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DETECTION OF SMALL-SCALE COASTAL OCEANOGRAPHIC PROCESSES THROUGH LANDSAT-TM/ETM+ IMAGES: IMPLICATIONS FOR THE STUDY OF BIOLOGICAL PROCESSES ALONG THE PATAGONIAN COASTS OF ARGENTINA

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ABSTRACT

The Argentine coastal zone, with its highly productive coastal waters, allows the existence of important seabird and marine mammal breeding assemblages, fish and crustacean spawning and nursery areas, and extensive macroalgae and mollusk beds. Knowledge of factors determining the dynamics of coastal waters is urgently needed to help understand their influence on biological processes and marine biodiversity. Available information in the region is currently scarce due to the low number of oceanographic cruises and oceanographic modeling studies. We evaluate the capacity of high-resolution satellite information for the identification and analysis of coastal processes such as fronts, upwellings, and small scale eddies. Using two case studies, we show how the analyses of temporal sequences of LANDSAT-TM and ETM+ images allow refining the formulation of biological

hypothesis. In the first case, we relate seabird colony distribution with small-scale coastal upwelling areas, and in the second, we analyze the influence of a frontal zone on the recruitment of a commercially important scallop species.

INTRODUCTION

The satellite systems LANDSAT-TM (Thematic Mapper) and LANDSAT-ETM+ (Enhanced Thematic Mapper Plus) were first designed for terrestrial applications, but the inclusion of channels in the blue-green and thermal wavelenght ranges makes both sensors very useful to study the ocean and coastal waters. Their capability to estimate the sea surface temperature and to detect suspended matter at the upper layer in addition to their high spatial resolution makes them excellent tools for observing smallscale oceanographic processes in coastal regions. Most of the work done in coastal areas using these satellite systems has been oriented to map, identify and classify habitats, to quantify aquatic vegetation biomass in the intertidal or subtidal zones, particularly in coral reefs or wetlands, and to estimate chlorophyll concentration (e.g Andréfouët *et al.* 2001; Dustan *et al.* 2001; Baban 1993; Johnston and Barson 1993; Ackleson and Klemas 1987). Given their potential, however, these remote sensing systems have been underrated as tools for identifying and studying oceanographic coastal processes (e.g. monitoring algal blooms, or studying fronts and upwellings). The use of LANDSAT information could also be used to further develop and test hypotheses in areas such as population dynamics, habitat selection, or coastal circulation.

The Patagonian coastal zone is highly productive and, therefore, important for regional and local economies and for the well-being of the marine life. Many species of seabirds, marine mammals, migratory birds, fishes, mollusks, and crustaceans breed and forage along these coasts. Although some important biological processes would be highly impacted by the dynamics of the coastal waters (e.g. Wing *et al.* 1998), oceanographic information for areas close to shore is incomplete. We evaluate the capacity of high-resolution satellite systems to provide valuable information for the identification and analysis of coastal small-scale oceanographic processes. Using two case studies from the coasts of Patagonia, Argentina, we show how the analyses of temporal sequences of LANDSAT TM and ETM+ images allow the detection of small-scale patterns and help in the formulation of biological hypotheses. In the first case, we aim to identify coastal smallscale oceanographic processes that could be influencing the distribution of breeding seabird colonies along the Chubut province, and in the second, we qualitatively describe the dynamics of main oceanographic features within the San José Gulf, specifically circulation and seasonal distribution of water temperature, and analyze its influence on spatial patterns of recruitment of an important shellfish resource, the Tehuelche scallop (*Aequipecten tehuelchus*).

MATERIAL AND METHODS

Sensors and images

The LANDSAT TM satellite was launched in a heliosynchronic orbit on March 1st, 1984, at the nominal height of 750 km while LANDSAT ETM+ was placed in a similar orbit on April 15th, 1999, with 8 days' shift. With both satellites operating, the frequency of observation of the same area is of one image every 8 days. The TM sensor possesses 7 spectral bands. The wavelengths associated with each channel are: 0.45 0.52 mm (blue), 0.52 0.60 mm (green), 0.63 0.69 mm (red), 0.76 0.90 mm (close IR), 1.55 1.75 mm (medium IR), 2.08 2.35 mm (middle IR) and 10.40 12.50 mm (thermal IR). The spatial resolution of 6 of the bands is 30 m, but that of the thermal channel is 120 m. The ETM+ sensor has the same 7 bands, but with significant radiometric improvements, and a panchromatic channel (0.52 0.90 mm) with 15 m spatial resolution. The resolution of the thermal channel is 60 m. The swath width is of approximately 185 km, for each orbit and for both sensors.

The TM sensor is 20 year old, suffering sensors degradation and since 2003 there is a problem with the Scan Line Corrector of the ETM+ sensor; thus only the middle of the scenes (approximately 22 km) has a quality comparable to that of previous LANDSAT 7 images (United States Geological Service 2004).

We analyzed 2 channels: channel 1 for the detection of suspended sediments and the study of its spatial distribution, and channel 6 for the inference of the horizontal distribution of sea surface temperature. There is only one infrared thermal channel, thus the atmospheric correction of temperature is not possible. Instead, we obtained the brightness surface temperature (SST, used here as a surrogate variable for the sea surface temperature), that corresponds to the temperature of a black body emitting the same quantity of electromagnetic radiation as that detected by the sensor. It is calculated according to Planck's equation, with water emissivity equal to 1. The brightness SST can provide a representative depiction of the spatial and temporal temperature variations under the assumption that the same atmospheric effects affect the entire area under study. As most of the thermal infrared radiation emitted by the sea surface is absorbed by the atmospheric water vapor, the brightness SST will always be lower than the real temperature and the magnitude of that difference depends on the amount of water vapor present in the atmosphere.

Cloud-free images were selected for the Argentinean Patagonian coastline and coastal area between 42 and 46S approximately (corresponding to province of Chubut), for the period 1997-2003. Those corresponded to pass 227 (rows 89 includes San José Gulf-, 90, and 91) and pass 228 (row 91). Images were grouped by month. Thirty images were used to analyze each case. The Comisión Nacional de Actividades Espaciales (CONAE, Argentina) provided all images.

One radiometrically-corrected map-oriented image for each path/row was georeferenced using GPS ground control points, while the other images were co-registered by using at least 25 points. The projection used was Transverse Mercator (Gauss Kruger projection in Argentina). Land was masked using channel 7 in order to provide more contrast to the observed oceanographic patterns. Channels 1 and 6 were represented in a gray scale: clear tones correspond to higher values of detected radiation, i.e. higher density of suspended matter or higher SST.

Case 1: seabird colony distribution and small-scale coastal upwelling areas

Seabird species breed in colonies whose location and size depend, among other factors, on the proximity of adequate food sources (Buckley and Buckley 1980). The quality and the quantity of the available food play a major role in the definition of seabird reproductive strategies (Croxall 1987; Lack 1968) and their population regulation (Croxall and Rothery 1991). Frontal areas are important foraging areas for many species of seabirds as they are usually areas of great biological productivity that often concentrate marine organisms (Olson and Backus 1985). Fourteen seabird species, including penguins, cormorants, gulls, and terns, breed along the coast of the Chubut province (42-46S). These species usually breed in multi-species assemblages of two to ten species, which are unevenly distributed along the coast (Yorio *et al.* 1998), and most forage relatively close to shore. Spatial and temporal food availability may play a crucial role in determining the distribution of breeding assemblages.

The coast of the Chubut province shows a wide variety of environments including islands, islets, inlets and low banks, muddy intertidals, cliffs, and sand and rocky beaches. Field current measurements are scarce. According to the model of Glorioso and Flather (1997) the mean flow is weak and towards the N-NE direction.

Energy dissipation areas have been identified along the coast by Palma *et al.* (2004) and Dragani *et al.* (2002), which may coincide, with topographically generated fronts. Tidal fronts have been described for the Patagonian shelf by Bogazzi *et al.* (2004), Palma *et al.*. (2004), Acha *et al.* (2003), and Bava (2002). The only watercourse in this area that flows into the sea is the Chubut River, at about 43°22'S. Information on the distribution of seabird breeding assemblages for the analysis of spatial relationship between colonies and coastal oceanographic processes was obtained from Yorio *et al.* (1998).

Case 2: the Tehuelche scallop metapopulation of San José Gulf

The Tehuelche scallop is a benthic bivalve, which is target of an artisanal commercial fishery in the San José Gulf (Figure 1). The stock is structured as a metapopulation (Orensanz 1986), i.e. grounds of sedentary adults connected during the planktonic larval phase. Understanding the spatial heterogeneity of processes that affect recruitment (i.e. incorporation of new individuals to the population) and growth patterns are key elements for designing robust management strategies for exploitation.

Systematic surveys of the metapopulation were conducted during 1995 and 1996 (Ciocco *et al.* 1997; Ciocco *et al.* 1996). Recruitment, measured as catch per unit effort (CPUE) of age 1+ individuals, was at least three times higher in Punta Tehuelche (Figure 3 a and b) than anywhere else in the Gulf in both years (Amoroso 2004). These results are consistent with the post-larval abundances on artificial collectors recorded in previous studies (Ciocco and Monsalve 1999; Ciocco and Aloia 1991).

The San José Gulf, situated in northern Patagonia (42°20´ S, 64°20W), is a small semi-enclosed bay of 814 km^2, connected with the San Matías Gulf by a narrow mouth of 9 km located in the northwestern side of the Gulf (Figure 1). It is approximately elliptical (minor and major axis of *ca.* 38 and 56 km long). The mean and maximum depths are 30 m and 120 m, the later in a narrow depression at the middle of the Gulf's mouth. The coastline is irregular, presenting several prominent points. The tidal regimen is semidiurnal with average amplitude that varies between 8.7 and 2.96 meters. Winds blow predominantly from the SW quadrant with a mean speed of 15 km h^{-1}. No permanent watercourses flow into the Gulf.

Oceanographic information, derived from few and restricted oceanographic surveys, is available mainly in the form of manuscripts or technical reports (Esteves *et al.* 1984; Palma and Serman, 1984; Rivas 1990; Pizarro 1975). Esteves *et al.* (1990) suggested the existence of two distinct broad areas (the West and East portions of the Gulf) based on the analysis of chemical and physical variables. Circulation was first described by Palma and Serman (1984) who used an hydrodynamic numerical model for the Northpatagonic Coast. An accepted oceanographic description of the Gulf is based on property gradients that extend from the mouth to the most distant sections. Indeed, the observed spatial variability in growth rates of the Tehuelche scallop (Ciocco 1991; Orensanz 1986) was explained by a spatial variability in productivity governed by a N-NO_3 gradient with a NW-SE orientation (Orensanz 1986).

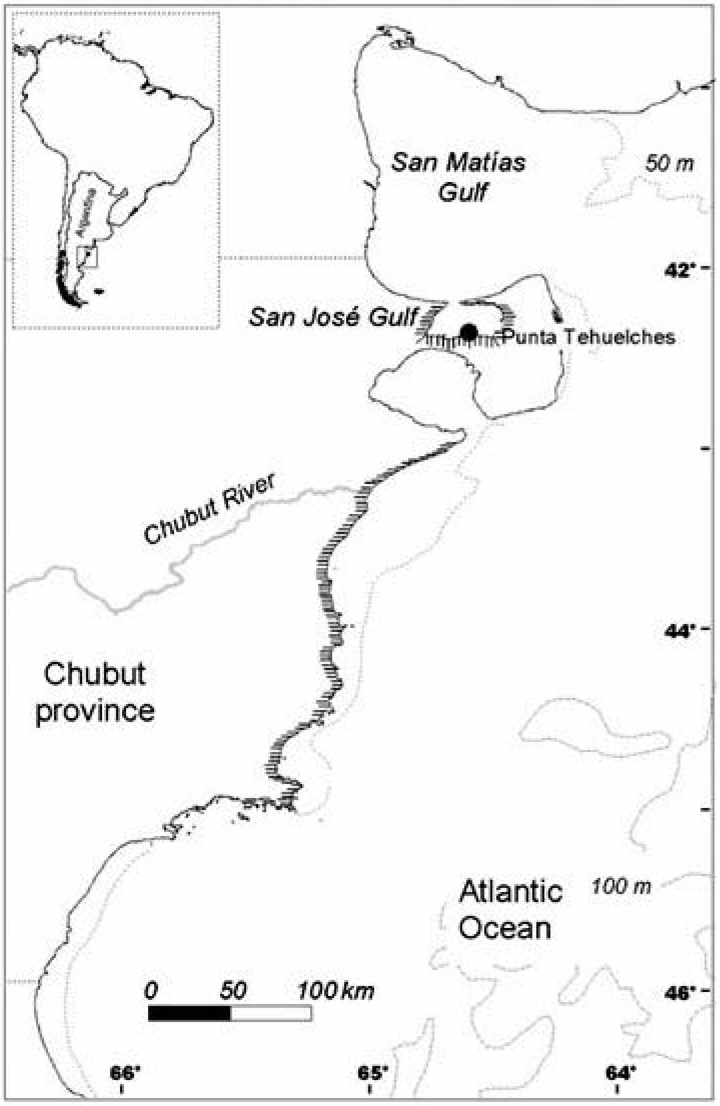

Figure 1. Northpatagonic coast. The shadowed areas indicate the study sites.

RESULTS AND DISCUSSION

Case 1

The analysis of Channel 1 in all images allowed inferring the circulation close to coast. Higher sediment contents in the form of eddie-like features and "turbulence" areas were exclusively associated with topography such as elevated bottom topography, islands, points, and other coastline features all year round (Figure 2 a). These features are predominant in the southern section of our study area. From November through February, colder SST indicating upwelling events were observed mostly associated with eddies (Figure 2 b), while SST's were homogeneous throughout the area during the rest of the annual cycle.

The interaction between currents and the bottom and/or coastal topography would generate secondary circulation (mainly island and headland wakes effects and similar processes), which may explain the spatial coincidence in our study of the patterns of suspended sediments and the upwelling of colder waters during warmer months. Most importantly, this interaction may result in physical and biological fronts (Wolanski and Hamner 1988). These fronts are predictable in space and time, since they are topographically controlled and they occur throughout late spring and summer months, when all seabirds breed. Interestingly, a strong spatial and temporal coincidence was observed between these small-scale oceanographic events and the location of seabird breeding assemblages (Figure 2 b). Future research should confirm the origin of these processes by *in situ* sampling of chemical, physical, and biological variables, and evaluate the relative importance of these small-scale processes with respect to other factors in determining seabird breeding distribution.

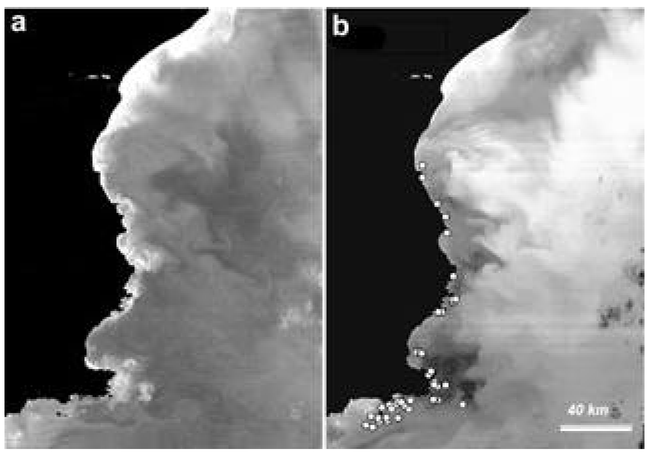

Figure 2. a) Channel 1 image showing suspended sediments. Areas with higher sediment content are clearer. The influence of the Chubut River discharge extends northwards. b) Sea surface temperature as derived from Channel 6. Darker areas indicate colder water of upwelling. Circles represent colonies of breeding seabird species. Image of January 2000.

Case 2

Channel 1 revealed a clear circulation pattern in the San José Gulf (Figure 3 a). At the flood tide, a water jet funnels out through the western side of the Gulf mouth to the San Matías Gulf, while water flows in from the eastern side. A big double eddie forms in the southwestern side of the Gulf. At the ebb tide, turbulence cannot be seen as clearly as during the flood tide, but the double eddie can still be observed. Turbulence and eddies are only present in the western side of the San José Gulf. These results show a different and more complex circulation pattern than that found by Palma and Serman (1984).

Channel 6 revealed a thermal front that extends from South to North. The southern limit is always coincident with Punta Tehuelche (Figure 3 b). The northern end-point has no fixed reference on the coast. The horizontal surface temperature pattern in the San José Gulf reverses along the year: the East/West zone is warmer/colder in summer but colder/warmer in winter. These observations confirm the suggestion made by Esteves *et al.* (1990).

It is hypothesized that the interaction between the tides and the sea floor topography is the main force determining the circulation pattern. Water from the San Matías Gulf circulates mostly in the West and Northeast section of the San José Gulf, governing its temperature. The western side seems to be very dynamic, the eastern side more stagnant. The thermal inertia of the water in the eastern section is low and its temperature is modulated only by the interchange with the atmosphere.

Two oceanographic phenomena converge in Punta Tehuelche area: the southern limit of the thermal front and the southern limit of the transition zone between the two circulation regimes. Two possible mechanisms are proposed to explain the higher recruitment in this area: a) the processes associated with the front formation enhance larval retention (Robinson *et al.* 1999; Tremblay and Sinclair 1991) or b) the presence of the big eddie just in front of Punta Tehuelche plays a role in the concentration retention of larvaes, that would be advected somehow to the southern coast.

This work suggests a different conception of the oceanographic dynamics of the San José Gulf, instead of property gradients between the mouth and the most distant points in the Gulf coastline, a frontal system has been found. The biological hypothesis that relies on the gradient conception, as the N-NO_3 hypothesis, should be reviewed in light of these new results.

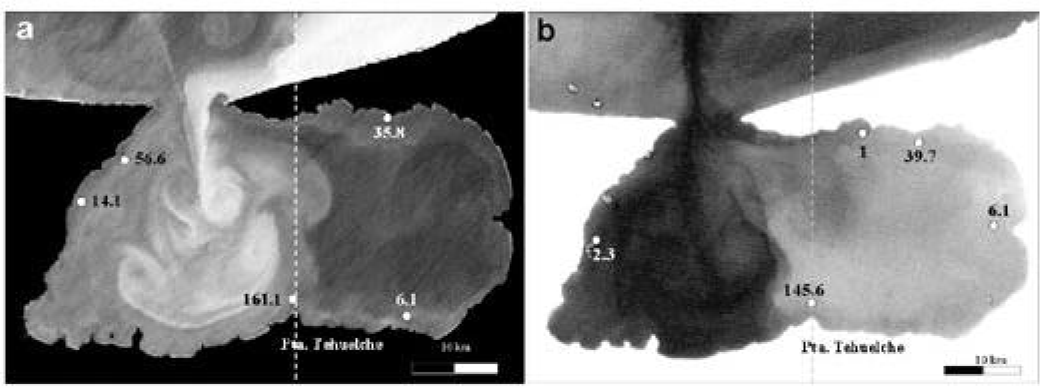

Figure 3. a) Suspended sediment pattern in the San José Gulf as indicator of surface circulation. Values indicate recruitment CPUE in 1995 (Amoroso 2004). b) Sea surface temperature (Brightness Temperature) during summer. Values indicate recruitment CPUE in 1996 according to Amoroso (2004). The dash line shows the imaginary line that divides the Gulf in two broad areas with different oceanographic dynamics.

CONCLUSIONS

Even with the present limitations on data quality and availability, the ability to detect sediment distribution, infer surface temperature at high spatial resolution and intermediate temporal coverage, make LANDSAT TM/ETM+ a valuable tool for detecting and studying small-scale oceanographic processes related to coastal oceanographic dynamics. Anyway, it should be considered that future research using these satellite systems should be based on the analysis of historical data.

These satellite systems have provided information at a fine spatial scale over a broad coastal area that allowed relating oceanographic events, with geomorphology and the ecology of seabirds and scallops. Nonetheless, *in situ* oceanographic studies should be conducted to evaluate the proposed oceanographic processes and explore the use of other sensors of intermediate resolution on board on satellite missions launched recently, such as SAC-C, TERRA, AQUA and ENVISAT.

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