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Sea-surface temperature gradients across blue whale and sea turtle foraging trajectories off the Baja California Peninsula, Mexico

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Abstract

Sea-surface temperature (SST) fronts are integral to pelagic ecology in the North Pacific Ocean, so it is necessary to understand their character and distribution, and the way these features influence the behavior of endangered and highly migratory species. Here, telemetry data from sixteen satellite-tagged blue whales (*Balaenoptera musculus*) and sea turtles (*Caretta caretta, Chelonia mydas,* and *Lepidochelys olivacea*) are employed to characterize 'biologically relevant' SST fronts off Baja California Sur. High residence times are used to identify presumed foraging areas, and SST gradients are calculated across advanced very high resolution radiometer (AVHRR) images of these regions. The resulting values are compared to classic definitions of SST fronts in the oceanographic literature.

We find subtle changes in surface temperature (between 0.01 and 0.10 °C/km) across the foraging trajectories, near the lowest end of the oceanographic scale (between 0.03 and 0.3 °C/km), suggesting that edge-detection algorithms using gradient thresholds >0.10 °C/km may overlook pelagic habitats in tropical waters. We use this information to sensitize our edge-detection algorithm, and to identify persistent concentrations of subtle SST fronts in the Northeast Pacific Ocean between 2002 and 2004. The lower-gradient threshold increases the number of fronts detected, revealing more potential habitats in different places than we find with a higher-gradient threshold. This is the expected result, but it confirms that pelagic habitat can be overlooked, and that the temperature gradient parameter is an important one.
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1. Introduction

Sea-surface temperature (SST) frontal features can be used to define pelagic habitat (Laurs et al., 1984; Podesta et al., 1993; Block et al., 2003), to

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identify biological hotspots (Worm et al., 2003), to discern migration corridors (Polovina et al., 2000), and to set marine conservation priorities (Yen et al., 2003; Etnoyer et al., 2004), but one outstanding problem for marine biologists is that the classic definitions of a front originate in physical oceanography. In oceanography, fronts are an interface between two dissimilar water masses, often characterized by a steep temperature gradient. High biological productivity is attributed to these features, due to density-driven aggregation, and increased vertical flux resulting in high primary and secondary production (Owen, 1981; Roughgarden et al., 1988; Franks, 1992; Olson et al., 1994; Bakun, 1996; Genin et al., 2005). However, we still have an incomplete understanding of the way marine species define their own 'biologically relevant' temperature gradients and some fundamental questions remain unanswered. For example, what sort of SST front is likely to be important to whales and turtles? How do SST fronts for whales and turtles compare to oceanographic definitions of a temperature front? Temperature gradients are important parameters in analyses of SST data because this parameter *defines* a frontal feature in an edge-detection algorithm. Gradient values less than this threshold may be overlooked, so the threshold value must be carefully considered.

In this study, we utilize transmission coordinates from satellite-tagged animals and satellite-derived SST data in a marine geographic information system (GIS) to calculate temperature gradients across the trajectories of 16 whales and sea turtles off the Baja California (BC) Peninsula (Fig. 1) between 1995 and 2002. We consider these gradients against a background of regional surface temperatures, chlorophyll, and upwelling conditions during times in which whales and sea turtles actively forage offshore, and we compare these gradients to descriptions of SST fronts in the oceanographic literature.

Our satellite surveys examine the character and distribution of temperature gradients in the Northeast Pacific at two extents. A regional extent (15–35N, 105–125W; Fig. 1) uses animal tracks with 9 km Advanced Very High Resolution Radiometer (AVHRR) SST to determine the character of fronts near foraging animals. A continental extent (12–72N, 90–180W; Fig. 6) uses 18 km interpolated multi-channel SST (MCSST) values to examine the distribution of these fronts in the Northeast Pacific.

Waters off BC Sur have long been known as a hotspot for commercial fisheries (McHugh, 1952; Alverson, 1960; Sosa-Nishizaki and Shimizu, 1991; Squire and Suzuki, 1991), and a region of complex meander and eddy formation for oceanographers (Griffiths, 1965; Legeckis, 1978). Large concentrations of SST fronts persist offshore BC Sur in both phases of the El Niño/La Niña Southern Oscillation, a quality shared with less than 1% of the Northeast Pacific Ocean (Etnoyer et al., 2004). Yet, the origin, character, and contents of these frontal features remain almost completely unknown. Satellite-tagged animals have been shown to meander along frontal features in the region for prolonged periods of time, including blue whales *Balaenoptera musculus* and several species of sea turtles. These animals are presumably foraging, so the region provides a good opportunity to study the interactions between marine species and oceanographic features.

2. Background

2.1. Classic definitions of frontal features

Japanese oceanographer Kitahara first proposed the principle of fish assemblage along lines of convergence in 1918 (Uda, 1959). Since that time, many researchers have described the regions of convergence and divergence, floating objects, plankton, and abundant sealife that characterize *siome*, or rip-currents, along the swift fluid boundaries between different water masses we know as a front. Uda (1938) described *siome* with rates of change in temperature between 0.5 and 0.05 °C/km in high-latitude temperate waters of the Kuroshio Current off Japan. Kuroshio gradients are remarkable, and extreme, so this definition is broad. More recently, Fedorov (1986) defined a frontal zone and a frontal interface or *front* as one and two orders of magnitude over background conditions (e.g., mean meridional temperature), respectively. In the Northeast Pacific, for example, the mean meridional temperature is 0.003 °C/km (Fedorov, 1986), so technically, a frontal zone is 0.03 °C/km and a frontal interface or *front* is 0.3 °C/km by this definition. Subtler fronts are on record. The Ensenada Front off BC Peninsula exhibits a 0.36 °C/km maximum gradient, with 99% of values less than 0.22 °C/km (Haury et al., 1993). We follow Fedorov's terminology when gradient information is available, but use the term *frontal feature* when

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