1948 to 2003: A model study. Global Biogeochemical cycles, 19, GB2005, doi:1029/2004GB002339, 2005