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Short-term variations in mesozooplankton, ichthyoplankton, and nutrients associated with semi-diurnal tides in a patagonian Gulf

L.R. Castro [a,*], M.A. Cáceres [b], N. Silva [c], M.I. Muñoz [a], R. León [a], M.F. Landaeta [b], S. Soto-Mendoza [a]

[a] Laboratorio de Oceanografía Pesquera y Ecología Larval (LOPEL), Departamento de Oceanografía and Centro FONDAP-COPAS, Universidad de Concepción, Chile
[b] Facultad de Ciencias del Mar, Universidad de Valparaíso, Av. Borgoño 16344, Viña del Mar, Chile
[c] Laboratorio de Biogeoquímica Marina, Escuela de Ciencias del Mar, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile

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ABSTRACT

The relationships between the distribution of different zooplankton and ichthyoplankton stages and physical and chemical variables were studied using samples and data (CTD profiles, ADCP and current meter measurements, nutrients, mesozooplankton, ichthyoplankton) obtained from different strata during two 24-h cycles at two oceanographic stations in a Chilean Patagonian gulf during the CIMAR 10-Fiordos cruise (November, 2004). A station located at the Chacao Channel was dominated by tidal mixing and small increments in surface stratification during high tides, leading to decreased nutrient availability. This agreed with short periods of increased phytoplankton abundance during slack waters at the end of flood currents. Increases in larval density for all zooplankton and ichthyoplankton taxa corresponded to the flooding phases of the tidal cycle. When the larval density data were fit to a sinusoidal model, the regression coefficients were high, suggesting that tides are important features that modulate short-term variations in plankton abundance. All larvae did not vary synchronously with the tidal phase; rather, time lags were observed among species. The abundances of older individuals of the copepodite *Rhincalanus nasutus* and all zoea stages of the squat lobster *Munida gregaria* increased during night flood tides, whereas younger stages increased during daytime flood tides. At a station located at the Queullin Pass, which was dominated by vertical stratification patterns, the variations in peak larval density were better fitted to the semi-diurnal sea level fluctuations. Other evidence indicated internal tides below the pycnocline, which could promote larval transport in deeper layers. In the overall picture that emerges from this study, planktonic organisms from different habitats and phylogenetic origins seem to respond to the local tidal regimes. In some cases, this response might be beneficial, transporting these individuals inshore to areas that are rich in food during the peak biological production season.

1. Introduction

Semi-enclosed coastal environments such as bays, estuaries, gulfs, and fjords are highly productive zones that, seasonally, show favorable living conditions for the earliest fish and invertebrate stages. During the high production seasons, the youngest life stages of organisms from offshore, the continental shelf, or coastal areas co-occur temporarily, taking advantage of elevated larval food availability, decreased turbulence, or warmer temperatures to enhance larval growth (Boehlert and Mundy, 1988; Epifanio, 1988; Castro et al., 1993, 2007; Landaeta and Castro, 2002, 2006; Palma et al., this issue). The presence of young stages in these coastal zones, however, is affected by coastal oceanographic processes (mixing, stratification, transport) that may occur regularly or occasionally, disrupting typical vertical and horizontal distribution patterns. If these oceanographic processes occur regularly throughout the season, similar behavioral adaptations to local conditions may sometimes be observed, even in individuals produced in different areas (i.e., selective tidal stream transport to avoid exportation from highly productive zones, Queiroga et al., 1997, 2006). In other cases, alternative behavioral responses conducive to achieving, for instance, the similar final goal of retention, may also occur, even in species that have a close phylogenetic relationship.

The association between larval vertical migration and tidal currents has received attention in terms of changes in abundance within the tidal cycle (DeVries et al., 1994; Tankersley et al., 1995; Welch and Forward, 2001), as a mechanism for subsequent horizontal transport (Hill, 1991; Christy and Morgan, 1998), and as a response to endogenous swimming rhythms (Tankersley et al., 1995; Zeng and Naylor, 1996; Forward et al., 1997). The effect of tidal currents on the abundance of different larval stages

* Corresponding autor. Tel.: +56 41 2203178; fax: 56 41 2256571.
E-mail address: lecastro@udec.cl (L.R. Castro).

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on intra-tidal time scales in mixed and stratified systems has received less attention. Tidally mixed systems are characterized by weak or absent stratification and an early onset of the annual production cycle (Mann and Lazier, 2006), homogeneous distributions of chlorophyll-*a* (chl-*a*) concentrations in the water column (O'Reilly et al., 1981), and year-round primary production at levels lower than those in stratified systems. Changes in the typical food web of diatoms-copepods-larval fishes to a system dominated by small copepods and microplankton – a less efficient chain for providing food to young fish – have also been reported (Williams et al., 1994). On the other hand, changes in water-column stratification are known to affect copepod fecundity through changes in phytoplankton abundance and size (Peterson and Bellantoni, 1987), but there is also evidence of increased copepod abundances in stratified systems due to more nutritious and available phytoplankton (Sullivan, 1993). The classical vertical distribution pattern of zooplankton in the open ocean shows the highest abundances just above the pycnocline (Longhurst, 1981), associated with the maximum phytoplankton biomass (Ortner et al., 1980) or maximum phytopklankton productivity (Longhurst and Harrison, 1989). But in stratified systems induced by buoyant estuarine plumes, entrainment may induce changes in grazing patterns by enhancing biological productivity and larval transport through tidal currents in the up-estuary direction in lower layers (Norcross, 1991).

The northern zone of Patagonian fjords and channels in southern Chile (41.4–43°S, Fig. 1) is known for its high biological production, which increases in austral spring and summer (Iriarte et al., 2007; González et al., this issue). During these seasons, the input of freshwater with low nitrate, low phosphate, and high silicic acid increases. Seasonal increments in rain and melting of ice from surrounding glaciers promote the stratification of estuarine waters, lowering their surface nitrate and phosphate contents but maintaining their high silicic acid contents (Silva, 2008) and increasing phytoplankton density (Iriarte et al., 2007).

A typical, two-layer pattern of estuarine circulation develops on the continental coastal margins of Ancud Gulf (Fig. 1) near the freshwater sources, with an upper layer flowing seaward and the layer beneath flowing landward (Sievers and Silva, 2008). The main source of freshwater emptying to the gulf comes from Reloncavi Estuary, a fjord-like inlet, known locally and hereinafter referred to as Reloncaví Fjord, where a plume of buoyant water develops a down-fjord surface current characterized by significant vertical stratification. The largest discharge into Reloncavi Fjord is provided by Puelo River, with an annual mean of 670 m^3/s and variations between 150 and 3590 m^3/s (Niemeyer and Cereceda, 1984). This river has the third highest discharge of all those emptying into the entire Chilean Inland Sea (41–56°S). A gulfward-flowing buoyant plume enters Reloncavi Sound and follows to the south mostly through Queullin Pass, the main way of exchanges between the two basins (Reloncavi Sound and Ancud Gulf). Other freshwater sources on the eastern side of the gulf play a less significant role in stratification. Stratification gradually decreases as the surface layer moves westward and southward into Gulf of Ancud (Silva et al., 1997). On the western side of this basin, Chacao Channel provides a way for water exchange with the shelf. This shallow, narrow passage is characterized by strong tidal currents (3–4 m/s) in its narrowest region (2 km) at Remolinos Rock (10 m depth), a pinnacle

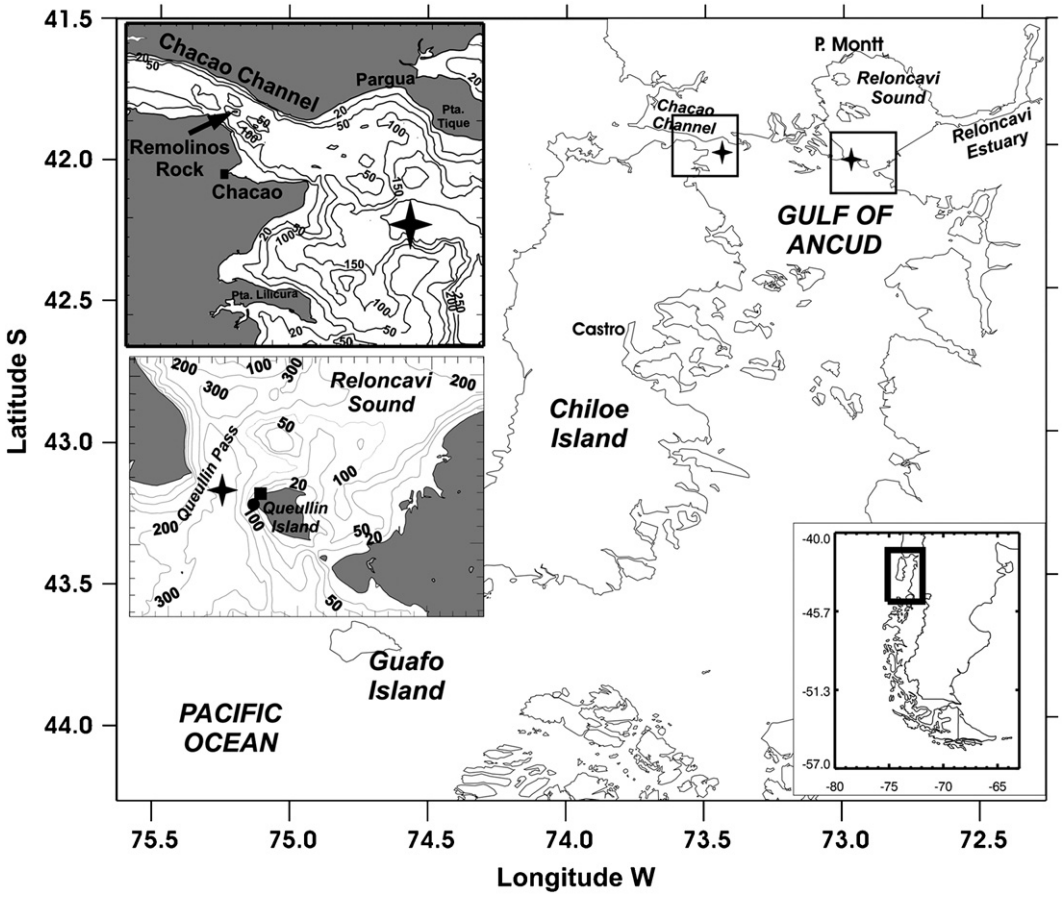

Fig. 1. Study area and position of sampling stations (depicted by stars) in Chacao Channel and Queullin Pass. The solid square off Queullin Island is the tidal gauge and the solid circle is the meteorological station.