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MULTI-SENSOR SYNERGETIC ANALYSIS OF MESOSCALE OCEANIC FEATURES IN A SAR IMAGE: CAMPOS BASIN, SOUTHEASTERN BRAZIL

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Abstract. This study presents a combined use of multi-sensor remote sensing and *in-situ* data for the analysis and interpretation of oceanic features observed at the continental shelf and slope of the Campos Basin, southeastern Brazilian coast. Ocean color (SeaWiFS), thermal infrared (AVHRR), scatterometer (QuikSCAT) and SAR (RADARSAT-1) data were integrated in a GIS environment in order to associate the different SAR backscatter patterns to physical and biological forcing processes. The interpreted SAR features included processes such as oceanic fronts, meandering and eddies, upwelling plumes, wind variability, algae bloom and natural films. The correct interpretation of these features was only possible through the use of the multi-sensor synergetic approach complemented by timely field verification.

Keywords: sensor synergy, ocean monitoring, algae bloom, coastal upwelling, shelf-break eddy.

1. Introduction

The monitoring and study of the Continental Shelf and Slope present numerous challenges for data sampling and analysis. Mesoscale oceanic phenomena normally rise in such areas in different spatial (10-100km) and time (hours to weeks) scales. For instance, the analysis of *in-situ* and satellite data should take into account various phenomena such as oceanic fronts associated with large-scale western boundary currents, meanders, eddies, upwelling plumes, and their effects on the ecosystem. Satellite sensors operating in the visible part of the spectrum can be used to monitor ocean color variations and the associated biomass changes. Thermal infrared radiometers are ideal to monitor thermal features like oceanic fronts and upwelling plumes. However, the major limitation for both types of sensors is the extensive and persistent presence of clouds. Fortunately, microwave sensors such as scatterometers, altimeters and imaging spaceborne

Synthetic Aperture RADAR (SAR) permit the acquisition of daily oceanic scenes regardless of cloud coverage.

SAR images of the sea surface provide high resolution expressions of atmospheric and oceanographic fronts and eddies, surface currents, internal waves, wind variability, pollution, algae blooms, natural films and rain cells (Johannessen, 2000). The physical mechanism that allows the detection of most oceanic features in SAR images is the differential dampening of capillary waves on the ocean surface. These capillary waves, which are only a few centimeters in length, produce backscattering of the incident radar pulse due to a Bragg scattering mechanism. As a result, ocean regions with lower surface roughness are darker in contrast with the background radar signal (clutter). Several ocean surface processes produce regions of lower radar backscatter, which in turn can lead to ambiguities during interpretation (Fingas and Brown, 1997). Examples of these processes are: (a) oil spills, (b) natural oil seepage, (c) natural films, (d) algae blooms, (e) very weak or no wind, (f) shadow zones behind islands or land, (g) rain cells, among others.

The dataset used in this study includes visible (SeaWiFS), infrared (AVHRR) and microwave (RADARSAT-1 and QuikSCAT) satellites data acquired, on April 2002, during an algae bloom event associated with a coastal upwelling, a western boundary current meandering and a shelf-break eddy formation in Campos Basin, Southeastern Brazilian coast.

2. Study Area

The study area is located in the Campos Basin, on the continental shelf and slope of the southeastern Brazilian Continental Margin, in front of the São Tomé Cape (Figure 1). It concentrates 82% of the Brazilian oil and gas production and offshore exploration efforts. Intense fishery activities also take place in the area.

The region's physiography is characterized by the abrupt change of coastline orientation from a N-S alignment above São Tomé Cape to a NE-SW alignment between Sao Tome and Cabo Frio Cape. The bathymetry of this oceanic region is relatively smooth with the isobaths parallel to the coastline. The shelf break is located at depths of 120m to 180m.

The oceanic flow in the region is particularly disturbed by the presence of the Cape and by the abrupt change of coastline orientation, inducing topographic steering of the flow and regular mesoscale activities such as eddies and meanders (Lima et al., 1999). The surface water wind-driven flow is primarily influenced by the South Atlantic high-pressure atmospheric cell. The main portion of the continental shelf is dominated by the Coastal Water (CW; $33<S<33.7$ and $4<T<21^oC$). Frequent and intense wind driven upwelling events are observed mostly from September through April associated with the inshore bottom intrusion of the South Atlantic Central Water (SACW; $34.5<S<36$; $6<T<20^oC$) (Kampel et al., 1997). The upwelling plumes are considered as one of the most important mechanisms responsible for the increase of biological productivity in the region. On the shelf break and slope the Tropical Water (TW; $S>36$ and $T>20^oC$) is observed at the surface layers. This high temperature, high salinity and low nutrients water mass is formed at low latitudes and it is carried southward by the Brazil Current (BC) (Miranda, 1982). Its flow is oriented from NE to SW all year round in the region. However, the presence of meanders and mesoscale vortices can induce large perturbation in the prevailing flow (Stech et al., 1996).

3. Dataset

The satellite dataset used in this study was acquired as close as possible to the time of the RADARSAT-1 image acquisition (**Table 1**). It includes data obtained by the Advanced Very-High Resolution Radiometer (AVHRR) on board the National Oceanic and Atmospheric Administration (NOAA) satellites, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) aboard the NASA/Orbview-2 Satellite, Synthetic Aperture Radar (SAR) board RADARSAT-1 and SeaWinds Scatterometer sensor on board the QuikSCAT satellite.

Sensor	Resolution (m)	Acquisition Date and Time (GMT)	Swath Width (km)
RADARSAT-1	50	April 03, 2002 - 21:11	300
SeaWiFS	1100	April 03, 2002 - 14:05	2200
AVHRR	1100	April 03, 2002 - 21:09	2200
QuikSCAT	25000	April 03, 2002 - 20:30	1800

Table 1 - Satellite dataset information.

RADARSAT-1 Data

The RADARSAT-1 is a right-side-looking instrument operating in the C-band (5.6 cm) HH polarization that can provide observations at multiple resolutions and swath widths through a large range of incidence angles. A ScanSAR Narrow (SCN) beam mode image was used in this study due to its ability to cover simultaneously all the offshore facilities operated by PETROBRAS, with suitable resolution and incidence angles (20^o to 40^o). The near real time processing and delivery of the SAR image (4 to 6 hours after acquisition) allowed the timely *in-situ* verification of the algae bloom event.

SeaWiFS Data

SeaWiFS data were recorded in HRPT (High Resolution Picture Transmission) and Store modes by INPE's station. The raw data were converted to a Level-1A file. The data processing was done with the routine Swl10 and SeaDAS software (Fu et al., 1998), both distributed by the SeaWiFS Project (NASA), using respective standard algorithms and masks. Chlorophyll-*a* (Chl) values were obtained using a global algorithm (O'Reilly *et al.* 1998) and daily atmospheric data acquired from NASA GSFC's Distributed Active Archive Center (GDAAC).

AVHRR Data

AVHRR data were acquired by the OCEANSAT's antenna. Sea Surface Temperature (SST) maps were derived from the thermal infrared (bands 3, 4, and 5) calibrated radiance values through the application of the nighttime NLSST (Non Linear Sea Surface Temperature) atmospheric correction global algorithm. The data used in this study were acquired by the NOAA–14.

QuikSCAT Data

Wind field intensity data were retrieved from the SeaWinds Scatterometer sensor on board the QuikSCAT satellite. The SeaWinds Scatterometer can provide information about wind speed and direction with an accuracy of $2 m.s^{-1}$ for speed and 20^o for direction. The along track data were used in this investigation.

In-situ Data

Field verification was carried out 15 hours after SAR image acquisition. Samples and photographs were acquired during a helicopter inspection. The air temperature was measured at an offshore platform (P19).

The dataset was analyzed in a GIS environment that allowed the synergetic interpretation carried out in this investigation.

4. Results and Discussion

The main features observed in the SAR image (**Figure 2A**) are low backscatter areas with different patterns (a, b, c, an d on **Figure 2B**) and linear features (dashed lines on **Figure 2B**) related with roughness boundaries. Among the observed features the most prominent one is a low backscatter area (a on **Figure 2B**) located in front of São Tomé Cape. This feature is associated with a mesoscale eddy also detected in the SST and Chl images (**Figures 3A** and **3B**, respectively). Smaller features with similar lower backscatter pattern are also detected aligned to the expected circulation regime (b on **Figure 2B**).

The SST map (**Figure 3A**) shows the Brazil Current (red and orange tones) clearly defined by the contrast between the shelf colder waters and the warmer Tropical Waters. A cyclonic eddy, with diameter of approximately 50 km, is visible at the shelf break region offshore São Tomé Cape. The SST range of the Tropical Waters carried southward by the Brazil Current (BC) was 25-28^{o}C; shelf waters surface temperatures varied from 22-25^{o}C and upwelling waters from 19-22^{o}C.

The strong thermal gradient that characterizes the inshore front of the BC (**Figure 3A**) is perfectly outlined in the SAR image as a roughness boundary, especially northward the São Tomé Cape (**Figure 2**). Variations in backscatter level associated with differences in SST can be explained by changes in the atmospheric boundary layer stability and indirectly due to the higher biologic productivity normally associated with upwelled colder waters (Clemente-Colón *et al*., 2002).

The air temperature in Campos Basin at the time of SAR image acquisition was 23-24^{o}C. The negative values of the difference between the Air Temperature and SST (AT<SST) over the Tropical Water are indicative of air instability and consequent higher sea roughness. The opposite (AT>SST) is observed over the upwelling plumes where a positive difference results in a higher stability in the atmospheric boundary layer and lower sea roughness. The lower backscatter regions limited by dashed lines (c on Figure 2B) are related to upwelling plumes observable in the SST and Chl maps (**Figures 3A** and **3B**).

In the chlorophyll concentration map (**Figure 3B**), we can observe patches of higher values over the shelf. These patches are associated with the upwelling events. The large dark feature observed in the SAR image (a on **Figure 2**) coincides with a Chl patch. It seems to be produced by an advection of upwelled waters formed north of São Tomé Cape, which is entrapped in the BC frontal zone and later captured by the cyclonic eddy. In addition, the clockwise rotation of the eddy and the shelf break effect could be acting to enhance this feature.

The *in-situ* verification revealed the occurrence of an algae bloom of filamentous blue-green algae (**Figure 4**) in the region of the SAR Feature a. This type of algae is easily detectable by remote sensing due to their tendency to float in large aggregates at the sea surface. The smaller features detected southwards São Tomé Cape (b on **Figure 2B**) are probably related to the algae bloom since they are also located close to a Chl patch.

The wind field intensity data (**Figure 5B**) show that the surface wind ranges from 3 to 7m.s^{-1}, in most of the study area, providing suitable wind conditions for SAR features detection. According to Staples and Hodgins (1998) the SAR ability to image ocean features is highly dependant on the presence of adequate wind conditions (3m.s^{-1}<wind intensity<8m.s^{-1}). A lower wind area (1m.s^{-1}<wind intensity<2m.s^{-1}) in the southeastern portion of the study area coincides with a lower backscatter region detected in the SAR image (d on **Figure 2B**). These lower backscatter features are probably related to a local reduction of capillary waves on the ocean surface due to a decrease in wind intensity.

5. Conclusions

Combining information from several sensors and satellites acquired in such a time frame offered opportunities to advance in the analysis and interpretation of remote sensing images. The use of visible (SeaWiFS), infrared (AVHRR) and microwave (RADARSAT-1 and QuikSCAT) satellites data allowed the identification of the physical and biological processes controlling the main backscatter features detected on the SAR image. These processes included oceanic fronts, meandering and eddy, upwelling plumes, changes in the atmospheric boundary layer stability and wind conditions, as well as an algae bloom and natural films associated with high biologic productivity.

The all-weather and high-resolution orbital SAR observations can clearly serve as a complement not only to lower resolution spaceborne thermal and ocean color imagery but also to *in-situ* observations.

Increased availability and use of SAR data should contribute to an improvement of our scientific knowledge of the Campos Basin by providing links among large, mesoscale and small-scale ocean dynamics. The synergetic use of all this information may further lead to better applications of remote sensing techniques in areas such as ocean-atmosphere interaction, physical/biological oceanography, fisheries management, and pollution monitoring, among others.

In view of the availability of ENVISAT data, the use of simultaneous multi-sensor information is becoming an important scientific issue to understand the physical/biological processes of the ocean and coastal areas.

6. References

Clemente-Colón, P.; Gagliardini, A. Legeckis V.; Pichel, W.G. Spaceborne synthetic aperture radar and Thermal observations of the Brazil-Malvinas (Falkland) confluence zone, In: 29th International Symposium on Remote Sensing of Environment, Buenos Aires, April, 8-12, CD-ROM, 2002.

Fingers, M.; Brown, C. Remote sensing of oil spill: *Sea Technology*, v. 38, p. 37-46, 1997.

Fu, G.; Baith, K. S.; and McClain, C. R. "SeaDAS: The SeaWiFS Data Analysis System", Proceedings of "The 4th Pacific Ocean Remote Sensing Conference", Qingdao, China, July 28-31, 1998, 73-79. 1998

Johannessen, J.A. Coastal observing systems: The role of synthetic aperture radar, *Johns Hopkins Apl. Technical Digest*, v. 21, n. 1, 2000.

Kampel, M.; Lorenzzetti, C.L.; Silva Jr., C.L. Observação por satélite de ressurgências na costa S-SE brasileira. In: VII COLACMAR, 22 a 26 de setembro de 1997, Santos, SP. IO-USP, ALICMAR, São Paulo, Anais, v.II, 38-40 p. 1997.

Lima, J.A.M.; Scofanno, A.M. New Oceanographic challenges in the Brazilian deepwater oil fields, Offshore Technology Conference - OTC – 1999.

Miranda, L.B. Análise de massas d'água da plataforma continental e da região oceânica adjacente: Cabo de São Tomé (RJ) e a Ilha de São Sebastião (SP). Livre Docência Thesis, Instituto Oceanográfico da USP, São Paulo, 194p. 1982.

O'Reilly, J.E.; Maritorena, S.; Mitchell, B.G.; Siegel, D.A.; Carder, K.L.; Garver, S.A.; Kahru, M.; McClain, C. Ocean color chlorophyll algorithms for SeaWiFS. Journal of Geophysical Research, 103(11):24937-24953. 1998.

Staples, G.C, and D.O. Hodgins, 1998, RADARSAT-1 emergency response for oil spill monitoring: Proceedings of the Fifth International Conference on Remote Sensing for Marine and Coastal Environment, San Diego, California, October 1998.

Stech, J.L.,Lorenzzetti, J.A., de Souza, J.M.C. and Araujo, C.E.S., 1996: A mesoscale Brazil Current eddy observed through AVHRR images and current meter moorings. International Archives of Photogrammetry and Remote Sensing. Vol. XXXI, Part B7. Vienna, July 1996, pp. 650-653.

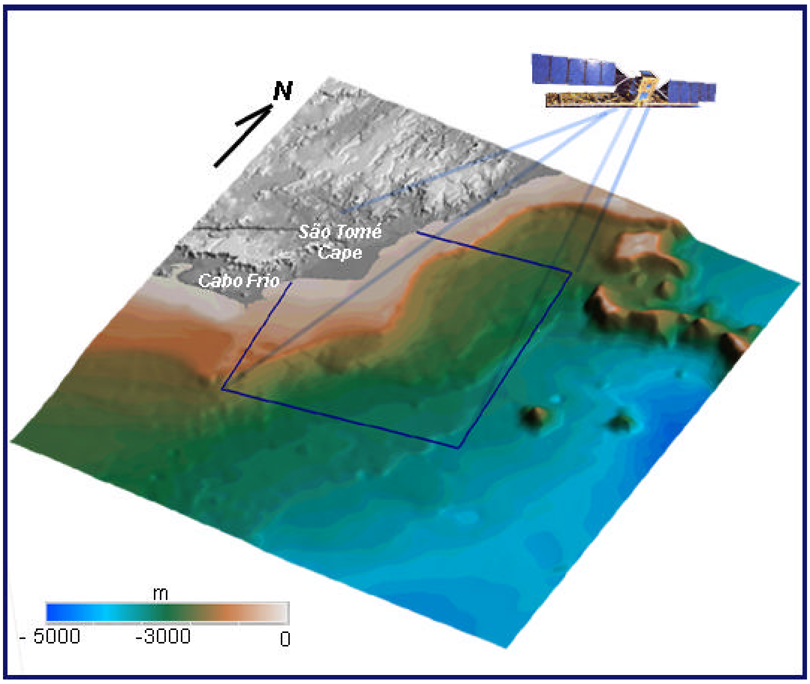

Figure 1 - Study area polygon over the 3D perspective-view of the relief.

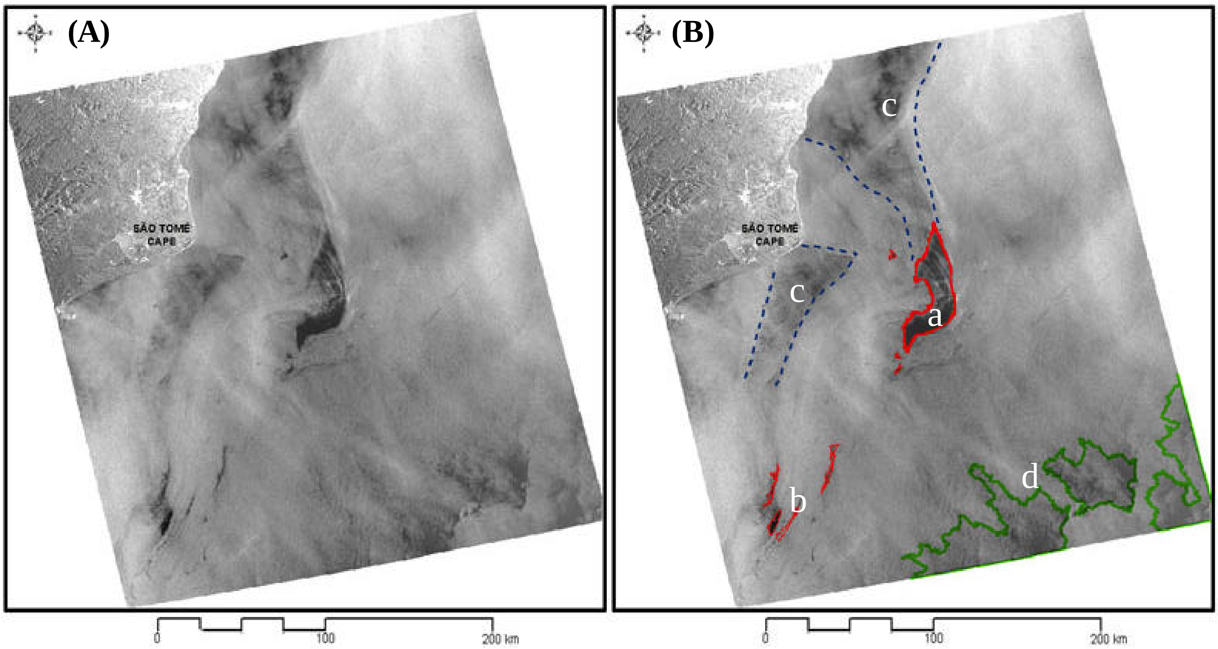

Figure 2 - (A) RADARSAT-1 (SCN) image acquired on April 3, 2002, at 21:11 (GMT). Main features observed in the SAR image (B).

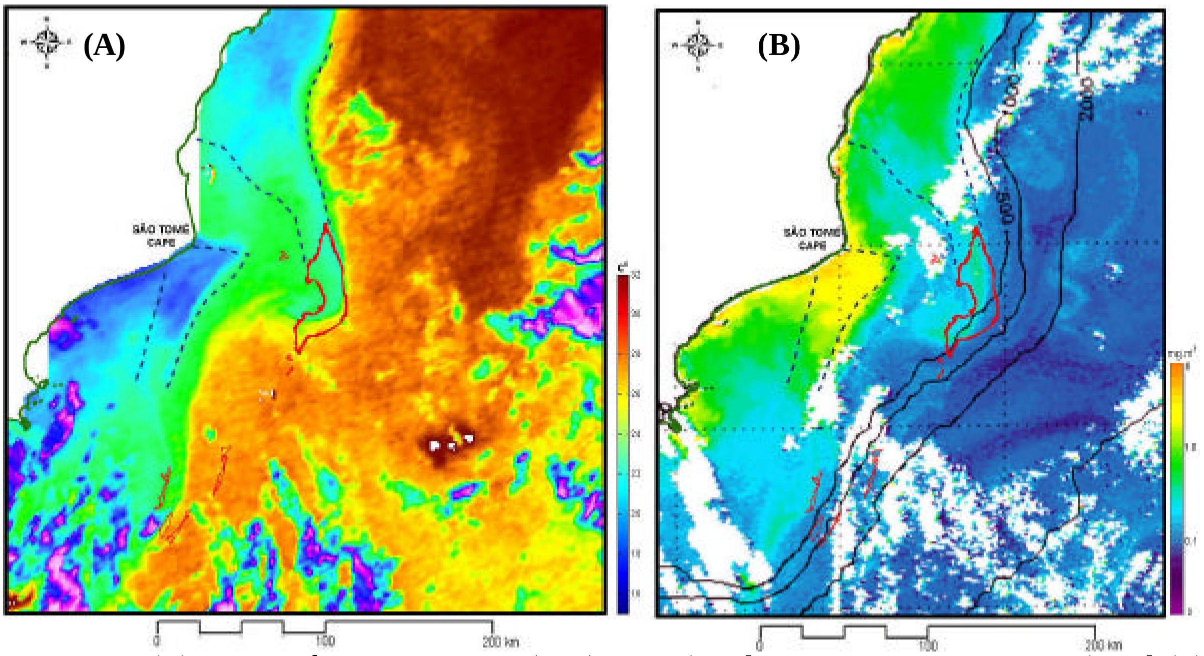

Figure 3 – (A) Sea Surface temperature (SST) map (April 3, 2002, at 21:09 -GMT) and (B) Chlorophyll-*a* (Chl) map (April 3, 2002, at 14:05 - GMT) with the main features observed in the SAR image. The 500, 1000 and 2000 isobaths are displayed in the Chl map.

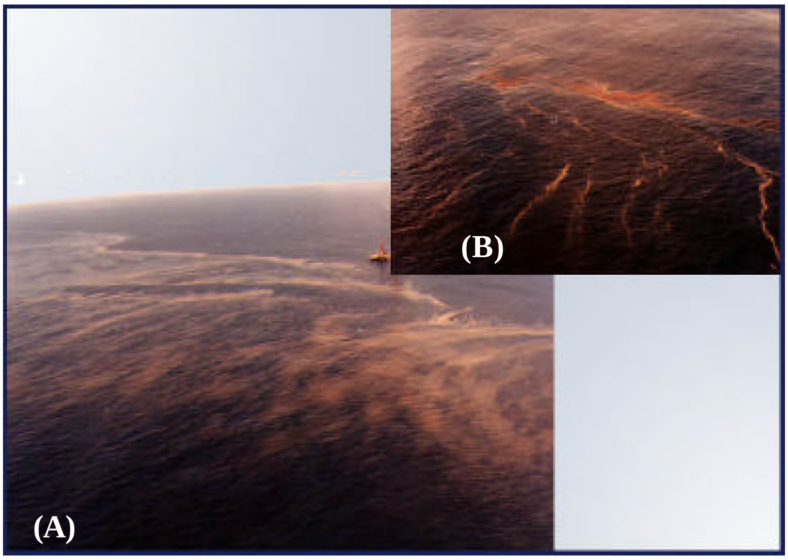

Figure 4 - Algae bloom viewed by a helicopter (A) inspection carried out 15 hours after the SAR image acquisition. Zoom of an algae patch (B).

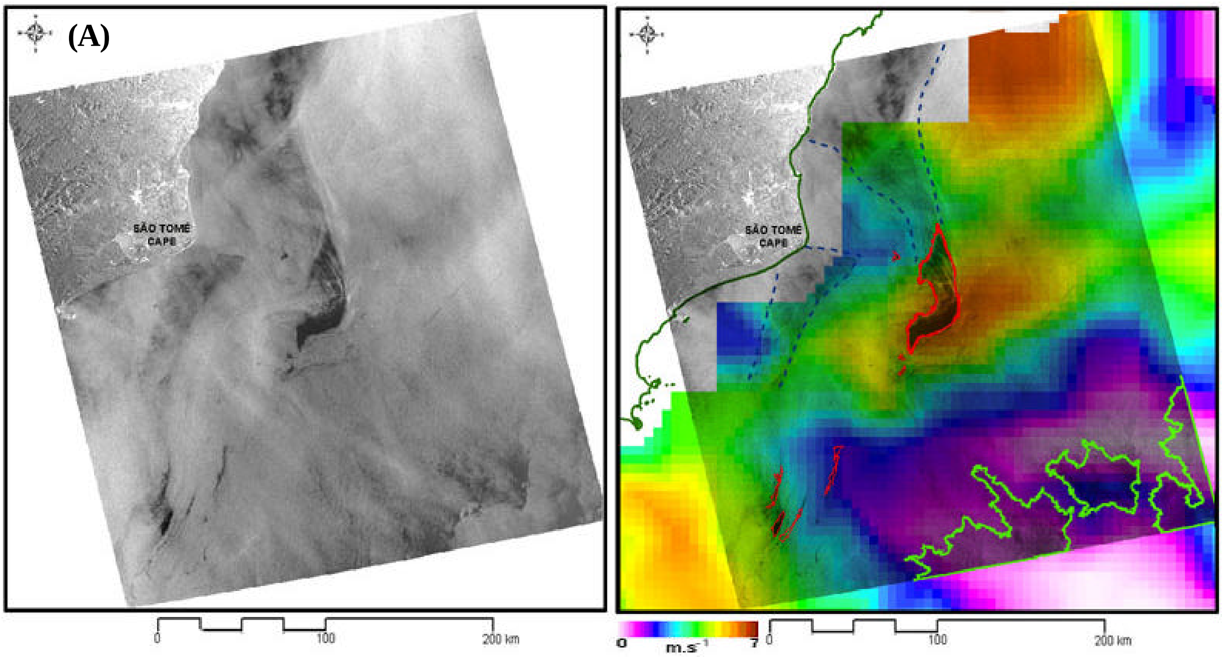

Figure 5 - (A) RADARSAT-1 (SCN) image (April 3, 2002 at 21:11 – GMT). (B) Wind field intensity map (April 3, 2002 at 20:30 - GMT) merged with the SAR image and the main features observed.