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Wind-driven diurnal temperature variability across a small bay and the spatial pattern of intertidal barnacle settlement

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ABSTRACT

Temperature variability under different wind conditions and its association with the spatial pattern of settlement of three intertidal barnacles – the chthamaloids *Jehlius cirratus* and *Notochthamalus scabrosus*, and the balanoid *Notobalanus flosculus* – were studied across Cartagena Bay, located in the upwelling region of central Chile. During days of strong winds, the diurnal signal in surface temperature at the protected end of the bay (site CTGN) was attenuated and decoupled from the northern sites (ECIM and PCHC) which are directly exposed to wind forcing, suggesting that wind intensity drives shifts in the relative importance of physical transport processes across the bay. Overall, the mean settlement rates of both chthamaloids were higher at PCHC, whereas *N. flosculus* settled at higher rates in CTGN. Under strong wind conditions, settlement rates of both chthamaloids decreased at the northern sites, while the settlement of *N. flosculus* reached minima at all three sites. Moreover, the effect of wind stress on the spatial pattern of settlement across the bay differed between species. A significant and positive correlation between the spatial heterogeneity of settlement and maximum daily wind stress – used as a metric for the intensity of the afternoon sea breeze – was found only for *J. cirratus*. It is concluded that daily changes in wind stress have a strong effect on the spatial pattern of diurnal temperature fluctuations, and on the spatial pattern of barnacle settlement around the bay. Such association emerges from the effect of wind on near-shore circulation and its differential modulation of thermal structure around an open embayment and, by extension, on the patterns of larval transport and onshore delivery to sites located at extremes of the bay, which probably is common in other bays with similar characteristics.

1. Introduction

Over the years, many studies have attempted to link the patterns of larval transport and settlement in marine benthic species with coastal physical processes (Lagos et al., 2008; Pineda, 1991; Pineda and López, 2002; Roughgarden et al., 1988; Shanks, 2009; Vargas et al., 2004; Wing et al., 1995). The interest stems from the fact that patterns of coastal circulation and larval transport can influence the structure and functioning of individual populations (Roughgarden et al., 1988), interacting species (Aiken and Navarrete, 2014; Salomon et al., 2010) and benthic communities (Caro et al., 2010), through their effect on the spatial pattern and timing of larval delivery to near-shore environments. Since planktonic larval stages of benthic invertebrates are small and have limited capabilities for horizontal swimming – relative to the typical speeds of surface currents in the coastal ocean – the cross-shore transport of invertebrate larvae is thought to be strongly modulated by physical processes (e.g. Cudaback et al., 2005; Kaplan and Largier, 2006; Kirincich et al., 2005).

Near-shore circulation is highly complex and variable, both temporally and spatially, due to the combined forcing of various physical processes and their interaction with coastal topography (e.g. Kirincich et al., 2005; Lentz and Fewings, 2012; Sobarzo et al., 2010). Along eastern-boundary regions, circulation on the continental shelf is largely influenced by wind-driven coastal upwelling, which dominates cross-shelf transport of water, its properties, and suspended particles over synoptic timescales. Synoptic variability and the seasonal variation in coastal winds that characterizes most temperate systems, have been the focus of most 'supply-side' studies. However, substantial variability in circulation and transport may result from diurnal fluctuations in wind forcing, i.e. over 24-hour cycles. The sea breeze, perceived in mid to low latitudes as an afternoon intensification of onshore winds, has been identified as one of the most important processes that modulate the thermal structure of the water column and circulation in near shore environments with a regular diurnal periodicity (Bonicelli et al., 2014;

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Dellatorre et al., 2012; Kaplan et al., 2003; Sobarzo et al., 2010; Tapia et al., 2004; Woodson et al., 2007). A number of studies have focused on diurnal variability in cross-shelf transport and settlement patterns (e.g. Jacinto and Cruz, 2008; Kaplan et al., 2003; Tapia et al., 2004), in an attempt to assess the effect of physical processes with a strong diurnal signal on larval transport in coastal environments. Establishing this connection is especially important for the understanding of mechanisms and scales of variability that shape settlement patterns of invertebrate species in subtidal and intertidal environments.

Recently published studies have documented the effects of diurnal fluctuations in wind forcing on local circulation in temperate bays embedded in upwelling regions (e.g. Bonicelli et al., 2014; Woodson et al., 2007). Work centered on small open bays provides a unique opportunity to study the effect that spatial changes in the interaction of wind and coastline configuration may have on nearshore circulation, and the resulting spatial changes in larval transport, onshore larval settlement, and population renewal in many species of coastal invertebrates.

Cartagena Bay is a small south-facing open embayment bay located in the lee (20 km north) of the Punta Toro upwelling center in central Chile (Narváez et al., 2004; Wieters et al., 2003). Diurnal wind variability has a strong influence on temperature variability and circulation around the bay (Kaplan et al., 2003; Narváez et al., 2004; Piñones et al., 2005). Surface waters tend to be warmer and the water column is usually more strongly stratified within this bay (Kaplan et al., 2003; Narváez et al., 2004). A recent study (Bonicelli et al., 2014) showed that patterns of diurnal variability in water-column temperatures may vary substantially across the bay, with a strong diurnal signal at the northern and more exposed end, and persistent stratification at the southern and more protected end, despite the strong sea breeze that develops during the afternoon (see Kaplan et al., 2003; Piñones et al., 2005). This spatial heterogeneity in temporal variability of water-column temperatures, largely induced by differential forcing of diurnal winds, may affect meroplankton distribution by modifying cross-shore transport processes, and ultimately may affect spatial patterns of larval settlement at the shoreline.

A previous study conducted in Cartagena Bay over three consecutive spring–summer seasons (Tapia and Navarrete, 2010) showed inter-annual changes in the persistence of spatial pattern in settlement, and hypothesized that such change could arise from inter-annual variation in coastal wind, through its effect on local circulation and larval supply to intertidal habitats. Here, the same set of daily settlement observations is used together with time series of water temperature and wind stress, to assess whether daily wind variability affects the spatial pattern of settlement of 3 intertidal barnacles (*Jehlius cirratus*, *Notochthamalus scabrosus*, and *Notobalanus flosculus*) around Cartagena Bay. Based on previous work (Bonicelli et al., 2014), it was hypothesized that changes in wind conditions affect settlement patterns by way of their effect on circulation and larval transport around the bay. Such changes in near-shore circulation should be reflected by changes in the pattern of temperature variability around the bay.

2. Material and methods

2.1. Barnacle settlement and study sites

Daily records of larval settlement rates were estimated for three species of intertidal barnacles which are numerically dominant in the mid to low intertidal zone of wave exposed rocky shores around Cartagena Bay: the chthamaloids *J. cirratus* and *N. scabrosus*, and the balanoid *N. flosculus*.

Settlement observations were conducted daily and simultaneously at three sites spanning Cartagena Bay on three consecutive spring to early summer seasons (October–December, 2006–2008), and for an average of 57 consecutive days. Settlement was monitored using 10 × 10 cm Plexiglas plates covered with a gray rubbery surface (Safety-walk, 3M), and attached to the substrate with stainless steel screws (see Tapia and Navarrete, 2010 for more details). Two sites (ECIM, PCHC) were located at the northern end of the bay, whereas a third site (CTGN) was located at the southern end (Fig. 1).

2.2. Environmental data

Wind data for October 2006 through December 2008 were obtained from a meteorological station maintained by the Chilean Navy's DIRECTEMAR at the lighthouse Faro Panul, located 3 km south of the southern end of the bay and at 30 m above sea level (33° 34.898′S, 71° 37.160′W) (Fig. 1). Records of shallow subtidal water temperature were gathered at all three sites using Stowaway TidBit loggers (Onset Computer Corp., USA) that were programmed to record temperature at 5 min intervals. Loggers were installed at 1 m below the Mean Lower Low Water (MLLW) from October 2006 until December 2008 (Fig. 1).

2.3. Data processing and analysis

Wind velocity vectors were rotated according to the wind's principal axis of variability. In this rotated coordinate system, the along-shore component of wind (y) is positive toward the northeast, whereas the cross-shore component (x) is positive toward the southeast (Fig. 1). Wind stress was then calculated following Large and Pond (1981).

Daily maxima for alongshore wind stress (τ_{ym}), recorded over the three consecutive settlement seasons, were used to classify days with temperature and settlement data into three categories according to their frequency distribution (Fig. 2): (1) "strong wind" days when stress was equal or greater than the 75th percentile of the distribution ($\tau_{ym} \geq 0.06$ N m^{-2}), (2) "moderate wind" days when wind stress was between the 25th and 75th percentiles of the distribution (0.01 N/m$^{-2} < \tau_{ym} < 0.06$ N m^{-2}), and (3) "weak wind" days when wind stress was equal or less than the 25th percentile of the distribution ($\tau_{ym} \leq 0.01$ N m^{-2}). To characterize the daily cycle in surface water temperature and its spatial variability as a result of wind changes, the canonical day was computed for each site under different wind conditions. Daily amplitudes in water temperature were also calculated and compared between sites for each wind scenario. Amplitudes were determined via the least-squares fitting of a sinusoidal polynomial to each temperature signal.

To evaluate the effect of wind intensity on the among-site synchrony of settlement, Kendall correlations between settlement rates at pairs of sites were computed for each wind condition (weak, moderate, strong). Positive and significant correlation may reflect synchrony in the timing of settlement across the bay. Only days with 12 or more larvae collected across the three sites were used for this analysis.

In order to evaluate the effect of wind stress on the spatial pattern of settlement, a spatial coefficient of variation (SCV) was computed and used as a proxy for the heterogeneity of barnacle settlement. The SCV was calculated between the settlement rates of the three sites on days with 12 or more settlers collected across the three sites. Since 4 plates were used to monitor settlement at each of the 3 sites, a minimum of 12 settlers corresponds to the count that would be found if settlement was completely homogeneous, i.e. one larva per settlement plate. For each day with settler counts meeting this criterion (118, 128, and 108 days for *J. cirratus*, *N. scabrosus*, and *N. flosculus*, respectively), a daily maximum for alongshore wind stress and the cumulative alongshore wind stress for the period of collector deployment were computed. Spearman's rank correlations between wind statistics and the SCV were then calculated for the three species.

3. Results

Canonical days for water temperatures recorded on days with weak, moderate, and strong wind showed that surface waters cooled