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Larval fish habitats and hydrography in the Biosphere Reserve of the Upper Gulf of California (June 2008)

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Dedicated to Biol. José Campoy (RIP), Director of the Upper Gulf of California Biosphere Reserve from1999 to 2011.

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ABSTRACT

The Upper Gulf of California (UGC) is a Biosphere Reserve that despite its extreme environmental conditions (macrotidal inverse estuary) houses a high fish species richness. An intensive sampling of fish larvae and hydrography was carried out during June 2008 in the UGC. From 56 zooplankton sampling stations with a maximum of three sampling strata (each 5 m deep, from 0 to 15 m), a total of 29,505 fish larvae were collected, included in 99 taxa and 32 families. The Bray–Curtis Index defined three main larval fish habitats that varied in composition. (i) The "Mixed" larval habitat was mostly defined in the vertically mixed western sector of the UGC; the coastal pelagic *Anchoa* spp. presented high abundance in this habitat, associated with demersal species such as *Gobulus crescentalis* and Scianidae type 1. The lowest diversity and abundance, and the highest salinity, temperature and chlorophyll distinguished this larval habitat. (ii) The "Front" habitat was located mostly on the physical–chemical frontal zone between the UGC and the Northern Gulf; it had the highest specific richness and larval abundance. The dominant species were the coastal pelagics *Anchoa* spp. and *Opisthonema* sp. 1; the latter was almost limited to the north by the frontal zone. (iii) The "Shelf" habitat, found over the shelf off the mainland, was the deepest and less salty, and was also dominated by *Opisthonema* sp. 1, but included epipelagic species such as Scombridae (e.g., *Scomber japonicus*, *Auxis* spp., *Scomberomerus sierra*), probably from the adjacent deeper zone. These larval fish habitats had well-defined limits that coincided with marked environmental gradients, with the lowest larval diversity in the saltiest environment; this suggests that the human-induced shift to hypersaline conditions may have reduced the preferred larval habitat for some species. The habitats most likely change with the seasons, with implications for the management of the reserve.

1. Introduction

Management and conservation of ecosystems is a complex task, since it involves defining and coupling physical and biological interactions at multiple spatial and temporal scales, as well as anthropogenic factors (Cudney-Bueno et al., 2009; Pollnac et al., 2010). Although marine reserves are considered an important tool for sustaining ocean ecosystems (Nowlis and Friedlander, 2005), they are often established using a precautionary approach, and without in-depth knowledge of the species that inhabit them, their spawning strategies (e.g. areas, periods and intensity) and their relationships with physical environmental processes (Borguez et al., 2009; Cudney-Bueno et al., 2009). In this article we describe summer-time oceanographic conditions and distinct fish larval communities in the Upper Gulf of California (UGC), and compare these bioregions to established conservation zoning.

The UGC (Fig. 1) was declared a Biosphere Reserve in 1993, largely due to its importance for endemic fish species, such as Totoaba (*Totoaba macdonaldii*), the Bigeye Croaker (*Micropogonias megalops*), the curvina golfina (*Cynoscion othonopterus*) and the endemic and critically endangered marine mammal Vaquita (*Phocoena sinus*; Rojas-Bracho et al., 2006). To provide additional protection for the Vaquita, in 2005 the Mexican Government decreed a "Vaquita Refuge" in the central part of the species range (e.g., Jaramillo-Legorreta et al., 1999,2005; Fig. 1).

The reserve is divided into two management areas: the "Buffer Zone" and the "Core Area" (marked B and C, respectively, in Fig. 1); the latter, located in the northwestern extreme of the UGC, is vertically mixed and so shallow that it is accessible only by small boats. The "Vaquita Refuge" (marked V in Fig. 1) is located on the western side of the Buffer Zone, and it has a small section

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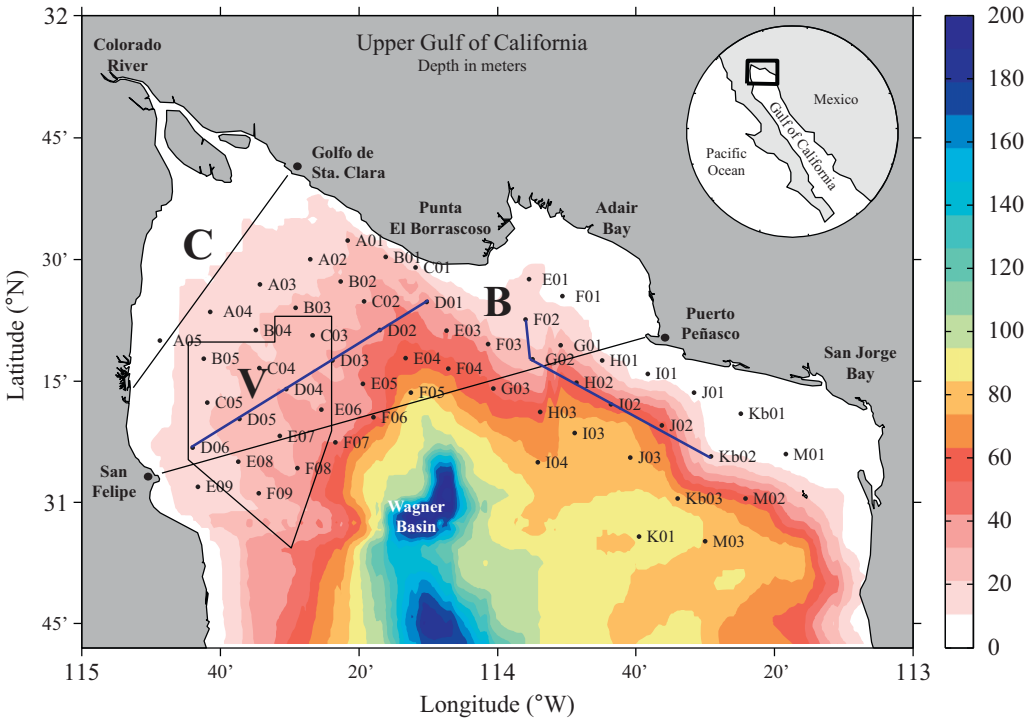

Fig. 1. The Upper Gulf of California, with bathymetry (in meters) and named coastal features. Capital letters indicate marine protected areas: C=core zone of the UGC Reserve, B=buffer zone of the UGC Reserve and V=Vaquita Refuge. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

extending outside the UGC Reserve. The Reserve is supported by a management program that is charged with promoting sustainable activities and maintaining biodiversity. In the Core Zone all fishing activities are banned, while in the Buffer Zone controlled fishing activities, including shrimping (*Litopenaeus stylirostris*), are allowed. In the Vaquita Refuge fishing activities have been restricted and gillnets banned since 2005, but effective enforcement did not begin until fall 2008 (Gerrodette and Rojas-Bracho, 2011).

From the physical oceanography perspective, the UGC is a highly seasonal, shallow (<30 m deep) macrotidal inverse estuary, with temperatures ranging from $\sim$14 °C in winter to over 32 °C in summer (Alvarez-Borrego and Galindo-Bect, 1974; Alvarez-Borrego et al., 1975; Lavín et al., 1998). The inverse-estuarine conditions that exist today, characterized by salinities that increase from 35.4 in the open Northern Gulf to above 39 in the shallowest areas of the UGC, are the consequence of the damming and diversion of the entire Colorado River flow for agricultural and domestic use, the almost null rainfall and the high evaporation rate ($\sim$0.9 m year^{-1}; Alvarez-Borrego et al., 1975; Lavín and Organista, 1988; Lavín et al., 1998). Tidal range is $\sim$6 m during spring tides, and strong tidal currents up to 1 m s^{-1} cause resuspensión of sediments and elevated turbidity (Alvarez and Jones, 2002), in addition to a tidal-mixing front separating the well-mixed UGC from the deeper and stratified Northern Gulf (Argote et al., 1995).

Despite these extreme physical conditions, the UGC holds a high diversity of fish species (260 species) representing 29% of the Gulf's total ichthyofauna (Hastings and Findley, 2007). High diversity has also been recorded for other taxonomic groups in the UGC (Felger and Broyles, 2007), such as birds (>350 species), marine mammals (12 species regularly sighted, but up to 22 other species occurring occasionally) and macroinvertebrates ($\sim$1045 species). In addition, Calderon-Aguilera et al. (2002) and Galindo-Bect et al. (2010) reported that the preferred spawning zone of the shrimp *L. stylirostris* in the Northern Gulf is in the eastern part of the Reserve's Buffer Zone, south of Punta El Borrascoso (Fig. 1).

The management zones in the UGC Reserve coincide approximately with areas with particular physical characteristics previously defined in hydrography and sediment studies. For example, during summer the highest temperature and salinity are found in the in the well-mixed NW side of the UGC, and the lowest values in the deeper, stratified SE side; in winter the thermal gradient reverses while that of salinity remains, as does the tidal-mixing front between the stratified and the well-mixed zones (Alvarez-Borrego and Galindo-Bect, 1974; Alvarez-Borrego et al., 1975; Argote et al., 1995; Lavín et al., 1998). There is also a sediment particle-size regionalization, with the largest particles (sands) in the north and east areas of the UGC, and the smallest (silts and clays) in the shallow western side (Carriquiry and Sánchez, 1999).

In this context, the hypothesis in the present work was that there should be at least two distinct larval fish habitats that respond to the UGC extreme environmental gradients: mixed and stratified. Based on observations carried out in the UGC in June 2008, this study aims to: (i) identify larval fish habitats indicated by fish larvae composition and abundance and (ii) relate these habitats to hydrographic characteristics or processes. The relationship between the larval habitats and the zonation of the reserve will be discussed.

2. Methods

2.1. Study area

The UGC Reserve is located in the northern part of the Gulf of California, Mexico (Fig. 1). It is triangular in shape, covering an area of approximately 5000 km^2. The southern limit is marked by an imaginary line between the town of San Felipe on the Baja