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Short-term variability of surface carbon dioxide and sea-air CO_2 fluxes in the shelf waters of the Galician coastal upwelling system

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SUMMARY: Using data collected during the DYBAGA and ECO cruises, remote sensing chlorophyll-*a* estimations and the averaged upwelling index of the previous fortnight (I_w'), we studied the variability of the sea surface CO_2 fugacity (fCO_2) over the Galician continental shelf during three seasonal cycles. Sea surface salinity (SSS) distribution controlled fCO_2 mainly in spring, while sea surface temperature (*SST*) did so during periods of intense cooling in November and warming in June. The uptake of carbon by photosynthetic activity, which was more intense during spring and autumn, masked the surface increase in the dissolved inorganic carbon concentration during upwelling events, especially during spring. A significant low correlation between fCO_2 and I_w' was found during spring and summer when upwelling events were observed, whereas no relationship was observed during the downwelling period. High fCO_2 exceeding atmospheric values was only found during the summer stratification breakdown. Although sea-air CO_2 fluxes showed a marked inter-annual variability, surface waters off the Galician coast were net sinks for atmospheric CO_2 in every seasonal cycle, showing a lower CO_2 uptake (~65%) compared to previously published values. Marked inter-annual changes in the sea-air CO_2 fluxes seem to be influenced by fresh water inputs on the continental shelf under different meteorological scenarios.

Keywords: carbon dioxide, coastal upwelling, sea-air gas exchanges, carbon sinks.

RESUMEN: VARIABILIDAD DE DIÓXIDO DE CARBONO Y FLUJOS DE CO_2 OCÉANO-ATMÓSFERA, A CORTO PLAZO, EN AGUAS DE LA PLATAFORMA DEL AFLORAMIENTO COSTERO EN GALICIA. – Durante tres ciclos estacionales se estudió la variabilidad superficial de la fugacidad de CO_2 (fCO_2) en la plataforma continental gallega, utilizando datos recogidos durante los proyectos DYBAGA y ECO, así como estimaciones de clorofila-*a* a partir de datos de satélite, y promedios quincenales del índice de afloramiento (I_w'). Los cambios de salinidad controlaron la variabilidad de fCO_2 en primavera, mientras que la temperatura lo hizo durante el máximo enfriamiento de Noviembre y máximo calentamiento de Junio. La captación de carbono por la actividad fotosintética, más intensa durante primavera y otoño, enmascaró el incremento superficial de carbono inorgánico durante los episodios de afloramiento, especialmente en primavera. Se observó una correlación significativa, aunque pequeña, entre fCO_2 e I_w' durante el período de afloramiento, mientras que no se encontró ninguna durante el hundimiento. Sólo se encontraron valores de fCO_2 superiores a los atmosféricos durante la ruptura de la estratificación estival. Aunque el intercambio de CO_2 océano-atmósfera mostró una marcada variabilidad interanual, la plataforma continental gallega fue un sumidero neto de CO_2 atmosférico. Los valores encontrados son inferiores a otros publicados anteriormente (~65% menos). Estos cambios interanuales parecen estar influidos por los aportes de agua dulce en la plataforma continental bajo distintas condiciones meteorológicas.

Palabras clave: dióxido de carbono, afloramiento costero, intercambios de gas océano-atmósfera, sumideros de carbono.

INTRODUCTION

Coastal upwelling develops on the eastern margins of subtropical gyres when predominant along-shore winds induce the rise of subsurface waters close to the coast into the photic layer (Wooster *et al.* 1976, Tomczak and Godfrey 2003, Arístegui *et al.* 2009). The entrance of cold and nutrient-rich deep water triggers the high phytoplankton production that supports rich coastal marine ecosystems and productive fisheries (Pauly and Christensen 1995). Furthermore, the exchange of large amounts of organic matter and energy with land, sediment and atmosphere (Walsh 1991, Mackenzie *et al.* 1998, Muller-Karger *et al.* 2005), makes coastal waters one of the most biogeochemically active areas of the biosphere in terms of sea-air CO_2 exchange, carbon recycling and offshore exportation.

Coastal environments are important components of the global carbon cycle, even though their role as sinks or sources of CO_2 has not been well defined in the past due to their strong spatial heterogeneity, temporal variability and the relative paucity of data (Borges *et al.* 2005). The carbon flows in these waters can shift rapidly (Gypens *et al.* 2009), making the estimate of the sea-air CO_2 flux subject to large uncertainties (Borges 2005, Borges *et al.* 2005, Chen and Borges 2009). Earlier publications described continental margins as net sources of CO_2 in agreement with the large CO_2 emissions observed in inner estuaries (Frankignoulle *et al.* 1998, Mackenzie *et al.* 2000, Gago *et al.* 2003a). However, this view of the coastal oceans has changed since the proposal of a "continental shelf pump" by Tsunogai *et al.* (1999), who described a mechanism for the atmospheric CO_2 absorption in shallow waters of continental shelves. After that, the studies reporting continental shelves as CO_2 sinks outweighed those reporting them as CO_2 sources. This diverging view on carbon cycling in the coastal oceans was solved by Rabouille *et al.* (2001), who split coastal waters into proximal continental shelves acting as a CO_2 source, and distal continental shelves acting as a CO_2 sink (Chen and Borges 2009).

The role of different coastal ecosystems as sinks or sources of atmospheric CO_2 allows opposing views on carbon cycling in the coastal ocean to be reconciled, but the integrated sea-air CO_2 flux in the global coastal ocean (estuaries and continental shelves) is still not clear. Chen and Borges (2009) recently evaluated these sea-air CO_2 fluxes as scaled estimates from a compilation of CO_2 measurements. They showed that the integrated sea-air CO_2 flux in the global coastal ocean resulted in continental shelves absorbing atmospheric CO_2 between –0.33 and –0.36 Pg C yr^{-1}; and inner estuaries, salt marshes and mangroves emitting up to 0.50 Pg C yr^{-1}. Laruelle *et al.* (2010) reported another estimation of the sea-air CO_2 flux, showing absorption by continental shelves (–0.21 Pg C yr^{-1}) close to that reported by Chen and Borges (2009), and emission from estuaries (0.27 Pg C yr^{-1}) lower than this previous estimation. The largest uncertainties of scaling approaches used to estimate the role of the continental shelf seas are the availability of CO_2 data that describe the spatial variability in the region and that capture relevant temporal scales. At present, the lack of sufficient data is the major limitation in the quantification of the spatial and temporal variability of CO_2 fluxes in the different coastal environments.

The Galician coast is located at the northern limit of the Canary Current Upwelling System, in the subtropical gyre of the North Atlantic Ocean (Wooster *et al.* 1976, Arístegui *et al.* 2004). The upwelling pattern on the Galician coast is marked by a strong seasonality (Wooster *et al.* 1976, Fraga 1981, Frouin *et al.* 1990, Pingree and Le Cann 1990, Bakun and Nelson 1991, Haynes *et al.* 1993) due to marked seasonal changes in wind stress determined by the Azores High and Icelandic Low pressure systems. Upwelling events are commonly observed during spring-summer with the predominance of northeasterly winds (Blanton *et al.* 1984). The offshore zonal Ekman transport of surface waters produces the rise of a cold, nutrient-rich, deep water mass called Eastern North Atlantic Central Water (ENACW) (Ríos *et al.* 1992). During these upwelling events, upwelling filaments of surface water extending westward also occur in the shelf waters to the south of Cape Finisterre (Álvarez-Salgado *et al.* 1993, Haynes *et al.* 1993, Barton *et al.* 2001, Borges and Frankignoulle 2001). These filaments are major routes of primary production exportation of shelf waters from the Rías Baixas, because they provide a mechanism through which organic material produced in shelf waters is transported hundreds of kilometers offshore into the ocean (Álvarez-Salgado *et al.* 2001). Although these filaments seem to be oligotrophic and relatively unproductive systems, they act as a stronger net sink for atmospheric CO_2 than the surrounding offshore waters (Borges and Frankignoulle 2001).

Although winter upwelling is sometimes observed in this area (Álvarez *et al.* 2009), the usual northward winds occurring in this season force the coastal downwelling of surface waters (Blanton *et al.* 1984). This season is also characterized by a poleward undercurrent of warm and salty waters of subtropical origin (Fraga *et al.* 1982), called the Iberian Poleward Current (IPC), that flows clearly constrained to the Iberian shelf break (Frouin *et al.* 1990). Moreover, run-off from local rivers contributes to the presence of river plumes over the shelf, which varies in fast response to wind event variability (Otero *et al.* 2008). This wind event variability, along with the development of filaments, eddies, the IPC and river plumes, turn the Galician coast into a region with variable physical processes with high rates of primary production. Furthermore, the absence of a shallow oxygen minimum zone, present in the upwelling systems of the Pacific and Indian Oceans, does not lead to an excess of dissolved inorganic carbon (Friederich *et al.* 2008) in subsurface waters, thus avoiding the intense release of CO_2 during the upwelling events.

High absorption rates of CO_2 ranging from –0.09 (during late autumn) to –0.51 mol C m^{-2} yr^{-1} (during spring) have been previously found for the Galician continental shelf (Pérez *et al.* 1999). During summer upwelling events, the continental shelf behaves as a marginal source of CO_2, with emission values of 0.10 mol C m^{-2} yr^{-1} (Pérez *et al.* 1999). On the contrary, Borges and Frankignoulle (2001) reported values ranging from –0.66 to –1.17 mol C m^{-2} yr^{-1} for the Galician continental shelf at the end of August. During the upwelling season, Borges and Frankignoulle (2002) computed CO_2 sea-air fluxes over the Galician continental shelf in the range of –0.84 to –1.72 mol C m^{-2} yr^{-1}. The oceanic zone of the Ría de Vigo also acts as a CO_2 sink during the upwelling period with values between –0.27 and –0.48 mol C m^{-2} yr^{-1}, and only releases CO_2 in October (Gago *et al.* 2003a). CO_2 in surface waters is mainly controlled by the input of upwelling deep cold waters with high CO_2 content, primary production (Borges and Frankignoulle 2002), vertical advection, turbulent diffusion and net ecosystem production of organic carbon components (Gago *et al.* 2003b).

In order to improve the description of this particular typology of continental shelf seas, we studied the variability of CO_2 observed in surface waters of the Galician continental shelf during three complete seasonal cycles. This database allowed us to obtain a broader view of the temporal variability of annual net sea-air CO_2 fluxes on the Galician continental shelf. The main aims were to improve estimates of the spatial and temporal variability of the sea-air CO_2 fluxes, and understand how natural drivers in a coastal upwelling affect these processes.

MATERIALS AND METHODS

The Dybaga and ECO cruises

Underway measurements collected during the DYBAGA (*Dynamics and Biogeochemical variability on the Galician continental shelf at short-scale*) and ECO (*Evolution of CO_2 increase using ships of Opportunity: Galicia and Bay of Biscay*) oceanographic cruises are gathered in this article (Fig. 1). The DYBAGA cruises were carried out along an across-shore section on the Galician continental shelf. During a complete seasonal cycle, from May 2001 to May 2002, one transect was sampled weekly, giving a total of 46 transects. The ECO cruises were carried out on board ships of opportunity from the Company Flota Suardíaz (*RO-RO L'Audace* and *RO-RO Surprise*) in a regular route that linked Vigo (Spain) and St. Nazaire (France). Throughout two entire seasonal cycles, between December 2002 and December 2004, 145 tracks were sampled over the Galician continental shelf with a frequency of around 10 transects per month.

Underway measurements of the seawater CO_2 molar fraction (xCO_2^{sw}), sea surface salinity (SSS) and temperature (*SST*) were collected using an autonomous homemade device called GASPAR (see detailed description in Padin *et al.* 2010). The device worked by pumping a water volume from 3 m below the waterline into the ship's hull; this volume was bifurcated so it passed through a sea-air equilibrator system. A thermosalinograph (SBE-45-MicroTSG) was connected to the same uncontaminated seawater supply, in parallel with the CO_2 measuring system, and recorded underway *SST* and *SSS* during the cruises with accuracies of ±0.002°C and ±0.003 respectively. Measurements of the CO_2 molar fraction were made with a non-dispersive infrared gas analyzer (Licor, LI-6262), which was calibrated at the beginning and end of each transit (which usually took 24 h) using two CO_2 gas standards: a synthetic free-CO_2 air and a high CO_2 standard of ~375 ppmv in synthetic air. The Instituto Meteorológico Nacional (Izaña, Canary Islands), belonging to the NOAA/ESRL Global Monitoring Division, certified the CO_2 concentration in both standards. Data reduction, the seawater CO_2 fugacity (fCO_2) calculation from raw data (with the exception of just using two gas standards) referenced to saturated water vapor pressure using in situ atmospheric pressure readings, was carried out following the recommendations of Dickson *et al.* (2007). The fCO_2 values were then corrected for the seawater temperature increase that occurs while the sample travels from the hull's inlet into the equilibration chamber. This temperature shift was usually <1°C. The temperature was tracked with platinum resistance thermometers and then the empirical equation proposed by Takahashi *et al.* (1993) was applied.

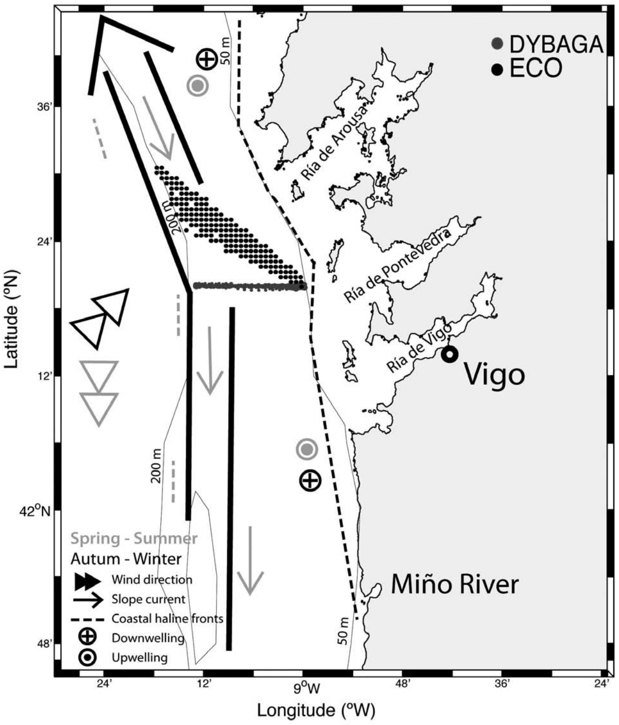

FIG. 1. – Map of the Galician continental shelf, showing DYBAGA (grey points) and ECO (black points) cruise tracks. The Rías of Vigo, Pontevedra and Arousa are shown, as well as the Miño River. Schematic circulation in the area during typical upwelling (spring and summer; light grey) and typical downwelling (autumn–winter; black) seasons is indicated. Note that a typical season is a simplification and the system is subject to event variability that can dominate the response of the system (Ruiz-Villareal *et al.* 2006). The black arrow heading northwards during autumn-winter represents the Iberian Poleward Current (IPC). The light grey arrows heading southwards during spring-summer represent the equatorward shelf-slope currents.

The underway measurements during these projects were initially logged with different frequencies, but were later averaged every 5 min cycle in order to homogenize the dataset. Surface observations measured between the 60 and 200 m isobaths were selected. The ETOPO2v2 bathymetry (U.S. Department of Commerce *et al.* 2006) was used for merging depth records using two-dimensional linear interpolation functions of every measurement. After applying all of these selection criteria, a final DYBAGA and ECO dataset comprising 348 and 1608 observations respectively, was obtained. Finally each cruise was averaged in order to obtain a mean value of each track crossing the continental shelf.

Remotely sensed chlorophyll-*a* (chl *a*) was included in the DYBAGA and ECO dataset as a proxy of the photosynthetic activity. Weekly fields of chl *a*, with a spatial resolution of 1/24° at the equator (~4.63 km) and a frequency of 8 days (which were continuous starting from the first day of each calendar year), were retrieved from the GlobColour global level-3 binned products (www.globcolour.info). The chl *a* selected product was generated from the GSM (Garver-Siegel-Maritorena) model, a merging technique based on Maritorena and Siegel (2005). The GSM model provided the best fit to in situ chl *a* and had the added advantage of providing other products (Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectrometer (MODIS) and Medium Resolution Imaging Spectrometer Instrument (MERIS)) that, compared to each of the original data sources, showed enhanced global daily coverage and lower uncertainties in the retrieved variables. The GSM model can also calculate pixel-by-pixel error bars. Selection criteria for the choice of pixels consisted in considering only chl *a* measurements taken within ±4 days (orbital over-passing) of the ship measurement date, and within ±3.3 km off the cruise track. The number of collocated observations of chl *a* achieved 85% of the 5-minute averages of fCO_2 measurements.

The upwelling index (I_w), calculated following Wooster *et al.* (1976) as the estimation of the upwelled water flow per kilometer of coast, was added as an ancillary variable:

$$I_W = \frac{\rho_{air} C_D V_y WS}{\rho_{SW} f} \quad (1)$$

where ρ_{air} is the air density (1.22 kg m^{-3} at 15°C), C_D is an empirical dimensionless drag coefficient (1.4 10^{-3}, according to Hidy 1972), WS is wind speed, ρ_{sw} is the seawater density (~1025 kg m^{-3}), f is the Coriolis parameter; and V_y is the wind speed component parallel to the coast, that is, the meridional component of wind speed due to coast orientation. Positive (negative) values of I_w correspond to upwelling (downwelling) in the Iberian Upwelling System. Wind speed data were obtained from the National Center for Environmental Prediction (NCEP) Reanalysis project maintained by the NOAA/OAR/ESRL/PSD at Boulder, Colorado, USA (http://www.cdc.noaa.gov/). These data have been widely used for forcing coastal ocean models because of their availability, the long and consistent time-series and full spatial coverage. We selected the NCEP/NCAR Reanalysis 1 project (Kalnay *et al.* 1996), which uses a state-of-the-art analysis/forecast system to perform data assimilation using data from 1948 to the present, in order to obtain wind speed in the location of 43°N 11°W as a reference point of the upwelling events on the Galician continental shelf (Pérez *et al.* 2010). Instead of the corresponding I_w attending to date, an averaged I_w during the previous fortnight (I_w') was preferred due to the more significant influence on the fCO_2 measurements, as was also found with the net production of the community (Álvarez-Salgado *et al.* 2002).

Estimation of sea-air CO_2 exchange

The CO_2 exchange between the ocean and atmosphere (FCO_2, in mol m^{-2} yr^{-1}) was calculated using the following equation:

$$FCO_2 = kS\,\Delta fCO_2 \quad (2)$$

where k is the monthly mean CO_2 transfer velocity (cm h^{-1}), calculated using Wanninkhof's parameterization (Wanninkhof 1992) and 6-hourly estimations of the zonal and meridional components of winds from the NCEP/NCAR Reanalysis project (NOAA-CIRES Climate Diagnostics Center, http://www.cdc.noaa.gov/); S is the CO_2 solubility in seawater (mol kg^{-1} atm^{-1}), calculated from Weiss (1974); and ΔfCO_2 is the fCO_2 disequilibrium between sea and air. The atmospheric CO_2 fugacity (fCO_2^{atm}) was estimated from the monthly values of the atmospheric CO_2 molar fraction (xCO_2^{atm}) recorded in the meteorological stations of the NOAA/ESRL Global Monitoring Division stations. The xCO_2^{atm} measurements were linearly interpolated versus latitude from observations at Azores (38.77°N) and Mace Head (53.55°N). The final xCO_2^{atm} dataset was then converted to atmospheric CO_2 partial pressure (pCO_2^{atm}), considering atmospheric pressure (P_{atm}) and water vapor partial pressure (pH_2O, in atm), which was calculated from in situ *SST* readings (T_{is}, Eq. 3 and 4) according to Weiss and Price (1980) and following Pierrot *et al.* (2009). The pCO_2^{atm} values were then converted to fCO_2^{atm} assuming a decrease of 0.3% from the pCO_2^{atm} value (Weiss 1974) due to the non-ideal behavior of carbon dioxide (Gago *et al.* 2003a).

$$pCO_2^{atm} = xCO_2^{atm}(P_{atm} - pH_2O) \quad (3)$$

$$pH_2O = 0.981\exp\left(14.32602 - \left(\frac{5306.83}{273.15 + T_{is}}\right)\right) \quad (4)$$

The measured xCO_2^{sw} data were converted to fCO_2 referenced to saturated water vapor pressure using in situ atmospheric pressure readings.

Biogeochemical variability and control of fCO_2

The processes controlling fCO_2 variability on the Galician shelf are due to several factors: thermodynamic control, biological production and respiration, alkalinity change, water mixing, and stratification of the water column. The influence of thermal and non-thermal processes on the fCO_2 variability was evaluated with the approach described by Takahashi *et al.* (2002). Using the well-known temperature control on fCO_2 of 4.23% $°C^{-1}$ (Takahashi *et al.* 1993), the impact of thermal (${}^{T}fCO_2$) and non-thermal (${}^{non\text{-}T}fCO_2$) processes forcing the fCO_2 seasonal cycle was estimated as:

$$ {}^{non\text{-}T}fCO_2 = fCO_2 \exp(0.0423(SST_{mean} - SST)) \qquad (5)$$

$$ {}^{T}fCO_2 = fCO_{2mean} \exp(0.0423(SST - SST_{mean})) \qquad (6)$$

where ${}^{non\text{-}T}fCO_2$ denotes the seawater fCO_2 normalized to the annual mean *SST* (SST_{mean}) and ${}^{T}fCO_2$ represents the effect of the *SST* distribution on the annual mean seawater fCO_2 (fCO_{2mean}). In other words, ${}^{non\text{-}T}fCO_2$ represents changes in the total CO_2 concentration, which include effects of the net CO_2 utilization, a small amount of net alkalinity change due to carbonate production and nitrate utilization, sea-air exchange of CO_2, and an addition of CO_2 and alkalinity by the vertical mixing of subsurface waters (Takahashi *et al.* 2002).

The analysis of the biogeochemical control of fCO_2 variability was extended by performing multiple linear regressions taking into account all the measured variables. However, the statistical analysis was performed on the ΔfCO_2 distribution because it also takes into account small changes in the fCO_2^{atm}. The correlations between ΔfCO_2 and the ancillary parameters in the shelf waters were assessed for the four seasons: winter (December-February), spring (March-May), summer (June-August) and autumn (September-November).

An empirical algorithm was computed fitting ΔfCO_2 values with second-order multiple polynomials using *SST* and chl *a* observations (Stephens *et al.* 1995, Ono *et al.* 2004, Padin *et al.* 2009), and linear relationships with *SSS*, *WS*, I_w', geographical position and depth as independent variables according to Equation 7:

$$\begin{aligned} fCO_2 = {} & fCO_2^{O} + ALat + BDepth + \\ & \sum_{i=1}^{2} \left(SST - \mu_{SST}\right)^i + C\left(SSS - \mu_{SSS}\right) + \\ & + \sum_{i=1}^{2} \beta_i \left(\text{chl}\, a\right)^i + DWS + EI'_W \end{aligned} \qquad (7)$$

The multiple linear regression coefficients were obtained using a forward stepwise method in which only significant parameters that accounted for at least 1% of the ΔfCO_2 variability were included in the algorithm. The μ parameter stands for the average *SST* or *SSS* value for the corresponding period.

RESULTS

Biogeochemical variability

The temporal variability of sea surface properties on the continental shelf of the Galician coast was analyzed from average values of each DYBAGA and ECO cruise that described three complete seasonal cycles from May 2001 to December 2004. Furthermore, I_w' was also included in Figure 2 in order to identify the upwelling and downwelling favorable wind events.

The temporal evolution of thermohaline properties showed a marked seasonality throughout the sampled period, even though significant differences were also found among the three seasonal cycles (Fig. 2, Table 1). The warmest waters were found at the beginning of October 2003 (19.6°C) and the coldest waters in January 2004 (12.0°C), setting a temperature range of 7.6°C throughout the entire sampling period. The lowest temperature range (5.1°C) and mean cold waters (15.3±1.4°C) were found during the first seasonal cycle measured in the DYBAGA cruises. The following seasonal cycles sampled during the ECO cruises showed warmer temperatures than the ones found during the first seasonal cycle, with the highest mean *SST* found in 2003 (15.8±1.9°C). The temperature ranges of the ECO cruises were 6.8°C and 7.4°C.

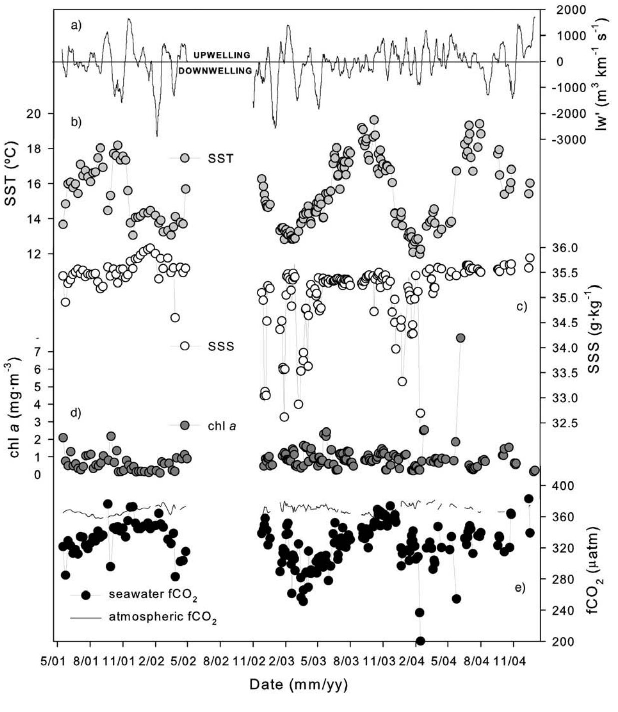

FIG. 2. – Biogeochemical variability observed during DYBAGA (May 2001 - May 2002) and ECO (December 2002 - December 2004) cruises; a) Average upwelling index during the previous fortnight (I_w'), which delimits upwelling and downwelling favorable wind events; b) Sea surface temperature (*SST*, light grey circles); c) Sea surface salinity (*SSS*, white circles); d) Chlorophyll-*a* concentration (chl *a*, dark grey circles); e) Seawater CO_2 fugacity (fCO_2, black circles) and atmospheric CO_2 fugacity (fCO_2^{atm}, continuous line).

Table 1. – Average values of sea surface temperature (*SST*), sea surface salinity (*SSS*), chlorophyll–*a* concentration (chl *a*), seawater CO_2 fugacity (fCO_2), sea–air CO_2 gradient (ΔfCO_2), wind speed (*WS*), sea–air CO_2 fluxes (FCO_2) and average upwelling index during the previous fortnight (I_w') measured in the continental shelf waters of the Galician coast during winter, spring, summer and autumn in each of the DYBAGA and ECO cruises. Annual and seasonal average values of these parameters are also shown.

Season	Cruise	*SST* °C	*SSS*	chl *a* mg m^{-3}	fCO_2 µatm	ΔfCO_2 µatm	*WS* m s^{-1}	FCO_2 mol C m^{-2} yr^{-1}	I_w' m^3 km^{-1} s^{-1}
Annual	DYBAGA	15.3±1.4	35.56±0.20	0.58±0.34	333±17	–34±17	4.9±1.7	–0.78±0.62	–6±774
	ECO 2003	15.8±1.9	35.13±0.33	0.84±0.29	324±24	–45±27	5.8±2.0	–1.38±1.14	–137±572
	ECO 2004	15.4±2.1	35.28±0.41	0.90±0.47	325±20	–47±23	5.8±2.0	–1.44±1.22	192±620
Winter	DYBAGA	14.1±0.2	35.82±0.13	0.24±0.16	348±4	–24±5	4.8±1.8	–0.54±0.35	–770±801
	ECO 2003	13.7±0.7	34.88±0.47	0.82±0.23	317±18	–54±19	6.7±2.2	–2.14±1.17	–549±1000
	ECO 2004	13.2±0.6	34.51±0.59	0.70±0.39	317±27	–58±29	7.8±2.2	–3.48±2.31	–52±735
Spring	DYBAGA	14.4±1.0	35.44±0.23	0.75±0.27	313±14	–57±15	4.8±1.1	–1.20±0.81	156±483
	ECO 2003	14.4±0.6	34.72±0.65	0.97±0.41	296±12	–76±11	5.5±1.9	–2.47±1.50	–464±689
	ECO 2004	13.9±0.7	35.48 ±0.07	1.42±1.34	316±18	–60±18	5.6±1.5	–1.90±0.68	218±558
Summer	DYBAGA	16.4±0.5	35.46±0.07	0.66±0.28	326±8	–37±10	4.5±1.8	–0.83±0.64	347±228
	ECO 2003	17.5±0.9	35.31±0.04	0.75±0.28	331±10	–34±11	4.9±1.4	–0.75±0.35	153±217
	ECO 2004	18.1±0.6	35.55±0.05	0.65±0.22	331±9	–37±9	4.5±1.4	–0.88±0.61	446±402
Autumn	DYBAGA	16.3±1.5	35.50±0.09	0.67±0.39	344±18	–14±12	5.7±1.7	–0.53±0.60	34±1101
	ECO 2003	17.5±0.8	35.32±0.15	0.88±0.22	351±10	–14±10	6.4±2.1	–0.54±0.54	24±371
	ECO 2004	16.2±1.0	35.33±0.35	1.13±0.23	340±23	–26±22	5.5±1.3	–0.60±0.90	117±723
Winter		13.7±0.6	35.07±0.69	0.58±0.35	329±22	–44±23	6.3±2.3	–1.82±1.53	–269±735
Spring		14.2±0.8	35.31±0.32	0.96±0.51	308±17	–64±17	5.3±1.5	–1.77±1.03	44±558
Summer		17.4±1.0	35.43±0.11	0.69±0.27	330±9	–36±10	4.6±1.6	–0.82±0.55	327±402
Autumn		16.7±1.1	35.44±0.22	0.90±0.36	344±18	–21±16	5.8±1.6	–0.56±0.68	67±773

The *SSS* distribution was nearly uniform for the three years (35.15±0.65) with some recurrent events of low *SSS* values during winter and spring (Table 1). A *SSS* minimum of 32.48 was measured in February 2004. Although high *SSS* values were also observed during summer (Fig. 2), the most saline waters were found in January 2002, with a value of 35.98.

Remote sensed measurements of chl *a* did not show a clear seasonal distribution (Fig. 2). High values of chl *a* reached an outstanding concentration in May 2004 (7.72 mg m^{-3}, Fig. 2); similar values were mainly recorded across two pulses in spring and autumn, usually exceeding 2 mg m^{-3}. Minimum values of chl *a* were observed in winter.

Several general features were shared by every seasonal fCO_2 cycle (Fig. 2). Surface waters of the continental shelf showed a general CO_2 undersaturation in relation to the atmosphere. The minimum value was found in winter 2003/2004 (–58±29 µatm), while CO_2 supersaturation in relation to the atmosphere was found only occasionally in autumn and winter. Minimum values were observed during spring blooms, followed by a constant increase until autumn. The fCO_2 trend closely followed the warming of surface waters, even extending beyond the warmer months. The lowest fCO_2 value (200 µatm) was found in February 2004, and the highest value was reached at the end of November 2004, when it exceeded the atmospheric value by around 17 µatm (Fig. 2).

In spite of these similarities, some differences were found in the fCO_2 distribution in the seasonal cycles. During the seasonal cycle described by the DYBAGA cruises, $^{non\text{-}T}fCO_2$ increased by around 67 µatm, from 311 µatm in August 2001, to 377 µatm in February 2002 (Fig. 3). During this period, the seasonal cooling caused a decrease in the $^{T}fCO_2$ from 357 µatm in October 2001, to 299 µatm in March 2002. The thermal control, with a seasonal range of 58 µatm, was similar in magnitude to the non-thermal effect on fCO_2. However, they were approximately 6 months out of phase, which makes them partially cancel each other out. The effect of biological processes vs. thermal control in Galician shelf waters was estimated as the ratio between the seasonal range of $^{T}fCO_2$ and $^{non\text{-}T}fCO_2$. A value of 0.87 indicates that over this period, the non-thermal effect exceeded the thermal effect in 16%. During the second seasonal cycle, biological utilization of CO_2 and other non-thermal processes, shifted fCO_2 values by about 55 µatm from 351 µatm in January-March 2002 to 296 µatm in August 2003. On the other hand, the effect of winter-to-summer warming on fCO_2 is seen in the $^{T}fCO_2$ distribution as an increase of around 83 µatm, from 293 µatm in February 2003 to 381 µatm in August 2003. The comparison of the two processes showed a thermal/non-thermal ratio of 1.59, highlighting that the temperature control has a significant impact. During the last seasonal cycle sampled in ECO cruises, $^{non\text{-}T}fCO_2$ values showed a decrease of about 67 µatm, ranging from 363 µatm in January 2004 to 296 µatm in June 2004. The temperature variability in the year 2004 took the $^{T}fCO_2$ distribution from about 292 µatm in January to 366 µatm in June, exceeding the $^{non\text{-}T}fCO_2$ range by 12%. Taking into account the complete database, thermal processes throughout the three seasonal cycles were 16% stronger than non-thermal processes in the fCO_2 dynamics in shelf waters.

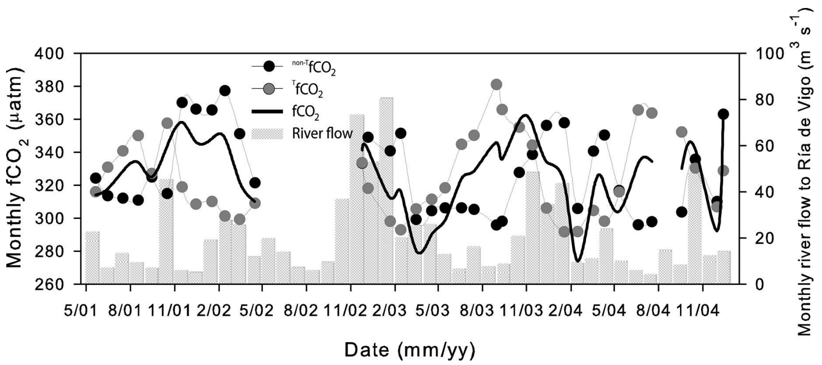

FIG. 3. – fCO_2 values normalized to the mean annual temperature ($^{non-T}fCO_2$, black circles) and corrected for temperature changes ($^{T}fCO_2$, grey circles). The seasonal variation of fCO_2 (continuous black line) and the monthly discharge of the Miño River (light grey bars), estimated according to Otero *et al.* (2010), are also shown.

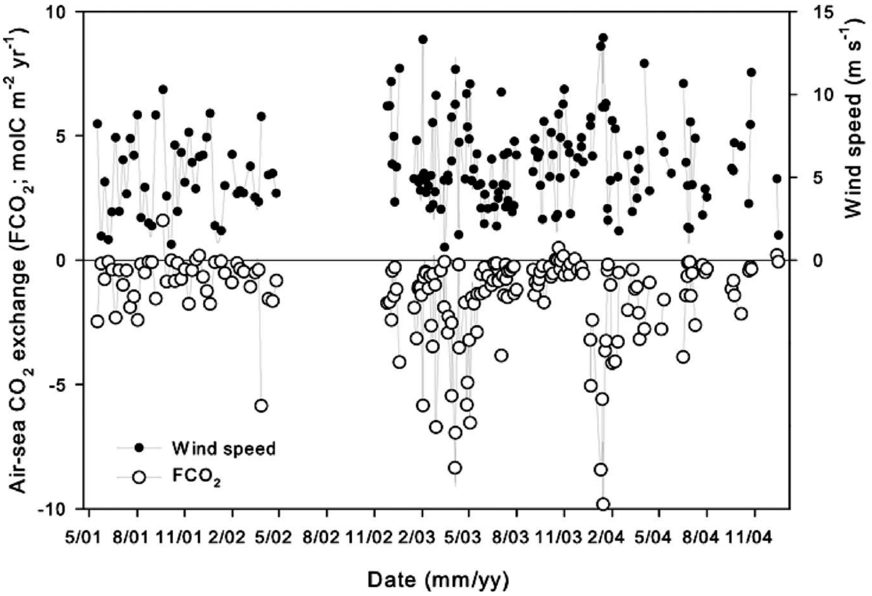

FIG. 4. – Sea-air CO_2 exchange (FCO_2, white circles) and wind speed (WS, black circles) observed during the DYBAGA and ECO cruises.

Sea-air CO_2 exchange

The measurements of CO_2 fluxes indicate that the shelf waters of the Galician coast were significant net sinks for atmospheric CO_2 in every seasonal cycle (Table 1, Fig. 4). The DYBAGA cruises showed minor annual absorption of –0.78±0.62 mol C m^{-2} yr^{-1}, estimated from a WS value of 4.9±1.7 m s^{-1}. The years 2003 and 2004 showed analogous annual CO_2 absorptions of –1.38±1.14 and –1.44±1.22 mol C m^{-2} yr^{-1} respectively, from annual ΔfCO_2 averages of –45±27 and –47±23 µatm respectively, and similar wind speed (WS) values of 5.8±2.0 m s^{-1}. The highest seasonal absorption was estimated in winter 2003/2004 (–3.48±2.31 mol C m^{-2} yr^{-1}) in which a cruise on the continental shelf showed a maximum mean uptake of –9.81 mol C m^{-2} yr^{-1} (Fig. 4), estimated from ΔfCO_2 and WS values of –60 µatm and 13.4 m s^{-1} respectively. Coinciding with this observation, mean CO_2 absorption in winter was higher than in any other season (–1.82±1.53 mol C m^{-2} yr^{-1}). However, the DYBAGA cruises and the 2003 ECO seasonal cycle achieved the highest CO_2 uptakes during spring, namely –1.20±0.81 and –2.47±1.50 mol C m^{-2} yr^{-1}. Only during some autumn events did the Galician shelf behave as a marginal source of CO_2, showing a maximum CO_2 emission of 1.58 mol C m^{-2} yr^{-1} in September 2001 (Fig. 4). In any case, the smallest uptake capacity was found during autumn, reaching a mean value of –0.56±0.68 mol C m^{-2} yr^{-1} (Table 1).

Biogeochemical control of fCO_2

A statistical analysis of the ΔfCO_2 distribution during the DYBAGA and ECO cruises was carried out in order to identify the environmental forcing factors that drive the sea-air CO_2 disequilibrium, fitting the ΔfCO_2 values according to Equation 7. The regression coefficients and the percentage of normalized ΔfCO_2 variability explained by each parameter in the different seasons are given in Table 2.

In general terms, seasonal empirical algorithms fitted the observed ΔfCO_2 variability during each sea-

TABLE 2. – Regression coefficients for Equation 7 are shown in the upper case of each variable. Percentage of normalized $\Delta f\mathrm{CO}_2$ variability explained by each parameter in each season is shown in bold in the lower case of each variable. The root mean square (rms) and the correlation coefficient (r^2) are also given ($p<0.05$). The "n" value stands for the number of valid data included in each analysis.

Season	rms **r^2**	$\Delta f\mathrm{CO}_2$ µatm n	Lat °N	Depth m	*SST-µ* °C	*(SST-µ)*^{2} °C^2	SSS-*µ* **$r^{2\prime}$**	chl *a*^{2} (mg m^{-3})^2	*WS* m s^{-1}	*I$_w$'* m^3 km^{-1} s^{-1}
Winter	16.5	–55±25		–0.3±0.2		–4.2±0.9		–13±3	–1.3±0.8	
	0.64	51		**3**		**39**		**19**	**3**	
Spring	13.3	–102±16		–0.3±0.1	24±7	16±4	19±4	–1.7±0.3		–0.006±0.002
	0.68	43		**3**	**9**	**11**	**27**	**15**		**3**
Summer	8.3	4116±1166	–98±27		18.2±4.4	–2.2±1.1				–0.011±0.005
	0.59	44	**9**		**40**	**6**				**4**
Autumn	15.3	–6±4			–3±1			–8±3		
	0.16	43			**4**			**17**		

son correctly. The $\Delta f\mathrm{CO}_2$ winter measurements were weakly reproduced showing a standard error of 16.5 µatm and an explained $\Delta f\mathrm{CO}_2$ variability of 64%. The main driver in this season was *SST* in its quadratic form, explaining 39% of the $\Delta f\mathrm{CO}_2$ changes with a coefficient of –4.2±0.9 µatm °C^{-2}. The algorithm was completed with the contribution of quadratic chl *a*, depth and WS, explaining 19%, 3% and 3%, respectively.

The highest regression coefficient was found in spring (0.68), mainly due to the significant control of *SSS* changes (27%), which exceeded the contribution of quadratic chla *a* in this season by 12%. During this season, depth was also a significant factor: it was inversely proportional to $\Delta f\mathrm{CO}_2$ values with a rate of –0.3±0.1 µatm m^{-1}, controlling 3% of the spring $\Delta f\mathrm{CO}_2$ distribution, as well as *I$_w$'*.

The empirical algorithm fitting the summer $\Delta f\mathrm{CO}_2$ observations reported a root mean square error of 8.3 µatm, the minimum of the four seasons. During this season, *SST* was again the main forcing factor, controlling 46% of the $\Delta f\mathrm{CO}_2$ changes with its two forms, showing positive and negative coefficients of 18.2±4.4 µatm °C^{-1} and –2.2±1.1 µatm °C^{-2}. Latitude and *I$_w$'* also played a significant role, explaining 9% and 4% of the $\Delta f\mathrm{CO}_2$ variability; their coefficients showed a northward $\Delta f\mathrm{CO}_2$ decrease and extended the inverse relationship between $\Delta f\mathrm{CO}_2$ and upwelling events to the summer.

Even though the autumn season only explained 16% of the total $\Delta f\mathrm{CO}_2$ variability, a low $\Delta f\mathrm{CO}_2$ error of 15.3 µatm was also found. The only contribution of chl *a* and *SST*, which showed an inverse control, closely reproduced the $\Delta f\mathrm{CO}_2$ measurements, explaining 17% and 4% of the total $\Delta f\mathrm{CO}_2$ variability respectively.

DISCUSSION

After the examination of the underway measurements of *SST*, *SSS*, $f\mathrm{CO}_2$ and other ancillary variables (average upwelling index of the previous fortnight, *I$_w$'*, and remotely retrieved chl *a*), the Galician continental shelf could be described as a complex, heterogeneous and highly biogeochemical active region from May 2001 to December 2004. The high variability observed, both at short and seasonal scales, was related to meteorological conditions, the presence of different water bodies and changes in chl *a* estimations. Winter and summer showed the expected downwelling and upwelling conditions respectively, with seasonal *I$_w$'* values of –269 and 327 m^3 km^{-1} s^{-1} respectively. On the contrary, every autumn season had wind conditions that showed noticeable seasonal changes (Fraga 1981, Blanton *et al.* 1984). Northerly winds were extended beyond the summer, so upwelling favorable conditions, with an average value of 67 m^3 km^{-1} s^{-1}, prevailed over the characteristic downwelling scenario of every autumn.

The winter dominance of southwesterly winds favored the coastal downwelling and the presence of subtropical waters transported by the IPC. The IPC was clearly sampled during winter 2001/2002, attending to the warm and saline water between November 2001 and February 2002. Very low levels of chl *a* and moderate undersaturation of CO_2 were also found during this period of time, coinciding with more intense downwelling conditions (–770 m^3 km^{-1} s^{-1}; Fig. 2, Table 1). These offshore waters of subtropical origin made winter 2001/2002 the warmest and saltiest with the lowest values of chl *a* sampled over the continental shelf out of our three analyzed winters. These waters also acted as a slight sink of atmospheric CO_2, absorbing –0.54 mol C m^{-2} yr^{-1}. In winter 2002/2003, under prevailing downwelling conditions (–549 m^3 km^{-1} s^{-1}) similar to those of winter 2001/2002, colder and less saline waters increased CO_2 absorption to –2.14 mol C m^{-2} yr^{-1}. On the other hand, in winter 2003/2004, colder and less salty waters were found (13.2°C and 34.51 respectively) under weaker downwelling conditions (–52 m^3 km^{-1} s^{-1}) than those of winter 2002/2003.

South of the Ría de Vigo, the run-off from the Miño River showed large variability during winter (estimation made following Otero *et al.* 2010). Average discharge values estimated for winters 2002/2003 and 2003/2004 (1251.7±670.8 and 612.4±89.9 m^3 s^{-1} respectively) were notably higher than the value reported for winter 2001/2002 (147.2±74.5 m^3 s^{-1}; Fig. 3). In spite of showing the highest river discharge, the strong downwelling conditions found for winter 2002/2003 seemed to have retained freshwater in the near coast, preventing lower *SSS* values in the studied zone. This is because downwelling events, as well as the IPC, block the spreading of fresh shelf water and form a convergence front at the shelf-break (Pérez *et al.* 1999) between coastal and ocean waters (Castro *et al.* 1997, Borges and Frankignoulle 2002). Therefore, under less intense downwelling conditions, the lower river discharge of winter 2003/2004 was able to spread offshore, so that the *SSS* variability measured on the platform showed minimum values.

The influence of coastal waters under different downwelling situations also led to differences in the CO_2 uptake capacity, so that the sea-air CO_2 exchange responded to the continental influence. During winter 2001/2002, chl *a* values were lowest under the oligotrophic conditions prevailing in the subtropical IPC, in which shelf waters showed a $\Delta f CO_2$ value of –24 μatm. On the contrary, low saline waters observed in winters 2002/2003 and 2003/2004 increased the stability of the water column on the continental shelf, triggering phytoplankton activity (Pérez *et al.* 1999) and causing a strong CO_2 undersaturation of –54 and –58 μam respectively. In spite of not being the highest disequilibrium of the seasonal cycle, both winters showed an outstanding CO_2 uptake that reached the highest CO_2 absorption in winter 2003/2004, with a mean FCO_2 value of –3.48 mol C m^{-2} yr^{-1}.

Reinforcing the importance of the biological CO_2 uptake in winter, chl a^2 explained 19% of the $\Delta f CO_2$ variability with a coefficient of –13 μatm $(mg^{-1}\ m^3)^{-2}$ (Table 2). However, the statistical analysis did not show any relationship between low saline waters and CO_2 undersaturation in winter despite the process described above. Temperature control represented by SST^2 was the dominant factor explaining 39% of the winter $\Delta f CO_2$ variability with a negative coefficient of –4.2 μatm °C^{-2}. This correlation coincides with the one determined by Gago *et al.* (2003a), who found that only temperature accounts for a large percentage of the $\Delta f CO_2$ variability during the winter period.

For every seasonal cycle, $\Delta f CO_2$ reached the lowest values during the spring phytoplankton bloom (Pérez *et al.* 1999, Gago *et al.* 2003a). The lowest mean $\Delta f CO_2$ value of –76 μatm during spring 2003 coincided with moderate average chl *a* values (0.97 mg m^{-3}) and strong downwelling favorable conditions (–464 m^3 km^{-1} s^{-1}). The maximum mean values of chl *a* (1.42 mg m^{-3}) were observed during spring bloom 2004 under upwelling favorable conditions (218 m^3 km^{-1} s^{-1}). During this season, a high chl *a* observation of 7.72 mg m^{-3} was found across the continental shelf coinciding roughly with the lowest fCO_2 measurement of 245 μatm (Fig. 2; Table 1). Biological CO_2 uptake remained for some weeks (Taylor *et al.* 1992) after the disappearance of chl *a*, so that the fCO_2 increase related to upwelling events (Lampitt *et al.* 1995) was notably reduced.

SSS explained 27% of the spring ΔfCO_2 variability (with a direct coefficient of 19 μatm), highlighting the balance between the intense CO_2 undersaturation resulting from freshwater inputs and the influence of upwelled waters. *SST* changes represented 20% of the $\Delta f CO_2$ variability, based on linear and quadratic coefficients that directly explained 9% and 11% respectively. The biological control represented by chl a^2 explained 15% of the $\Delta f CO_2$ variability with a coefficient of –1.7 μatm $(mg^{-1}\ m^3)^{-2}$. I_w' showed a significant inverse correlation of –0.006 μatm m^{-3} km^{-1} s^{-1} with a minimum influence of 3% on the $\Delta f CO_2$ distribution. The entrance of CO_2-rich water from the subsurface seems to be represented by the direct control of SST^2 and *SSS* in the empirical algorithm. Colder and saltier waters represent the expected CO_2 supersaturation observed during upwelling events. Spring 2002 and 2004, with flux values of –1.20 and –1.90 mol C m^{-2} yr^{-1} respectively, showed the expected response to the upwelling favorable conditions during this season. The supersaturation of these waters led to lower uptake capacities, while maximum CO_2 uptakes of –2.47 mol C m^{-2} yr^{-1} were reached in spring 2003 under downwelling conditions.

According to the *SST* and *SSS* distributions, no upwelling filaments or recently upwelled waters off the Galician coast were sampled on the continental shelf. Consequently, $\Delta f CO_2$ summer values remained around –36 μatm. This season behaved as a moderate CO_2 sink of –0.82 mol C m^{-2} yr^{-1} (Table 1), coinciding with the results of Borges and Frankignoulle (2001). Values of chl *a* decreased after spring blooms, returning to the values observed in winter. However, unlike in winter, chl *a* did not show any role in the control of summer $\Delta f CO_2$, which was mainly explained by the *SST* (46%). The estimated linear *SST*-fCO_2 coefficient of 18.2 μatm °C^{-1} slightly exceeded the theoretical temperature effect on $\Delta f CO_2$, which would be around 14 μatm °C^{-1} for an average fCO_2 of around 330 μatm, based on the coefficient of 4.23% °C^{-1} described by Takahashi *et al.* (1993). Latitude was also significant showing a growing CO_2 undersaturation northward with a rate of –98 μatm per latitudinal degree. According to the cruise tracks, latitude could represent the increasing distance from the coast, that is, the landward CO_2 saturation of surface waters observed in the proximal continental shelf during upwelling seasons.

Strong winds during late summer and early autumn broke the summer stratification and activated phytoplankton growth in September. In autumn, the upward input of nutrients through water mixing triggered chl *a* values, closely reaching those seen in spring but exceeding the percentage of variation explained (17% of the $\Delta f CO_2$ changes). A negative correlation coefficient between chl *a* and $\Delta f CO_2$ was also found (–8 μatm $(mg\ m^{-3})^{-2}$), coinciding with the results found by Pérez *et al.* (1999) for a region further south (40-41.7°N, and from coast to 11°W). *SSS* and *SST* values were also a result of vertical mixing, and high SSS values, repeating those found in summer, were related to intense evaporation. These mixing processes seemed to weakly drive $\Delta f\mathrm{CO_2}$ according to an inverse *SST*-$\Delta f\mathrm{CO_2}$ correlation coefficient of –3 µatm °C^{-1}. Even though these features responded to normal autumn conditions, no features of the IPC were observed in distributions of *SST*, *SSS* or chl *a*; this signal was only found in winter 2001/2002 under the downwelling scenario. Unlike other seasons, atmospheric $f\mathrm{CO_2}$ values were slightly exceeded in certain events during autumn, leading to the highest seasonal $f\mathrm{CO_2}$ value of 344 µatm. This is probably due to degradation of organic matter, as stated by Gago *et al.* (2003a). In any case, these waters behaved as a $\mathrm{CO_2}$ sink as well, with an average uptake of –0.56 mol C m^{-2} yr^{-1}.

The ECO cruises analyzed for the area near the Bay of Biscay showed seawater $f\mathrm{CO_2}$ ranges of 72 µatm estimated during 2003 and 2004 (Padin *et al.* 2009). The same ECO cruises analyzed in the present work showed annual seawater $f\mathrm{CO_2}$ ranges of 126 and 185 µatm on the Galician shelf, reflecting the stronger impact of the changing drivers on seawater $\mathrm{fCO_2}$ variability on the continental platform (*SST*, *SSS*, chl *a*, latitude, WS and I_w'). The impact of these drivers should be taken into account at different scales, including those that respond to climate variability, especially in relation to warming, weakening of the upwelling (Pérez *et al.* 2010), river discharges and photosynthetic activity on the continental shelf.

The steady $\mathrm{CO_2}$ undersaturation makes the Galician continental shelf a significant $\mathrm{CO_2}$ sink in spite of the variability at different temporal scales. The largest variability in $\mathrm{CO_2}$ uptake at a seasonal scale was measured during winter and spring, in which $\mathrm{CO_2}$ uptake was determined by the downwelling/upwelling conditions, the strength of water runoff to the continental shelf and the development of a phytoplankton community. Annual $\mathrm{CO_2}$ absorption values estimated from the years 2002 to 2004 ranged from –0.78 to –1.44 mol C m^{-2} yr^{-1}, showing a lower uptake capacity than the –2.2 mol C m^{-2} yr^{-1} reported by Borges *et al.* (2005) for the same region. In the most recent estimations of sea-air $\mathrm{CO_2}$ exchange in the global coastal ocean (Tsunogai *et al.* 1999, Chen and Borges 2009, Laruelle *et al.* 2010), this estimation of annual $F\mathrm{CO_2}$ on the continental shelf of the Galician coast was averaged with other scarce observations, globally extrapolating them as a reference uptake of a temperate upwelling in the North Atlantic region. The success of such scaling approaches depends on how representative the $F\mathrm{CO_2}$ estimations are for a given coastal environment. In this particular case, the annual $\mathrm{FCO_2}$ measurements show large seasonal variability that could lead to estimates of the $\mathrm{CO_2}$ uptake of the Galician continental shelf that are 65% lower than previous studies, which would affect the regional estimations. Long time-series of $p\mathrm{CO_2}$ measurements evenly distributed on continental shelves would allow a more robust evaluation of $\mathrm{CO_2}$ fluxes in continental shelf seas.

CONCLUSIONS

The Galician continental shelf showed a marked seasonality throughout the sampling period, with winters showing the lowest values of *SST*, *SSS* and chl *a*. However, strong inter-annual variability was found between the sampled winters, especially during winter 2001/2002, when the dominance of southwesterly winds favored coastal downwelling and the presence of subtropical waters conveyed northward on the continental shelf in the Iberian Poleward Current. The main variable explaining $\Delta f\mathrm{CO_2}$ variability in winter was SST^2. In spring, chl a^2 was found to be a significant driver of the changes in $\Delta f\mathrm{CO_2}$. Intense decreases in $f\mathrm{CO_2}$ coincided with moderate average chl *a* values, showing an effective biological $\mathrm{CO_2}$ uptake. Upwelling pulses of $\mathrm{CO_2}$-rich waters minimized the effect of the spring bloom on $f\mathrm{CO_2}$ distribution by shortening the time span of biological $\mathrm{CO_2}$ uptake, even though no $\mathrm{CO_2}$ oversaturation of surface waters was observed. Low *SSS*, $f\mathrm{CO_2}$ and high chl *a* values were found for this season. In summer, northerly component winds prevailed, and so did upwelling favorable conditions. The main factor explaining $f\mathrm{CO_2}$ variability in summer was *SST*. In autumn the strong winds caused the summer stratification to break down, activating the autumn phytoplankton bloom and increasing $f\mathrm{CO_2}$ values until $f\mathrm{CO_2}^{atm}$ was exceeded in some events. In general, the Galician continental shelf behaved as a steady and significant $\mathrm{CO_2}$ sink, in spite of the variability noted at different temporal scales. The largest variability was measured during winter and spring due to important changes in fresh water inputs reaching the region at an inter-annual scale. $F\mathrm{CO_2}$ annual measurements showed lower values than those previously reported, showing an outstanding variability that could lead to the $\mathrm{CO_2}$ uptake of the Galician continental shelf being underestimated by 65% at an annual scale. Long time-series of $f\mathrm{CO_2}$ measurements would reduce the $F\mathrm{CO_2}$ uncertainties and improve the use of scaling methods for studying the sea-air $\mathrm{CO_2}$ exchange in the global coastal ocean.

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