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pCO$_2$ and CO$_2$ exchange during high bora winds in the Northern Adriatic

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ABSTRACT

Episodic high wind events have a potential for significantly mixing surface water partial pressure of CO_2 (pCO_2). Their effect on estimates of air–sea CO_2 flux, especially in the coastal ocean, has not been adequately assessed. Here we show the response of surface water pCO_2 and CO_2 fluxes during high bora wind in the Northern Adriatic for a range of conditions including: stratified and oversaturated with respect to atmospheric CO_2, stratified and undersaturated, and non-stratified and undersaturated. Three representative bora cases of 1.5–2 day duration with wind speeds over 10 m s^{-1} indicate that in all three studied cases, regardless of pre-bora conditions, pCO_2 in the surface water increases by 30–50 μatm and CO_2 flux magnitudes peak up to 4 folds (−22.6 and −24.1 mmol m^{-2} day^{-1} day in the winter cases and 29 mmol m^{-2} day^{-1} in the summer case) over the magnitude of the mean annual value. Oceanic data measured simultaneously to surface pCO_2 measurements suggest that the most likely responsible mechanisms for the observed pCO_2 increases were oceanic vertical mixing and/or oceanic horizontal advection. Our study contributes to a very limited set of observations currently available on the biogeochemical response to episodic high wind events in coastal areas and their role in CO_2 exchange. In such coastal environments the presence of shallow depths and short horizontal spatial scales of variation facilitate the exchange of pCO_2 both vertically within ocean layers and horizontally across ocean basins, which can then alter air-sea pCO_2 difference across the ocean surface during high wind events and affect gas exchange.

1. Introduction

Previous studies have suggested that episodic high wind events have a potential for influencing surface water pCO_2 and air–sea CO_2 exchange (Bates 2007; Bates et al., 1998; Edson et al., 2011; Hood et al., 2001). These studies have mostly been performed in the open ocean and have reported an enhancement in air–sea flux due to high transfer velocity (k) and increase of surface water pCO_2 caused by upward mixing of water relatively enriched in CO_2, and/or movement of water masses with different properties through the system. A very limited set of observations is currently available on the biogeochemical response to high wind events, such as bora in coastal areas and their subsequent role in air–sea CO_2 exchange.

The pCO_2 of surface seawater is controlled by thermodynamic changes, air–sea exchange, biological activity, vertical mixing, and horizontal advection. Temperature increases lead to higher pCO_2 and biological production to lower pCO_2, while gas exchange reduces (increases) water pCO_2 when water concentration is higher (lower) than atmospheric CO_2. Vertical mixing and horizontal advection from areas where wind strength, stratification and water pCO_2 may be different could play particularly important roles in a coastal environment due to the shallow depths and small horizontal spatial scale of variation respectively. For example, during high wind events, bottom water with higher pCO_2 can suddenly mix with surface water that has lower pCO_2 increasing surface and decreasing bottom pCO_2. In ocean CO_2 sink conditions (i.e. the ocean undersaturated with respect to atmospheric CO_2), this increase in surface pCO_2 can have a negative feedback by decreasing the amount of ocean pCO_2 undersaturation faster than would happen by gas exchange alone.

Bora is a cold katabatic wind prevailing from a northeasterly direction and is the most common wind in the Northern Adriatic. Bora forms thin sea surface wind jets that are spatially influenced by the local topography and are characterized by a sudden startup and a short duration (order of one to a few days in the summers and six to fourteen days in the winter), with mean speeds over 15 m s^{-1} and with gusts greater than 30 m s^{-1} (Stravisi, 2001). Bora winds normally occur more than 40 days per year. Bora is most common in autumn and winter, but can also be present during the summer period. The strength, mean positions and extension of bora jets vary considerably between different events (Pullen et al., 2007) and therefore the response of the system cannot be determined based on a single bora episode.

It has been well established that bora has a strong effect on the physical environment of the Northern Adriatic, such as its circulation, stratification, and heat and momentum fluxes (Dorman et al., 2006; Jeffries and Lee, 2007; Kuzmić et al., 2006; Malačič and Petelin,

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2006; Pullen et al., 2007; Signell et al., 2010). It generates a wind-induced "double gyre" circulation, with a cyclonic gyre in the northern part of the basin and an anticyclonic gyre in front of the Southern Istrian coast (Kuzmić and Orlić, 1987; Kuzmić et al., 2006). In the Gulf of Trieste (GOT), the most northern semi-enclosed basin in the Northern Adriatic (Fig. 1), Malačič and Petelin (2009) show a generally cyclonic circulation in the deeper layer in all seasons with an inflow into the GOT which is enhanced during spring time. Tidal currents can exceed 20 cm s^{-1} in the GOT and are particularly enhanced along the Croatian/Slovenian coast at the southern entrance to the gulf (see Fig. 7 of Malačič et al., 2000). At the surface, the circulation of the gulf is predominantly anticyclonic during the stratified season due to the inertial plume of the Isonzo River, and there is an outflow from the gulf (Malačič and Petelin, 2009; Zavatarelli and Pinardi, 2003). During the intense bora episodes in the winter, studies have suggested that bora winds drive flow downwind at the surface, forming an outflow from the gulf in the surface layer (Kuzmić et al., 2006; Malačič and Petelin, 2009), and compensating intensified inflow at depth.

It has also been suggested that pre-bora ambient stratification plays a role in the response of the Northern Adriatic to bora (Jeffries and Lee, 2007). Typically, the water column in the GOT during the winter period is well mixed (Bogunović and Malačič, 2009; Celio et al., 2006). In April, surface heating and fresh water input lead to stratification and the months between May and September are characterized by strong density stratification (Malačič et al., 2006). In October, convective and mechanical mixing of the surface and subsurface

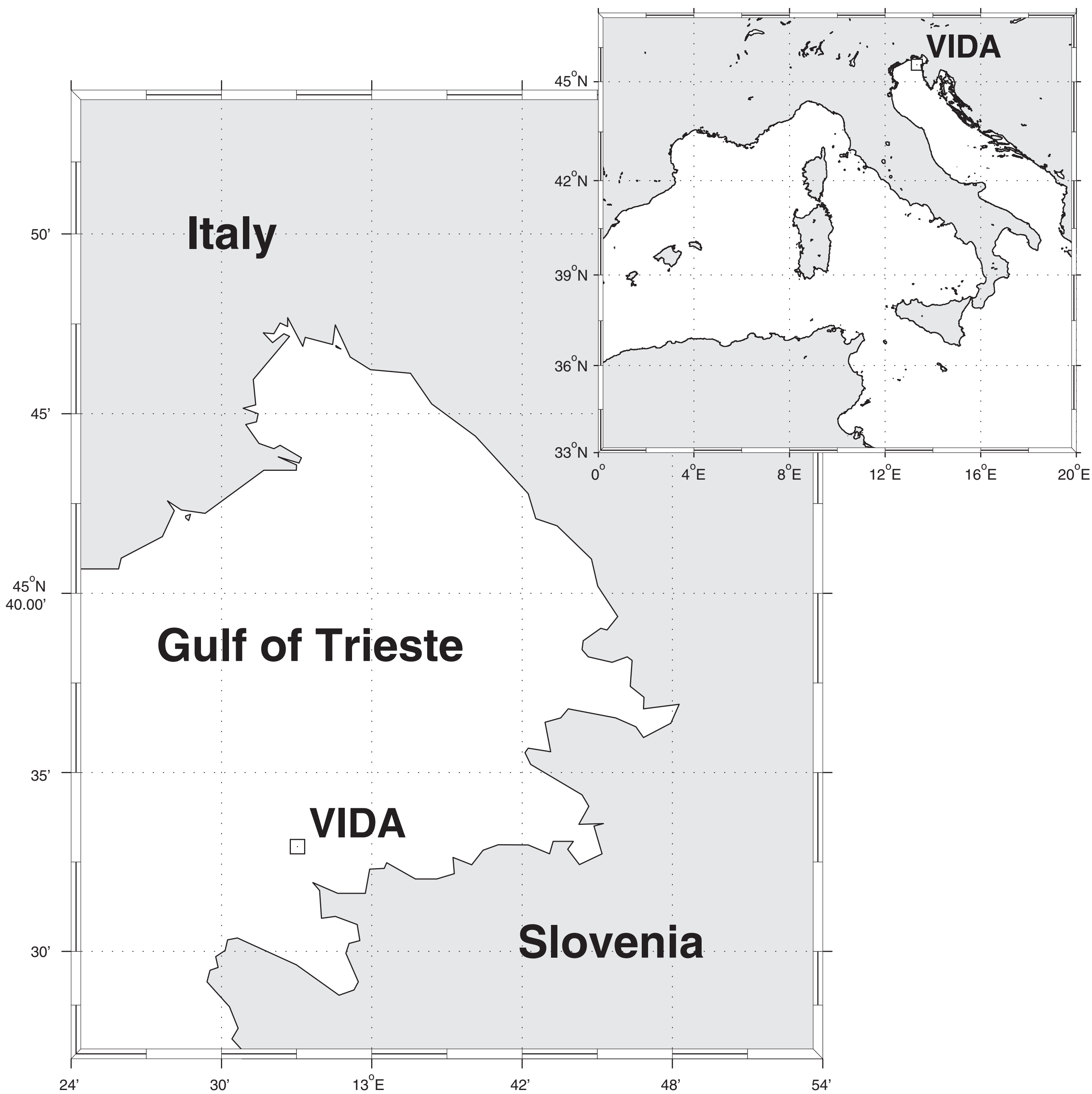

Fig. 1. Map of the (top) Mediterranean with the northern Adriatic Sea Gulf of Trieste and (bottom) GOT with location of the coastal oceanographic buoy Vida.