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Net sea-air CO₂ flux uncertainties in the Bay of Biscay based on the choice of wind speed products and gas transfer parameterizations

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Abstract

The estimation of sea-air CO₂ fluxes are largely dependent on wind speed through the gas transfer velocity parameterization. In this paper, we quantify uncertainties in the estimation of the CO₂ uptake in the Bay of Biscay resulting from using different sources of wind speed such as three different global reanalysis meteorological models (NCEP/NCAR 1, NCEP/DOE 2 and ERA-Interim), one regional high-resolution forecast model (HIRLAM-AEMet) and QuikSCAT winds, in combination with some of the most widely used gas transfer velocity parameterizations. Results show that net CO₂ flux estimations during an entire seasonal cycle may differ up to 240 % depending on the wind speed product and the gas exchange parameterization. The comparison of satellite and model derived winds with observations at buoys advises against the systematic overestimation of NCEP-2 and the underestimation of NCEP-1. In this region, QuikSCAT has the best performing, although ERA-Interim becomes the best choice in areas near the coastline or when the time resolution is the constraint.

1 Introduction

The accurate estimation of net CO₂ fluxes through the sea-air interface is a key factor in our understanding of the global carbon cycle and the prognosis of future climate scenarios. The reliability of the inferred CO₂ fluxes (FCO_2) is intimately linked to the accuracy of the determinations of sea-air pCO_2 gradient (ΔpCO_2), the solubility of CO₂ and the gas transfer – or piston – velocity (k). The correct estimation of in-situ ΔpCO_2 is a priority activity for the marine carbon community, being different international projects as the Global Carbon Project involved in the production of high quality and comparable datasets. However, the scarcity of ΔpCO_2 data in certain regions, such as coastal areas, is a handicap to properly describe the spatiotemporal variability of sea-air CO₂ disequilibrium (Laruelle et al., 2010). The uncertainty in determining the solubility of CO₂, that depends on temperature and salinity, is relatively small

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(Weiss, 1974). Nowadays, the main uncertainty remains in the estimation of k , which is computed in most of its different expressions as a function primarily of wind speed (WS) although it is also dependent on other minor processes, as thermal stability (e.g. Erickson, 1993), the presence of surface surfactants (Tsai and Liu, 2003) or rainfall (Takagaki and Komori, 2007) among others. Various studies assume a linear (Liss and Merlivat, 1986), quadratic (Wanninkhof, 1992; Nightingale et al., 2000; Ho et al., 2006; Sweeney et al., 2007) or cubic (Wanninkhof and McGillis, 1999) relationship of k with the wind speed.

Due to the non-consensus with respect to the best k parameterization, special attention should be paid to the biases of the different WS products, which directly affect the piston velocity (Wanninkhof, 1992; Naegler et al., 2006), particularly using quadratic or cubic k parameterizations. Whereas the use of in-situ measurements – typically estimated from meteorological buoys and ships – is usually the preferred option, WS observations do not always coexist in space and time with $\Delta p\text{CO}_2$ measurements. In these cases, model- or satellite-derived winds are the alternative because of the synoptic nature and the uniformity of the datasets, although they present intrinsic uncertainties. Model-derived winds, from both analysis and forecast, have broad-coverage and high temporal resolution, and account for a recent improvement due to the assimilation of satellite observations (e.g. Chelton and Wentz, 2005). Despite these advances, most atmospheric models have been developed to provide weather forecast over land regions and hence, minor efforts have been done to prove their skill over the ocean and coastal regions (Otero and Ruiz-Villarreal, 2008). Differences among models are mainly related to the spatial resolution, data assimilation, boundary forcing, smoothing of the topography and parameterization of physical processes, especially those in the marine boundary layer. Satellite-derived winds are expected to provide top-quality results in most of the weather conditions. However, these estimations from remote sensors are affected by the presence of land in near-coastal regions and have a lower temporal resolution.

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In addition, the coastal regions were usually excluded from the budgets of sea-air CO₂ exchange at global scale (Sabine et al., 2004; Takahashi et al., 2009) due to the high spatial and temporal variability of $\Delta p\text{CO}_2$ of these environments. Recent efforts have included net CO₂ flux from coastal systems (estuaries and continental shelves) in the global budget (Chen and Borges, 2009; Laruelle et al., 2010) in order to reduce the gap between the carbon stock and inverse modeling approaches (Borges et al., 2006). In any case, recent integrated $F\text{CO}_2$ estimation in these highly active biogeochemical environments (Mackenzie et al., 1998; Wollast, 1998; Muller-Karger et al., 2005) is close to neutral (Laruelle et al., 2010) after using a new scaling approach of surface areas of different coastal typologies. Continuing this effort, another unresolved task is to understand the sensitivity of coastal $F\text{CO}_2$ estimations to different k parameterizations and wind speed products such as was addressed in the global ocean (Boutin et al., 2002; Olsen et al., 2005).

In this study, we analyze the agreement of the different wind speed typologies at several sites of the Bay of Biscay and the effect for the net $F\text{CO}_2$ estimation of using various gas transfer expressions in combination with a selection of WS products available to the scientific community. Since this region is characterized by a high uptake of anthropogenic atmospheric CO₂ (Gruber, 1998), it strongly contributes to the prime role that the North Atlantic Ocean plays in the global carbon cycle (Takahashi et al., 2009) and has profusely being described in numerous articles (Perez et al., 1999; Borges and Frankignoulle, 2002; Padin et al., 2008; de la Paz et al., 2010). We will analyze these uncertainties aiming at: (i) directly evaluating the differences among wind products in comparison with buoy observations, (ii) constraining the previous dataset to match the low-frequent satellite-derived winds, (iii) examining the associated bias in relation to k and (iv) evaluating the spatial and temporal variability in the net $F\text{CO}_2$. The main goal is to clarify the effect of WS typologies in our coastal sea to identify suitable products for $F\text{CO}_2$ estimations.

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2 Data and methods

2.1 $\Delta p\text{CO}_2$ measurements

The database was obtained in the Bay of Biscay using ships of opportunity (RO-RO L'Audace and Surprise) of the *Suardíaz* Company that regularly covered the route from Vigo, Spain, to St. Nazaire, France, and occasionally to Southampton, UK (Fig. 1). A total of 75 journeys were performed from September 2002 to September 2003. Mole fractions of CO_2 in air, that it is in equilibrium with a flowing stream of seawater, and surface values of salinity and temperature were recorded and averaged every minute throughout each transit and used to derive $\Delta p\text{CO}_2$ measurements (methods are detailed in de la Paz et al., 2010). Sea-air $F\text{CO}_2$ is the result of multiplying the seawater solubility calculated from (Weiss, 1974), k and $\Delta p\text{CO}_2$. In this paper, various of the most used expressions for k are evaluated: k_W (Wanninkhof, 1992) and $k_{L\&M}$ (Liss and Merlivat, 1986) as the most frequent parameterizations used in the $F\text{CO}_2$ estimations integrated in the global coastal balance, k_N (Nightingale et al., 2000) as a transfer velocity adequate for field studies on a local scale, k_S (Sweeney et al., 2007); as the recent recalculation of transfer velocity from the ocean inventory of bomb-produced ^{14}C and k_{Ho} (Ho et al., 2006) as a field computation using $^3\text{He}/\text{SF}_6$ dual gas tracer technique. The cubic wind speed dependency such as k expression (Wanninkhof and McGillis, 1999) was not included in the analysis for being more sensitive to changes in wind speed, leading to greater biases.

2.2 Wind products

Wind products will be compared with observations (see Fig. 1) at the ocean buoys of Gascogne (45.20° N 5.00° W) in the central part of the Bay of Biscay, owned and maintained by UK Met Office (<http://www.metoffice.gov.uk/>) and Silleiro (42.10° N 9.39° W), Vilano (43.49° N 9.21° W), Bares (44.06° N 7.62° W), Peñas (43.73° N, 6.16° W) and Bilbao (43.63° N 3.04° W), all of them supported by the Deep Water

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Network (Álvarez-Fanjul et al., 2003) of the Spanish institution Puertos del Estado (<http://www.puertos.es>). Records below the accuracy of the instrument ($\pm 0.3 \text{ m s}^{-1}$) and anomalies higher than 3σ have been removed and subsequently height-adjusted to 10 m following the neutral drag law of Vera (1983, unpublished manuscript and published as Eq. (8) in Large et al., 1995). Differences due to the atmospheric stability are expected to be below 0.2 m s^{-1} (e.g. Chelton and Freilich, 2005; Sanchez et al., 2007) and hence, are not taken into account. The availability of data during the study period is 98 % at Gascogne, 91 % at Peñas, 89 % at Silleiro, 73 % at Vilano and 29 % at Bilbao.

Wind data from the widely used NCEP/NCAR Reanalysis 1 (hereafter NCEP-1; Kalnay et al., 1996; Kanamitsu et al., 2000) and the NCEP/DOE Reanalysis 2 projects (hereafter NCEP-2; Kanamitsu et al., 2002) were selected. Both datasets are maintained by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA and provided through their website at <http://www.cdc.noaa.gov/>. In the second version, the planetary boundary layer non-local vertical diffusion scheme was implemented (Hong and Pan, 1996), more observations were added, assimilation errors corrected, the orography smoothed and parameterizations of physical processes were updated – specially those concerning convection. Both datasets are obtained in a 1.875° spatial resolution T62 Gaussian grid with 6 h of temporal resolution. The only available and best guess for the 10 m wind speed within the reanalysis comes from the forecast time step, that is valid six hours after the reference time.

ERA-Interim is the latest global atmospheric reanalysis produced by the ECMWF. This project was conducted in part to replace ERA-40 (Uppala et al., 2005), in order to address several difficult data assimilation problems encountered and to improve on various technical aspect of reanalysis such as data selection, quality control, bias correction and performance monitoring (Dee et al., 2011). Wind gridded data have a spatial T255 horizontal resolution, which corresponds to a spacing of approximately 79 km on a reduced Gaussian grid, and are produced with a temporal resolution of 6 h.

To include some of the various regional forecast models available in the Bay of Biscay, we have also analyzed winds from the HIRLAM model, running operationally at

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AEMet, Spain, (<http://www.aemet.es>). Results used in this study comes from a configuration run over Europe and the North Atlantic Ocean with 0.2° of spatial and 6 h of temporal resolution. Lateral open boundaries are forced with results of the global configuration of the ECMWF. Details on the physics of this model can be found in Undén et al. (2002).

Finally, Level 2B QuikSCAT winds have been obtained from the CERSAT extraction service (<http://www.ifremer.fr/cersat>), which distributes the data as a mirror site of NASA PO.DAAC-JPL for Europe. This processing level estimates winds with a 25×25 km resolution using the Direction Interval Retrieval (DIR) algorithm that determines the most likely wind vector. Cells with poor azimuth diversity, land contamination and derived winds outside the optimum modulus range were removed. Additionally, the Impact-based Multidimensional Histogram (IMUDH) (Huddleston and Stiles, 2000) was applied in heavy rain areas. After the processing, an accuracy of the modulus of $\pm 2 \text{ m s}^{-1}$ (independent of the wind speed in a range of $3\text{--}20 \text{ m s}^{-1}$) and $\pm 20^\circ$ in direction is obtained. Uncertainties related to higher and older wind waves which may cause enhancing of backscattering under the same wind conditions in the range of $9\text{--}12 \text{ m s}^{-1}$ (Ebuchi et al., 2002) were not considered.

3 Results and discussion

Figure 1 shows the problem associated with the selection of a specific wind product and its spatial and temporal interpolation to the position of the vessel taking underway $\Delta p\text{CO}_2$ measurements during its first route. The wind speed clearly differs along the route from one product to another, with a noticeable bias exceeding 4.5 m s^{-1} among QuikSCAT and NCEP-2. These winds, in combination with the various expressions for k , will constitute the final ensemble of $F\text{CO}_2$ estimations that we will be evaluated in the present study.

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3.1 Comparison of ocean buoys and meteorological models

Which model performs better along the Bay of Biscay? Does this performing differ among different locations? To answer these questions the observed time-series have been sub-sampled at 0Z, 6Z, 12Z and 18Z in order to match the temporal resolution provided by the models, which have been interpolated to the location of the buoys.

With the previous criterion, Table 1 compares mean winds during the whole study year and during two periods mainly characterized by downwelling (when south-southwesterly wind events are dominant) and upwelling (north-northeasterly) conditions (October 2002–February 2003 and April 2003–August 2003, respectively; note that transition months between seasons have been discarded). The separation of the seasonal cycle was done in order to know the consistency of the WS products under both scenarios, which have a noticeable impact on the biogeochemical cycles, especially in the Iberian coast (Perez et al., 2010).

Regarding the in situ observations, Silleiro is the location with the highest annual mean WS (7.06 m s^{-1}) followed by the open ocean buoy of Gascogne and Vilano that showed, respectively, the highest WS values during the downwelling (8.60 m s^{-1}) and upwelling (6.93 m s^{-1}) periods. On the contrary, Gascogne and Vilano buoys showed low WS measurements in the downwelling and upwelling seasons, whereas Silleiro site equally reported high WS values in both periods. Lower WS measurements for any period are found at the coastal enclosed buoys of Peñas and Bilbao.

With the exception of the Peñas buoy, that is the one closest to the coastline (16 km), NCEP-1 showed an underestimation of mean winds. This underestimation was especially intensified when data were constrained to the upwelling period. These results contrasted with the general positive bias of NCEP-2, that was up to 23 % during the downwelling season. In the comparison at Peñas, both products overestimate winds, and in the case of NCEP-2 the positive bias is up to 45 % during the downwelling period.

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The mean bias of NCEP-2 respect to NCEP-1 was $1-1.6 \text{ m s}^{-1}$, which is similar to the bias up to 2 m s^{-1} reported by Winterfeldt (2008) in the English Channel – in the northern area of our region – and is in accordance with other studies in different regions around the world (e.g. Jiang et al., 2005; Kubota et al., 2008). Here, both products had similar correlations (r) with the observations (< 0.6 at Peñas and Bilbao and ranging from 0.7 to 0.82 in the rest of the stations). The root mean square (rms) computations, with values ranging from 2.2 m s^{-1} in Gascogne to 3.0 m s^{-1} in Bilbao, were $0.4-0.7 \text{ m s}^{-1}$ lower in NCEP-1. Nevertheless, this fact does not necessarily imply a worst comparison of NCEP-2 with observations from buoys in other regions since none of the reanalysis products are uniformly superior in all basis as reported by Jiang et al. (2005) in the equatorial Pacific Ocean or Winterfeldt (2008) in the English Channel.

HIRLAM and ERA-Interim winds had a heterogeneous pattern, with positive anomalies at the stations off NW Spain and negative anomalies at the rest of locations, particularly at the Bilbao buoy. In general terms, these products simulated the variability of the observed time-series better than the NCEP-1 and NCEP-2 winds, especially in the case of ERA-Interim. Actually, this was the best product in terms of r (> 0.8) and rms ($< 2.6 \text{ m s}^{-1}$), although its performance was reduced in Bilbao and Peñas. In the last station, similar performance was achieved in both models.

The better performing of ERA-Interim may be related to its higher spatial resolution in contrast to NCEP products, although the reduction of model biases is also dependent on model physics and configuration (e.g. Tinis et al., 2006; Otero and Ruiz-Villarreal, 2008). In fact, the high-resolution HIRLAM-AEMet configuration did not perform as well as initially expected during the study period, with the exception of the results at Peñas. Better results are expected with subsequent improvements of the model configuration, which includes, among others, a short range ensembled prediction, 3DVAR assimilation scheme and the upgrade of physical parameterization (Yang, 2007). In the near-shore zone, where the wind drop-off does not seem to converge as model resolution increases (Capet et al., 2004), the improvement could be limited. Thus, different spatial

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resolutions in the same model will influence the estimation of CO₂ fluxes across these areas. Hence, further studies are required to gain insight into this aspect.

3.2 Observations from QuikSCAT

From the total of 1037 QuikSCAT satellite passes over the Bay of Biscay region during the study year, only the 49% had an observation over the Gascogne buoy, lowering the number of observations due to land contamination at Silleiro (27%), Bares (4%) and Vilano (3%). Peñas and Bilbao – located ~ 21 km and ~ 16 km of the coast, respectively – were permanently out the observed valid area of the scatterometer. Mean satellite retrieved wind speeds were higher than those observed at buoys (collocated data with a time criterion limit of 30 min; similar criterion that Pickett et al. (2003), ranging from a bias of 0.24 m s⁻¹ in Vilano to 0.60 m s⁻¹ in Silleiro (rms < 1.5 m s⁻¹, *r* > 0.9 in all stations), performing even better (rms < 1 m s⁻¹) when data were restricted to the upwelling season in Bares and Gascogne. These associated errors are in similar range than previous comparisons with buoys in other areas (e.g. Ebuchi et al., 2002; Pickett et al., 2003; Sanchez et al., 2007).

The inter-comparison of satellite (semidiurnal), model (6 hourly) and buoy winds demands a more restrictive criterion to limit synoptic scale differences. Satellite ascending passes between 05:30 and 06:30 UTC and descending between 17:30 and 18:30 UTC were selected to compare with coexisting model and observations at 00:60 and 18:00 UTC. This restrictive criterion reduces the dataset to 111 observations at Silleiro and 230 at Gascogne and none at the other stations. The mean biases at Gascogne and Silleiro were, respectively, -0.27 m s⁻¹ and -1.33 m s⁻¹ for HIRLAM, -0.06 m s⁻¹ and -0.41 m s⁻¹ for NCEP-1, -0.27 m s⁻¹ and 0.21 m s⁻¹ for ERA-Interim, 0.14 m s⁻¹ and 0.17 m s⁻¹ for QuikSCAT and 1.61 m s⁻¹ and 1.03 m s⁻¹ for NCEP-2. Figure 2 summarizes the main statistics by using a Taylor's diagram (Taylor, 2001), a useful tool in evaluating the relative skill of many different models. All wind products performed better at the open ocean station of Gascogne than at Silleiro; QuikSCAT was the best product in statistical terms, closely followed by ERA-Interim, contrasting again with the higher

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amplitude and normalized rms difference of NCEP-2. In this sense, the good performing of ERA-Interim is related to the assimilation of scatterometer ocean surface winds, which includes data from QuikSCAT (aggregated at 50 km resolution), introduced on February 2000 and to the end of 2009 (Dee et al., 2011).

Errors associated to the fact that satellite scatterometers retrieve winds relative to a moving sea surface (Kelly et al., 2001) are expected to be low, at least off Western Iberia, as stated by the low speed ocean surface currents observed at the outer shelf buoy of Silleiro ($0.14 \pm 0.1 \text{ m s}^{-1}$). The bias with models may increase due to mesoscale fluctuations during weak wind events of the upwelling season, when diurnal breezes establish, or during atmospheric convective processes related to the influence of sea surface temperature (Austin and Pierson, 1999).

Finally, a cautionary note on using QuikSCAT Level 3 gridded data instead of Level 2B. This product consists of separate maps for both the ascending and descending passes – to facilitate studies with diurnal trends – grouped in the same grid at nearly the original Level 2B sampling resolution. Consecutive satellite passes systematically overlap their swaths at latitudes higher than 48° N and, when this occurs, values are overwritten, not averaged. However, at the latitude of the Cantabrian slope (44° N), a gap ($\sim 2^\circ$ wide) between the swaths of two consecutive passes is formed with a 4 days frequency, avoiding sometimes the complete collocation of QuikSCAT winds along a route at these latitudes.

3.3 Wind speed, gas transfer velocity and CO_2 flux in the ECO route

How much does the selection of a specific wind product influence the estimation of the net sea-air F_{CO_2} in combination with different k parameterizations? Figure 3 shows the mean F_{CO_2} computed throughout a complete seasonal cycle by using only the ECO routes with satellite data close in space ($< 12.5 \text{ km}$) and time ($< 3 \text{ h}$). This selection criterion (in the same way as the QuikSCAT subplot in Fig. 1), that was chosen to allow the use of all outputs of the meteorological model and to limit synoptic scale differences, retained 22 % of the original data. All results confirmed the role of the Bay

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of Biscay as a CO₂ sink during the study period even though the estimations of net CO₂ uptake estimated from the use of the different combinations of wind speed and *k* parameterizations showed noticeable differences. As an example, the annual CO₂ uptake was overestimated in 39–42 % when the NCEP-2 wind was used instead of NCEP-1, and in 73–78 % if *k_W* was used instead of the lowest estimation with *k_{L&M}*. These differences could reach up to 2.4 times if the pair NCEP-2 and *k_W* was used instead of NCEP-1 and *k_{L&M}*.

The distribution of underway Δ*p*CO₂ measurements in the Bay of Biscay gathered during ECO cruises from November 2002 to September 2003 is shown in Fig. 4a. A general CO₂ undersaturation of the surface waters in the Bay of Biscay was observed during the entire seasonal cycle that reached minimum Δ*p*CO₂ values during April and May related to biological activity. Only summer months showed a slight oversaturation because of the warming of the surface waters (Padin et al., 2008). This behavior contrasted with the Δ*p*CO₂ variability in the Loire estuary – that permanently exceeded the atmospheric *p*CO₂ values – reaching values up to 1200 μatm. The intensification of the dominant heterotrophic processes in the Loire plume extended this oversaturation area in the French continental shelf during autumn 2002 (de la Paz et al., 2010). However, surface waters of the Galician continental shelf were undersaturated, even during summertime, probably because the prevalence of cold upwelled waters in the area. Figure 4b represents the spatiotemporal distribution of the WS anomalies between NCEP-2 and ERA-Interim that showed the worst and the best performance in the Bay of Biscay, respectively, of the evaluated models. The intense overestimation of NCEP-2 winds was clearly observed during the winter (within the downwelling period of Table 1), especially at the end of February; the inner Bay of Biscay showed differences up to 9 m s⁻¹. In spite of the described overestimation of the NCEP-2 wind fields, the difference was reverted in 31 % of the cases included in Fig. 4b.

By considering the most widely used parameterization *k_W*, *F*CO₂ anomalies along ECO cruises were estimated from Δ*p*CO₂ and the wind speed differences between NCEP-2 and ERA-Interim (Fig. 4c). The main *F*CO₂ differences were observed during

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the intense spring uptake (end April and in the beginning of May) because of the intense CO_2 undersaturation (Fig. 4a) and the notable overestimation of NCEP-2 winds (Fig. 4b). These strong differences contrast with the maximum agreement from June to September, with the exception of a particular route in the Galician shelf, when wind speed differed between both models. On the other hand, the behavior as CO_2 source of the Loire plume ($> 47^\circ \text{N}$), with the exception of short periods of CO_2 absorption, was also overestimated during the maximum $\Delta p\text{CO}_2$ events (see first fortnight of December and May) when NCEP-2 was used in comparison with ERA-Interim. Although these noticeable $F\text{CO}_2$ differences came from strong sea-air CO_2 disequilibrium, the WS disagreement between both models also had a significant impact on the $F\text{CO}_2$ values such as it was observed at the end of February. These differences are resumed in a higher CO_2 uptake using NCEP-2 ($-2.60 \pm 9.56 \text{ mmol m}^{-2} \text{ day}^{-1}$) than ERA-Interim ($-1.82 \pm 7.77 \text{ mmol m}^{-2} \text{ day}^{-1}$).

Besides the quality performance of the meteorological models under particular conditions and regions (Otero and Ruiz-Villareal, 2008), these results show that the $\Delta p\text{CO}_2$, representing the thermodynamic driving force on the CO_2 flux, considerably determines the impact of the choice of the WS product. Thus, the selection of the WS source is a decisive factor, especially if $F\text{CO}_2$ values at short-term are estimated under intense $\Delta p\text{CO}_2$ conditions. On the other hand, $F\text{CO}_2$ differences at seasonal scale could minimize the importance of WS anomalies if the seasonal $\Delta p\text{CO}_2$ variability at this region covered from undersaturation to supersaturation periods on the same scale. Thus the importance of the typology of wind speed on the $F\text{CO}_2$ estimations depends on the CO_2 saturation of the area and on its conditions during the study period.

Finally, and reintroducing the initial question in this section, an applet was built using Processing (<http://www.processing.org>). This applet can be found at <http://www.indicedeafloramiento.ieo.es/eco> and allows to explore the spatio-temporal variability of air-sea CO_2 flux in our dataset.

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The results presented above show that the mean CO_2 uptake estimated in the Bay of Biscay may differ up to 240 % depending on the wind speed product and the gas exchange parameterization used, where 25 % of the uncertainty is directly related to the selection of k (Wanninkhof, 2007). Wind speed is the key parameter controlling the long-term variability, estimated to be 57 % in the Bay of Biscay by Padin et al. (2008). Therefore, the community of CO_2 researchers should be aware of the inherent uncertainties of the employed data source, because of the large impact on their results. These differences can be maximized during certain meteorological events, as stated by Otero and Ruiz-Villarreal (2008), who proved that getting similar mean values from different meteorological models does not necessarily imply an adequate description of temporal and spatial variations.

In the absence of in-situ observations at buoys, QuikSCAT Level 2B data is the best choice to estimate $F\text{CO}_2$. However, land contaminated regions preclude its use over coastal regions, and in these situations, the use of reanalysis and forecast meteorological models is the best choice. In that case, NCEP-2 overestimates winds in the Bay of Biscay region, and although this pattern can revert during certain periods – especially during upwelling events – this product should not be considered for further $F\text{CO}_2$ studies, at least, with the current model configuration. The opposite effect is observed when using NCEP-1. Consequently, ERA-Interim – mainly due to its higher spatial resolution and the assimilation of scatterometer ocean surface winds – becomes a balanced choice. Even though the HIRLAM-AEMet configuration shown in this study did not achieve optimum results, recent advances in data assimilation and computing capabilities should convert the use of limited area models in the preferred choice. In fact, strong updates in the current configuration has been performed by AEMet since the study period (Yang, 2007), which encourages to use models from national or regional agencies.

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Table 1. Mean difference and standard deviation of the difference of the models with the observations at buoys. Values are computed (a) during the complete study period, (b) during the downwelling period, defined here from October to February and (c) during the upwelling period, defined from April to August. The number of compared pairs (observation-model) at each buoy location are shown in parentheses.

		<i>Differences with in-situ observations</i>				
		Buoy	NCEP	NCEP2	HIRLAM	ERA-Interim
(a)						
ANNUAL	Silleiro (1301)	7.06 ± 3.71	-0.59 ± 0.14	1.04 ± 0.16	0.28 ± 0.15	-0.33 ± 0.14
	Vilano (1063)	6.82 ± 3.60	-0.89 ± 0.15	0.33 ± 0.16	-0.03 ± 0.16	0.04 ± 0.15
	Bares (906)	6.68 ± 3.47	-0.21 ± 0.16	1.22 ± 0.18	0.40 ± 0.18	0.09 ± 0.16
	Peñas (1336)	5.61 ± 3.29	0.65 ± 0.13	2.17 ± 0.15	0.27 ± 0.13	0.03 ± 0.12
	Bilbao (429)	5.31 ± 2.70	-0.89 ± 0.17	0.11 ± 0.19	-0.40 ± 0.18	-1.27 ± 0.16
	Gascogne (1425)	6.98 ± 3.61	-0.04 ± 0.14	1.38 ± 0.16	-0.13 ± 0.14	-0.09 ± 0.14
(b)						
DOWNWELLING PERIOD	Silleiro (575)	8.19 ± 3.63	-0.53 ± 0.21	1.44 ± 0.25	0.21 ± 0.23	-0.19 ± 0.22
	Vilano (219)	7.41 ± 3.77	-0.61 ± 0.36	0.78 ± 0.42	0.12 ± 0.39	0.20 ± 0.37
	Bares (316)	7.63 ± 3.68	-0.02 ± 0.29	1.76 ± 0.35	0.60 ± 0.31	0.25 ± 0.29
	Peñas (597)	6.64 ± 3.62	0.99 ± 0.21	3.00 ± 0.25	0.47 ± 0.22	0.38 ± 0.20
	Bilbao (9)	–	–	–	–	–
	Gascogne (580)	8.60 ± 4.02	0.07 ± 0.24	2.04 ± 0.27	-0.02 ± 0.24	0.11 ± 0.23
(c)						
UPWELLING PERIOD	Silleiro (601)	6.39 ± 3.64	-0.78 ± 0.18	0.61 ± 0.20	0.34 ± 0.21	-0.46 ± 0.19
	Vilano (601)	6.93 ± 3.56	-1.17 ± 0.19	0.02 ± 0.21	-0.17 ± 0.21	-0.10 ± 0.20
	Bares (392)	6.17 ± 3.20	-0.25 ± 0.23	0.99 ± 0.25	0.15 ± 0.25	-0.03 ± 0.23
	Peñas (592)	4.76 ± 2.69	0.38 ± 0.15	1.45 ± 0.17	0.05 ± 0.16	-0.29 ± 0.15
	Bilbao (285)	5.32 ± 2.73	-0.84 ± 0.21	0.04 ± 0.24	-0.42 ± 0.23	-1.21 ± 0.20
	Gascogne (602)	5.79 ± 2.71	-0.23 ± 0.16	0.71 ± 0.18	-0.36 ± 0.16	-0.41 ± 0.16

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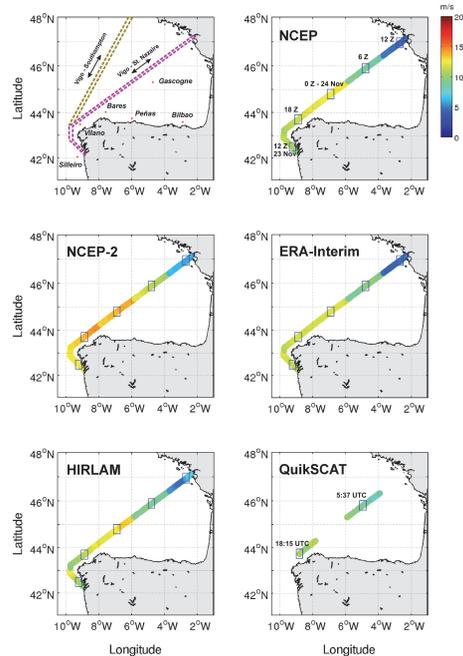


Fig. 1. Map of the Bay of Biscay showing ECO routes with $\Delta p\text{CO}_2$ measurements from September 2002 to September 2003 (top and left panel). These routes departed from the port of Vigo (Spain), usually to Saint Nazaire (France) and rarely to Southampton (UK). The ocean buoys used in the study (Silleiro, Vilano, Bares, Peñas, Bilbao and Gascogne) are also shown. The rest of panels show the wind field interpolated in space (cubically in the case of models and collocated in satellite-derived winds) and time (< 3 h) to the first available route on 23 and 24 November 2002 as taken from different products (NCEP-1, NCEP-2, HIRLAM, ERA-Interim and QuikSCAT). The reference times of the wind products are marked over the route (blue boxes).

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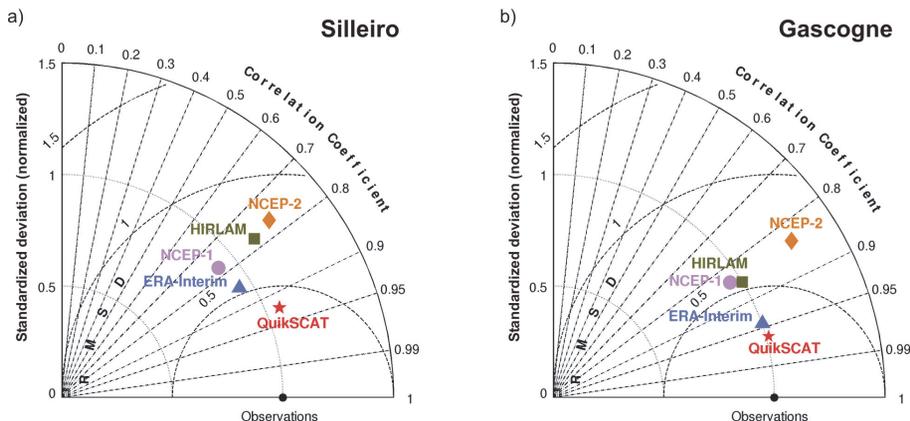


Fig. 2. Taylor diagrams showing the comparison of various wind products and anemometer winds at the Silleiro and Gascogne buoys. The diagram is constructed in terms of the correlation among time series, their centered root-mean-square (rms) difference and the standard deviation (σ) normalized by the amplitude of the observations.

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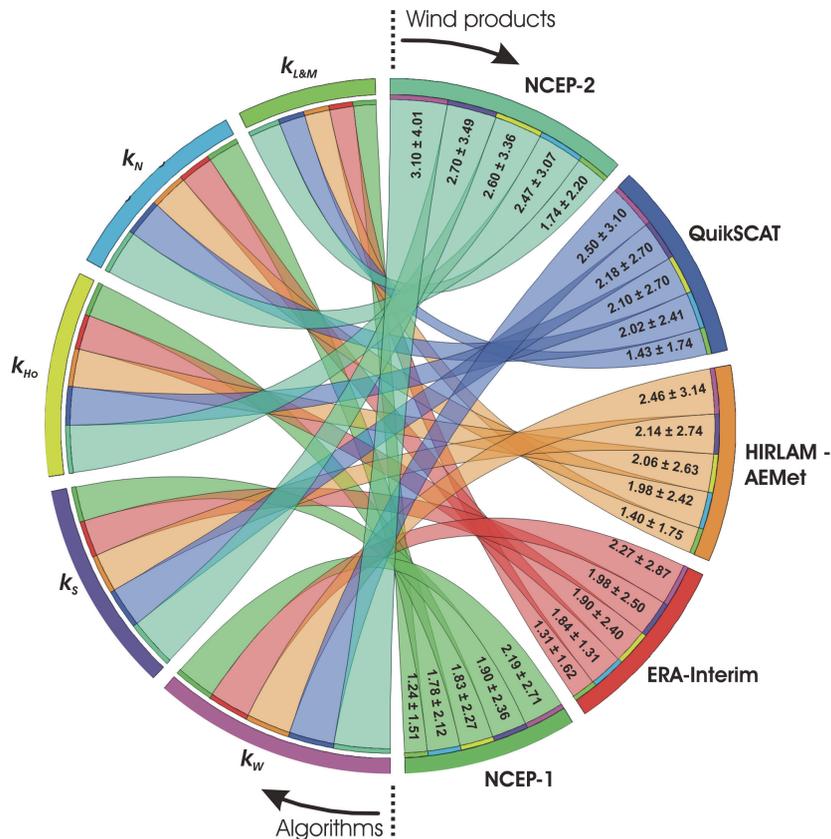


Fig. 3. Relative contribution of the mean sea-air CO₂ flux during the study period computed with different wind products (right semicircle) and k parameterizations (left semicircle): k_W (Wanninkhof, 1992), $k_{L\&M}$ (Liss and Merlivat, 1986), k_N (Nightingale et al., 2000), k_S (Sweeney et al., 2007) and k_{Ho} (Ho et al., 2006). The circular representation allows to explore relationships between winds and algorithms. Data are shown clockwise in decreasing relative order. This graph has been created using CIRCOS (<http://circos.ca/>).

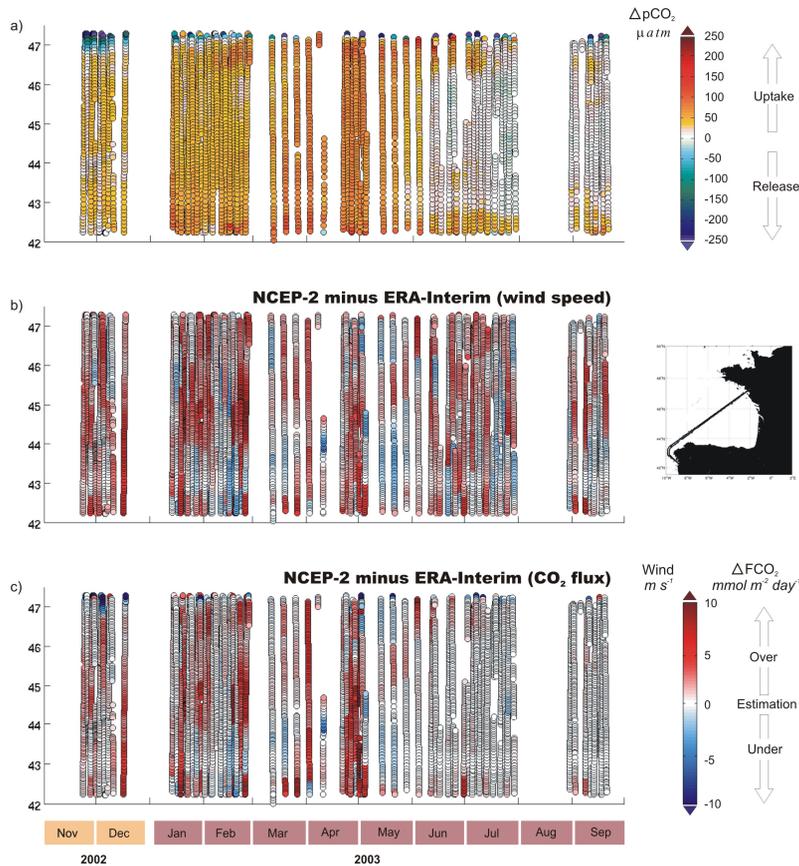


Fig. 4. (a) Distribution of underway $\Delta p\text{CO}_2$ measurements in the Bay of Biscay gathered during ECO cruises. Positive (negative) means uptake (release). (b) Wind speed difference between NCEP-2 and ERA-Interim. (c) Difference of FCO_2 computed using NCEP-2 and ERA-Interim, both with the same algorithm by Wanninkhof (1992). Points along the route are drawn approximately each 30 min of navigation.

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