

Dear Editor:

The authors are very grateful with your revision. In the new revised version of the manuscript, all the suggestions and comments have been taken into account. Some suggestions have also been clarified and changed wording in the text.

- 5 Below you will find the comments you made and our comments as authors (marked AC) on each point. In response to all your comments the manuscript has been modified, resulting in some changes to line numbers. Therefore, we have included the new line numbers (whenever applicable) so that you can refer to either the current or (former) version if you wish.

Thank you very much for your consideration.

10

Sincerely,

Dolores Jiménez-López, on behalf of all co-authors.

15 ***Topic Editor Decision: Publish subject to minor revisions (review by editor) (06 Aug 2019) by Mario Hoppema***

Comments to the Author:

Dear Dr. Jiménez-López and co-authors,

20 *Thanks for your revised manuscript, which I have read and corrected. My comments and listed below. Your manuscript is almost there. Please prepare another revised version taking into account the below comments:*

L28 de Haas (typo)

AC: Corrected.

25 *L29 I suggest: ... total carbon sequestration through the mechanism of the biological pump ...*

AC: Changed.

L33 ... lower than that ...

AC: Modified.

30 *L42 I suggest: At the continental shelf a high spatiotemporal variability of the air-sea CO₂ fluxes occurs due to ...*

AC: Modified.

L42-43 “upwelling zones” and “input” are not processes. Please change wording.

AC: The wording has been changed.

35 *Line 42-43: “At the continental shelf, a high spatiotemporal variability of the air-sea CO₂ fluxes occurs due to various effects, such as the thermodynamic effects, the biological processes, the gas exchange, the upwelling zones and the continental inputs”.*

L58 “more affected” More than what?

AC: Included.

Line 59: “... than the outer shelf”.

40 *L62 shows (instead of: presents)*

AC: Changed.

L63 “in this zone” This formulation is not clear; is this the former or the latter? Please make clear

AC: Clarified in the text.

Line 63: “... in the inner zone”.

45 *L64 “The Gulf of Cádiz is a geographical domain of considerable interest due to its location.” This is a strange formulation. I guess it holds for every oceanic region. Please specify and change wording.*

AC: The wording has been changed.

Line 65-67: “The Gulf of Cádiz is strategically located connecting the Atlantic Ocean with the Mediterranean Sea through the Strait of Gibraltar and in addition it receives continental inputs from several major rivers, i.e. the Guadalquivir, Tinto, Odiel and Guadiana”.

L133 Please define CTD here

AC: Defined and included.

Line 133: “...SeaBird CTD 911+ (Conductivity-Temperature-Depth system)”.

L148 Please use SI units instead of mile

55 AC: Modified and included.

Line 149: “...to 0.9 km around the location of the fixed stations approximately”.

L196 please add “water depth” to the > 50 m and < 50 m, as this is not clear now

AC: Added in the text.

Line 199-200: “...between coastal (water depth < 50 m) and distal (water depth > 50 m) areas”.

60 *L212 add USA after NY (and write full New York, correct?)*

AC: You are right, NY is New York. Modified and added USA in the text.

Line 215: “Statistical analyses were performed with IBM SPSS Statistics software (Version 20.0. Armonk, New York, USA)”.

L219 delete: sampling

65 AC: Deleted (Line 221).

L221-222 I suggest: During 2014, SST values were found to be higher than those in 2015 and 2016

AC: Changed (Line 224).

L222 delete: for both seasons

AC: Deleted (Line 225).

70 *L224 delete: spatially*

AC: Deleted (Line 226).

L234-236 This sentence is not clear; I suggest: Sampling during our cruises did not detect the highest temperatures occurring in the Gulf of Cádiz during August, which may indicate that the real range of pCO₂ variation be greater than that determined in this study.

75 AC: Modified (Line 237-239).

L237 Change to: The highest mean values ... (since in the previous sentence a higher value was given)

AC: Changed (Line 240).

L245-246 This sentence is not clear; change to: These mean values are not significantly different and the standard deviations are high, indicating high spatial and inter-annual variability.

80 AC: Modified (Line 248-249).

L273 variable (instead of: parameter)

AC: Modified (Line 274).

L294 ... in the CO₂ fluxes ... (delete: dataset of)

AC: Deleted (Line 295).

85 L294 ... similar to pCO₂ ... (not: as in the values of pCO₂)

AC: Changed (Line 295).

L305-306 The sentence is unclear. I suggest: In our study, all data from all seasons together exhibited a linear relationship between pCO₂ and SST ($r^2 = 0.37$, Fig. 5A).

AC: Sentence changed (Line 305-306).

90 L306 becomes even more significant ... (add: even)

AC: Added (Line 306).

L326-327 Is there any additional evidence, or only indications, from research on land that such is happening in this region?

95 AC: We believe that this effect could be one of the causes of the increase of pCO₂ in the surface waters of the Gulf of Cádiz. But for now we do not have any additional evidence to confirm it. This sentence has been modified and added this information in the text.

100 Line 326-330: "The cause of this increase could be a greater input of anthropogenic nutrients and inorganic carbon from land (Mackenzie et al., 2004) since the direction and magnitude of estuarine and continental shelf CO₂ exchange with the atmosphere is highly dependent on the terrestrial organic budget and nutrient supplies to the coastal ocean (Borges and Abril, 2011; Cai, 2011). Although we do not have any additional evidence to confirm this effect in our area of study currently".

L337 "the shallower areas as a source of CO₂ (mean = 0.2 ± 22.7)" I wouldn't call that a source. This is clearly neither source nor sink, i.e., neutral.

AC: Sentence modified in the text.

105 Line 335-337: " δpCO_2^{sw} presents a similar variation between deep and coastal areas, but with small differences in the mean values between the distal zones ($\delta pCO_2^{sw} = -3.4 \pm 28.9 \mu\text{atm}$) and the shallower areas ($\delta pCO_2^{sw} = 0.2 \pm 22.7 \mu\text{atm}$)".

L340 biological processes

AC: Modified (Line 340).

110 L342-343 ... the changes produced by air-sea CO₂ exchange are relatively small.

AC: Modified (Line 343).

L344-345 I suggest to change this to: In regions with shallower mixed layers, the effect of air-sea exchange on the pCO₂ variation is larger (Olsen et al., 2008).

AC: Changed (Line 345-346).

115

L351-352 ... *except for an area influenced by continental runoff where pCO₂ decreases.*

AC: Modified (Line 352-353).

L353 *biological processes*

AC: Modified (Line 354).

120 L353-355 ... *a dependence between the mean values of pCO₂ and pH, AOU and the concentration of chlorophyll-a has been observed at the fixed stations (n = 126, Fig. 7)*

AC: Changed (Line 354-356).

L355 *AOU and pCO₂ show a positive relationship ...*

AC: Modified (Line 356).

125 L358 *delete: However, (this relationship is expected, no surprise)*

AC: Deleted (Line 359-360).

L366-367 *I suggest to change to: Something that could affect the distribution of pCO₂ (and be considered to be part of mixing and biology sensu Olsen et al., 2008), is vertical and lateral transport.*

AC: This suggestion has been accepted and modified in the text (Line 367-368).

130 L380 *delete: Additionally,*

Or for that reason delete the whole sentence in L380-381: “Additionally, several authors have described the influence of the continental inputs on the distribution of pCO₂ in surface waters.” (because the authors are mentioned in L383-384)

AC: The wording has been changed in the text.

135 Line 381-382: “Additionally, related with the lateral transport on the distribution of pCO₂ in surface waters, several authors have described the influence of the continental inputs”.

L380-384 *Why is this, what you describe? It would be interesting to read the reason here.*

AC: We describe the effect of the lateral transport on the distribution of pCO₂. For this reason, the wording has been clarified in the text, as you can see in the previous point.

140 L385 *derive (instead of: take place)*

AC: Modified (Line 387).

L402-405 *It is not clear to me what you mean here. Please modify sentence.*

AC: This sentence has been clarified in the text.

145 Line 403-406: “The intensity of this effect decreases towards offshore areas, since the influence of the primary production and the continental supplies on the deposition of the particulate organic matter are less (Friedl et al., 1998; Burdige, 2007; Al Azhar et al., 2017), which could be related with the greater effect determined by the mixing and biology processes in the coastal areas using the Olsen et al. (2008) method”.

150 L407-408 “These authors found a mean benthic flux of $27 \pm 8 \text{ mmol C m}^{-2} \text{ d}^{-1}$ for stations with a mean depth of 23 m. This flux of DIC is equivalent to a CO_2 flux of $198 \pm 80 \text{ } \mu\text{mol C m}^{-2} \text{ d}$, considering a well-mixed water column, a $\text{pH} = 8 \dots$ ” I do not understand this calculation. A benthic C flux is given, and from this another C flux is calculated with quite a different amount of C involved. Is the derived flux over a different interface? Please explain what you mean and how you did the calculation.

155 AC: We calculate the CO_2 benthic flux ($198 \pm 80 \text{ } \mu\text{mol C m}^{-2} \text{ d}$) through the CID benthic flux ($27 \pm 8 \text{ mmol C m}^{-2} \text{ d}^{-1}$) with the program CO2SYS (Lewis et al., 1998) but in the same interface. For this, the variables indicated in the text are necessary; the pH (8), the mean temperature and salinity in the Gulf of Cádiz ($18.8 \text{ }^\circ\text{C}$ and 36.19, respectively) and the K1 and K2 acidity constants proposed by Lueker et al. (2000) in the total pH scale that they are chosen in the own program. And to estimate the influence of this CO_2 benthic flux about the pCO_2 values in the water column, it is also necessary to considerate the depth of this water column (23m).

165 This sentence has been clarified in the manuscript. Line 409-414: “This flux of DIC is equivalent to a CO_2 flux of $198 \pm 80 \text{ } \mu\text{mol C m}^{-2} \text{ d}^{-1}$ through the sediment-water interface, considering a well-mixed water column, a $\text{pH} = 8$, in the conditions of mean temperature and salinity in the Gulf of Cádiz ($18.8 \text{ }^\circ\text{C}$ and 36.19, respectively) and using the K1 and K2 acidity constants proposed by Lueker et al. (2000) in the total pH scale through the program CO2SYS (Lewis et al., 1998). Moreover, this estimated CO_2 benthic flux would produce an increase of pCO_2 of $0.25 \pm 0.10 \text{ } \mu\text{atm d}^{-1}$ in the water column”.

L425 Please add here what high values (of which variable?)

AC: Variable added in the text (ΔpCO_2 non-thermal) (Line 428-429).

170 L440-441 delete: that have been cruised for sampling in the study zone (not necessary, the transects have been introduced earlier in the text)

AC: Deleted (Line 443).

L441 delete: It can be appreciated that

AC: Deleted (Line 443).

175 L445 upwelling (no -s)

AC: Modified (Line 447).

L447 show (not: present)

AC: Modified (Line 449).

L457 the air-sea flux ...

180 AC: Added in the text (Line 458).

L457 shows, or exhibits (not: presents)

AC: Changed (Line 458).

L458-459 I suggest to change to: As can be seen in Fig. 10, seasonal and spatial variations were observed in the air-sea fluxes during the period studied.

185 AC: This sentence has been modified (Line 459-460).L463 As discussed above for pCO_2 , temperature change is ...

AC: Modified (Line 464).

L466 as a consequence of the biological utilization of the CO₂ and the subsequent tendency for CO₂ undersaturation ... (please note, biological utilization as such does not cause air-sea fluxes)

190 AC: Modified (Line 467-468).

L467 Such relationships

AC: Changed (Line 468).

In §4.4 several times CO₂ fluxes are mentioned, where air-sea fluxes are meant. Please insert air-sea in some cases for clarity.

195 AC: All the terms of “air-sea” have been added in this section. Thank you for your suggestion.

L489 during the sampling period

AC: Modified (Line 491).

L489 With the number of $-0.18 \text{ mmol m}^{-2} \text{ d}^{-1}$ including the order of magnitude larger standard deviation it is not very convincing to call the region a CO₂ sink. Please change the wording, and consider to use neither source nor sink.

200 AC: This sentence has been modified in the manuscript.

Line 491-492: “The Gulf of Cádiz, during the sampling period, shows a mean rate of $-0.18 \pm 1.32 \text{ mmol m}^{-2} \text{ d}^{-1}$, even though it is necessary to consider the intrinsic variability of the database that generate a high standard deviation”.

205 *L498-499 My suggestion for this sentence: A high variability in pCO₂ in the Gulf of Cádiz was observed which is associated with its location as a transition zone between coastal and shelf areas, superimposed on the usual seasonal variation due to thermal and biological effects.*

AC: This sentence has been modified in the text with your suggestion (Line 499-500).

L499-500 “The mean value of pCO₂ found in this study ($398.9 \pm 15.5 \text{ } \mu\text{atm}$) indicates that the eastern part of the Gulf of Cádiz could be slightly undersaturated in CO₂ with respect to ...” This is not sound. A mean value for the entire region is given, which you couple to (only) the eastern part of the Gulf that may be undersaturated. Please correct, or explain and modify the text.

210 AC: Sentence modified in the manuscript. We refer to the Gulf of Cádiz now.

Line 500-502: “The mean value of pCO₂ found in this study ($398.9 \pm 15.5 \text{ } \mu\text{atm}$) indicates that the Gulf of Cádiz could be slightly undersaturated in CO₂ with respect to the atmosphere ($402.1 \pm 3.9 \text{ } \mu\text{atm}$)”.

215 *L502 littoral (typo)*

AC: Corrected (Line 503).

L502-503 delete: in this work

AC: Deleted (Line 503).

220 *L503-504 biological activity, represented by chlorophyll-a*

AC: Added in the text (Line 505).

L510 The mean T/B ratio (1.15) of the region suggests ...

225 AC: Modified (Line 512). But in our work, we calculate the total T/B ratio, it is not mean T/B ratio, because we obtain a T/B ratio for the 8 cruises.

L510 ... by temperature changes.

AC: Modified (Line 512).

230 L510-512 I suggest the following: However, the situation is more complicated if the ratio is considered as a function of bottom depth, which is associated with the existence of non-thermal processes.

AC: Modified with your suggestion (Line 513-514).

L515-516 “In contrast, the highest T/B ratio values have been found in the SP transect, where values of up to 1.54 are obtained for depths greater than 100 m.” With those explanations for the lower ratio earlier, what is the reason for this higher ratio? Please add some text on this.

235 AC: This sentence has been clarified in the manuscript.

Line 517-519: “In contrast, the highest T/B ratio values have been found in the SP transect, where values of up to 1.54 are obtained for depths greater than 100 m, probably related to the greater effect of thermal processes”.

240 L520-521 “... since the $p\text{CO}_2$ has increased from $360.6 \pm 18.2 \mu\text{atm}$ (Ribas-Ribas et al., 2011) to $398.9 \pm 520 15.5 \mu\text{atm}$ in the actuality.” It is important to provide the years for these values and the accompanying increase of $p\text{CO}_2$ in the atmosphere to be able to judge the contention. Please add text.

AC: The years have added and the increase of $p\text{CO}_2$ in the atmosphere was included in the Line 325 of the manuscript, although we have also added in this section.

245 Line 523-525: “...since the $p\text{CO}_2$ has increased from $360.6 \pm 18.2 \mu\text{atm}$ in a study realised between 2006 and 2007 (Ribas-Ribas et al., 2011) to $398.9 \pm 15.5 \mu\text{atm}$ in the actuality and this exceeds the rate of increase of $p\text{CO}_2$ in the atmosphere ($2.3 \mu\text{atm year}^{-1}$ for the last 10 years)”.

L905 suggest to write here: data from González-García et al. (2018).

AC: Added (Line 906).

title Table 3: mention that this concerns: air-sea CO_2 fluxes

250 AC: Modified.

title Table 4: idem ditto

AC: Modified.

L939 caption Figure 2: please add units of variables shown

AC: Variables added in the figure caption.

255 L989 caption Figure 6: Observed changes in $p\text{CO}_2$ (first row) and $p\text{CO}_2$ changes broken down due to:

AC: Caption modified.

L994 caption Figure 7: Relationships (instead of: Dependence)

AC: Caption modified

pCO₂ variability in the surface waters of the eastern Gulf of Cádiz

(SW Iberian Peninsula)

Dolores Jiménez-López¹, Ana Sierra¹, Teodora Ortega¹, Soledad Garrido², Nerea Hernández-Puyuelo¹, Ricardo Sánchez-Leal³, Jesús Forja¹

¹ Dpto. Química-Física, INMAR, Facultad de Ciencias del Mar y Ambientales, Universidad de Cádiz, Campus Universitario Río San Pedro, 11510 - Puerto Real, Cádiz, Andalucía, España

² Instituto Español de Oceanografía. Centro Oceanográfico de Murcia. Varadero 1. E-30740, San Pedro del Pinatar, Murcia, España

³ Instituto Español de Oceanografía. Centro Oceanográfico de Cádiz. Puerto Pesquero, Muelle de Levante s/n. Apdo. 2609. E-11006, Cádiz, España

Correspondence to: Dolores Jiménez-López (dolores.jimenez@uca.es)

Abstract

Spatiotemporal variations of the partial pressure of CO₂ (pCO₂) were studied during 8 oceanographic cruises conducted between March 2014 and February 2016 in surface waters of the eastern shelf of the Gulf of Cádiz (SW Iberian Peninsula) between the Guadalquivir River and Cape Trafalgar. pCO₂ presents a range of variation between 320.6 and 513.6 µatm, with highest values during summer and autumn and lowest during spring and winter. For the whole study, pCO₂ shows a linear dependence with temperature, and spatially there is a general decrease from coastal to offshore stations associated with continental inputs and an increase in the zones deeper than 400 m related to the influence of the eastward branch of the Azores Current. The study area acts as source of CO₂ to the atmosphere during summer and autumn and as a sink in spring and winter, with a mean value for the study period of -0.18 ± 1.32 mmol m⁻² d⁻¹. In the Guadalquivir and Sancti Petri transects, the CO₂ fluxes decrease towards offshore, whereas in the Trafalgar transect fluxes increase due to the presence of an upwelling. ~~These results highlight the Gulf of Cádiz as a CO₂ sink, with an~~ The annual uptake capacity of CO₂ in the Gulf of Cádiz is 4.1 Gg C year⁻¹.

1. Introduction

Continental shelves play a key role in the global carbon cycle, as this is where the interactions between terrestrial, marine and atmospheric systems take place (Mackenzie et al., 1991; Walsh, 1991; Smith and Hollibaugh, 1993). These zones are considered to be among the most dynamic in biogeochemical terms (Wollast, 1991; Bauer et al., 2013), as they are affected by several factors, particularly high rates of primary production, remineralization and organic carbon burial (Walsh, 1988; Wollast, 1993; de Haass et al., 2002). Continental shelves account for about 10 – 15 % of the ocean primary production and they contribute approximately 40 % of the ~~total ocean's total~~ carbon sequestration through the mechanism of the, by biological pump (Muller-Karger et al., 2005).

Generally, waters over the continental shelf account for ~15 % of the global ocean CO₂ uptake (-2.6 ± 0.5 Pg C yr⁻¹, Le Quéré et al., 2017). Using direct surface ocean CO₂ measurements from the global Surface Ocean CO₂ Atlas (SOCAT) database, Laruelle et al. (2014) estimated a sea-air exchange of CO₂ in these zones of -0.19 ± 0.05 Pg C yr⁻¹, lower than ~~the~~ heat estimated in other studies published in the last decade (e.g. Borges et al., 2005; Cai et al., 2006; Chen and Borges, 2009; Laruelle et al., 2010; Chen et al., 2013). The discrepancies with respect to this estimation derive from the different definitions of the continental shelf domain and the skewed distribution of local studies (Laruelle et al., 2010). In several

works, it has been observed that the continental shelves present different behaviour according to their latitude: they tend to act as a sink of carbon ($-0.33 \text{ Pg C yr}^{-1}$) at high and middle latitudes ($30 - 90^\circ$) and as a weak source ($0.11 \text{ Pg C yr}^{-1}$) at low latitudes ($0 - 30^\circ$) (Cai et al., 2006; Hofmann et al., 2011; Bauer et al., 2013; Chen et al., 2013; Laruelle et al., 2014, 2017). Laruelle et al. (2010) found differences between the two hemispheres: the continental shelf seas of the Northern Hemisphere are a net sink of CO_2 ($-0.24 \text{ Pg C yr}^{-1}$) and those of the Southern Hemisphere are a weak source of CO_2 ($0.03 \text{ Pg C yr}^{-1}$).

~~At The behaviour of~~ the continental shelf, ~~presents~~ a high spatiotemporal variability of the air-sea CO_2 fluxes ~~occurs~~ due to various ~~effects~~ processes, ~~such as the~~ particularly thermodynamic ~~effects,~~ ~~the biological processes~~ effects, ~~biological processes,~~ the gas exchange, the upwelling zones and the continental inputs (e.g. Chen and Borges, 2009; Ito et al., 2016). Thermodynamic effects are controlled by the inverse relationship between temperature and solubility ($0.0423 \text{ }^\circ\text{C}^{-1}$, Takahashi et al., 1993). Biological processes can induce CO_2 uptake or release, deriving respectively from phytoplankton photosynthesis that decreases the concentration of inorganic carbon, and respiration by plankton and all other organisms, which increases the concentration of inorganic carbon (Fennel and Wilkin, 2009). Both factors, thermodynamic effects and biological processes, are associated with the sea-air CO_2 exchange by physical and biological pumps (Volk and Hoffert, 1985). The effects of upwelling systems are not clearly defined (Michaels et al., 2001). Although this process produces a vertical transport that brings up CO_2 and remineralized inorganic nutrients from deep seawater (Liu et al., 2010), upwellings are also responsible for high rates of primary production and a reduction of pCO_2 under the equilibrium with the atmosphere (e.g. van Geen et al., 2000; Borges and Frankignoulle, 2002; Friederich et al., 2002). Several studies indicate that these systems act as either a source or sink of CO_2 depending on their location (Cai et al., 2006; Chen et al., 2013). Upwelling systems at low latitudes act mainly as a source of CO_2 but as a sink of CO_2 at mid-latitudes (Frankignoulle and Borges, 2001; Feely et al., 2002; Astor et al., 2005; Borges et al., 2005; Friederich et al., 2008; González-Dávila et al., 2009; Santana-Casiano et al., 2009). Upwelling systems in the Pacific and Indian Oceans act as sources of CO_2 to the atmosphere, whereas in the Atlantic Ocean they are sinks of atmospheric CO_2 (Borges et al., 2006; Laruelle et al., 2010). Additionally, the inner shelf is more affected by riverine inputs of nutrients and terrestrial carbon (e.g. Gypens et al., 2011; Vandemark et al., 2011) and by human impact (Cohen et al., 1997) ~~than the outer shelf~~. The influence of both factors, riverine inputs and human impact, decrease towards offshore (Walsh, 1991). Several studies have determined that the inner shelf tends to act as a source of CO_2 and the outer shelf as a sink (e.g. Rabouille et al., 2001; Cai, 2003; Jiang et al., 2008, 2013; Arruda et al., 2015). The inner platform (depth less than 40 m) also ~~show~~ presents greater seasonal variability of temperature than the outer platform, and consequently the effect of temperature on pCO_2 will be greater in the ~~inner~~ zone (Chen et al., 2013).

The Gulf of Cádiz is ~~strategically located connecting the Atlantic Ocean with the Mediterranean Sea through the Strait of Gibraltar and in addition a geographical domain of considerable interest due to its location. In addition to receiving the outflow of Mediterranean waters through the Strait of Gibraltar,~~ it receives continental inputs from several major rivers, i.e. the Guadalquivir, Tinto, Odiel and Guadiana. Various studies have been conducted in this area to evaluate the variability of the sea surface partial pressure of CO_2 (pCO_2), although they cover smaller areas and a shorter duration of time than this work (González-Dávila et al., 2003; Ait-Ameur and Goyet, 2006; Huertas et al., 2006; Ribas-Ribas et al., 2011) or only a specific area like the Strait of Gibraltar (Dafner et al., 2001; Santana-Casiano et al., 2002; de la Paz et al., 2009). All of these studies, however, have determined that this zone behaves as a sink of CO_2 , with seasonal variations induced mainly by the combination of the fluctuations of biomass concentration and temperature.

In this paper we evaluate the spatial and seasonal variation of the sea-surface pCO_2 on the eastern shelf of the Gulf of Cádiz. In addition, we aim to assess the relative contribution of the thermal and non-thermal effects to pCO_2 distribution, and to determine if the area as a whole acts as a sink or a source of CO_2 to the atmosphere over time. It has also been possible to

estimate the influence that various sea surface currents have on pCO₂ variability, since this study considers deeper areas than previous works. Therefore, we can analyse the change that has occurred in relation to the CO₂ uptake capacity in the Gulf of Cádiz in the last 10 years, in comparison with other studies that analyse the seasonal variation underway of pCO₂ in this area (Ribas-Ribas et al., 2011). In this work we have analysed a surface measurement database of >26000 values of pCO₂ obtained during cruises made between 2014 and 2016 and covering an area of 0.8° x 1.3° of the Gulf of Cádiz.

2. Material and methods

2.1. Study area

This study was carried out over the eastern shelf of the Gulf of Cádiz (Fig. 1), which forms a large basin between the southwest of the Iberian Peninsula and the northwest of Africa, where the Atlantic Ocean connects with the Mediterranean Sea through the Strait of Gibraltar. In the Strait of Gibraltar a bilayer flow takes place, with an upper Atlantic layer flowing towards the Mediterranean basin and a deeper outflow of higher-density Mediterranean waters to the Atlantic Ocean (e.g. Armi and Farmer, 1988; Baringer and Price, 1999; Sánchez-Leal et al., 2017). A similar circulation pattern of opposing flows is found in the Gulf of Cádiz where three main water masses are distributed at well-defined depth intervals and areas: the Surface Atlantic Water (SAW), with coastal and atmospheric influence, inflowing at the shallowest depths; the Eastern North Atlantic Water (ENACW), at an intermediate depth, characterised by low salinity; and the Mediterranean Outflow Water (MOW), entering at the deepest level (Criado-Aldeanueva et al., 2006; Bellanco and Sánchez-Leal, 2016).

The Gulf of Cádiz is part of one of the four major Eastern Boundary Upwelling System of the world, the North Atlantic upwelling (e.g. Alvarez et al., 2009), that extends from south of Cape Verde (Senegal) to Cape Finisterre (northwest of Spain). For this reason, the Gulf of Cádiz presents characteristics typical of this system: seasonal variability of a winds system favourable to the coastal upwelling (Fiúza et al., 1982), high biological productivity (Navarro and Ruiz, 2006), a system of fronts and zonal currents (García Lafuente and Ruiz, 2007) and a zone of water exchange between the coastal zone and open ocean (Sánchez et al., 2008). However, the fact that the coastline of the study area runs more in a W-E direction than the overall N-S direction common to all the Eastern Boundary Upwelling System phenomena, and the bilayer flow through the Strait of Gibraltar, are two factors that complicate the simple Eastern Boundary Upwelling System conceptual model (Aristegui et al., 2009; Peliz et al., 2009).

In addition, the surface circulation in the Gulf of Cádiz is characterised by several different processes. These are: the presence of an anticyclonic water flow towards the east over the shelf edge as far south as the Strait of Gibraltar, known as the Gulf of Cádiz Current (Sánchez and Relvas, 2003; Peliz et al., 2007); an upwelling process occurs in the Trafalgar area, produced by tidal interaction with the topography of the zone; and the mixing of surface layers induced by the wind (Vargas-Yáñez et al., 2002; Peliz et al., 2009; Sala et al., 2018). The centre of the Gulf is also under the influence of the eastern-end branch of the Azores Current, producing a front subjected to a mesoscale variability (Johnson and Stevens, 2000; García-Lafuente and Ruiz, 2007; Peliz et al., 2007; Sala et al., 2013) (Fig. 1).

2.2. Field sampling and analysis

The database for this study has been obtained following two different sampling strategies. The first consisted of taking sea surface measurements while underway. The second strategy was to obtain measurements at several discrete surface stations along three transects at right angles to the coastline: the Guadalquivir transect (GD), the Sancti Petri transect (SP) and the Trafalgar transect (TF) (Fig. 1). Data was collected during 8 cruises carried out with a seasonal frequency (spring: ST1 and ST5; summer: ST2 and ST6; autumn: ST3 and ST7; winter: ST4 and ST8) during 2014, 2015 and 2016 (Table 1). All the

375 cruises were made on the R/V Ángeles Alvariño, except the summer 2015 cruise (ST6) that was undertaken on the R/V Ramón Margalef. The study area is located between 35.4 and 36.7° N and 6.0 and 7.2° W ($52.8 \cdot 10^2 \text{ km}^2$).

2.2.1. Underway measurements

380 Sea surface temperature (SST), sea surface salinity (SSS) and the pCO_2 were recorded continuously and were averaged with a frequency of 1 min intervals, from the surface seawater supply of the ship (pump inlet at a depth of 5m). SST and SSS were measured using a SeaBird thermosalinograph (SeaBird 21) with an accuracy of $\pm 0.01 \text{ }^\circ\text{C}$ and ± 0.003 respectively. The equilibrator design for determining the pCO_2 is a combination of a laminar flow system with a bubble type system, similar to that developed by Körtzinger et al. (1996) and described by Padin et al. (2009, 2010).

385 The surface water CO_2 molar fraction ($x\text{CO}_2$) and H_2O were determined using a non-dispersive infrared gas analyser (Licor®, LI 6262) that has a minimum accuracy of $\pm 0.3 \text{ ppm}$. It was calibrated daily using two standards: a CO_2 free-air for the blank and a CO_2 sub-standard gas of known concentration (413.2 ppm). CO_2 concentration of the sub-standard gas was determined from the comparison with standard gases of NOAA with an uncertainty of 0.22 ppm and measured with a Licor 6262 ($\pm 1 \text{ ppm}$). The temperature inside the equilibrator was measured continuously by means of a platinum resistance thermometer (PT100 probe, $\pm 0.1 \text{ }^\circ\text{C}$). A pressure transducer (Setra Systems, accurate to 0.05 %) was used to measure the pressure inside the equilibrator. The $x\text{CO}_2$ was converted into pCO_2 according to the protocol described in DOE (2007).
390 Corrections between the equilibrator and SST were made following Takahashi et al. (1993). The temperature difference between the ship's sea inlet and the equilibrator was less than $1.5 \text{ }^\circ\text{C}$.

2.2.2. Fixed stations

395 Discrete surface samples were collected at 5 m depth, using Niskin bottles (10 L) mounted on a rosette-sampler coupled to a SeaBird-CTD ~~(Conductivity Temperature Depth)~~ 911+ ~~(Conductivity-Temperature-Depth system)~~, to measure pH and dissolved oxygen, chlorophyll-a and nutrients concentration.

The pH was measured by potentiometer in duplicate using 100 mL of seawater with a glass-combined electrode (Metrohm, 905) calibrated on the total pH scale using a TRIS buffer solution (Zeebe and Wolf-Gladrow, 2001). Dissolved oxygen values were obtained with the sensor of the rosette (SeaBird 63) pre-calibrated using Winkler titration ($\pm 0.1 \text{ } \mu\text{mol L}^{-1}$) of samples collected from several water depths at selected stations (Parsons et al., 1984). Apparent Oxygen Utilization (AOU)
400 was determined as the difference between the solubility calculated applying the expression proposed by Weiss (1974) and the experimental values of dissolved oxygen. For chlorophyll-a determination, 1 L of seawater was filtered (Whatman, GF/F $0.7 \text{ } \mu\text{m}$) and frozen ($-20 \text{ }^\circ\text{C}$) until analysis in the laboratory. Total chlorophyll-a was extracted with 90 % pure Acetone, and quantified after 24 hours by fluorometry analysis (Hitachi F-2500) (Yentsch and Menzel, 1963). Nutrient samples for analysis of nitrate and phosphate content were filtered through pre-combusted glass-fibre filters (Whatman, GF/F $0.7 \text{ } \mu\text{m}$)
405 and frozen at $-20 \text{ }^\circ\text{C}$. Analyses were performed in a segmented flow autoanalyzer (Skalar, San Plus) based on classic spectrophotometric methods (Grasshoff et al., 1983). The accuracies of the determinations obtained are the following: ± 0.003 for pH, $\pm 0.1 \text{ } \mu\text{mol L}^{-1}$ for dissolved oxygen, $\pm 0.1 \text{ } \mu\text{g L}^{-1}$ for chlorophyll-a, $\pm 0.10 \text{ } \mu\text{mol L}^{-1}$ for nitrate, and $\pm 0.02 \text{ } \mu\text{mol L}^{-1}$ for phosphate.

410 The corresponding data of SST, SSS and pCO_2 for the fixed stations were obtained by the underway measurements averaging data corresponding to ~~0.9 km5-mile~~ around the location of the fixed stations approximately. SST and SSS data

were compared with the values collected with the CTD coupled to the rosette-sampler and they do not show differences greater than 0.04 °C and 0.01 units, respectively.

415 2.3. Thermal and non-thermal effects on pCO₂ calculations

To determine the relative importance of the thermal and non-thermal effects on the changes of pCO₂ in seawater (e.g., Landschützer et al., 2015; Reimer et al., 2017), we follow the method described by Takahashi et al. (2002). To remove the thermal effect from the observed pCO₂, the data were normalized to a constant temperature, the mean in situ SST depending on the focus considered, according to Eq. (1).

$$420 \text{ pCO}_2 \text{ at SST}_{\text{mean}} = (\text{pCO}_2)_{\text{obs}} \cdot \exp[0.0423 \cdot (\text{SST}_{\text{mean}} - \text{SST}_{\text{obs}})] \quad (1)$$

where the subscripts “mean” and “obs” indicate the average and observed SST values, respectively.

To analyse the effect of the thermal changes on pCO₂ at the given observed temperatures (SST_{obs}) the following expression has been used:

$$\text{pCO}_2 \text{ at SST}_{\text{obs}} = (\text{pCO}_2)_{\text{mean}} \cdot \exp[0.0423 \cdot (\text{SST}_{\text{obs}} - \text{SST}_{\text{mean}})] \quad (2)$$

425 When the thermal effect is removed, the remaining variations in pCO₂ are due to the non-thermal influences, such as the biological utilization of CO₂, the vertical and lateral transport, the sea-air exchange of CO₂ and terrestrial inputs (e.g. Qu et al., 2014; Arruda et al., 2015; Ito et al., 2016; Xue et al., 2016). The non-thermal effects on the surface water pCO₂, (ΔpCO_2)_{n-T}, can be calculated from the seasonal amplitude of pCO₂ values normalized to the mean SST, (pCO₂ at SST_{mean}), using Eq. (1):

$$430 (\Delta\text{pCO}_2)_{\text{n-T}} = (\text{pCO}_2 \text{ at SST}_{\text{mean}})_{\text{max}} - (\text{pCO}_2 \text{ at SST}_{\text{mean}})_{\text{min}} \quad (3)$$

And the seasonal amplitude of pCO₂ values normalized to the observed SST, (pCO₂ at SST_{obs}), represents the thermal effect of changes on the mean annual pCO₂ value, (ΔpCO_2)_T and it is calculated with the following expression:

$$(\Delta\text{pCO}_2)_T = (\text{pCO}_2 \text{ at SST}_{\text{obs}})_{\text{max}} - (\text{pCO}_2 \text{ at SST}_{\text{obs}})_{\text{min}} \quad (4)$$

435 The ratio between the thermal effects (T) and non-thermal effects (B) quantifies the relative importance of each effect, (Takahashi et al., 2002):

$$T/B = (\Delta\text{pCO}_2)_T / (\Delta\text{pCO}_2)_{\text{n-T}} \quad (5)$$

440 A T/B ratio greater than 1 implies the dominance of thermal effects over non-thermal on the pCO₂ dynamics. However, a T/B lower than 1 reveals a greater influence of non-thermal processes. This method was originally designed for open oceanic systems, but it has been widely used by other authors in coastal areas (e.g. Schiettecatte et al., 2007; Ribas-Ribas et al., 2011; Qu et al., 2014; Burgos et al., 2018).

In addition, Olsen et al. (2008) propose a method in which the seasonal signal of pCO₂ data is decomposed into individual components due to variations in SST, in air-sea CO₂ exchange, in SSS, and in combined mixing and biological processes, according to Eq. (6).

$$d \text{ pCO}_2^{\text{sw},i} = d_{\text{SST}} \text{ pCO}_2^{\text{sw},i} + d_{\text{AS}} \text{ pCO}_2^{\text{sw},i} + d_{\text{SSS}} \text{ pCO}_2^{\text{sw},i} + d_{\text{MBP}} \text{ pCO}_2^{\text{sw},i} \quad (6)$$

445 where the superscripts “sw” makes reference to the surface pCO₂ in the seawater and “i” to the mean value between consecutive cruises for all variables; $d \text{ pCO}_2^{\text{sw},i}$ is the observed change in pCO₂; $d_{\text{SST}}\text{pCO}_2^{\text{sw},i}$ is the change due to SST changes; $d_{\text{AS}}\text{pCO}_2^{\text{sw},i}$ is the change due to air-sea exchange; $d_{\text{SSS}}\text{pCO}_2^{\text{sw},i}$ is the change due to salinity variations; and $d_{\text{MBP}}\text{pCO}_2^{\text{sw},i}$ is the change due to mixing plus biology. At the same time, each process is calculated with the following equations (Olsen et al., 2008):

450
$$d_{\text{SST}}\text{pCO}_2^{\text{sw},i} = \text{pCO}_2^{\text{sw},i} \cdot e^{0.0423(\Delta\text{SST})} - \text{pCO}_2^{\text{sw},i} \quad (7)$$

where ΔSST is the SST difference between two cruises

$$d_{\text{AS}}\text{pCO}_2^{\text{sw},i} = - (d \cdot F^i) / \text{MLD}^i \quad (8)$$

where d is the number of days passed between two cruises (90 days approximately); F^i is the mean flux of CO₂; and MLD^i is the mean mixed layer depth.

455
$$d_{\text{SSS}}\text{pCO}_2^{\text{sw},i} = \text{pCO}_2^{\text{sw},n+1} (\text{DIC}^{n+1}, \text{TA}^{n+1}, \text{SSS}^{n+1}, \text{SST}^i) - \text{pCO}_2^{\text{sw},n} (\text{DIC}^n, \text{TA}^n, \text{SSS}^n, \text{SST}^i) \quad (9)$$

where the superscript “n” refers to the mean value of each cruise and the variables DIC (dissolved inorganic carbon) and TA (total alkalinity) have been estimated from pH and pCO₂, using the K1 and K2 acidity constants proposed by Lueker et al. (2000) in the total pH scale through the program CO2SYS (Lewis et al., 1998). $d_{\text{MBP}}\text{pCO}_2^{\text{sw},i}$ is calculated as a residual, that is, as the change in pCO₂ that is not explained by other processes. Additionally, this study includes both coastal areas and deeper areas, the analysis is divided in function of the system depth, between coastal ([water depth < 50 m](#)) and distal ([water depth > 50 m](#)) areas. Thus, MLD^i in distal areas (Table 3) was calculated derived from the thermocline position that separates the SAW and the ENACW (71.3 - 96.8 m), while the coastal areas correspond to the depth of these areas (15 - 50 m).

2.4. Estimation of CO₂ fluxes

Fluxes of CO₂ across the sea-air interface were estimated using the relationship:

465
$$\text{FCO}_2 = \alpha \cdot k \cdot (\Delta\text{pCO}_2)_{\text{sea-air}} \quad (10)$$

where k (cm h⁻¹) is the gas transfer velocity; α is the solubility coefficient of CO₂ (Weiss, 1974); and ΔpCO_2 is the difference between the sea and air values of pCO₂. The atmospheric pCO₂ (pCO₂^{atm}) values were obtained from the monthly atmospheric data of xCO₂ (xCO₂^{atm}) at the Izaña Atmospheric Station in Spain (Earth System Research Laboratory; <https://www.esrl.noaa.gov/gmd/dv/data/index.php>, last access: 9 January 2019). The xCO₂^{atm} was converted to pCO₂^{atm} as described in DOE (2007).

The gas transfer velocity, k , was calculated using the parameterization formulated by Wanninkhof (2014):

$$k = 0.251 \cdot u^2 (\text{Sc}/660)^{-0.5} \quad (11)$$

where u (m s⁻¹) is the mean wind speed at 10 m height on each cruise, obtained from the Shipboard Weather Station; Sc is the Schmidt number of CO₂ in seawater; and 660 is the Sc in seawater at 20 °C.

475 2.5. Statistical analysis

Statistical analyses were performed with IBM SPSS Statistics software (Version 20.0. Armonk, [New York, USA](#)). The dataset was analysed using one-way analysis of variance test (ANOVA) for analysing significant differences between cruises

for discrete and continuous surface data on hydrological and biogeochemical characteristics. The threshold value for statistical significance was taken as $p < 0.05$. Moreover, all reported linear correlations are type I and they are statistically significant with p -values smaller than 0.05 in the entire manuscript unless indicated otherwise.

3. Results

3.1. Underway variables

Table 1 gives the ranges of variation and the mean and standard deviation of SST, SSS and $p\text{CO}_2$ during the 8 sampling cruises and figure 2 shows the underway distribution of SST and $p\text{CO}_2$ in the Gulf of Cádiz. Among all the cruises the SST values vary between 14.3 and 23.4 °C. ~~During 2014, SST values were found to be higher than those in 2015 and 2016. The samplings made during 2014 presented SST values higher than those in 2015 and 2016~~ (Table 1). For the whole period, the averaged values ~~for both seasons~~ were highest during summer (21.0 ± 0.8 °C) and autumn (21.1 ± 1.2 °C), with the lowest values during spring (15.5 ± 0.5 °C) and an intermediate value during winter (17.5 ± 0.6 °C). In general, ~~spatially~~ SST tended to increase from coastal to offshore areas during spring and winter, while in summer and autumn this SST gradient was inverse (Fig. 2A). No substantial differences were found between the three transects studied (GD, SP and TF), although near the Guadalquivir River mouth and Cape Trafalgar (36.19° N, 6.03° W) the lowest values of SST due to freshwater inputs and the frequent upwelled waters, respectively, were detected.

Since the cruises were carried out at the beginning of each meteorological season, it is appropriate to analyse how representative is the range of temperatures that has been obtained. Figure 3 shows the mean value over the last 10 years of the maximum and minimum temperatures in the Gulf of Cádiz acquired by a oceanographic buoy (bottom-mounted at 36.48° N - 6.96° W; Puertos del Estado; <http://www.puertos.es/es-es/oceanografia/Paginas/portus.aspx>, last access: 12 July 2018); the mean values and standard deviations of the 8 cruises are superimposed. It can be observed that the mean values for each cruise are within the range of variation of the typical temperature in the Gulf of Cádiz, and the mean temperature found, 18.8 °C, is very close to the mean value obtained at the oceanographic buoy (19.2 °C, Fig. 3). ~~Sampling during our cruises did not detect the highest temperatures occurring in the Gulf of Cádiz during August, which may indicate that the real range of $p\text{CO}_2$ variation be greater than that determined in this study. Although the samplings carried out do not register the highest temperatures found during August in the Gulf of Cádiz, which it could cause that the range in the $p\text{CO}_2$ variation would be greater than the determined in this work.~~

Average values of SSS varied significantly among the cruises, ranging between 35.03 and 37.06. The highest mean values were recorded during February 2016 (36.44 ± 0.09) and lowest during September 2015 (35.64 ± 0.08) (Table 1). The lowest salinity value (35.03) and the most notable spatial variation (35.03 - 36.36) was observed during December 2014 in the area of the Guadalquivir River, associated with a period of storms with consequent major freshwater discharges. The area that presented the highest mean salinity value for the whole study was TF (36.19 ± 0.25).

During our study period, $p\text{CO}_2$ values ranged from 320.6 to 513.6 μatm . The highest values were recorded during summer and autumn of 2014 and 2015 (Table 1), with a similar mean value, 411.6 ± 13.2 μatm and 410.6 ± 10.5 μatm respectively, found for both seasons. And the lowest mean value was logged during spring (382.5 ± 16.9 μatm), while winter presented an intermediate value (390.8 ± 15.4 μatm). ~~These mean values are not significantly different and the standard deviations are high, indicating high spatial and inter-annual variability. Although these values do not present significant differences and the standard deviations are high since they are associated at the spatial and inter-annual variability.~~ In general, the $p\text{CO}_2$ tended to decrease with the distance to the coast (Fig. 2B). Comparing these values with $p\text{CO}_2$ values in the atmosphere, an undersaturation of CO_2 was observed during spring and winter (15.3 ± 15.7 and 18.0 ± 11.4 μatm , respectively) and an

oversaturation in summer and autumn (-20.4 ± 24.6 and -8.0 ± 15.3 μatm , respectively). In Fig. 2 a sharp variation of SST and pCO_2 can be observed in some zones that coincides with the stations where discrete water samples were taken. This may be due to the different sampling time at these stations, which varied between 2 and 8 hours in function of the depth of the system.

The database of this study includes the transition from coastal zones with depths of the order of 20 m to distal shelf waters with depths greater than 800 m. Figure 4 shows the general trend of the mean values of pCO_2 and SST for different intervals of depth of the water column based on the information obtained in the 8 cruises. Although there is no statistical difference in pCO_2 or SST with bottom depth, it can be observed that the highest values of pCO_2 (408.3 ± 26.7 μatm) correspond to the coastal zone (< 50 m), and that values decrease down to a depth of 100 - 200 m (396.1 ± 23 μatm). In addition, towards open waters (> 600 m) there is a progressive increase of pCO_2 and SST (404.3 ± 16.5 μatm and 20.1 ± 2.4 $^\circ\text{C}$, respectively).

3.2. Discrete surface variables

Table 2 shows the average values and standard deviation for the underway averaged measurements of SST and SSS, and for the discrete samples of pH, AOU, chlorophyll-a, nitrate and phosphate at fixed stations along the three transects during the 8 cruises. The pH presented significant differences among the cruises with a range of variation from 7.84 to 8.34. Lowest mean values were found during summer (8.00 ± 0.04) and autumn (7.96 ± 0.05) of 2014 and 2015 (Table 2), coinciding with the highest average values of pCO_2 recorded (Table 1). The pH values for spring and winter were equal practically for both years (8.08 ± 0.08 and 8.07 ± 0.05 , respectively). AOU was significantly different between all the cruises, but a clear seasonal variability was not observed. Values measured ranged from -31.9 to 12.3 $\mu\text{mol L}^{-1}$, with the highest values in December 2014 (7.7 ± 2.1 $\mu\text{mol L}^{-1}$) and the lowest in March 2015 (-19.1 ± 9.4 $\mu\text{mol L}^{-1}$) (Table 2). For both years, the lowest mean value was recorded in spring (-11.3 ± 8.9 $\mu\text{mol L}^{-1}$), and the highest in winter (1.3 ± 2.6 $\mu\text{mol L}^{-1}$). All mean values were negative except for those of December 2014; that exception may have been due to the exceptional mixing of the water column caused by the storms. No general trend in the spatial variations of pH and AOU was found.

Chlorophyll-a values presented significant differences among the cruises and between the same seasons of each year. This ~~parameter-variable~~ varied from 0.02 to 2.37 $\mu\text{g L}^{-1}$, with the highest mean value measured in March 2015 (0.76 ± 0.55 $\mu\text{g L}^{-1}$), which coincides with the lowest (negative) mean value of AOU (Table 2). The lowest mean value was in June 2014 (0.18 ± 0.14 $\mu\text{g L}^{-1}$). With reference to the seasons of both years, the highest value was in spring (0.71 ± 0.46 $\mu\text{g L}^{-1}$), followed by winter (0.58 ± 0.33 $\mu\text{g L}^{-1}$), autumn (0.26 ± 0.30 $\mu\text{g L}^{-1}$) and the lowest value in summer (0.23 ± 0.25 $\mu\text{g L}^{-1}$). The SP transect presented the lowest mean value of the whole study (0.33 ± 0.31 $\mu\text{g L}^{-1}$), and the TF zone the highest (0.49 ± 0.37 $\mu\text{g L}^{-1}$).

Nitrate concentration did not show significant differences among the cruises, ranging between 0.00 and 1.93 $\mu\text{mol L}^{-1}$. The highest mean value was recorded in spring (0.82 ± 1.09 $\mu\text{mol L}^{-1}$) and the lowest in summer (0.25 ± 0.35 $\mu\text{mol L}^{-1}$) of both years. The TF transect presented the highest mean concentration for the whole study (0.77 ± 0.76 $\mu\text{mol L}^{-1}$). Phosphate concentration showed significant differences among all the cruises. By season, the highest mean value was obtained during autumn (0.31 ± 0.30 $\mu\text{mol L}^{-1}$), although the average data in October 2014 (0.09 ± 0.03 $\mu\text{mol L}^{-1}$) was lower than that of 2015 (0.50 ± 0.55 $\mu\text{mol L}^{-1}$) (Table 2). The lowest mean value was observed during summer (0.10 ± 0.05 $\mu\text{mol L}^{-1}$). The GD transect presented the highest mean value of the whole study (0.28 ± 0.39 $\mu\text{mol L}^{-1}$), and the lowest values were found in the TF and SP transects, with a similar value in each, 0.15 ± 0.07 $\mu\text{mol L}^{-1}$ and 0.14 ± 0.09 $\mu\text{mol L}^{-1}$, respectively. The mean N/P ratio in surface waters for the whole study was 3.5 ± 2.0 , similar to that estimated by Anfuso et al. (2010) in the

northeast continental shelf of the Gulf of Cádiz, which indicates a relative phosphate deficit with respect to the Redfield ratio (Redfield et al., 1963).

3.3. Air-sea CO₂ exchange

Table 3 summarizes the mean values and standard deviation for atmospheric pCO₂, wind speed, gas transfer velocity and the air-sea CO₂ fluxes measured in this study. The mean wind speeds were relatively similar for the whole study period, ranging between 5.5 ± 2.8 m s⁻¹ (March 2015) and 7.7 ± 4.2 m s⁻¹ (December 2014). The gas transfer velocity varied between 6.9 ± 0.1 cm h⁻¹ in March 2015 and 14.4 ± 0.3 cm h⁻¹ in June 2015, since it is very sensitive to changes in wind speed. There was a slight seasonal variation in the ~~dataset of~~ CO₂ fluxes ~~similar to as in the values of~~ pCO₂, because they are associated to the spatiotemporal variability and they present a high standard deviations. The study area acted as source of CO₂ to the atmosphere during summer and autumn (0.7 ± 1.5 mmol m⁻² d⁻¹ and 1.2 ± 0.9 mmol m⁻² d⁻¹, respectively) and as a sink in spring and winter (-1.3 ± 1.6 mmol m⁻² d⁻¹ and -1.3 ± 1.6 mmol m⁻² d⁻¹, respectively).

4. Discussion

4.1. Thermal influence in pCO₂

Numerous research studies have determined that temperature is one of the most important factors that control the variability of pCO₂ in the ocean (e.g. Millero, 1995; Bates et al., 2000; Takahashi et al., 2002; Carvalho et al., 2017), as a consequence of the dependence of the solubility of CO₂ with the temperature (Weiss, 1974; Woolf et al., 2016). When pCO₂ is affected only by the temperature, Takahashi et al. (1993) determined a relative variation of pCO₂ of 0.0423 °C⁻¹, equivalent to 16.9 µatm °C⁻¹ for experimental pCO₂ of 400 µatm. In our study, ~~all data from all seasons together exhibited a linear relationship between a seasonal variation was observed with a linear increase of the values of~~ pCO₂ ~~and with~~ SST ~~for the entire database~~ ($r^2 = 0.37$, Fig. 5A). This relationship becomes even more significant when it is obtained from the mean values of pCO₂ and SST of each cruise ($r^2 = 0.71$, Fig. 5B). The slope, 4.80 µatm °C⁻¹, is lower than the thermal effect on pCO₂ described by Takahashi et al. (1993), and indicates the influence of other non-thermal processes on the distribution of pCO₂ in this zone of the Gulf of Cádiz.

There are previous studies in which the seasonal variations of pCO₂ in more coastal zones of the Gulf of Cádiz (depth < 100 m) are described (Table 4). Ribas-Ribas et al. (2011) found in the north eastern shelf during June 2006 and May 2007 a dependence of pCO₂ with temperature similar to that found in this study (5.03 µatm °C⁻¹, $r^2 = 0.42$), and a pCO₂ that ranged between 338 and 397 µatm. In 2003, Huertas et al. (2006) found variations of pCO₂ ranging between 196 µatm in March and 400 - 650 µatm in August in a zone situated more to the west, between the rivers Guadalquivir and Guadiana. In addition, de la Paz et al. (2009) established a variation of pCO₂ between 387 µatm in September 2005 and 329 µatm in March 2006 in the Strait of Gibraltar, a deeper zone situated at the south eastern limit of the Gulf of Cádiz. This dependence of pCO₂ with temperature has also been determined in other studies of continental shelves, such as in the east China Sea (Wang et al., 2000), in the northern east China Sea (Shim et al., 2007) and in the northern Yellow Sea (Xue et al., 2012).

Comparing the data given in previous studies of the Gulf of Cádiz with the mean value found in this study (398.9 ± 15.5 µatm), it is evident that there has been an increase of pCO₂ during the last decade, even taking into account the uncertainty associated with the different measurement techniques employed. When we compare this mean value with the value found in the shallower and deeper zones of the Gulf of Cádiz studied by Ribas-Ribas et al. (2011) (360.6 ± 18.2 µatm), who used the same methodology, there has been an increase of pCO₂ of 38.3 ± 16.9 µatm in the last decade. For the period of time

595 between 2006 and 2016, the rate of growth of pCO₂ in the surface waters of the Gulf of Cádiz ($3.8 \pm 1.7 \mu\text{atm year}^{-1}$) exceeds the rate of increase of pCO₂ in the atmosphere ($2.3 \mu\text{atm year}^{-1}$ for the last 10 years in Izaña (Earth System Research Laboratory; <https://www.esrl.noaa.gov/gmd/dv/data/index.php>, last access: 9 January 2019)). The cause of this increase could be a greater input of ~~This suggests a possible increase of the~~ anthropogenic nutrients and inorganic carbon ~~inputs~~ from land (Mackenzie et al., 2004) since the direction and magnitude of estuarine and continental shelf CO₂ exchange with the atmosphere is highly dependent on the terrestrial organic budget and nutrient supplies to the coastal ocean (Borges and Abril, 600 2011; Cai, 2011). Although we do not have any additional evidence to confirm this effect in our area of study currently.

4.2. Non-thermal factors controlling pCO₂

In accordance with Olsen et al. (2008), Fig. 6 shows the decomposition of the variations of pCO₂ between cruises due to changes in SST, in air-sea CO₂ exchange, in SSS and in combined mixing and biology, in distal and coastal areas. In general, the variations are greater than those found in other works (Olsen et al., 2008; Omar et al., 2010) because this study considers 605 seasonal changes against the monthly change analysed in previous applications. The average time between cruises is 86 ± 8 days, with the exception of the last period (between September 2015 and February 2016) that was 140 days. $d\text{pCO}_2^{\text{sw}}$ presents a similar variation between deep and coastal areas, but with small ~~the~~ differences in the mean values between that the distal zones ~~act a sink of CO₂ of the system~~ ($\text{mean } d\text{pCO}_2^{\text{sw}} = -3.4 \pm 28.9 \mu\text{atm}$) and the shallower areas ~~as a source of CO₂~~ ($\text{mean } d\text{pCO}_2^{\text{sw}} = 0.2 \pm 22.7 \mu\text{atm}$). The high standard deviations associated to this variable are due to the own spatiotemporal variability of the database. In distal areas (Fig. 6), pCO₂ changes are mainly brought about by SST ($-58.4 - 106.2 \mu\text{atm}$) together with mixing and biological processes ($-90.8 - 36.2 \mu\text{atm}$). An inverse coupling is observed between $d_{\text{SST}}\text{pCO}_2^{\text{sw}}$ and $d_{\text{MB}}\text{pCO}_2^{\text{sw}}$, since with the increase of the system SST (increase $d_{\text{SST}}\text{pCO}_2^{\text{sw}}$) there is greater biological uptake of CO₂ (decrease $d_{\text{MB}}\text{pCO}_2^{\text{sw}}$). As reported in the studies of Olsen et al. (2008) and Omar et al. (2010), the changes 610 produced by the air-sea CO₂ exchange are relatively small ~~is lower~~. Instead, in coastal areas (Fig. 6), the dominant effects on pCO₂ changes are produced by air-sea CO₂ exchange ($-196.2 - 103.4 \mu\text{atm}$) and mixing plus biology ($-101.1 - 198.5 \mu\text{atm}$). In regions with shallower mixed layers, the effect of ~~A larger effect of the~~ air-sea ~~CO₂~~ exchange on the pCO₂ variation is larger ~~observed in the shallower mixed layers~~ (Olsen et al., 2008). A relative inverse coupling between the two factors was also observed; outgassing is produced (decrease $d_{\text{AS}}\text{pCO}_2^{\text{sw}}$) when the system receives greater inputs/production of CO₂ (increase $d_{\text{MB}}\text{pCO}_2^{\text{sw}}$). There is a different behaviour between the transition from spring to summer of 2014 (ST1 and ST2) 615 and 2015 (ST5 and ST6) for $d_{\text{MB}}\text{pCO}_2^{\text{sw}}$, which may be due to a greater quantity of continental inputs, as reflected in the Guadalquivir river flow rate in these periods ($85.1 \pm 75.4 \text{ m}^3 \text{ s}^{-1}$ and $25.3 \pm 10.2 \text{ m}^3 \text{ s}^{-1}$, respectively). Changes in SSS do not have a substantial effect on pCO₂ during the whole period in both areas, with a range of variation of $d_{\text{SSS}}\text{pCO}_2^{\text{sw}}$ between -11.3 and $11.0 \mu\text{atm}$. This behaviour was also described by Olsen et al. (2008) in the subpolar North Atlantic, ~~to~~ except for an area influenced by continental runoff ~~phenomenon~~ where pCO₂ decreases.

625 In relation to the factors that affect to the pCO₂ changes brought about by mixing and biological processes, a it has been observed the dependence between the mean values of pCO₂ and pH, AOU and the concentration of chlorophyll-a has been observed at the fixed stations ($n = 126$, Fig. 7). AOU and pCO₂ shows ~~presents~~ a positive relationship ($\text{pCO}_2 (\mu\text{atm}) = 410 + 1.1 \text{ AOU } (\mu\text{mol L}^{-1})$, $r^2 = 0.21$), with a slope close to what would be obtained taking into account the processes of formation/oxidation of the organic matter phytoplankton considering a Redfield-type relationship. Inverse relationships 630 between pCO₂ and dissolved oxygen were also found in other studies of continental shelf (Zhai et al., 2009; de la Paz et al., 2010; Xue et al., 2012, 2016). ~~However,~~ pCO₂ and pH presents an inverse relationship ($\text{pCO}_2 (\mu\text{atm}) = 1710 - 162.8 \text{ pH}$, $r^2 = 0.34$), due to the effect of the uptake or production of CO₂ on the pH (Tsunogai et al., 1997; Shaw et al., 2014). The variation

of pCO₂ with chlorophyll-a (pCO₂ (µatm) = 413 - 20.8 [chlorophyll-a] (µg L⁻¹), r² = 0.14) also show the influence of the processes of photosynthesis and respiration (e.g. Cai et al., 2011; Clargo et al., 2015), with a slope value similar to that obtained in the study of Huertas et al. (2005), (pCO₂ (µatm) = 274 - 19.6 [chlorophyll-a] (µg L⁻¹), r² = 0.32; n = 28). Other authors have also described the interrelationships existing between pCO₂ and chlorophyll-a in other coastal areas (Borges and Frankignoulle, 1999; Tseng et al., 2011; Zhang et al., 2012; Qin et al., 2014; Litt et al., 2018).

~~Something that could affect the distribution of pCO₂ in the Gulf of Cádiz (and be considered to be part of mixing and biology sensu Olsen et al. (2008)). Another factor presents in the Gulf of Cádiz and that could affect the distribution of pCO₂ and be considered as a process of mixing and biology (Olsen et al., 2008),~~ it is the vertical and lateral transport. For example, there are two upwelling systems in our study zone, one more permanent situated in the coastal zone (depth between 50 and 100 m) of the Trafalgar section (Prieto et al., 1999; Vargas-Yáñez et al., 2002) and the other located between the Cape of Santa María and the Guadalquivir River and more sensitive to meteorological forcing (Criado-Aldeanueva et al., 2006). In our database, experimental evidence of the upwelling was found only in the TF transect. A local decrease of the mean values of SST (17.4 °C) and pCO₂ (399.1 µatm) was observed in this coastal area of TF, with respect to the deeper areas (18.8 °C and 405.1 µatm, respectively) for the whole period. This input of colder waters could cause higher or lower concentrations of CO₂ (e.g. Liu et al., 2010; Xue et al., 2015; González-Dávila et al., 2017). There is a progressive increase of SST and pCO₂ with increasing depth of the system measured below 100 - 200 m (Fig. 4); this is associated with the presence of a branch of the Azores Current that introduces warmer waters in the central part of the Gulf of Cádiz (Gould, 1985; Käse et al., 1985; Johnson and Stevens, 2000). The influence of warmer surface currents on the variability of pCO₂ has been observed in other studies, such as the Gulf Stream in the south-eastern continental shelf of the United States (Wang et al., 2005; Jiang et al., 2008), and the Kuroshio Current in the northern East China Sea (Shim et al., 2007).

~~Additionally, related with the lateral transport on the distribution of pCO₂ in surface waters, s~~~~Additionally,~~ several authors have described the influence of the continental inputs ~~on the distribution of pCO₂ in surface waters~~. In general, the continental shelf as a whole acts as a sink of atmospheric CO₂ (e.g. Rabouille et al., 2001; Chen and Borges, 2009), whereas the coastal zone is usually oversaturated with CO₂ (Fig. 4). This behaviour has been described in other systems, including the southern part of the Yellow Sea (Qu et al., 2014), the southwestern part of the Atlantic Ocean (Arruda et al., 2015), the North Sea (Clargo et al., 2015), and on the continental shelf of Maranhense (Lefèvre et al., 2017).

The principal continental inputs in the northeast zone of the Gulf of Cádiz ~~take place~~~~derive~~ from the estuary of the Guadalquivir and from the systems associated with the Bay of Cádiz. De la Paz et al. (2007) found values of pCO₂ higher than 3000 µatm in the internal part of the estuary of the Guadalquivir, and Ribas-Ribas et al. (2013) established that this estuary acts as an exporter system of inorganic carbon, nutrients and water oversaturated with CO₂ to the adjoining coastal zone. The importance of the contributions from the Guadalquivir on the distribution of pCO₂ depends on the river's flow rate, as can be appreciated in Fig. 2B. The highest values of pCO₂ (up to 500 µatm) were observed during March 2014 in the zone close to the Guadalquivir River mouth, as a consequence of the river's high flow rate (between 192.7 and 299.2 m³ s⁻¹, Confederación Hidrográfica del Guadalquivir; <http://www.chguadalquivir.es/saih/DatosHistoricos.aspx>, last access: 19 July 2018). In contrast, the lowest values of pCO₂ were recorded in spring of 2015 in this zone (as low as 320 µatm) in a period of drought (flow rate 20 m³ s⁻¹) and subject to intense biological activity associated with the highest value found of the concentration of chlorophyll-a (2.4 µg L⁻¹). The Bay of Cádiz occupies an area of 38 km², and receives urban effluents from a population of 640,000 inhabitants. This shallow zone is oversaturated with CO₂ (Ribas-Ribas et al., 2011) due largely to the inputs of inorganic carbon, organic matter and nutrients that are received from the Guadalete River and Sancti Petri Channel and the Río San Pedro tidal creeks (de la Paz et al., 2008a, b; Burgos et al, 2018).

Moreover, in the coastal zone another source of CO₂ results from the net production of inorganic carbon derived from the processes of remineralization of the organic matter in the surface sediments originating from the continuous deposition of organic matter through the water column (de Haas et al., 2002; Jahnke et al., 2005). The intensity of this effect decreases towards offshore areas, since in line with the increasing depth of the system, and the influence of the primary production and the continental supplies on the deposition of the particulate organic matter are less (Friedl et al., 1998; Burdige, 2007; Al Azhar et al., 2017), which could be related with the greater effect determined by the mixing and biology processes in the coastal areas using the Olsen et al. (2008) method. Ferrón et al. (2009) quantified the release from the sediment of DIC related to the processes of oxidation of organic matter in the coastal zone (depth < 50 m) of the Gulf of Cádiz, between the Guadalquivir and the Bay of Cádiz. These authors found a mean benthic flux of $27 \pm 8 \text{ mmol C m}^{-2} \text{ d}^{-1}$ for stations with a mean depth of 23 m. This flux of DIC is equivalent to a CO₂ flux of $198 \pm 80 \text{ } \mu\text{mol C m}^{-2} \text{ d}^{-1}$ through the sediment-water interface, considering a well-mixed water column, a pH = 8, in the conditions of mean temperature and salinity in the Gulf of Cádiz (18.8 °C and 36.19, respectively) and using the K1 and K2 acidity constants proposed by Lueker et al. (2000) in the total pH scale through the program CO2SYS (Lewis et al., 1998). Moreover, this estimated CO₂ benthic flux would produce an increase of pCO₂ of $0.25 \pm 0.10 \text{ } \mu\text{atm d}^{-1}$ in the water column.

4.3. T/B ratio

In this study, the total T/B ratio is 1.15, which indicates that the thermal effect is an important factor controlling intra-annual variation of pCO₂. This value is similar to that determined by Ribas-Ribas et al. (2011) (see date and study zone in Table 4), in the northeast zone of the shelf of the Gulf of Cádiz, with a ratio of 1.3. De la Paz et al. (2009) (see date and study zone in Table 4) propose a T/B ratio of 2.4 in the Strait of Gibraltar, indicating very significant thermal control in this relatively deep zone situated to the east of the Gulf of Cádiz.

Figure 8 presents the values of the T/B ratio grouped in different bottom-depth intervals of the water column in the system. The variations of ΔpCO_2 non-thermal and ΔpCO_2 thermal found have been superimposed. In the coastal zone (depth < 50 m), the T/B ratio is below 1 (0.9), and increases to values of 1.3 in the central zone of the Gulf of Cádiz, at depths ranging from 100 to 400 m. However, in the deepest zone (depth > 600 m), a progressive decrease to values of 1.1 is found. Qu et al. (2014) also reported the variation in the values of the T/B ratio with the distance from the coast in the southern Yellow Sea, between 0.4 - 0.6 in the nearshore area (depth < 50 m) to more than 1 (up to 2.4) in the offshore area (depth > 50 m).

This variation of the T/B ratio is largely caused by the variations of ΔpCO_2 non-thermal, which is observed to decrease from coast to deeper zone regardless which method is used (Takahashi et al., 2002; Olsen et al., 2008). High values of ΔpCO_2 non-thermal close to the coast were observed (120.2 μatm), affected by continental inputs, processes of remineralization in the sediment and biological utilization of CO₂. The increase of the T/B ratio and the decrease of ΔpCO_2 non-thermal (75 μatm) from the coastal zone to the central part of the Gulf of Cádiz are associated with the variations of the chlorophyll-a and nutrient concentrations that diminish exponentially with the depth of the system. Thus, the mean concentrations of chlorophyll-a, nitrate and phosphate in the distal zone are 66.3, 81.9 and 44.8 % less, respectively, than the concentrations found close to the coast. However, the concentrations of chlorophyll-a and nutrients are relatively constant in waters with bottom-depth greater than 200 m, and do not explain the decrease of the T/B ratio and the increase of ΔpCO_2 non-thermal (90.7 μatm) in waters with bottom-depth greater than 400 m. These variations have been associated with the change in the origin of the surface water masses. In the central zone of the Gulf of Cádiz, the origin of the surface waters is a branch of the larger-scale Portuguese-Canaries eastern boundary current that circulates around a cyclonic eddy off Cape St. Vincent and

veers eastward into the Gulf of Cádiz (García-Lafuente et al., 2006). The deepest zone is under the influence of a branch of the Azores current, which is a warmer stream that could lead to an increase in primary production; in addition it is the northern border of the subtropical gyre (Klein and Siedler, 1989); these two factors favour the accumulation of CO₂ in this area as a convergence zone (Ríos et al., 2005).

The T/B ratios have also been calculated for the different transects at right angles to the coast ~~that have been cruised for sampling in the study zone~~, as shown in Fig. 9. ~~It can be appreciated that t~~The T/B ratio increases with the distance from the coast on the three transects, and that the temperature generally has a greater influence on the distribution of pCO₂ than the non-thermal effects. The T/B ratio varies to the east, with values between 1.0 in the zone of the GD and 1.4 in SP, and an intermediate value of 1.2 in the TF zone. These variations are related to changes in the biological activity and the presence of coastal upwellings. The Guadalquivir zone receives substantial continental supplies that lead to high relative concentrations of chlorophyll-a and nutrients; these give rise to high values of ΔpCO₂ non-thermal. In particular, coastal waters near the mouth of the Guadalquivir River ~~show present~~ the highest primary production of all waters within the Gulf of Cádiz (Navarro and Ruiz, 2006). The coastal zone close to Cape Trafalgar has been characterized as a region with high autotrophic productivity and biomass associated mainly with the nutrients input due to upwelling waters (e.g. Echevarría et al., 2002; García et al., 2002). The presence of these emerging water masses could be related to the relatively low values of ΔpCO₂ thermal found in this zone; in fact, the mean temperature in this area is 18.4 ± 2.3 °C, about 0.5 °C lower than in the other two zones. The Sancti Petri zone is the one that receives a smaller supply of nutrients, and presents the lowest concentrations of chlorophyll-a in this study. The high values of ΔpCO₂ thermal in this part of the Gulf of Cádiz are associated with a higher mean temperature (19.0 °C) and a wider range of variation (6.8 °C).

4.4. Ocean-atmosphere CO₂ exchange

In the Gulf of Cádiz, the ~~air-sea-sea-air~~ flux of CO₂ ~~exhibit present~~s a range of variation from -5.6 to 14.2 mmol m⁻² d⁻¹. These values are within the ranges observed by other authors in different areas of the Gulf of Cádiz (Table 4). As can be ~~seen appreciated~~ in Fig. 10, ~~the fluxes of CO₂ presented~~ seasonal and spatial variations ~~were observed in the sea-air-sea fluxes~~ during the period studied. The Gulf of Cádiz acts as a source of CO₂ to the atmosphere during the months of summer (ST2, ST6) and autumn (ST3, ST7), and as a sink in spring (ST1, ST5) and winter (ST4, ST8). Previous studies conducted in the Gulf of Cádiz are consistent with the behaviour found in this study (González-Dávila et al., 2003; Aït-Ameur and Goyet, 2006; Ribas-Ribas et al., 2011).

As ~~discussed above for has been observed with~~pCO₂, temperature ~~change~~ is one of the principal factors that control the fluxes of CO₂. In fact, for each cruise, a linear and positive relationship has been found between the mean values of the CO₂ fluxes and SST (r² = 0.72, Fig. 11). In parallel, there is a linear and negative relationship between the mean values of the CO₂ fluxes and the concentration of chlorophyll-a at the discrete stations sampled (r² = 0.74, Fig. 11), as a consequence of the biological utilization of the CO₂ ~~and the subsequent tendency for CO₂ undersaturation~~ (Qin et al., 2014). ~~These~~Such relationships have also been found in various studies carried out in zones similar to the area studied (Zhang et al., 2010; Arnone et al., 2017; Carvalho et al., 2017).

The ~~air-sea-sea-air~~ fluxes of CO₂ in the Gulf of Cádiz tend to decrease with the distance from the coast (Fig. 10). The coastal zone (< 50 m) presents a mean ~~sea-air-sea~~ CO₂ flux of 0.8 ± 1.8 mmol m⁻² d⁻¹ that reduces progressively to reach a value of -0.3 ± 1.6 mmol m⁻² d⁻¹ in open waters with bottom-depth greater than 600 m. Although these differences are not statistically significant by the high standard deviations associated to the seasonal variations. This dependence of ~~the sea-air-sea~~ CO₂

fluxes with distance from the coast has also been reported in other systems, such as in the South Atlantic Bight of the United States (Jiang et al., 2008), in the south-western part of the Atlantic Ocean (Arruda et al., 2015), in the Patagonian Sea (Kahl et al., 2017) and on the continental shelf of Maranhense (Lefèvre et al., 2017). This dependence is the consequence of the decrease of influence of the continental supplies on the CO₂ fluxes as one moves towards the open sea. Ribas-Ribas et al. (2011) also found that in the Gulf of Cádiz the air-sea CO₂ fluxes vary with the distance from the coast; the zone close to the estuary of the Guadalquivir and the Bay of Cádiz acts as a source (1.39 mmol m⁻² d⁻¹) and the zone comprising the rest of the shelf acts as a sink (-0.44 mmol m⁻² d⁻¹).

In addition, on both the GD and SP transects a decrease of the sea-air-sea CO₂ flux is found towards the open ocean, due to the continental inputs associated with the estuary of the Guadalquivir and with the Bay of Cádiz, respectively. On the TF transect, in contrast, it was observed that the zone close to the coast acts as a sink of CO₂ (-0.4 ± 1.2 mmol m⁻² d⁻¹), and the deeper zone is a weak source of CO₂ to the atmosphere (0.3 ± 1.3 mmol m⁻² d⁻¹), although these variations are not statistically significant due to the seasonal variability associated to the values. This finding can be explained by the presence of an upwelling close to the coast that is likely to be causing an increase of the production (e.g. Hales et al., 2005; Borges et al., 2005). With reference to this, on the TF transect there are significant differences between the mean surface concentrations of chlorophyll-a and nitrate in the coastal zone (0.63 ± 0.43 µg L⁻¹ and 1.09 ± 0.77 µmol L⁻¹, respectively) and in deeper zones (0.17 ± 0.12 µg L⁻¹ and 0.32 ± 0.33 µmol L⁻¹, respectively).

The Gulf of Cádiz, during the e-period of this sampling period, showseould act as a sink of CO₂, with a mean rate of -0.18 ± 1.32 mmol m⁻² d⁻¹, even though it is necessary to consider the intrinsic variability of the database that generate a high standard deviation. With the total surface of the study area (52.8·10² km²) and the mean annual flux during the 8 cruises, the uptake capacity estimated for the Gulf of Cádiz will be 4.1 Gg C year⁻¹. The findings of previous studies carried out in the Gulf of Cádiz coincide with the behaviour observed in this study (Santana-Casiano et al., 2002; González-Dávila et al., 2003; Huertas et al., 2006; de la Paz et al., 2009; Ribas-Ribas et al., 2011), with the exception of the study by Aït-Ameur and Goyet (2006) in which it was estimated that the Gulf of Cádiz acts as a source of CO₂ to the atmosphere, although that study only corresponds to the summer season.

5. Conclusions

A high variability in pCO₂ in the Gulf of Cádiz was observed which is associated with its location as a database presents a high variability in the Gulf of Cádiz associated with its location, it is a transition zone between coastal and shelf area, superimposed on the usual seasonal variation due to thermal and biological effects, and the own seasonal variation. The mean value of pCO₂ found in this study (398.9 ± 15.5 µatm) indicates that the Gulf of Cádiz hat the eastern part of the Gulf of Cádiz could be slightly undersaturated in CO₂ with respect to the atmosphere (402.1 ± 3.9 µatm). The spatiotemporal variation of pCO₂ found responds to the influence of different factors that usually affect its distribution in the littoral oceans. The temporal variability of pCO₂ is principally explained by two factors in this work, considering the mean values of the 8 cruises, SST (pCO₂ (µatm) = 302.0 + 5.16 SST (°C), r² = 0.71) and biological activity, represented by chlorophyll-a (pCO₂ (µatm) = 425.0 - 59.15 [chlorophyll-a] (µg L⁻¹), r² = 0.76). Over and above these general tendencies, there are spatial variations associated fundamentally with other processes. Firstly, the dominant effects in the shallower areas are also due to the continental inputs, the biological activity and the air-sea CO₂ exchange. Then pCO₂ values diminish progressively in line with increasing distance from the coast, out as far as an approximate depth of some 400 m. There is a relative increase of SST and pCO₂ as consequence of a change in the origin of the surface water, with the arrival of waters in a warm branch of the Azores current and the change produced by the biological activity.

790 The ~~total~~ T/B ratio (1.15) of the region suggests that the distribution is principally controlled by ~~the~~ temperature changes. However, the situation is more complicated if the ratio is considered as a function of there is a different behaviour in this ratio if it is determined by bottom-depth intervals, which is associated with the existence of non-thermal processes.related to the existence of non thermal processes. In the proximity of the Guadalquivir estuary the ratio takes a value of 0.93 due to the continental inputs of C and nutrients, and in the zone around the coastal upwelling off Cape 795 Trafalgar the ratio is 1.09. Furthermore, the actual characteristics of the surface water mass that originates under the influence of a branch of the Azores current also produce a decrease of the T/B ratio in the deeper zone studied (1.05 for depths > 600 m). In contrast, the highest T/B ratio values have been found in the SP transect, where values of up to 1.54 are obtained for depths greater than 100 m, probably related to the greater effect of thermal processes.-

800 The annual uptake capacity of CO₂ by the surface waters in our study area is 4.1 Gg C year⁻¹. The air-sea CO₂ fluxes present seasonal variation: these waters act as a source of CO₂ to the atmosphere in summer and autumn and as a sink in winter and spring. Based on the information available in the zone, there seems to have been a decrease in the capacity for CO₂ capture in the zone in recent decades, since the pCO₂ has increased from 360.6 ± 18.2 μatm in a study realised between 2006 and 2007 (Ribas-Ribas et al., 2011) to 398.9 ± 15.5 μatm in the actuality and this ,exceeds the rate of increase of pCO₂ in the atmosphere (2.3 μatm year⁻¹ for the last 10 years).

Author contributions

D.J.-L. wrote the manuscript with contributions from A.S., T.O. and J.F. D.J.-L. and J.F. processed the experimental data. D.J.-L., T.O. and J.F. conceived the original idea. All authors contributed to collecting the data.

810 Competing interests

The authors declare that they have no conflict of interest.

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Table 1: Date, number of measurements (n), range, average values and standard deviation of underway sea surface temperature (SST), sea surface salinity (SSS) and pCO₂ during the 8 cruises undertaken: March 2014 (ST1), June 2014 (ST2), October 2014 (ST3), December 2014 (ST4), March 2015 (ST5), June 2015 (ST6), September 2015 (ST7) and February 2016 (ST8).

Cruise	Date	n	SST (°C)		SSS		pCO ₂ (µatm)	
			Range	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD
ST1	28/03 - 01/04, 2014	3874	14.3 - 16.4	15.4 ± 0.6	35.57 - 37.06	36.11 ± 0.18	365.4 - 513.6	396.5 ± 19.0
ST2	25/06 - 01/07, 2014	4118	17.0 - 22.9	21.1 ± 0.9	35.90 - 36.45	36.21 ± 0.15	368.7 - 459.5	412.9 ± 12.6
ST3	01/10 - 07/10, 2014	4233	16.1 - 23.4	21.5 ± 1.3	35.80 - 36.79	36.26 ± 0.22	391.6 - 444.5	413.5 ± 9.8
ST4	10/12 - 16/12, 2014	2938	15.6 - 19.1	18.1 ± 0.7	34.68 - 36.72	36.36 ± 0.21	369.6 - 444.5	388.7 ± 12.9
ST5	28/03 - 01/04, 2015	3180	14.6 - 16.9	15.6 ± 0.4	35.54 - 36.52	36.12 ± 0.14	320.6 - 416.5	368.6 ± 14.9
ST6	19/06 - 25/06, 2015	3677	17.4 - 22.1	20.9 ± 0.8	35.63 - 36.92	36.40 ± 0.08	372.1 - 464.1	410.3 ± 13.8
ST7	15/09 - 18/09, 2015	2575	17.0 - 21.9	20.6 ± 1.1	35.03 - 36.79	35.64 ± 0.08	387.6 - 457.1	407.6 ± 11.2
ST8	02/02 - 03/02, 2016	1812	15.1 - 17.5	16.8 ± 0.4	35.83 - 36.55	36.44 ± 0.09	346.2 - 442.6	392.9 ± 17.9

Table 2: Number of samples (n) and mean values and standard deviation for the averaged underway measurements of sea surface temperature (SST) and sea surface salinity (SSS), and pH, apparent oxygen utilization (AOU), chlorophyll-a ([data from González-García et al. \(2018\)](#)), nitrate and phosphate in surface water samples (at depth of 5m) at fixed stations during the 8 cruises: March 2014 (ST1), June 2014 (ST2), October 2014 (ST3), December 2014 (ST4), March 2015 (ST5), June 2015 (ST6), September 2015 (ST7) and February 2016 (ST8).

Cruise	n	SST (°C)	SSS	pH	AOU ($\mu\text{mol L}^{-1}$)	Chlorophyll-a ($\mu\text{g L}^{-1}$) ^{*†}	Nitrate ($\mu\text{mol L}^{-1}$)	Phosphate ($\mu\text{mol L}^{-1}$)
ST1	18	15.2 \pm 0.5	36.05 \pm 0.13	8.06 \pm 0.03	-3.6 \pm 8.4	0.65 \pm 0.37	0.96 \pm 1.01	0.14 \pm 0.06
ST2	16	21.0 \pm 1.3	36.11 \pm 0.11	7.97 \pm 0.03	-10.3 \pm 5.7	0.18 \pm 0.14	0.42 \pm 0.60	0.12 \pm 0.04
ST3	17	21.6 \pm 0.7	36.09 \pm 0.28	7.97 \pm 0.06	-4.6 \pm 3.2	0.24 \pm 0.29	0.34 \pm 0.27	0.09 \pm 0.03
ST4	17	17.7 \pm 0.7	36.03 \pm 0.13	8.05 \pm 0.05	7.7 \pm 2.1	0.46 \pm 0.33	1.05 \pm 1.96	0.23 \pm 0.09
ST5	16	15.4 \pm 0.3	36.03 \pm 0.13	8.09 \pm 0.12	-19.1 \pm 9.4	0.76 \pm 0.55	0.68 \pm 1.17	0.17 \pm 0.09
ST6	16	21.1 \pm 1.0	36.37 \pm 0.05	8.01 \pm 0.03	-2.4 \pm 3.2	0.26 \pm 0.34	0.12 \pm 0.14	0.10 \pm 0.05
ST7	17	20.6 \pm 1.2	35.63 \pm 0.03	7.94 \pm 0.03	-2.6 \pm 5.0	0.29 \pm 0.31	0.37 \pm 0.50	0.50 \pm 0.55
ST8	6	16.8 \pm 0.3	36.44 \pm 0.04	8.09 \pm 0.05	-5.1 \pm 3.1	0.69 \pm 0.32	0.41 \pm 0.31	0.14 \pm 0.11

^{*}[González-García et al., \(2018\)](#).[†]~~[González-García et al. \(2018\)](#)~~.

Table 3: Mean values and standard deviation of mixed layer depth (MLD) in distal areas (depth > 50 m), atmospheric pCO₂ (pCO₂ μatm), wind speed, gas transfer velocity (k) and sea-air-sea CO₂ fluxes for the underway measurements during the 8 cruises: March 2014 (ST1), June 2014 (ST2), October 2014 (ST3), December 2014 (ST4), March 2015 (ST5), June 2015 (ST6), September 2015 (ST7) and February 2016 (ST8).

Cruise	MLD in distal areas (m)	pCO ₂ atm (μatm)	Wind speed (m s ⁻¹)	k (cm h ⁻¹)	CO ₂ fluxes (mmol m ⁻² d ⁻¹)
ST1	71.3 ± 26.4	398.7 ± 1.8	7.7 ± 3.4	13.4 ± 0.2	-0.3 ± 2.3
ST2	88.6 ± 34.4	404.5 ± 0.5	7.4 ± 3.4	14.0 ± 0.3	0.9 ± 1.4
ST3	90.3 ± 34.0	397.7 ± 0.6	6.7 ± 4.0	11.8 ± 0.4	1.4 ± 0.8
ST4	96.8 ± 34.1	399.4 ± 2.2	7.7 ± 4.2	14.3 ± 0.2	-1.3 ± 1.7
ST5	91.5 ± 31.6	405.5 ± 0.6	5.5 ± 2.8	6.9 ± 0.1	-2.3 ± 0.9
ST6	89.0 ± 33.0	406.1 ± 0.8	7.5 ± 4.1	14.4 ± 0.3	0.5 ± 1.5
ST7	90.2 ± 32.0	398.4 ± 0.7	7.0 ± 3.2	12.3 ± 0.3	0.9 ± 1.1
ST8	87.0 ± 40.3	406.4 ± 0.3	6.8 ± 3.1	10.6 ± 0.1	-1.3 ± 1.6

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Table 4: Range and mean and standard deviation of pCO₂, sea-air-sea CO₂ fluxes (FCO₂) and T/B ratio found in different areas of the Gulf of Cádiz.

Site	°E	°N	Date	pCO ₂ (µatm)	FCO ₂ (mmol m ⁻² d ⁻¹)*	T/B	Reference
Strait of Gibraltar	-5.5 - -5.2	35.6 - 36.0	September 1997	352.8 ± 2.0 339 - 381	3 ± 8 ^a	-	Santana-Casiano et al. (2002)
Gulf of Cádiz	-7.0 - -6.5	36.3 - 36.7	February 1998	360.2 ± 27.9 334 - 416	-19.5 ± 3.5 ^a	-	González-Dávila et al. (2003)
Gulf of Cádiz	-8.3 - -6.0	33.5 - 37.0	July 2002	- 300 - 450	18.6 ± 4 ^a	-	Aït-Ameur and Goyet (2006)
Northeastern shelf of the Gulf of Cádiz	-7.5 - -6.3	36.6 - 37.3	March 2003 to March 2004	- 130 - 650	-2.5 - 1.0 ^a	-	Huertas et al. (2006)
Strait of Gibraltar	-6.0 - -5.2	35.8 - 36.1	September, December 2005; March, May 2006	- 320 - 387	-1.9 - 1.9 ^a	2.4	de la Paz et al. (2009)
Northeastern shelf of the Gulf of Cádiz	-6.8 - -6.3	36.4 - 36.9	June, November 2006; February, May 2007	360.6 ± 18.2 338 - 397	-2.2 - 3.6 ^a	1.3	Ribas-Ribas et al. (2011)
Gulf of Cádiz	-6.0 - -7.2	35.4 - 36.7	March, June, October, December 2014; March, June, September 2015; March 2016	398.9 ± 15.5 321 - 514	-2.3 - 1.5 ^b	1.15	This work

*Gas transfer coefficient (k): ^a Wanninkhof (1992) and ^b Wanninkhof et al. (2014).

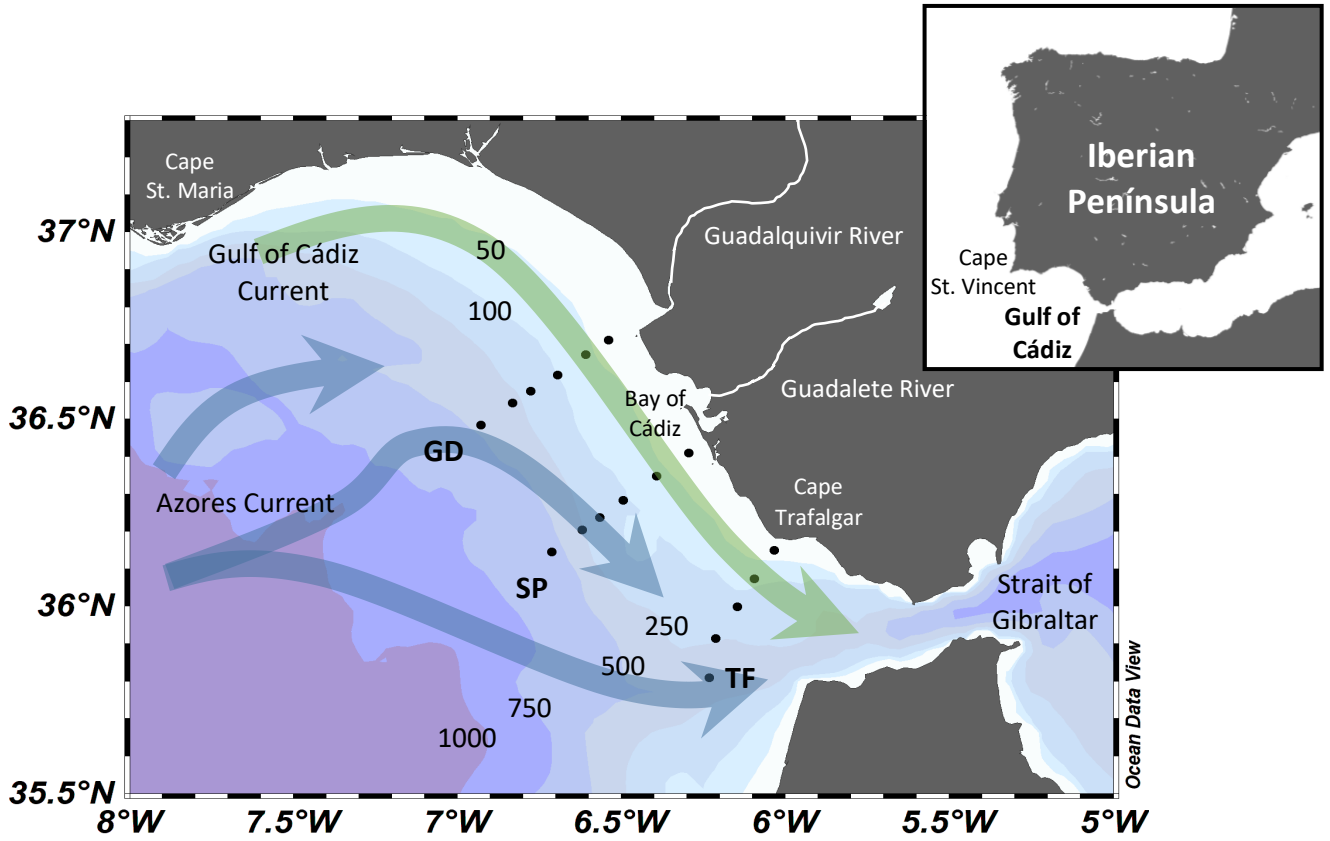


Figure 1: Map of the eastern shelf of the Gulf of Cádiz showing the location of the fixed stations located on 3 transects at right-angles to the coastline: Guadalquivir (GD), Sancti Petri (SP) and Trafalgar (TF). The location of the principal surface currents, rivers and capes of the study area are also noted.

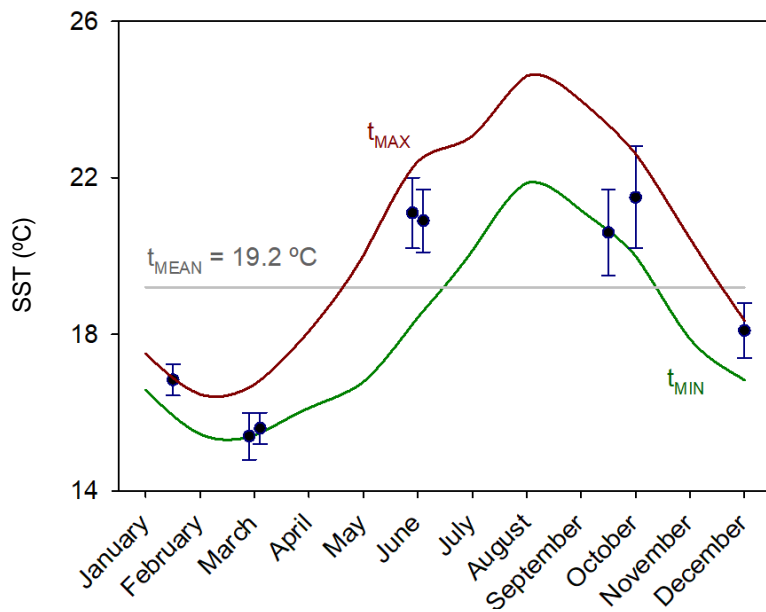
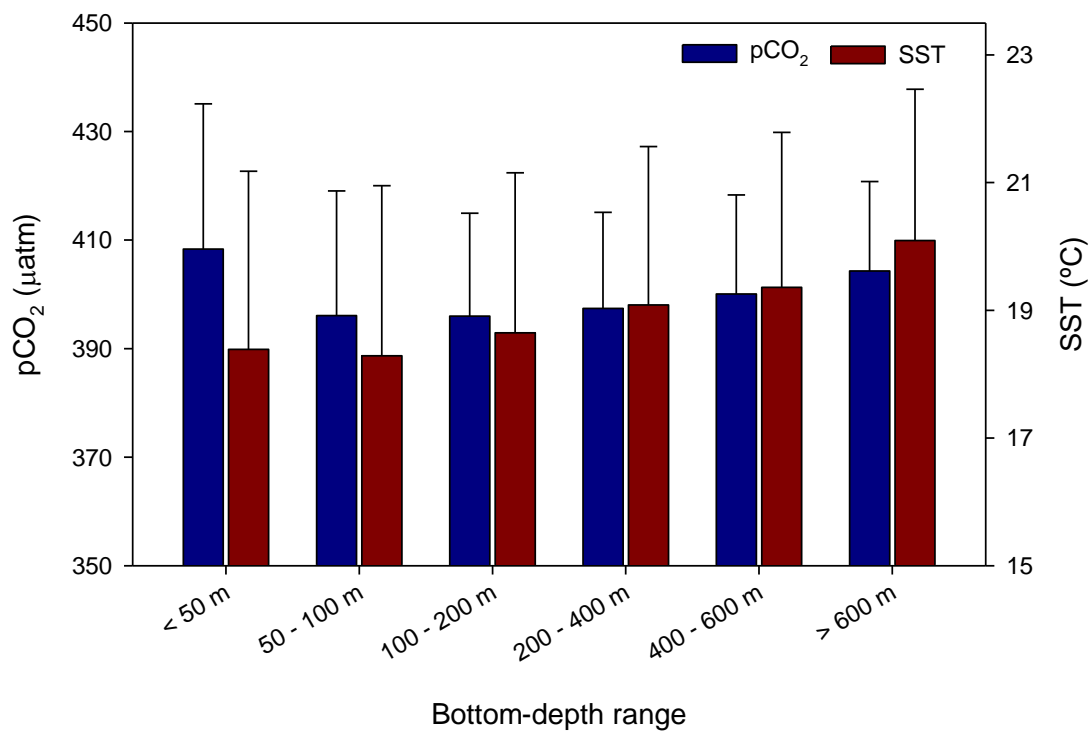


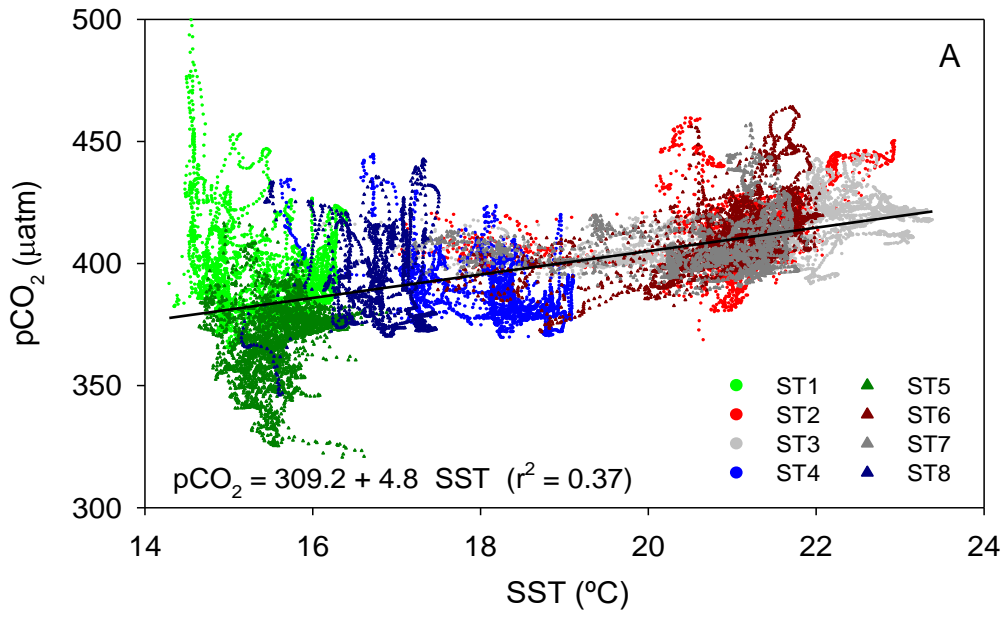
Figure 3: Maximum and minimum sea surface temperature (SST) variation during a 10-year period recorded by an oceanographic buoy located in the Gulf of Cádiz (36.48°N - 6.96°W). The red line shows maximum SST variation. The green line shows minimum SST variation. The grey line shows the average temperature for the 10-year period. Blue circles show mean values and standard deviations of underway SST measured during the eight cruises carried out during this study.

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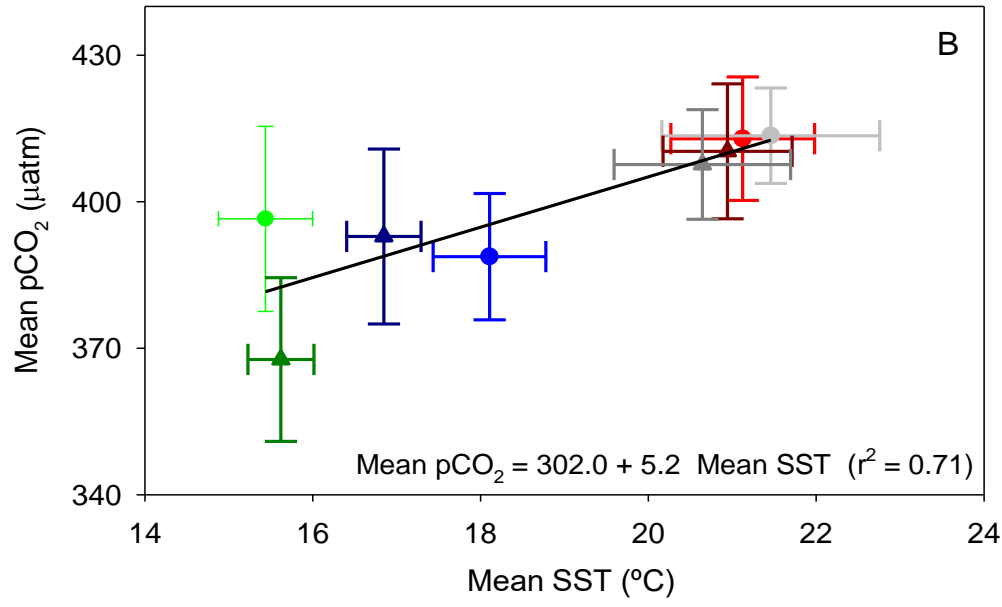
1245 **Figure 4: Underway variation of pCO₂ and sea surface temperature (SST) at different bottom-depth ranges of the water column (m) during the 8 cruises. The mean values and standard deviations of pCO₂ (blue) and SST (red) for each range of depth are represented. High standard deviations are associated with the seasonal and inter-annual variability for the whole sampling period.**

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Figure 5: Dependence of pCO₂ with sea surface temperature (SST) for the complete underway database during all the cruises (A) and for the mean values of pCO₂ and SST for each cruise showing their standard deviations (B). The solid line shows the linear correlation.

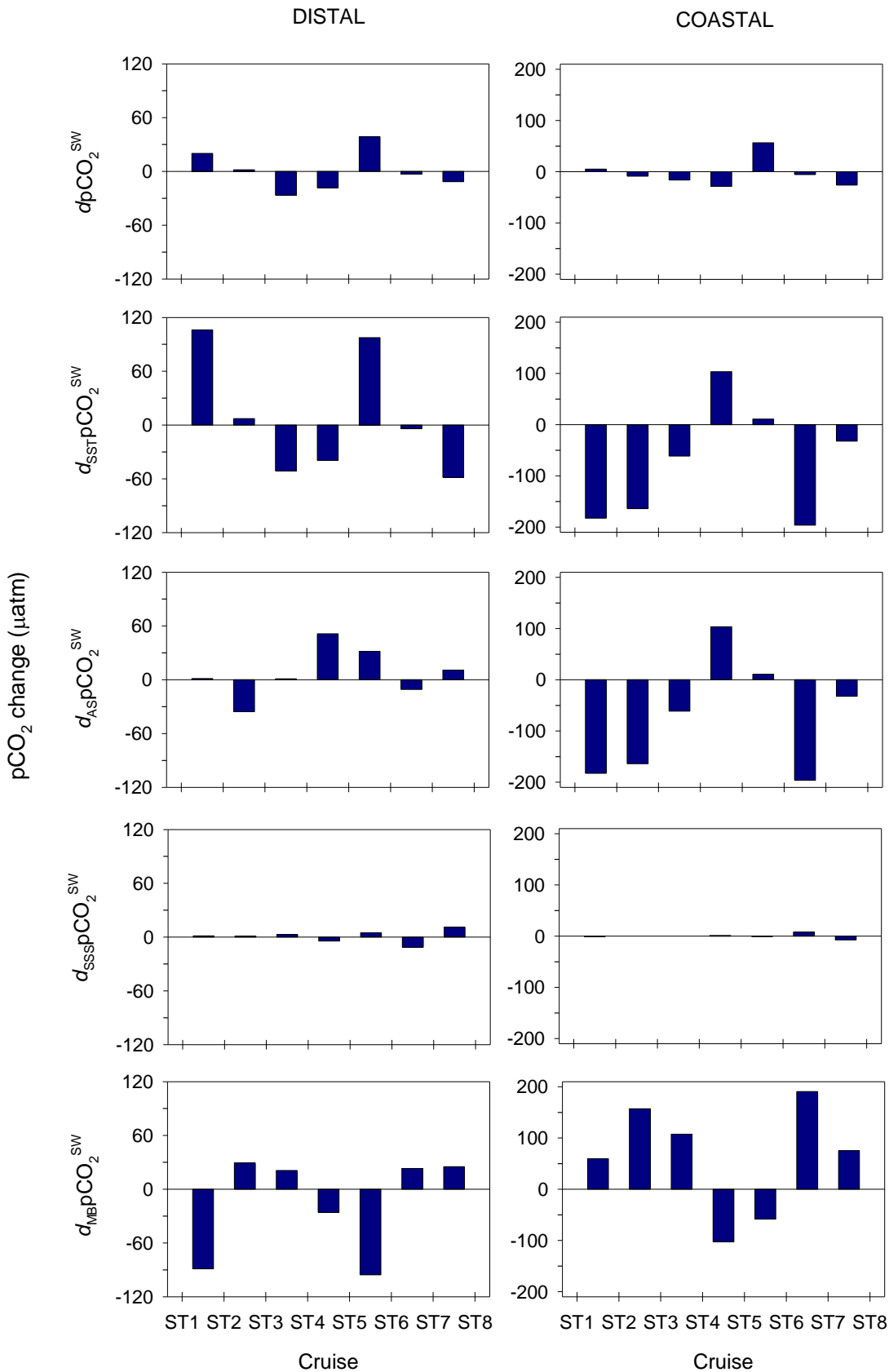
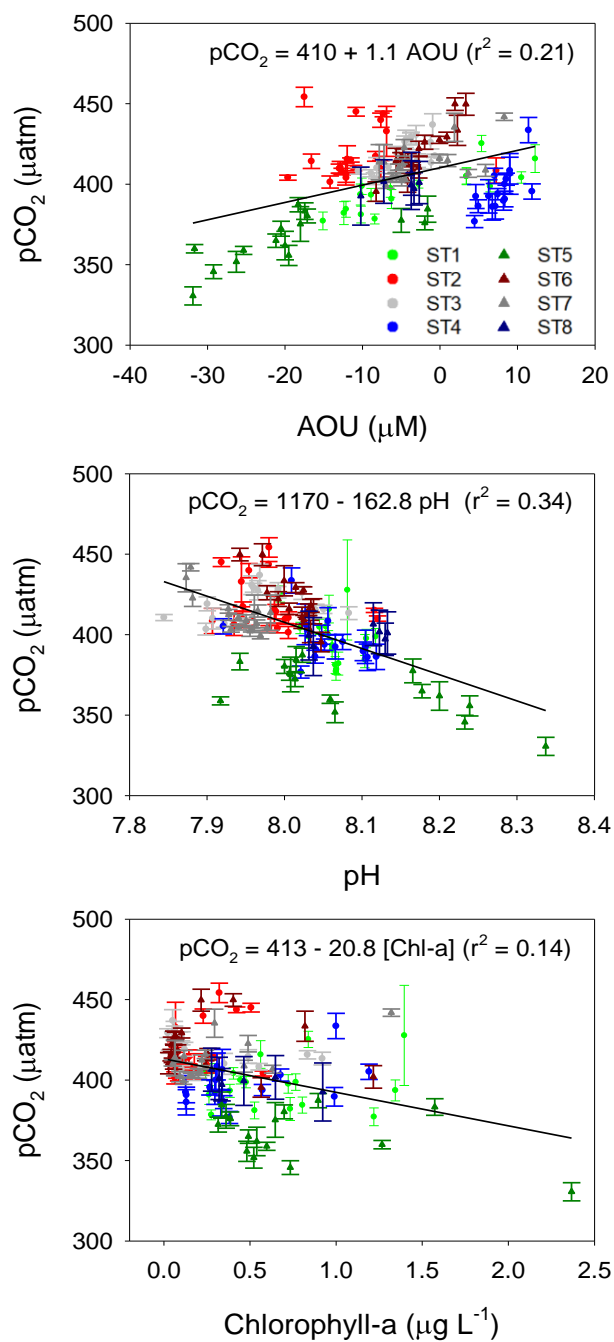
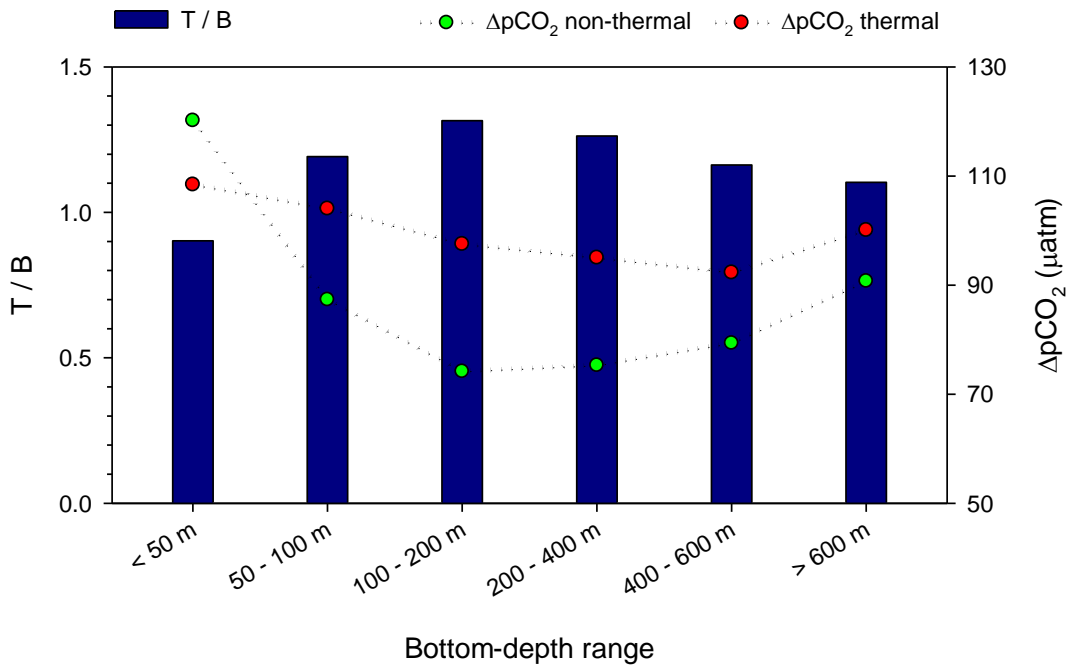


Figure 6: Observed changes in pCO₂ (first row) and pCO₂ changes broken down expected due to: SST changes (second row), air-sea CO₂ exchange (third row) SSS changes (fourth row) and biology plus mixing (last row) in the distal (left column) and coastal areas (right column) between the periods of each cruise: ST1 (March 2014), ST2 (June 2014), ST3 (October 2014), ST4 (December 2014), ST5 (March 2015), ST6 (June 2015), ST7 (September 2015) and ST8 (February 2016).



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Figure 7: Dependence-Relationships between the surface values of pCO₂ and Apparent Oxygen Utilization (AOU), pH, and chlorophyll-a (Chl-a) at the 16 discrete stations during the 8 cruises. pCO₂ presents the standard deviation associated with the mean value obtained from the underway measurements.



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Figure 8: Variation of the T/B ratio (blue bar), ΔpCO₂ non-thermal (green point) and ΔpCO₂ thermal (red point) at different bottom-depth ranges of the water column (m) for the 8 cruises.

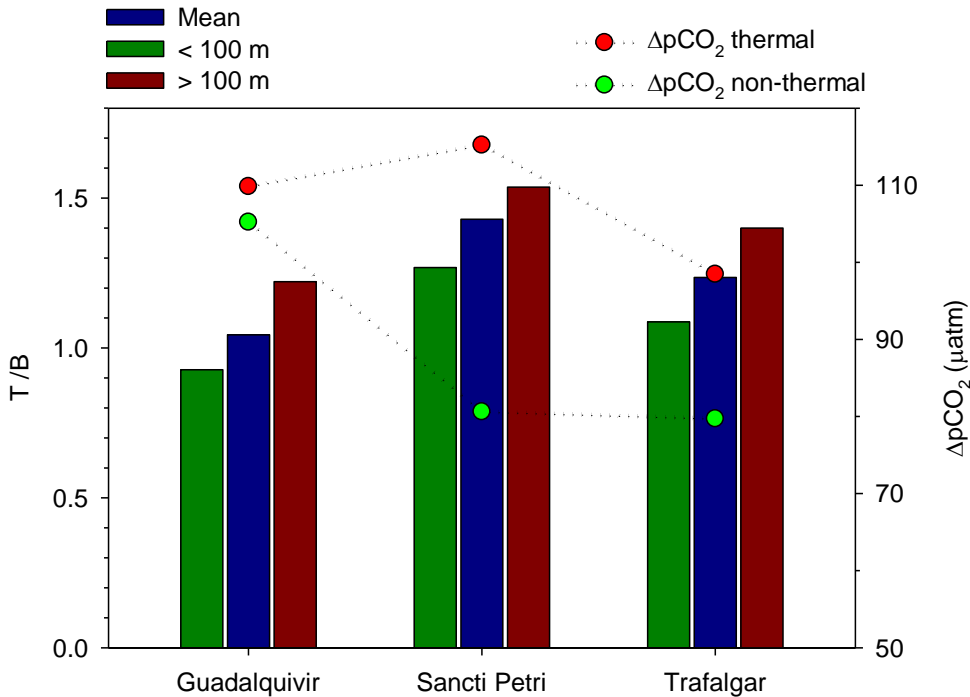


Figure 9: Variation of the T/B ratio (blue bar), the T/B ratio at depths < 100 m (green bar), the T/B ratio at depths > 100 m (red bar), ΔpCO₂ non-thermal (green point) and ΔpCO₂ thermal (red point) on the 3 transects of the study (Guadalquivir, Sancti Petri and Trafalgar) during the 8 cruises.

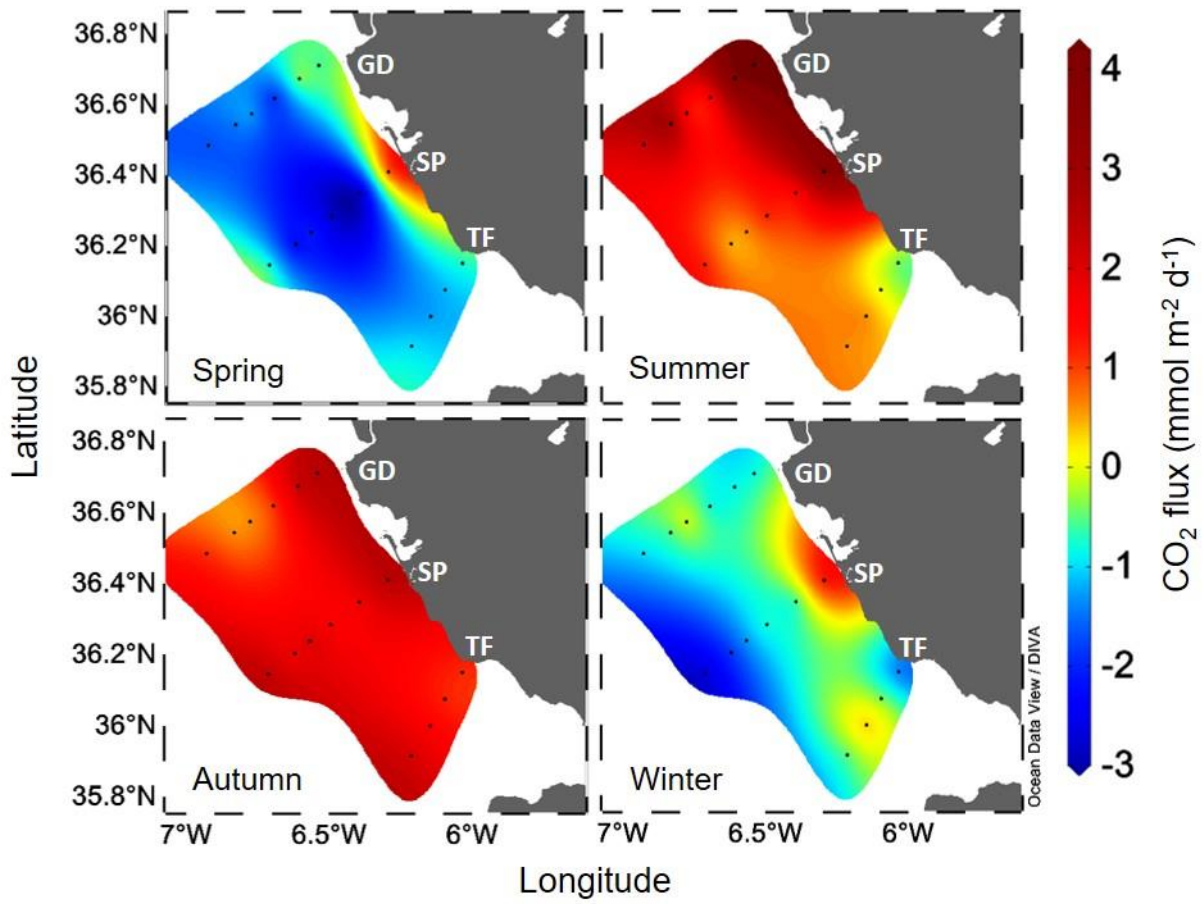


Figure 10: Spatial distribution of mean values of sea-air-sea CO₂ fluxes in the eastern shelf of the Gulf of Cádiz at the 16 discrete stations during spring (ST1, ST5), summer (ST2, ST6), autumn (ST3, ST7) and winter (ST4, ST8).

1300

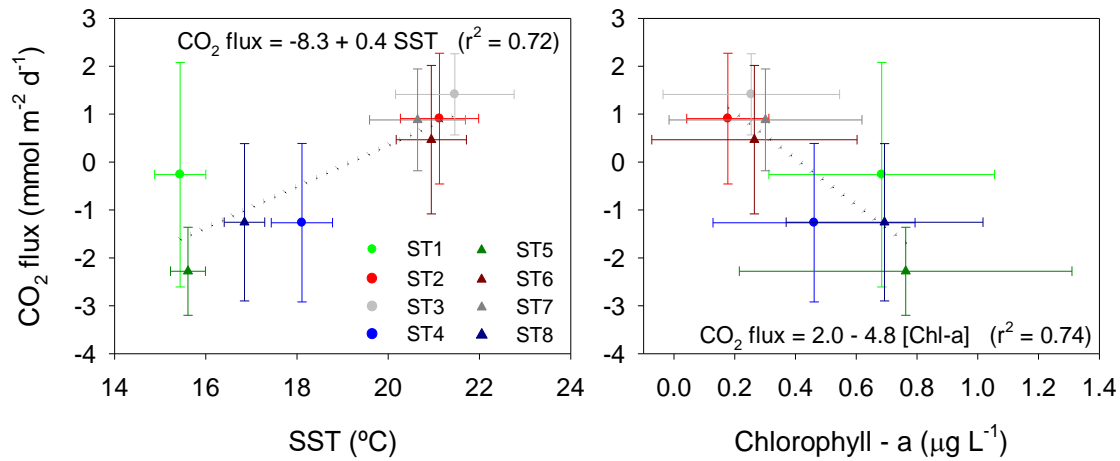


Figure 11: Correlations between the mean values of sea-air-sea CO₂ fluxes and sea surface temperature (SST) for the underway database (left), and the CO₂ fluxes and chlorophyll-a (Chl-a) at the 16 discrete surface stations (right) for each cruise and showing the standard deviations.

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