Air-sea carbon dioxide exchange during upwelling

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Abstract. Direct measurements of carbon dioxide flux were made during an upwelling event in late summer in the Baltic Sea. Measurements were made from a research vessel and at a meteorological mast. During the upwelling event both platforms measured upward CO_2 fluxes of the same magnitude. Before the upwelling event the two platforms showed a relatively large difference in the magnitude of the fluxes even if they were only one kilometer apart. The measured fluxes at both platforms were much higher than the values calculated with a wind-speed dependent transfer velocity formula. The results suggest that in coastal regions the representativeness of the measured or calculated values of the fluxes is strongly dependent on the representativeness of the conditions in the footprint area of the measurements due to the horizontal variability of the parameters controlling the exchange of the CO_2, e.g. the oceanic partial pressure of carbon dioxide, the sea surface temperature and the sea state.
Key Words: Carbon dioxide flux, upwelling, coastal region

1. Introduction

The oceans act as a net sink for the anthropogenic carbon dioxide and the carbon dioxide is transported to greater depths by the ocean circulation. Upwelling of the deeper carbon dioxide rich water to the surface layers may cause a release of carbon dioxide to the atmosphere. The up-welled water is usually also rich in nutrients, which enhances the primary production in the surface layer. The resulting biological activity can be so strong that the area is a net sink during the upwelling event. The upwelling events are typical for coastal areas, which, due to the intense primary production during the growth season, are also important sinks for the carbon dioxide in global scale. There have been several studies of the carbon dioxide exchange in continental shelves and attempts to estimate the seasonal and annual net fluxes from these areas. According to these studies the coastal areas can act as a sink or a source, depending on the local physical and biochemical properties of the sea area (Ito *et al*. 2005). Hales *et al.* (2005) studied the coastal area of Oregon during summer months and found that in spite of a strong source area close to the shore the area as a whole was still a net sink for the carbon dioxide due to a high primary production. Astor *et al*. (2005) found only two periods of CO_2 transfer from the atmosphere to the ocean from their measurements in the Caribbean Sea, both during upwelling events. They concluded that the area is a net source for the carbon dioxide. The above mentioned studies are based on carbon dioxide fluxes calculated from the difference of partial pressures of carbon dioxide in the sea water and in the atmosphere using the existing wind speed dependent relations for the transfer velocity. The factors other than the wind speed affecting the transfer velocity are under intensive research and suggests wave-breaking, bubbles, surfactants, convection in the water (e.g. MacIntyre *et al*. (2002), Woolf (2005), Zappa *et al*. (2007), Soloviev *et al.* (2007), Rutgersson and Smedman (2010), see Wanninkhof *et al*. (2009) for a review). For further understanding of the transfer velocity and the important processes, direct measurements of carbon dioxide fluxes and the factors influencing the exchange are needed. Such measurements are still relatively rare, in particularly during events with large horizontal and vertical heterogeneity such as upwelling events. In this study we use direct measurements to investigate the carbon dioxide exchange during an upwelling event in the Baltic Sea.

2. Experiment

During a research cruise in 2005 an upwelling event was observed near the Swedish island Gotland in the Baltic Sea in northern Europe. The cruise was made in late summer (August - September) when the primary production was already low. The carbon dioxide fluxes were measured onboard the research vessel *R/V Aranda* and at a meteorological tower situated on the small, very flat island Östergarnsholm. The area is situated in the largest basin of the Baltic Sea, the Baltic Proper (Figure 1).

2.1 The research vessel Aranda

The bow mast of *R/V Aranda* was equipped with a sonic anemometer Metek USA-1 for measurements of the wind components and with a LI-7500 open path CO_2/H_2O analyser to record the fluctuations of the humidity and carbon dioxide. These sensors were installed at a height of approximately 16.2 metres above the

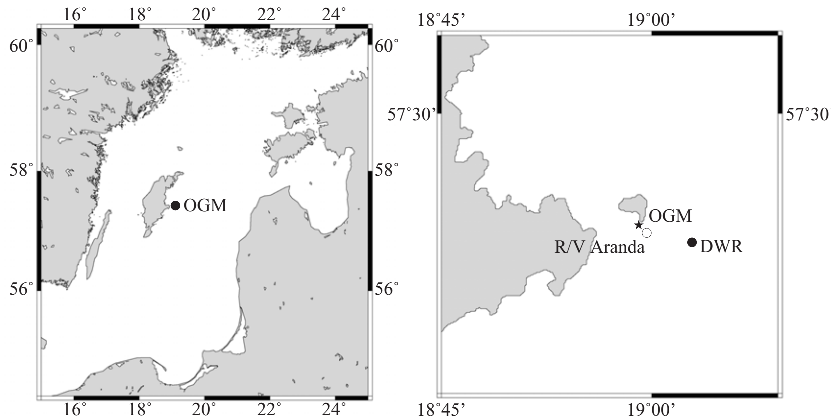

Figure 1 Study area in the Baltic Sea in Northern Europe. Panel on the left shows the Baltic Proper and the Gotland Island. OGM indicates the measuring site Östergarnsholm. Panel on the right: open circle denotes the position of *R/V Aranda*, star the meteorological mast OGM at the southern tip of the small island Östergarnsholm and bullet the position of the Directional Waverider DWR.

sea surface. The structure of the bow and the mast are such that there are no significant obstacles for the air flow (Figure 2). The bow of the vessel was also equipped with a microwave Miros Range Finder and a capacitive wave staff to measure the waves.

To get reliable measurements from a moving platform, the motions of the platform have to be known. A motion reference unit MRU-6 was mounted below the sonic anemometer and the CO_2/H_2O analyser. MRU-6 measures the three components of acceleration and the three components of the rotational motion. During the measurements the vessel was kept in one position with small corrections of the orientation to keep the bow against the wind direction with an accuracy of ＋/－ 20 degrees. After synchronizing the timeseries of the sensors they were corrected for the motions of the ship with the method of Drennan *et al*. (1994).

In addition, the mean meteorological parameters were also measured at the vessel's weather station. The sea surface temperature was measured with a sensor attached to the bulk of the vessel at a depth of four meters. Sea surface temperature at a depth of forty-five centimeters as well as the directional wave data was measured with a Directional Waverider (DWR) situated four kilometres to the southeast from the Östergarnsholm tower (Figure1).

The partial pressure of carbon dioxide in the sea surface water (pCO_2) was measured onboard by means of an underway equilibrator – CO_2 analyser system. A constant side flow of 200 ml/min was taken from the main pump flow from the

Figure 2 *R/V Aranda* and the meteorological tower at the southern end of the small island Östergarnsholm (OGM). The distance between the two platforms in this figure is approximately 500 m. During the upwelling event discussed in this study the distance between the platforms was approximately one kilometre.

depth of four metres and equilibrated with airflow by means of bubbling. A LiCor 6262 instrument was used to monitor the CO_2 concentration in the airflow circuit. For the daily calibration of the instrument, standard gas mixtures prepared by Aga Ltd at zero, 360 and 507 ppm CO_2 were used. The measured CO_2 partial pressure was corrected to in situ values by means of the experimental equation (DOE 1994)

$$pCO_{2\ in\ situ} = pCO_{2\ eq} \exp\left(0.0423\left(T_{in\ situ} - T_{eq}\right)\right) \tag{1}$$

The salinity and temperature of the surface water were measured simultaneously from the main pump flow. The salinity computed from the conductivity measurements was checked daily against Guildline Autosal 8400A salinometer. The performance of the salinometer is regularly checked by means of IAPSO salinity reference (Ocean Science International, Petersfield, U.K.). The system uncertainty is ± 0.005 units.

2.1 The Östergarnsholm site

Simultaneous measurements were taken at a land-based tower at Östergarnsholm (OGM). The location of this very small, flat island is 57º27'N, 18º59'E. Data are collected from a 30-metre tower situated at the south tip of the island (Figures. 1 and 2). An analysis of the changes in the wave field in

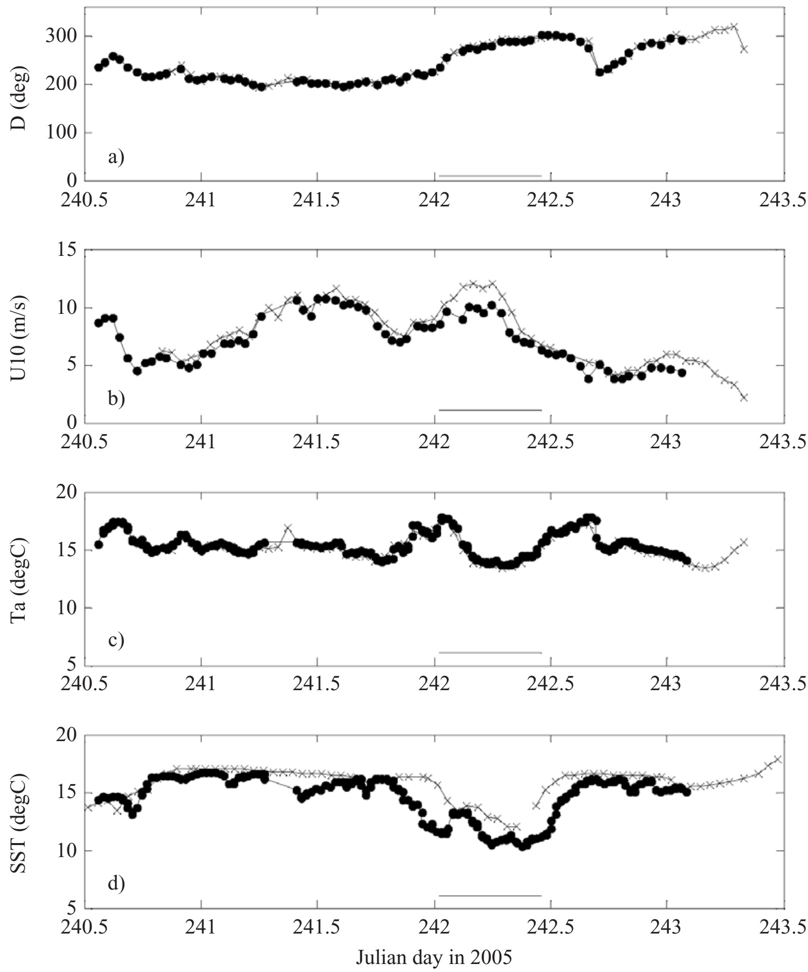

Figure 3 The conditions before and during the upwelling event in August 2005. Panel a) shows wind direction (bullets: *R/V Aranda*, crosses OGM), b) wind speed at ten metres (bullets: *R/V Aranda*, crosses OGM), c) air temperature (bullets: *R/V Aranda*, crosses OGM) and c) the sea surface temperature (bullets: *R/V Aranda*, crosses: DWR). The horisontal line denotes the time period when the measured flux was positive. Figure 1 shows the location of the platforms.

combination with a foot-print analysis of the momentum flux showed a very small impact of the limited water depth near the shore for the wind directions between 80º and 210º and the data from this sector can be regarded as representative of open sea conditions (Smedman *et al*. 1999, Högström *et al*. 2008). The tower is instrumented with high-frequency instrumentation for the turbulence data as well as slow response sensors for profile measurements. Measurements of high frequency wind components are taken with a SOLENT 1012R2 sonic anemometer. Like onboard *R/V Aranda*, the humidity and carbon dioxide fluctuations are measured with a LI-7500 open-path CO_2/H_2O analyser. These sensors were installed at approximately ten metres above the sea surface. For a further description of the instrumentation and data, see Rutgersson *et al*. (2008).

3. Results

The measurements on *R/V Aranda* were made approximately one kilometer southeast from the Östergarnsholm tower (Figure 1). Before the upwelling event in the end of August 2005, the wind direction was parallel to the coast of the Gotland Island and turned offshore during the upwelling event itself (Figures 1 and 3a-b). The sea temperature at the location of Aranda decreased 6ºC. The decrease in the sea surface temperature at the location of the Directional Waverider three kilometres offshore from *R/V Aranda* occurred about five hours later and lasted a couple of hours less (Figure 3d). The satellite observations (Swedish Meteorological Institute, not shown) on thirtieth August (Julian day 242) show sea surface temperatures between 5 ºC and 11 ºC in the southeast coastal regions of Gotland Island, but the exact measuring area was covered by clouds. On thirty-first August (Julian day 243) the colder water had moved along the coast to the south: at the measurement area the sea surface temperature was 14-15 ºC. The air temperature decreased few degrees but remained higher than the sea surface temperature (Figure 3c).

The partial pressures of carbon dioxide (pCO_2) in the seawater and in the atmosphere are shown in Figure 4a. The partial pressure of the seawater during the upwelling event was most of the time higher than the pCO_2 in the atmosphere. The fluctuations of the pCO_2 in the seawater suggest that the upwelling water masses did not proceed with constant velocity but moved back and forth during the process. The sea surface temperature at the position of the vessel shows some fluctuation as well. These fluctuations are not so clearly visible further out at the location of the Directional Waverider where the sea surface temperature was measured closer to the surface (Figure 3d). The fluctuations measured deeper in the surface layer may not have reached the surface.

The carbon dioxide fluxes measured at *R/V Aranda* and at the OGM tower are shown in Figures 4b and 4c. During the upwelling event both platforms show upward fluxes of the same magnitude and duration, the highest values at OGM were measured later than at the vessel. The carbon dioxide flux calculated with the transfer velocity parametrisation given by Wanninkhof (1992), $k_{600} = 0.31 \cdot U^2_{10}$, is shown in Figure 4c. The measured values are much higher than the calculated ones. The oceanic and atmospheric partial pressure difference change sign about

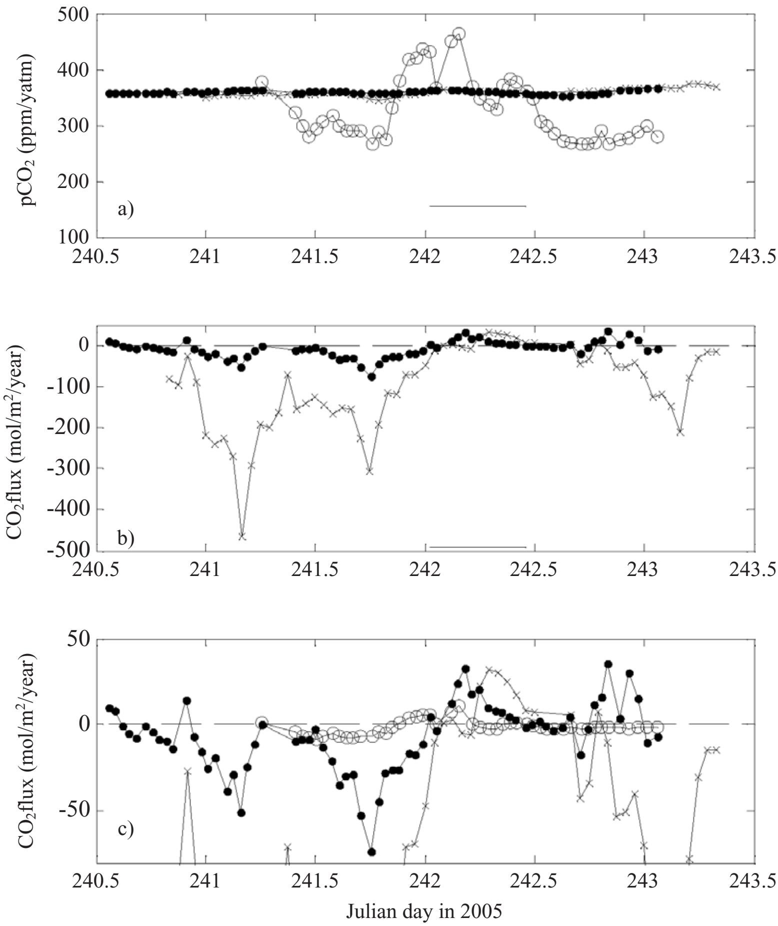

Figure 4 Panel a) shows the partial pressure of CO_2 in the atmosphere (bullets: *R/V Aranda*, crosses: OGM) and in the surface water (open circles: *R/V Aranda*). Panel b) and c) the CO_2 flux (bullets: *R/V Aranda*, crosses: OGM and open circles: the flux calculated with the transfer velocity given by Wanninkhof (1992)). The horisontal line denotes the time period when the measured flux was positive. Figure 1 shows the location of the platforms.

three hours before the measured carbon dioxide fluxes: it took some time before the carbon dioxide rich water reached the surface from the measurement depth of four meters. Before the upwelling event the fluxes measured at these two platforms show a large difference in magnitude although the shapes of the timeseries of the both CO_2 fluxes are the same. During this period, the wind, direction and other fluxes (momentum, heat, humidity) were very similar at both platforms that where only one kilometer apart.

4. Discussion

Before the upwelling event, when there was a large difference between the carbon dioxide fluxes measured from the vessel and at the tower, the atmospheric stratification was slightly unstable. For the measurement height of ten metres at the tower most of the turbulence originated from a distance less than one kilometre and for the height of 16.2 metres at the vessel the footprint was a little bit further out (Högström *et al*. 2008). The wind direction was along the island Gotland, around 210º. The partial pressure of carbon dioxide in the seawater was measured only from *R/V Aranda* and there is no information about the horisontal variability of the partial pressure of carbon dioxide in the sea surface water. *R/V Aranda*'s position was to 140º from the tower, which is somewhat outside the footprint area of the sensors at tower (Rutgersson *et al*. 2008) in this wind direction. At this time of the year, the biological activity is slowing down and it is unlikely that there were a stronger primary production closer to the shore in the footprint area of the tower than in the little more offshore footprint area of *R/V Aranda.* Horisontal variability in the footprint area during the period prior to the upwelling event can also be caused by fresh water run-off from the coast of Gotland. This would add water with high carbon content, give a smaller air-sea difference in the partial pressure, and could partly explain the large difference between measured flux at the two platforms and the calculated flux.

The Directional Waverider three kilometres offshore measured rather unidirectional waves approaching from 200º with a peak period of 5.9 s. The sea area close to the tower is shallow enough that 5.9 s waves will refract. Refraction creates both convergence areas and divergence areas of wave energy. In convergence areas waves are steep and mixing due to the wave breaking is enhanced. In divergence areas wave slope is small and wave induced mixing reduced. The flux footprint of the sensors at *R/V Aranda* was situated along the depth curve of twenty metres, i.e. at least partly over water deeper than twenty metres, while for the footprint of the sensors at the tower the depth was less than twenty where refraction is strong. The horisontal changes in the wave field and consequently the differences in the wave breaking intensity can be one of the reasons for the large differences in the magnitude of the measured carbon dioxide fluxes between the two platforms.

During the upwelling event itself the atmospheric stratification was slightly stable. This means that the flux was originating from a distance over several kilometres (Högström *et al*. 2008). The wind turned from southwest to west-northwest, so the fluxes measured both at the tower and the vessel were affected by the island of Gotland (Figure 1), as at least part of the footprint area being over land. Both footprints were, however, over areas of comparable water depths.

5. Conclusions

Carbon dioxide exchange before and during an upwelling event was studied with direct measurements of CO_2 fluxes from a research vessel and a land-based tower situated one kilometre apart. Both platforms measured an upward CO_2 flux of the same magnitude during the upwelling event. Before the upwelling event the two platforms measured both downward fluxes but disagreed significantly on the magnitude of the fluxes, the tower measurements were much higher than the values from the ship. The direct measurements of carbon dioxide flux involve the footprint which distance is dependent on the atmospheric stratification. In coastal areas the properties of the sea surface waters controlling the carbon dioxide exchange can have large changes over relatively short distances and time periods. The representativeness of the CO_2 fluxes obtained (measured or calculated from the partial pressure difference) from one location for a larger coastal area depends on the representativeness of the conditions in the footprint area. Measurements from few locations may bias the influence of coastal regions on the global net flux.

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