The Effect of Climate Variability on the Abundance of the Sandy Beach Clam (*Mesodesma mactroides*) in the Southwestern Atlantic

Gastón Manta ‡*, Marcelo Barreiro †, Leonardo Ortega ‡, and Omar Defeo ‡‡

1Departamento de Ciencias de la Atmósfera
Universidad de la República
Montevideo 11400, Uruguay

2Dirección Nacional de Recursos Acuáticos
Montevideo 11200, Uruguay

3Unidad de Ciencias del Mar
Universidad de la República
Montevideo 11400, Uruguay

ABSTRACT

Manta, G.; Barreiro, M.; Ortega, L., and Defeo, O., 0000. The effect of climate variability on the abundance of the sandy beach clam (*Mesodesma mactroides*) in the southwestern Atlantic. *Journal of Coastal Research, 00(0), 000–000. Coconut Creek (Florida), ISSN 0749-0208.*

The yellow clam *Mesodesma mactroides* is a fast-growing, short-lived species that inhabits sandy beaches of the southwestern Atlantic Ocean (SAO). The purpose of this study was to relate interannual fluctuations of the yellow clam population in Uruguay to climate circulation anomalies in the SAO. Twenty-three years of clam abundance, as well as sea-surface temperature anomalies (SSTA), salinity, and wind stress anomalies (WSA) from oceanic reanalyses were used. Composites and linear regressions showed that the best scenario for high abundance of *M. mactroides* is characterized by cold and salty waters and onshore WSA on the Uruguayan Atlantic coast. These local WSA are part of a cyclonic configuration of WSA in the SAO that forces negative SSTA in the region. High and low *M. mactroides* abundance tended to occur along with La Niña and El Niño events in the equatorial Pacific Ocean, respectively. These results suggest that interannual fluctuations in *M. mactroides* abundance are not only locally but also remotely controlled by regional- and global-scale climate variability modes.

ADDITIONAL INDEX WORDS: ENSO, composites, oceanic reanalyses, SODA, C-GLORS.

INTRODUCTION

Exposed sandy beaches dominate the ice-free shores of all continents and provide important commercial resources in many areas (McLachlan et al., 1996). Many beaches, especially those of the dissipative type, support rich biotas, of which clams are often an important component, especially in terms of biomass (Defeo and McLachlan, 2005). Contractions or expansions in the geographic range of clams, as well as changes in biomass (Defeo and McLachlan, 2005). Contractions or expansions in the geographic range of clams, as well as changes in their population structure, vary according to environmental conditions in the geographic range of clams, as well as changes in their population structure, vary according to environmental settings. Indeed, direct environmental variables (e.g., temperature, oxygen, grain size) have an unequivocal physiological influence on habitat suitability for benthic species (e.g., Huntley and Scarponi, 2015; Peterson et al., 2011). Recruitment tends to occur regularly in source areas and to be irregular or spasmodic in sink areas or marginal portions of the habitat (i.e. the habitat favorability hypothesis: Caddy and Defeo, 2003; Defeo et al., 2013). Thus, management of clam fisheries through harvest controls alone will be ineffective if these environmentally driven variations in abundance and habitat quality are not taken into account (Caddy, 2007).

The southwestern Atlantic Ocean (SAO) surface winds drive an open ocean circulation characterized by intense western boundary currents, with a poleward-flowing warm and salty Brazil Current and an equatorward-flowing cold and relatively fresh Malvinas Current (Peterson and Stramma, 1991). These two currents converge near 38°S, generating the highly energetic and productive Brazil/Malvinas Confluence (Machado, Barreiro, and Calliari, 2013; Olson et al., 1988). These currents in turn influence the continental shelf circulation (Piola et al., 2000). The Uruguayan shelf hydrography is characterized by a marked seasonality related to the southward displacement of the South Atlantic high-pressure cell during summer, with northward wind and shelf currents in winter and southward in summer (Möller et al., 2008; Strub et al., 2015). Interannual variability is strongly linked to El Niño–Southern Oscillation (ENSO). During El Niño years, positive sea-surface temperature anomalies (SSTA) and northerly wind stress anomalies (WSA) are observed in the SAO. In Uruguay, particularly in spring, precipitation, and consequently freshwater discharge, tends to increase, freshening waters along the coast. During La Niña years, the opposite condition tends to occur (e.g., Barreiro, 2010).

The yellow clam *Mesodesma mactroides* Reeve, 1854 is a fast-growing, short-lived species (<4 y) found in sandy beaches of the SAO from Brazil (24° S) to Argentina (41° S) (Defeo, Jaramillo, and Lyonnet, 1992; Fiori and Defeo, 2006). Large interannual fluctuations in *M. mactroides* abundance have been observed in Barra del Chuy (Uruguay), even in the absence of fishing (Defeo et al., 2013; Ortega et al., 2016), suggesting a role for environmental conditions. Previous studies have shown that the distribution and abundance of *M. mactroides* appear to be modulated by recruitment pulses driven by environmental factors (Ortega et al., 2012). In the present paper, the response of *M. mactroides* at Barra del Chuy...
Environmental data and statistical analysis used are also detailed. Environmental data used from oceanic reanalysis and the beach and the sampling design of the yellow clam. The Collection Beach Description, Environmental Settings, and Data Collection

Mesodesma mactroides in Uruguay mainly occurs at Barra del Chuy beach (33°40′ S, 53°29′ W), a 22-km stretch of uninterrupted microtidal sandy beach with dissipative characteristics limited by two freshwater outlets, the Andreoni Canal and the Chuy Stream (Ortega et al., 2013). Sea-surface temperature (SST) ranges from 12 to 24°C over the year and interannual variability is also high (2°C). Moreover, sea-surface salinity (thereafter salinity) strongly fluctuates, mainly due to the effect of the Andreoni Canal, the Chuy Stream, and the Rio de la Plata (RdIP) discharges. Mean wind direction is from NE in spring–summer and SW in autumn–winter, when RdIP discharge is also higher (Ortega and Martinez, 2007; Strub et al., 2015; Figures 1, S1, and S2). Mesodesma mactroides is artfully harvested with hand-gathering techniques in the intertidal zone of sandy beaches from Brazil, Uruguay, and Argentina (Defeo, 2003). In Uruguay, fishing started in the 1960s and evolved from an open-access system to a regulated fishery during the 1980s, and the fishery was closed because of overexploitation in April 1987. Two years after the closure, adult clam density increased by more than 400% and the fishery was reopened from December 1989 onward under a co-management framework (Defeo, 1996). This governance mode lasted until late 1994, when mass mortalities decimated populations of M. mactroides throughout its range (Ortega et al., 2016). The fishery was reopened as a co-management system in 2008 after a partial recovery of the stock, using a precautionary approach that included very low harvesting levels (Gianelli, Martinez, and Defeo, 2015).

METHODS

This section provides information about Barra del Chuy beach and the sampling design of the yellow clam. The environmental data used from oceanic reanalysis and the statistical analysis used are also detailed.

Environmental Data and Statistical Analysis

Environmental Data and Statistical Analysis

Yellow clams were obtained from seasonal surveys carried out in Barra del Chuy beach during 23 consecutive years (1986 to 2008). A systematic sampling design was used by setting 22 equidistant transects perpendicular to the shoreline. Along each transect, sampling units were obtained with a corer 28.2 cm in diameter and 40 cm in depth at 4-m intervals, starting at the sand dunes and continuing seaward until two consecutive sampling units yielded no yellow clams (Lima, Brazeiro, and Defeo, 2000). Specimens were measured (maximum valve length) and counted, covering the full range of individual sizes (1 to 76 mm). Annual abundance was estimated by averaging seasonal estimates of the number of individuals per strip transect (ind. m⁻²) following Defeo (1996).

Environmental Data and Statistical Analysis

The Uruguayan coast is a very poorly environmentally sampled region, which hampers the identification of local environmental conditions that modulate the interannual abundance of M. mactroides. However, since coastal variability responds to regional patterns of atmospheric and oceanic circulation, reanalysis data could be used to determine the main anomaly patterns associated with clam abundance. The Simple Ocean Data Assimilation (SODA 2.1.6) reanalysis (Carton and Giese, 2008) and Global Ocean Physics Reanalysis (C-GLORS) (Storto, Masina, and Navarro, 2016) were used. Both reanalyses assimilate a historical archive of hydrographical profiles supplemented by ship intake measurements, moored hydrographical observations, Argos drifters, and remotely sensed SST and sea level to an ocean general circulation model. Annual averages from 1986 to 2008 of wind stress, SST, and salinity in the SAO (15–45°S and 65–25°W) were used, and the corresponding anomalies were calculated by subtracting the mean of the study period. SODA has horizontal resolution of 0.5° × 0.5° and C-GLORS 0.25° × 0.25° near Barra del Chuy. The main differences between the SODA and C-GLORS are grid size, the data assimilation method used, and the number of observations assimilated in each interpolation. C-GLORS assimilates a larger number of observations for the salinity field. A correlation analysis between C-GLORS and SODA data revealed that, for SST, all grid points had values higher than 0.7 \( p < 0.05 \) (Figure 2a). On the other hand, for salinity there was no significant correlation is high only over the southern Brazilian and Uruguayan shelf.
correlation between reanalyses in the study region of the SAO (Figure 2b). Highest correlations (above 0.7) were observed over the Uruguayan and southern Brazilian shelf. Thus, for SST both SODA and C-GLORS were used, whereas C-GLORS was used for salinity because it assimilates more observed data and better represented the RdIP’s complex dynamics.

The spatial dependence between annual variations in abundance of *M. mactroides* in Barra del Chuy and annual mean anomalies at each grid point in the SAO were assessed using Pearson correlation coefficient values. Statistical significance was determined by a Student’s t test (α = 0.05). Composites were also used to study the behavior of environmental variables associated with yellow clam abundance:

\[
\hat{\mu}_h = \frac{1}{N} \sum \mu(i) - \bar{\mu}_n
\]

where \(\hat{\mu}_h\) = composite associated with (high-) low-abundance years, \(\mu(i)\) = mean of environmental anomalies during (high-) low-abundance years, \(\bar{\mu}_n\) = mean of environmental anomalies during neutral-abundance years. (High-) low-abundance years are those (above) below \(\mu \pm \sigma\), whereas neutral years are those between \(\mu \pm \sigma\); the mean abundance \(\pm\) its standard deviation, respectively (Figure 3). The significance of the composite was determined using the difference of means test (α = 0.05) following section 6.6 of Von Storch and Zwiers (2001). To explore the potential relationship between abundance of *M. mactroides* and SST in the SAO and tropical Pacific and Atlantic oceans, composites were constructed using the optimum interpolation SST data set of Reynolds et al. (2002) with a horizontal resolution of 1° × 1°.

RESULTS

Long-term variations in abundance of *M. mactroides* in Barra del Chuy (Uruguay) are observed (Figure 3). The spatial pattern of the correlation between *M. mactroides* abundance in Barra del Chuy and SST and WSA shows that increased yellow clam abundance is associated with an SST pattern characterized by negative and positive anomalies south and of 20° S, respectively, as well as with a cyclonic configuration of WSA in the SAO. Along the Uruguayan coast, a locally significant negative correlation between clam abundance and SST is observed (p < 0.05) together with a positive, although nonsignificant, correlation with an onshore WSA configuration in Barra del Chuy (Figure 4a).

Composites show overall linearity in the structure of the regional anomalies associated with high yellow clam abundance years (Figure 5). Positive and negative SST north and south of 20°S are observed respectively, concurrently with a cyclonic configuration of WSA in the SAO during high-abundance years. An opposite behavior during low-abundance years is found in the open ocean, with negative and positive SST north and south of 20°S, respectively, accompanied by an anticyclonic configuration of WSA in the SAO. Over the Uruguayan and southern Brazilian shelves, the SST composites for high- and low-abundance years are not opposite: the SST in the shelf near Barra del Chuy is about −0.8°C (p < 0.05) from SODA.

Figure 3. Long-term variations in abundance of *Mesodesma mactroides* in Barra del Chuy (Uruguay) estimated from sampling surveys conducted between 1986 and 2008. Dotted lines show the mean long-term abundance ± 1 standard deviation, which was used for the classification of composites. Black circles indicate years with a beginning of a moderate or strong El Niño event; white circles show years with a beginning of a moderate or strong La Niña event. Gray circles indicate neutral ENSO years. Large interannual variability in clam abundance is observed. Minimums of abundance tend to occur mainly during an El Niño year. Data from ENSO 3.4 index.

Figure 4. Pearson correlation coefficient values between abundance of *Mesodesma mactroides* in Barra del Chuy (Uruguay) and annual mean anomalies of: (a) sea-surface temperature (SSTA, in shades, °C) and wind stress (WSA, in arrows, N m−2) and (b) sea-surface salinity. Bold contours and bold arrows indicate significant regions (p < 0.05). Low abundance is correlated with negative SST and southerly WSA over a large region between 25 and 40°S. At the same time, increased abundance is related to salty conditions over the Uruguayan shelf and diluted waters to the south of the Rio de la Plata outlet. Environmental data from (a) SODA and (b) C-GLORS.

Figure 5. Composite associated with: (a) high and (b) low annual values of *Mesodesma mactroides* abundance in Barra del Chuy (Uruguay) for the period 1986–2008. Mean sea-surface temperature anomalies (SSTA) in shades (°C) and mean wind stress anomalies (WSA) in arrows (N m−2). Bold contours enclose significant SST data regions (p < 0.05). Only high-abundance cases are significantly related to environmental anomalies over the shelf. No significant regions are observed for WSA. SSTA and WSA data from SODA.
The best scenario for high-abundance years of *M. mactroides* was characterized by a cyclonic configuration of WSA in the SAO, with cold and salty waters and onshore WSA in Barra del Chuy. It is worth stressing that the cyclonic configuration of WSA in the SAO that accompanies an increase in clam abundance has a much larger spatial scale than the study site, thus affecting a large oceanic region. It is hypothesized that these atmospheric circulation anomalies increase and decrease the oceanic heat loss south and north of 20° S respectively, leading to the observed SSTA dipole in the open ocean (Barreiro et al., 2004). Dynamic processes on the shelf may further modify this large-scale thermodynamic forcing, increasing the influence of local SSTA in yellow clam abundance (see Figure 5).

A higher abundance of *M. mactroides* associated with negative SSTA in Barra del Chuy and all along the southern Brazilian shelf was identified. Moreover, whereas composites suggest that cold years are a trigger for high abundance, warm years do not necessarily negatively affect the yellow clam population. This preference for cold conditions may reflect the remote influence of El Niño, which has been already identified as a driver of mass mortalities in clams of the same genus along the Pacific coast (Ortega et al., 2012). Of the three years with low abundance, two (1997 and 2002) occurred during the beginning of an El Niño event and the other one (1995) was preceded by the mass mortality event that occurred in November 1994. The link between El Niño and low-abundance years could also be related to increased rainfall in the RdlP basin that leads to a higher river discharge and, consequently, fresher waters along the coast. High-abundance years, on the other hand, are mainly La Niña years with onshore WSA, coming mainly from the SE, that push the plume against the Argentinean coast. This is consistent with laboratory observations that showed reduced or no clam survival exposed to low salinity for a few days (Sauco et al., 2013). This is also in agreement with the fact that no yellow clam populations are found in sandy beaches of the RdlP estuarine region. It is worth pointing out, however, that no significant correlation between abundance and salinity along the coast was detected, possibly because the large coastal variability of this variable is not captured by the reanalysis. In addition to the increased freshwater discharge, El Niño events have been shown to promote cyclogenesis in the region (Gan and Rao, 1991), which may induce increased beach erosion and sea-level change (Ortega et al., 2013), causing habitat degradation and potential mass stranding and mortality of benthic organisms.

High yellow clam abundance years in Barra del Chuy were associated with wind stress having a SE (onshore) direction. These onshore winds favor the advection of sub-Antarctic waters over the shelf during cold periods, and could promote blooms of surf phytoplankton that accumulate in the surf zone. Indeed, the passage of cold fronts associated with onshore winds favor the accumulation and growth of the surf zone diatom *Asterionellopsis glacialis* (Odedrech et al., 2010 and references therein), which is the main food source of *M. mactroides* (Lercari, Bergamino and Defeo, 2010). This is consistent with observations made at Cassino Beach (Brazil),
which is located in the same ecoregion (250 km NE of Barra del Chuy) with similar beach orientation and morphodynamics (Odebrecht et al., 2010). This supports high yellow clam abundance during cyclonic atmospheric events, which represents a regional weakening of the semipermanent subtropical high pressure in the SAO, favoring the passage of cold fronts in the region. High yellow clam abundance years were also modulated by ENSO (see also Lima, Brazeiro and Defeo, 2000). Clam abundance could be negatively affected by increasing SST, favoring warm-water species such as the wedge clam Donax hanleyanus and the mole crab Emerita brasiliensis, which are subordinate competitors for space and food in this suspension-feeding guild (Defeo et al., 2013; Ortega et al., 2012).

Several studies have reanalyzed to assess the role of environmental factors in marine populations (i.e. Bertrand et al., 2008; Maunder et al., 2006; Pacariz, Westerberg, and Björk, 2014), though it still remains infrequently used. In this paper, oceanic reanalyses were useful to determine the environmental configuration associated with ecological processes and allowed the identification of large-scale patterns in atmospheric and oceanic conditions as putative explanatory factors of long-term fluctuations in abundance of M. mactroides. This could set the basis for future research efforts in modeling the abundance and spatial distribution of shellfish, which should be taken into account by fisheries management schemes.

**CONCLUSIONS**

The best scenario for high abundance of M. mactroides is characterized by a cyclonic configuration of WSA in the SAO, with cold and salty waters and onshore WSA in the Uruguayan Atlantic coast (Figures 4 and 5). On the other hand, low abundance tends to occur during El Niño years, due to high SST and fresher waters along the coast resulting from increased rainfall in the RdlP basin that leads to a high runoff (Figures 3 and 6). These results suggest that the interannual fluctuations in M. mactroides abundance are not only locally but also remotely controlled by regional- and global-scale climate variability modes.

**ACKNOWLEDGMENTS**

We thank the Benthic Ecology Group of Unidad de Ciencias del Mar for field and laboratory assistance and the creators of SODA and C-GLORS for the data provided. Zen Faulkes and other three anonymous referees provided useful suggestions that improved the manuscript. Gastón Manta is grateful for the support provided by Agencia Nacional de Investigación e Innovación (ANII, INI_2013_1_101134) and Programa de Desarrollo de las Ciencias Básicas (PEDECIBA). Omar Defeo and Leonardo Ortega are grateful for Inter-American Institute for Global Change Research (grant CRN3070), which is supported by the U.S. National Science Foundation (grant GEO-1128040).

**LITERATURE CITED**


