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Regional scale estimation of carbon fluxes from long-term monitoring of intertidal exposed rocky shore communities

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ABSTRACT

The observed increase in the atmospheric concentration of carbon dioxide due to anthropogenic emissions is predicted to lead to significant changes in climate. Recent studies highlight the importance of identifying the role of marine coastal communities in carbon exchanges. Our objective was to couple macrozoobenthos abundance data from long-term monitoring with species metabolism rates to contribute to the estimation of CO_2 fluxes from an intertidal exposed rocky shore community at a regional scale. The carbon fluxes due to respiration and calcification were calculated both during emersion and immersion, and the effect of temperature variation on carbon emissions was then predicted. Spatial and temporal natural variations of carbon fluxes were investigated and the contribution of exposed intertidal rocky shore communities to regional carbon emissions was calculated. The method was used to calculate the carbon budget allowed to account for the natural spatial variability of the community composition and carbon emissions. Mean annual calculated CO_2 emission was 14.3 mol C m^{-2} yr^{-2}, and the annual regional CO_2 flux was estimated at 2978 t C yr^{-1}. Simulations showed that the potential feedback of a rise in temperature of 1 °C would lead to an increase of 4–7% in carbon emissions for this type of community. The results give a first quantification of intertidal exposed rocky shore carbon emissions that could be considered in evaluating further the global CO_2 budget.

1. Introduction

Coastal marine ecosystems are among the most ecologically and socioeconomically important ecosystems (Harley et al., 2006). Although the continental margins, considered here to extend from the coastline to a depth of 200 m, occupy only a little over 7% of the seafloor and less than 0.5% of the ocean volume, they play a major role in oceanic biogeochemical cycling (Chen and Borges, 2009). Unfortunately, the contribution of the coastal zone to carbon global cycles is not yet clarified because coastal ecosystems are characterized by strong temporal and spatial heterogeneities (Middelburg et al., 2005). The metabolism of rocky shore organisms has mostly been studied in the laboratory, with each species examined separately (Babarro et al., 2000; Bjelde and Todgham, 2013; Branch and Newell, 1978; Houlihan and Newton, 1978). Carbon fluxes of the intertidal hard-bottom communities have only been directly estimated for macroalgae dominated shores (Golléty et al., 2008b) and isolated rocky blocks through benthic chamber techniques (Lejart, 2009). A recent indirect estimation of CO_2 fluxes performed on the Brittany rocky shores communities emphasized the importance of calcified intertidal invertebrates for the carbon budgets (Hily et al., 2013). Although the importance of coastal areas to the global CO_2 budget is irrefutable, our current knowledge of carbon fluxes is still lacking. One of the major obstacles in our understanding is the lack of a typology for the European coastal areas (Gazeau et al., 2004). Information on near-shore and intertidal areas is often missing because of the difficulty of applying traditional measurement techniques. Previous estimations of coastal carbon fluxes on global scales have considered only data measured on soft-bottom communities (Borges, 2011; Cai et al., 2003; Chen and Borges, 2009). Although benthic communities living in continental margins could either be a sink or a source for atmospheric carbon (Siefert and Plattner, 2004; Staehr et al., 2012), different studies indicate that this zone is generally a source of CO_2 to the atmosphere (Smith and Hollibaugh, 1993; Smith and Mackenzie, 1987, 1987). Considering such uncertainty, the estimation of total carbon emissions related to these communities still requires further investigation.

Increasing concentrations of CO_2 and other greenhouse gases in the atmosphere are considered to have been a major cause of global mean surface air temperature rise during the twentieth century and are projected to accelerate the rate of climate change (Meeht and Stocker, 2007). Because temperature generally influences metabolism, carbon emissions can change depending on temperature variations. According

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Abbreviations: IPCC, Intergovernmental Panel on Climate Change; MDS, non-metric multidimensional scaling; REBENT, REseau BENThique; SHOM, Service Hydrographique et Océanographique de la Marine; SST, sea surface temperature.

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to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-2013), the globally averaged combined land and ocean surface temperatures show a warming of 0.85 °C over the period 1880–2012 (Hartmann et al., 2013; Levitus et al., 2009). Such warming, however, has been neither steady nor the same in different locations. Thus, European seas have experienced a rapid increase in temperature of about 0.67–0.80 °C between 1982–2006 (Belkin, 2009). Measurements performed in the English Channel during the period 1986–2006 indicate that warming is not homogeneous either in this area and that the central part of the Channel and the western part of the French Brittany exhibit a lower warming rate (around 0.6 °C) compared to the northern part of the Channel (around 1.6 °C) (Saulquin and Gohin, 2010). Reliable predictions of climate change in the immediate future are difficult, especially at the regional scale where natural climate variations might amplify or mitigate anthropogenic warming (Lean and Rind, 2009). In long-term projections extending towards the end of this century and beyond, a large part of the uncertainty is associated with the trend of anthropogenic greenhouse gas emissions and the resulting external forcing of the climate system. The mean climate change for the period 2016–2035 estimated by the IPCC multi-model varies from 0.3 °C to 0.7 °C (medium confidence) (Kirtman et al., 2013), and mean temperature in Europe is predicted to increase more than the global average. Consequently, the greatest climate warming is expected to occur in northern Europe, especially in winter, while cooling would rather occur in southern Europe throughout the year as well as in central Europe in summer (Christensen et al., 2007).

Coastal perennial monitoring programs are powerful tools for understanding the natural variability of benthic community structures and the relationship with environmental factors and their variations. The French monitoring network, REseau BENThique (REBENT), was launched by the Ministry of the Environment in 2003 following the 1999 Erika oil spill. REBENT aimed to acquire baseline knowledge on biodiversity and structure of several coastal benthic habitats through time. It aims at defining a reference state and provides monitoring of these habitats to detect changes at various scales over time and space (Ehrhold et al., 2006). This network has focused on 7 different habitats, four sedimentary habitats (sandy beaches, zostera beds, infralittoral fine sands, maerl beds) and three rocky habitats (fauna dominated rocky shore, algae dominated rocky shore, infralittoral rocky communities) (Derrien-Courtel et al., 2013; Hily et al., 2013). Here, we only focus on fauna dominated rocky communities, the most prominent and widely distributed communities living in the intertidal rocky shore in Brittany (EUNIS — A1.11 habitat “mussel and barnacle communities” see http://eunis.eea.europa.eu/habitats/5395). In such exposed and semi-exposed habitats, the macrozoobenthos is very largely predominant, representing from 90 up to 100% of the benthic biomass, while algal cover is very limited or absent (Lewis, 1964).

Compared to other coastal communities, the intertidal rocky shore is characterized by considerable biodiversity and various adaptations to aerial exposure (Davidson et al., 2004). CO_2 release from the intertidal macrozoobenthic community is the result of both respiration and calcification processes (Frankignoulle et al., 1994). Quantification of carbon fluxes from intertidal rocky shore communities requires the consideration that immersion and emersion succession cause variation in different physico-chemical parameters (such as temperature, light, desiccation, salinity) and changes in community composition along the coast.

The present study aimed to generate estimates of annual CO_2 emissions from intertidal exposed rocky shore communities at a regional scale. For this, mean annual biomass of species, obtained from REBENT intertidal rocky shores data set, was coupled with specific respiration–temperature relationships and mean calcification rates. To examine the spatiotemporal variability of these estimates, calculation was performed at two shore levels in nine sites and for six years. The effect of different scenarios of annual mean temperature variation on mean CO_2 emission was also tested for the two levels.

2. Material and methods

2.1. Sampling strategy

Data on the abundance of the studied benthic species were provided by the REBENT network. REBENT has been monitoring rocky intertidal fauna at 9 sites (Fig. 1) with similar hydrodynamic conditions between 2004 and 2012. These sites are representative of exposed or moderately exposed shores where the algal cover is limited or nil. Abundance was monitored at two shore levels; here we use the term “high-shore” to refer to communities living in the upper eulittoral zone and “low-shore” for animals living in the lower part of the eulittoral zone.

Since 2004, non-destructive methods have been used annually to estimate the macrozoobenthic community composition and abundance in each studied zone. Samples were collected at the beginning of spring in order to include winter mortalities and avoid late spring recruitments. Such a design was employed, to sample communities at their ‘baseline’ and thus avoid yearly variability. Ten quadrats of 0.1 m^2 divided into 40 smaller quadrats of 25 cm^2 are sampled once a year at the same position on the shore. On each 0.1 m^2 quadrat, abundance of large macrofauna (more than 0.5 cm) is evaluated directly in situ. Photographs of five randomly selected 25 cm^2 quadrats are taken on each 0.1 m^2 quadrat, and photo analysis is performed using Quantum GIS software to assess barnacle and small gastropod abundances.

In this study, we have used data from six years of monitoring (2004–2007 and 2009–2010) since data from 2008 were not available. Species abundance was averaged from seven quadrats of 0.1 m^2 for large species and 21 quadrats of 25 cm^2 (3 for each 0.1 m^2 quadrat) for small animals to standardize the data. Some samples were not available because of technical problems or poor weather conditions. Carbon fluxes were estimated for five species groups that contained all the species found during the sampling period: barnacles (*Semibalanus balanoides*, *Elminius modestus*, *Chthamalus stellatus*, *Chthamalus montagui*), limpets (*Patella vulgata*, *Patella depressa*, *Patella ulyssiponensis*), mussels (*Mytilus* spp.), oyster (*Crassostrea gigas*), and gastropods (*Gibbula pennanti*, *Gibbula umbilicalis*, *Littorina littorea*, *Littorina obtusata*, *Littorina saxatilis*, *Melarhaphe neritoides*, *Nucella lapillus*, *Osilinus lineatus*).

2.2. Environmental parameters

Immersion/emersion times as well as aerial and underwater temperatures were considered in order to extrapolate carbon fluxes on an annual scale. Water height was calculated every 15 min according to SHOM (Service Hydrographique et Océanographique de la Marine) tide tables. The high-shore was immersed for 640 h yr^{-1} while the low-shore was immersed for 4103 h yr^{-1}. Average annual air and sea surface temperatures were calculated from data recorded in the vicinity of each sampling site by Météo-France and PREVIMER (IFREMER) (Table 1).

2.3. Biomass measurements

During summer 2012 specimens of each group have been collected at low tide from rocky shores near Brest, France (48°21′5″N, 4°34′11″ W). For each species, average biomass for each level and season was calculated by multiplying the average individual biomass (g ash-free dry weight, AFDW) by the number of individuals. To obtain more accurate biomass estimates for larger animals, limpets and mussels were divided into two size classes (above 25 mm or below 25 mm in length) during photo analysis, and the average individual biomass was then estimated accordingly.

To calculate average individual biomass of each species, five groups with 1 to 5 individuals of the same species were dried at 60 °C for 24 h and subsequently calcinated at 450 °C for 4 h in a muffle furnace. Average individual biomass was calculated from the regression between biomass and number of individuals.