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Potential environmental drivers of a regional blue mussel mass mortality event (winter of 2014, Breton Sound, France)

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ABSTRACT

In the context of global change, increasing mariculture production has raised particular concerns regarding its environmental impact and sustainability. Molluscs and particularly blue mussel account for a significant part of this total production. Although blue mussels are considered to be pretty resilient to environmental disturbances, we report in this study an unprecedented mussel mortality event that occurred during the winter of 2014 in the Breton Sound. 9000 metric tonnes of mussels were lost and mortality rates up to 100% were recorded at some farming areas. Through a coupling approach, the present work aims to better understand the potential environmental drivers associated with those mortalities. Firstly, we analysed long-term *in situ* and satellite data from environmental monitoring networks (available since 1998) to characterize the variability of seawater masses of the sound during the winter of 2014. Secondly, we used modelling simulations to study the possible relationship between seawater hydrodynamics and observed spatio-temporal patterns of mussel mortalities. From January to April 2014 at the long-line culture site where mortalities started, seawater temperatures ranged from 8.3 to 13.3 °C (10.2 ± 0.8 °C). Salinity and turbidity values showed successive and short drops (below 16; 29.3 ± 2.3) and numerous peaks (above 70 NTU; 17.4 ± 13.4 NTU) respectively. Winter conditions of 2014 were encountered along the entire French Atlantic coastline and linked to the sixth highest positive North Atlantic Oscillation (NAO+) index recorded since 1865. These particular environmental variations characterized the winter of 2014 but also others whereas no comparable mussel mortality rates were reported. Exact causes of the 2014 mortality event are still unknown but we showed these environmental variations could not alone be responsible. These have likely affected the sensitivity of the blue mussel populations that were already weakened by early spawning. Meanwhile, these may have facilitated the apparition of a pathogenic strain of *Vibrio splendidus* isolated on moribund mussels at that time. Our modelling simulations suggested that this pathogenic strain could spread through hydrodynamic patterns and drive the observed mussel mortalities. If this pathogenic strain recurs in future years, particularly with the added stress associated with climate change, mussel mass mortality events may exceed the resilience of this species.

1. Introduction

Globally marine ecosystems are among the most valuable and heavily used natural systems (Staudinger et al., 2012). They provide many ecosystem services including shoreline protection, tourism activities, seawater filtration, nursery grounds, food from fisheries and aquaculture (MEA, 2005; Ruckelshaus et al., 2013). Worldwide, aquaculture has grown rapidly and currently represents the fastest growing sector of the food industry. It has increased at a rate of approximately 8% per year since the 1970′s (Mckindsey et al., 2011; FAO, 2013). Global mariculture production is now close to 40% of total aquaculture production. 75% of mariculture results from shellfish production with molluscs (*i.e.* mussel, oyster, and abalone) accounting for 71% of the total production (Bouwman et al., 2013). This increased production and the associated issues have raised concerns regarding interactions between mariculture and local environments (Black, 2001). Several studies have aimed to understand the role of bivalve farming in terms of ecosystem services and

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also environmental impact and sustainability (Davenport et al., 2003; Holmer et al., 2008). For example, enhanced localized biodeposition (Mattsson and Lindén, 1983), seawater column filtration (Troost et al., 2009), and nutrient and oxygen exchange modifications (Richard et al., 2007) as a result of the presence of bivalve farms are commonly addressed. Disease transfer and hitchhiking species are also major concerns (McKindsey et al., 2007). Similarly the wider ecological effects including the novel habitat emergence from exotics or/and aquaculture escapees are studied (Forrest et al., 2009; Lallias et al., 2015).

Europe currently produces approximately 800000 t of molluscs. This represents 24% of the overall EU aquaculture production in mass and approximately 50% in value (Robert et al., 2013). Annual French production accounts for approximately 160000 t of bivalves with nearly 50% of the oyster *Crassostrea gigas* (79000) and 48% of mussels (*Mytilus edulis* and *M. galloprovincialis*: 77000 issued from aquaculture) (Agreste, 2014). French oyster production has undergone a drastic decline from 108000 to 80000 t over the last ten years due to epizootic events (Samain et al., 2007; Nicolas et al., 2007; Agreste, 2014; Pernet et al., 2012, 2016). Despite a 5.4% increase in mussel production along the French Atlantic coastline since 2001, a particular decrease in *M. edulis* growth performance has been recorded, especially in 2011 (Rodriguez, 2013).

During the winter of 2014, unprecedented mass mortalities of *M. edulis* occurred in a coastal inlet of the mid-French Atlantic Ocean, the Breton Sound. 9000 t of mussels were lost and mortality rates up to 100% were recorded at some farming areas. This mortality event had high economic consequences since this area shelters important blue mussel farming sites with an overall marketed production representing 8705 t or 12% of the total French volume (Agreste, 2014). This rearing area also plays a critical role for spat collecting operations at a national level and sustains the spat supply to several other French rearing areas.

This 2014 event was particularly surprising since *M. edulis* was so far considered to be a resilient cultivated species and sustainable aquaculture production. Contrarily to the Pacific oyster *C. gigas* culture, very few mass *M. edulis* mortalities occurred along the French Atlantic coast and specifically over the Breton Sound until the winter of 2014. For example, the parasite *Mytilicola intestinalis* induced mortality rates up to 100% locally at off-bottom culture sites in 1960 and 1961 (Brienne, 1964). Mussel production declines have been related to abnormal hydroclimatic conditions, such as in the spring of 1989 where abundant rainfall and sudden salinity variations with values below 13 led to reduced growth rates rather than mussel mortality (Dardignac et al., 1990). Similarly, strong summer sunshine radiation associated with dry winds, particularly during emersion periods, induced a reduction mussel spat survival during heat waves in 1989, 1990 and 1991 (Dardignac and Prou, 1995). Massive mussel declumping from off-bottom culture sites due to a weakened byssus by high seawater temperatures (above 25 °C) were also observed during the heat wave in the summer of 2003 (Robert and Le Moine, 2003). Eventually in 2011 during the third hottest spring since 1976, low mussel production characterized the entire French Atlantic coast without a significant mortality rate (Rodriguez, 2013).

On a global scale, few mass mortality events were reported in farmed mussels either (Eggermont et al., 2014). Munford et al. (1981) attributed a *M. edulis* mass mortality event in Italy to a trematode infection. In the spring of 2001, 10000 t of mussels were lost in the Oosterschelde Estuary (Netherlands) due to a combination of high river discharge, strong northerly winds and the transport and sedimentation of a Phaeocystis bloom (Peperzak and Poelman, 2008). Earlier, Dutch mussel volumes were significantly impacted by the high abundance of the parasite copepod *M. intestinalis* during the autumn and spring of 1949 and 1950, respectively (Meyer and Mann, 1951).

Because of its singularity, the blue mussel mass mortality event observed in the winter of 2014 in the Breton Sound led to preliminary consulting studies (Béchemin et al., 2014; Garcia et al., 2015; François, 2015). These latter studies suggested two potential causes of mortality (i) the existence of particular environmental conditions over winter and (ii) the apparition of a pathogenic organism that could both weaken mussels' populations and lead to observed mortalities. A pathogenic *Vibrio splendidus* bacterial strain was specifically detected in 80 to 100% of the analysed mussels in the sound at that period (Garcia et al., 2015; François, 2015). We proposed in this work to study in more detail the potential environmental drivers associated to the specific spatio-temporal patterns of mussel mortalities. Firstly, through an original coupling approach, we described and characterized the sub-surface seawater masses (from January to April 2014) using *in situ* measurements from Ifremer monitoring networks and satellite-derived chlorophyll *a* and non-algal suspended particulate matter. We statistically compared the specific environmental conditions from the winter of 2014 to larger temporal scales using a multi-decade time-series of *in situ* and satellite data available since 1998. Secondly, through 3D hydrodynamic model simulations, we discussed the potential links between field observed patterns of mussel mortality rates and the existence of a pathogenic organism (*V. splendidus* in that case) that could have spread progressively from one culture site to others. In conclusion, a plausible scenario endorsed by the different observations and *in situ*-satellite-modelling approach was developed.

2. Materials and methods

2.1. Study site

The Breton Sound represents a coastal area inlet of the Poitou-Charentes region located on the French Atlantic coast between Ile de Ré and the continent (Fig. 1). The sound is characterized by a mean surface area and volume of 425 km^2 and 4920 million m^3, respectively (Stanisière et al., 2006; Soletchnik et al., 2015). Nearly 20% of this 13.8 meter deep coastal bay correspond to intertidal areas. It allows the settlement of both off-bottom ("bouchots") and long-line ("filières") mussel culture farms (4.5 km^2 in total) where blue mussels have been farmed since the 13th and 20th centuries respectively. Off-bottom farms ("bouchots") consist of rows of wooden poles where mussels are grown directly on it (Fig. 1); they're deployed perpendicularly to the shore and stuck in the sandy/muddy bottom within the gently sloping intertidal strip. Long-line farms ("filières") consist of long-line systems with dropper sleeves or mussel socks (Garen et al., 2004). The Breton Sound is under the influence of a main watershed of 4074 km^2. The Lay and the Sèvre Niortaise Rivers, with mean discharges of 14 and 44.4 $m^3\ s^{-1}$, respectively, represent the main freshwater inputs to the sound (Soletchnik et al., 2015) (Fig. 1). It also receives significant external inputs from the Loire and Gironde Estuaries at the north and south, depending on hydrodynamic and meteorological forcing (Soletchnik et al., 2015). Semi-diurnal tides from the Atlantic Ocean enter the sound by openings between 2 and 10 km long (Fig. 1). Along with winds and river discharges, these determine the general circulation and renewal time of seawater masses. The renewal times for the Breton Sound are generally above 85 days compared to solely 2 to 18 days for the Marennes-Oléron Bay further south (Stanisière et al., 2006; Kenov Ascione et al., 2015).

2.2. Sampled seawater stations and in situ data

Two main stations were monitored during the present study to permit spatial and temporal *in situ* data comparisons in the sound: Station A, associated to a long-line mussel culture site in the centre of the sound where the mortalities first appeared, and Station C up north associated to off-bottom farms reached by mortalities later (Fig. 1 and Table 1). Phytoplankton communities and related water column variables (sub-surface ~0.50 m seawater temperature, salinity, chlorophyll *a* concentration and turbidity, Table 1) were evaluated *via* the French Phytoplankton Monitoring Network REPHY (Ifremer) at least twice a month (Belin and Raffin, 1990).