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Seasonal dynamics of air-sea CO_2 fluxes in the inner and outer Loire estuary (NW Europe)

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ABSTRACT

We investigated partial pressure of CO_2 (pCO_2) dynamics in the inner and outer Loire estuary (coastal margin of north-western Europe) over an annual cycle (2009–2010) using a comprehensive dataset of pCO_2, dissolved oxygen concentration (DO) and ancillary data collected during four cruises conducted in different seasons. In the inner estuary, pCO_2 exhibited very large spatial and inter-seasonal amplitudes (from 294 to 2744 μatm) mainly driven by strong heterotrophic respiration from spring to fall, thermodynamic effects in summer and mixing during winter floods. In the outer estuary, during spring and to a lesser extent during summer, the large extension of the plume resulted in stratification of the water column and autotrophic processes induced pCO_2 below atmospheric equilibrium in the plume's surface waters (mean values of −65 μatm compared to the atmosphere). During fall, mixing with inner estuary waters influenced by heterotrophic processes induced pCO_2 above atmospheric equilibrium (mean values of +86 μatm) in the very restricted and shallow plume. During winter floods, thermodynamics as well as episodic winter phytoplankton blooms were responsible for pCO_2 values below atmospheric equilibrium in the plume (mean values of −42 μatm), whereas the adjacent surface waters were at equilibrium with the atmosphere. Air-sea CO_2 fluxes in the inner estuary ranged from 41 ± 4 mmol m^{-2} d^{-1} during spring to 140 ± 18 mmol m^{-2} d^{-1} during fall, compared to an outer estuary minimum of -9.0 ± 1.0 mmol m^{-2} d^{-1} during spring and maximum of 7.7 ± 1.1 mmol m^{-2} d^{-1} during fall. Integrated over their respective areas, annual CO_2 emissions from the inner estuary of 3.2 10^9 mol C yr^{-1} were offset by the annual CO_2 sink of −17.9 10^9 mol C yr^{-1} from the plume alone. Based on four seasonal cruises, it seems that because of its large size during spring and to a lesser extent during winter, the Loire plume significantly impacted estimates of air-sea CO_2 fluxes at a regional scale. Comparison with other major estuarine plumes in diverse continental shelf zones seems to indicate a predominance of CO_2 sinks in these systems suggesting that other estuarine plumes might counteract inner estuary CO_2 emissions at seasonal to annual level.

1. Introduction

Coastal and marginal seas play a key role in the global carbon cycle by linking terrestrial, oceanic, and atmospheric reservoirs (Walsh, 1991; Mackenzie et al., 2004). Over the past decade, the coastal oceans have been the focus of several studies highlighting the role of these ecosystems in the global budget of air-sea CO_2 fluxes (Tsunogai et al., 1999; Thomas et al., 2004; Borges et al., 2005; Cai et al., 2006). The spatial variability of air-sea CO_2 fluxes is large and Chen and Borges (2009) recently proposed classification of continental shelves as sinks and near shore ecosystems as sources of atmospheric CO_2. A robust estimation of air-sea CO_2 fluxes in the coastal ocean at the global scale remains a challenge because of the large diversity and heterogeneity of coastal ecosystems. Such global estimations depend on more intensive and globally integrated observations of different coastal regions and ecosystems that, to date, are poorly studied.

Plumes are critical areas of land–ocean interaction where transformation takes place for the export of sediments, nutrients, and organic material from land to the oceans (Dagg et al., 2004) and references therein). Ketchum (1983) defined estuarine plumes as plumes of freshened water that float on denser coastal seawater and can be traced for many miles from the geographical mouth of the estuary. Estuarine plumes are characterized by large nutrient

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inputs and much lower turbidity than inner estuaries, thus allowing light penetration. These conditions are favourable for the occurrence of phytoplankton blooms (Cloern, 1996; Guillaud et al., 2008). Dai et al. (2008) suggested that intense and episodic summer phytoplankton blooms in plumes could be responsible for significant air-sea CO_2 exchange at regional to global scales. Several other processes, such as winter floods from the inner estuary or stratification/mixing of the plume water column, add to the complexity of such near shore ecosystems and can significantly impact air-sea CO_2 exchanges (Borges et al., 2005; Laruelle et al., 2010). Inter-seasonal investigations of air-sea CO_2 fluxes in estuarine plumes are scarce (Borges and Frankignoulle, 2002; Borges et al., 2008; Zhai and Dai, 2009) and supplementary studies are necessary to assess the role of these critical components of the land–ocean interaction. In European coastal waters, it is well established that emissions from inner estuaries almost fully balance the sink of atmospheric CO_2 computed for continental shelves (Borges et al., 2006), but the role of estuarine plumes has not been established. In addition, air-sea CO_2 fluxes over annual cycles have rarely been investigated simultaneously in inner and outer estuaries except for the Scheldt and to a lesser extent the Rhine outer estuaries (Frankignoulle et al., 1998).

In this study, we focus on the processes driving the air-sea CO_2 fluxes in the inner and outer Loire estuary (NW Europe). The Loire estuary is situated on the French Atlantic coast (Armorican shelf) and receives average annual river discharge of 850 m^{-3} s^{-1} (see below). Spring and winter floods in the inner estuary create large estuarine plumes in the region, usually covering a 2° by 3° area. For the first time, a comprehensive dataset of partial pressure of CO_2 (pCO_2), dissolved oxygen (DO) and ancillary data was acquired during 4 seasonal cruises, each covering both the inner and outer estuary. We firstly discuss the seasonal pCO_2 dynamics in both systems. We then discuss the impact of the Loire estuarine plume on regional air-sea CO_2 fluxes and the potential role of estuarine plumes on air-sea CO_2 fluxes at the global scale.

2. Material and methods

2.1. Study site

The river Loire is the longest river in France; it flows for more than 1000 km with a catchment area equal to 1/5 of the total surface area of France (118 000 km^2). The average annual fluvial flow over the last century was 850 m^3 s^{-1} (Dauvin, 2008). At Saint Nazaire, located at the mouth of the estuary, the proportion of seawater at low tide ranges between 10 and 40% and the maximum tidal amplitude is 6 m. The residence time of freshwater within the Loire estuary ranges from 3 days in floods to 30 days at times of low river flow (Guillaud et al., 2008). Lazure and Jegou (1998) modelled the hydrodynamic features of the Loire river plume on the Atlantic

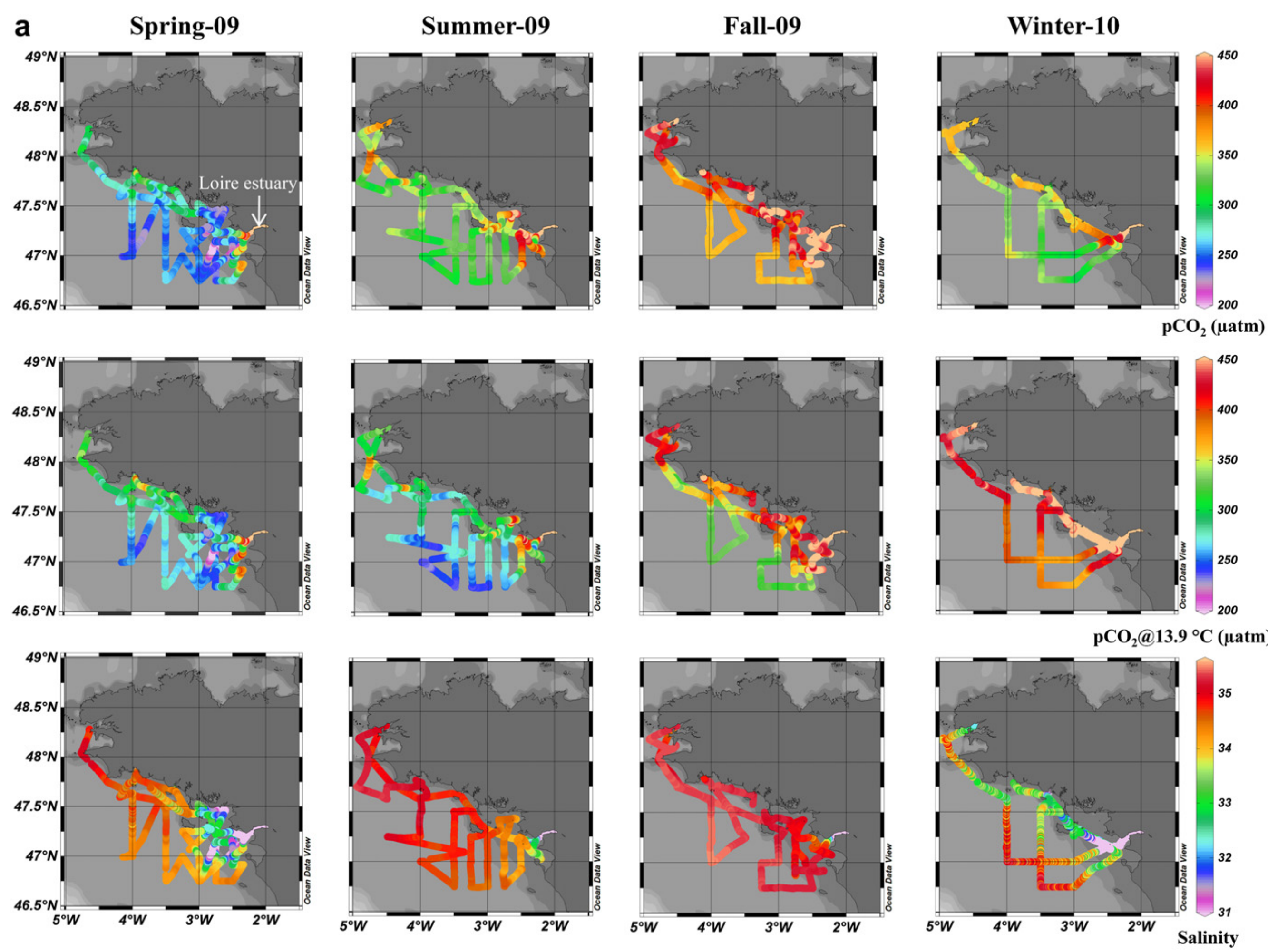

Fig. 1. Surface distribution of (a) pCO_2, pCO_2 normalized to the annual mean temperature of 13.9 °C (pCO_2@13.9 °C), salinity, (b) temperature, DO% and Chl a in the Loire estuary plume and adjacent surface waters during the spring, summer, fall 2009 and winter 2010 CO2ARVOR cruises.