Sea Surface Temperature and Chlorophyll-a spatial-temporal variation using MODIS-Aqua in the Todos os Santos Bay, Bahia, Brazil

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Abstract: In this study, the importance of MODIS sensor multispectral imagery on monitoring coastal and oceanic areas as well as marine ecosystems is demonstrated. As an example, the Todos os Santos Bay (TSB), BA, Brazil, was selected. Four 250m Sea Surface Temperature and Chlorophyll-a satellite-derived images were processed to characterize the TSB in 2009, as well as monthly time-series from July 2002 to January 2010 and monthly maps of 2009 off the coast of Bahia. These results were compared to the Brazilian Water Agency (ANA) discharge data and tidal data. They showed the importance of the latter in physical forcing compared to the former. Benefits from MODIS high temporal and spatial resolution data compared to other sensors to date allowed the characterization between different areas within the TSB.

Key Words: Freshwater discharge, tidal analysis, coastal monitoring, satellite oceanography

1. Introduction

The launching of the Earth Observing System (EOS) –Aqua Satellite in 2002, caring the Moderate Resolution Imaging Spectroradiometer (MODIS) enhanced the accuracy of interpretating the ocean's surface bio-physical response. The ascending, 1:30 PM Equator crossing time Aqua Satellite instrument became of environmental relevance since it provides measurement of Sea Surface Temperature (SST) and Surface Chlorophyll-a Concentration (SCC) simultaneously without the time lag of data from different platforms, favouring coastal and marine monitoring.

With a swath of 2,330 Km wide, MODIS covers the entire surface of the Earth in 36 high spectral resolution bands between 0.415 and 14.235µm with spatial resolution of 250m (2 bands), 500m (5 bands), and 1000m (29 bands). The radiance measured at high spatial resolution provides improved and valuable information about the physical structure of the Earth's atmosphere and surface (Barnes et al., 1998).

SST plays an important role in the biogeographical distribution of living organisms and in ocean-atmosphere flux exchanges, exerting a major influence on meteorological systems and human activities. Despite the difference between the skin temperature and the bulk temperature, satellite-derived SST has demonstrated its importance in several fields including coral reef monitoring (Leão et al, 2008; Soppa, 2008; Krug, 2008), commercial fishing exploitation (Finney et al., 2000; Lehodey et al., 1997), ocean modelling and climate variability studies (Reynolds et al., 2002; Lau and Nath, 1994).

SCC estimated from space can be used to assess total primary production- the amount of organic matter produced in a given period of time through the photosynthetic process (Winarso et al, 2006). In phytoplankton-rich areas, Chlorophyll-a strongly absorbs the blue light (peaks around 440 nm) and thus is widely used to interpret oceanographic processes (Hu et al, 2010). Nutrient input will commonly lead to increased phytoplankton productivity and thus on a higher concentration of remotely-sensed SCC chlorophyll (Acker et al, 2009).

Therefore, in this paper, multispectral MODIS data of SST and SCC were used to monitor coastal and marine environments in Todos os Santos Bay (TSB), the 2nd largest bay of Brazil, allowing temporal-spatial differentiation of areas.

1.1 Study area

The TSB is the largest bay of Brazilian eastern coast (1223km^2 during high tide and 919km^2 during low tide) (Bonfim et al 2003, Carvalho 2003), surrounded by 12 coastal cities and inhabited by around 3 million people (IBGE, 2007).

It's a geologic structurally controlled tidal bay (Lessa et al, 2000) associated with the Reconcavo sedimentary basin, an assimetric Lower Cretaceous (Medeiros and Pontes, 1981) rift system, delimited by the Salvador and Maragojipe faults (figure 1). Dias (2003) presented the most updated distribution of the surface sedimentary facies for the bay with 11 distincted textural facies in total. Sand facies occur in the Salvador and Itaparica channels. Muddy facies cover the middle-northern part of TSB, and Gravelly facies are found in the Paraguaçú river and as isolated areas along the muddy deposits.

Mangroves cover an area of 152 km^2, specially in the vicinities of Jaguaripe, Iguape and S.F.Conde (Carvalho 2003), while coral reefs occur bordering the south-eastern part of Itaparica island, as well as, between Frades island and the city of Salvador.

TSB has two entrances separated by Itaparica island. The Salvador Channel is the major water exchange body between the bay and the ocean (Lessa et al 2001, Cirano & Lessa 2007), with an average depth of 25m (maximum of 102m), while the shallower Itaparica channel reaches an average depth of only 10m. The average depth inside the bay is between 3m (intertidal areas included) and 6m (if only areas below 0m, in relation to the Navy Authority Datum were used) (Carvalho 2003). The adjacent continental shelf off Salvador is the narrowest of all Brazilian shelves, extending for only 8km (Knoppers 1999).

The climate around the bay is tropical humid, with annual mean temperature of 25.2ºC. Maximum temperatures occur between January and March, whilst minimum temperatures arrive between July and September. Annual mean precipitation is 2,100mm with the wet season between April and June (>300mm) and the dry season (<150mm) between august and may (INMET, 1992).

Three main drainage basins and 93 peripheral drainage systems debouch into the bay, providing a mean freshwater discharge of 111.1m^3/s after 1985. The Paraguaçu river has the largest drainage basin (56,000km^2) and the highest water discharge with an annual mean of 52.79m^3/s, while Jaguaripe River and Subaé River discharge only 14.94m^3/s and 4.48m^3/s, respectively. The 29.98m^3/s annual mean discharge left accounts for the peripheral drainage systems (Lima & Lessa 2001).

TSB is the only bay in Brazil, whose tropical waters penetrate inside. Its well mixed water column with small/little vertical density gradient, due to the small fluvial discharge compared with the volume of it (Lessa et al 2009)

The currents inside the TSB are clearly tide driven, with semi-diurnal characteristics and range of 2.2m during spring tide (Lessa et al 2001). Tidal range increases up bay by a factor of 1.5 (Cirano & Lessa 2007). Maximum current velocities occur at the two entrances of the bay. In the main channel (Salvador channel) measured maximum superficial currents reached up to 0.89m/s (S) during winter time and 0.12m/s (NNO) during the summer, while in the Itaparica channel, registered values were 0.77m/s (S), during the winter, and 0.1m/s (S), during the summer. In the northern part of the bay, maximum currents of 0.34m/s (SSO) and 0.38m/s (S) occurred during winter and summer, respectively (Xavier 2002; Cirano and Lessa 2007)

SST increases toward the bay (Lessa et al 2009). CTD profiled in stations #1 to #8 (CRA 2000), in Jan/2000 and May-June/2000 were analysed by Xavier (2002) and Cirano & Lessa (2007), and showed that maximum vertical temperature difference was inferior to 1°C, and maximum surface temperature difference (3.4°C), among all stations, was registered between station #1 (30.5°C) and station #8 (27.1°C) during spring tide in the summer.

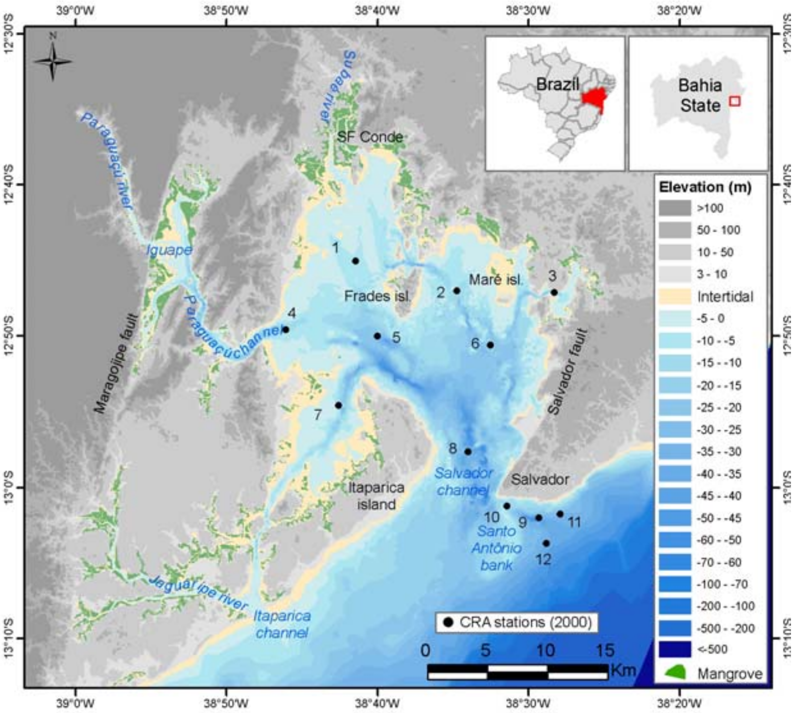

Figure 1- Location map of Todos os Santos Bay and CRA (2000) stations 1-12.

2. Methodology

Data from 4 different dates (15/01/2009 16:20h, 05/04/2009 16:25h, 12/07/2009 16:10h, 06/11/2009 16:25h GMT) were used to characterize 2009 TSB surface. The data was downloaded from http://daac.gsfc.nasa.gov/MODIS/ and processed using SEADAS (http://oceancolor.gsfc.nasa.gov/seadas).

9Km MODIS monthly data from July/2002 to January/2010 was generated for the coastal state of Bahia and a TSB area-averaged time series (13.17S-12.58S & 38.92W-38.33W) using the GES-DISC Interactive Online Visualization and ANalysis Infrastructure (GIOVANNI, http://reason.gsfc.nasa.gov/Giovanni/).

Tidal curve based on harmonic constituents retrieved from FEMAR (2010) and used in PACMaré, were created in order to match the dates of these 4 images.

Brazilian Water Agency (ANA) monitoring stations of Argoim (51350000), in the Paraguaçu watershed, Subaé II (51060100), in the Subaé watershed, and Nazaré (51560000), in the Jaguaripe watershed, provided discharge information for the main freshwater input.

3. Results and Discussion

January, 15th image (figure 2) showed SST inside TSB with temperatures around 29.2°C in the central part of the bay, with higher temperatures (30-31.2°C) toward the western part between Paraguaçu channel and SFConde. An abrupt drop in SST can be clearly observed in the Salvador channel. Outside the bay, SST varying between 27°C and 28.2°C were found in the Atlantic coast off Salvador, whereas warmer waters (up to 29.4C) were registered off Itaparica channel. For CRA stations 1-12 values see table 1.

The warmest SST values were observed on April 05th, with temperatures varying between 28.5°C and 32.5°C inside TSB and cooler waters over the continental shelf and slope. A sudden drop in SST was also observed in the Salvador channel, although it was displaced toward the north.

The July 7th image showed the coldest SST presented in all images, with SSTs reaching a maximum of 28.8°C (W) inside TSB. The eastern part of TSB shares SST similarities with the surrounding waters with temperatures between 26 and 27.4°C. Colder SSTs are found over the ebb-tidal delta of Santo Antonio bank

The November 6th processed image showed an increase SST inside the bay, with the highest temperatures (30.1°C) being recorded in the shallow low hydrodynamics waters of the northern and western parts of the bay, while on the eastern part, a gradual drop from 28.3 °C

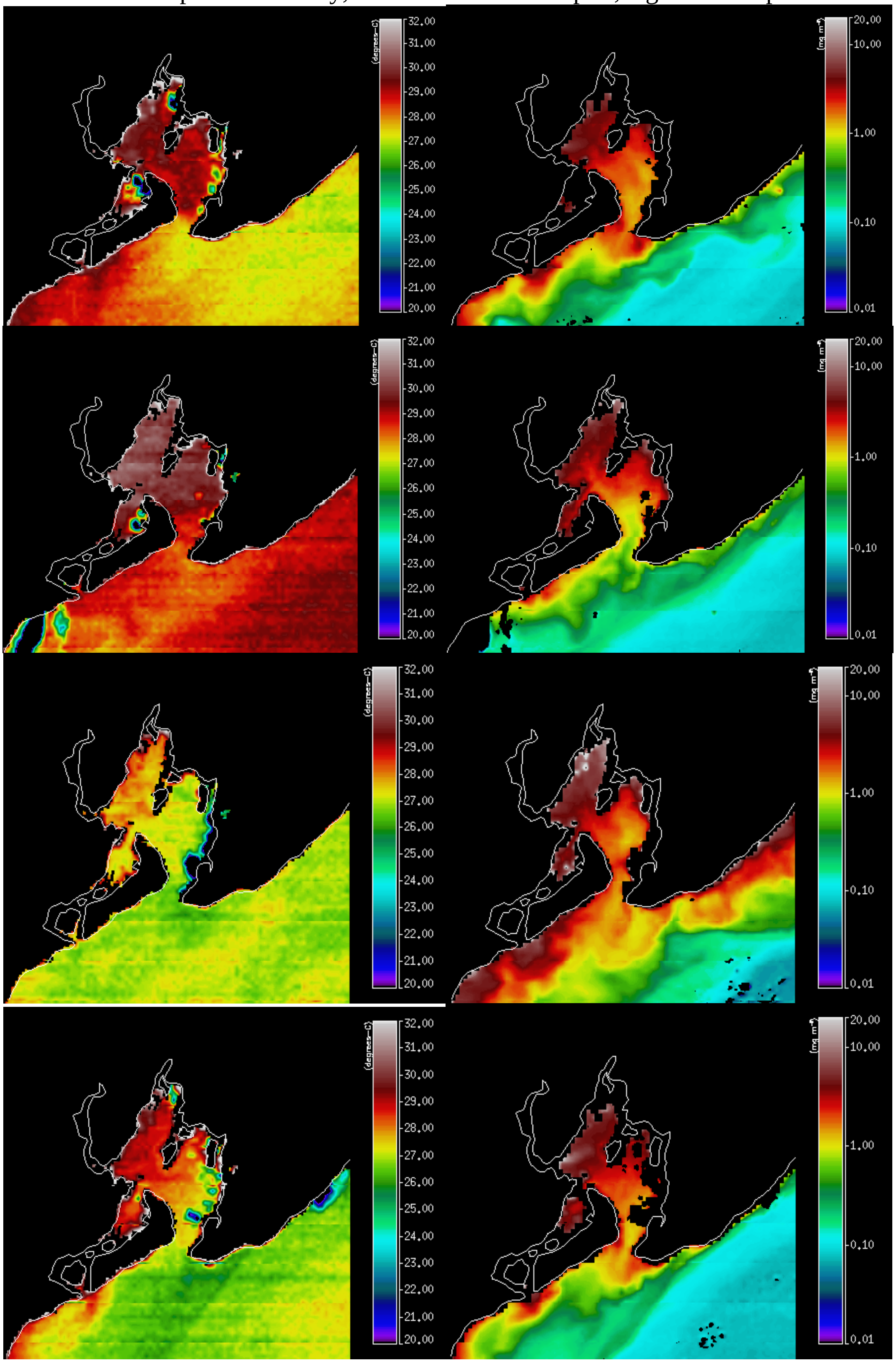

Figure 2- SST (left) and Chlorophyll-a (right) data processed days 15/01/2009, 05/04/2009, 12/07/2009 and 06/11/2009

to 25.7 °C in temperature happens as latitude decreases towards the open ocean. The Itaparica channel entrance presented SSTs higher (28.7°C) than the surrounding waters (26.5C).

The spotted Blue-Green areas in all 4 processed images represent cloudy areas and not low temperatures. Therefore, these areas should not be included in our analysis.

These images are in agreement with monthly data recorded for the coast of Bahia for the year 2009. Figure 3 shows the monthly SST recorded for the 12 months of the year. Notice an increased SST in ocean waters, during March and April, and a decrease in the July-August period. A close look is this dataset at the TSB shows a matching scenario regarding the SST behavior. In the 12 monthly images (Figure 3), SSTs inside TSB gradually increased from January to April, reaching around 30°C, then sharply decreased almost 2°C in May. In July, SST continued to decrease (26-27°C) and in August, reached the lowest SST in 2009. After that, SST increased (reaching 26-27°C) in November and continued to warm till December.

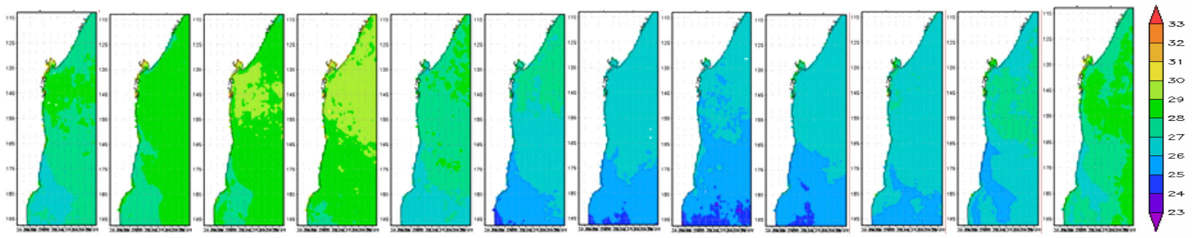

Figure 3- 2009' 12 month SST (°C) retrieved for the coast of Bahia

Although SSTs show a clear seasonal cycle, if we take into consideration the mean Jul2002-Jan2010 month period (Figure 4) recorded for TSB, 2009 might be considered as a year with warmer SSTs from May to December, with temperatures reaching 0.8°C higher than the expected during the month of august.

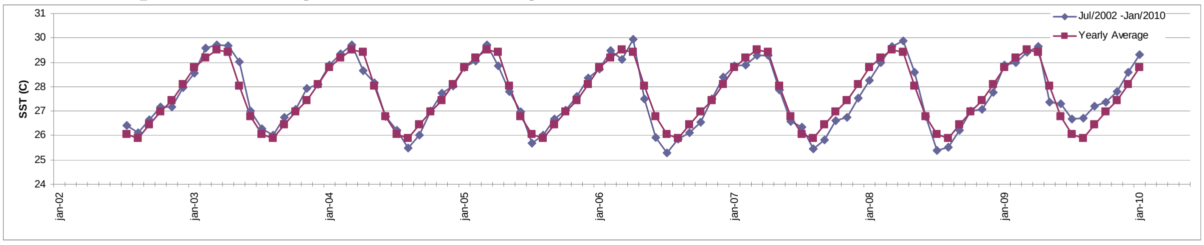

Figure 4- SST Jul2002-Jan2010 TSB area-averaged time series

Table 1. SST values retrieved on CRA stations

MODIS	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*	*#9*	*#10*	*#11*	*#12*
15/01/2009	29,6	29,1		29,6	30,0	29,1		29,1	27,3	30,6	27,3	27,4
05/04/2009	30,4	30,7		30,9	30,1	29,6	30,2	28,8	28,3	28,5	28,1	28,2
12/07/2009	27,6	26,5		27,4	28,0	27,2	27,2	26,9	26,2	27,3	26,3	26,5
06/11/2009	28,8	26,9		29,1	28,5	27,0	27,5	27,5	26,3	27,9	26,5	25,9

A look into the SCC images catches one attention to the tide regime for the selected images. The Jan 15th, Jul 12th and Nov 6th images were taken close to low tide peak while on Apr 5th, the satellite passage happened during high tide as showed below (figure 5).

The January 15th image (figure 2) showed SCC inside TSB reaching 5.9 mg.m^{-3} in the western part and between 1.3 mg.m^{-3} and 1.8 mg.m^{-3} in the central. Both Salvador and Itaparica channels registered SCC values superior to 1 mg.m^{-3} and this concentration could be seen 20km away from their bay entrances, as a result of the flood stream caused by the low tide scenario.

On April 5th the incoming tide kept the rich nutrient waters of inner TSB away from the oligothophic waters of the open Atlantic. SCC values superior to 1 mg.m^{-3} were only seen close to the Itaparica channel entrance and 20 km up to the Salvador channel. The N-S gradient registered in the main channel varied from 3.3 mg.m^{-3} to 0.5 mg.m^{-3}. SCC reached 5.3 mg.m^{-3} close to S.F.Conde and 2 mg.m^{-3} in the central area.

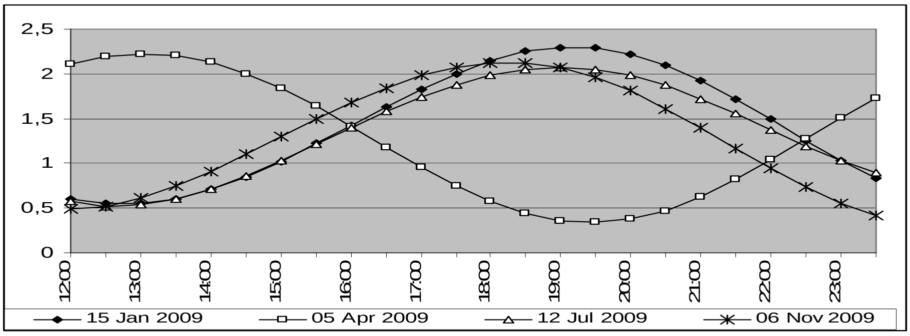

Figure 5- Local time image acquisition (13:10h to 13:25h).

On July 7th, the highest SCC of all images was observed, with values above 1 mg.m^{-3} seen for more than 30km off the Salvador channel and off Itaparica channel. Partially explained by the elevated Jaguaripe river discharge during June-July months of 2009 (figure 6). SCC reached a value superior to 5 mg.m^{-3} in all northwest, with peaks above 12 m. gm^{-3} in several locations. For the central part of the bay, concentration varied between 1.5 mg.m^{-3} and 2.5 mg.m^{-3}.

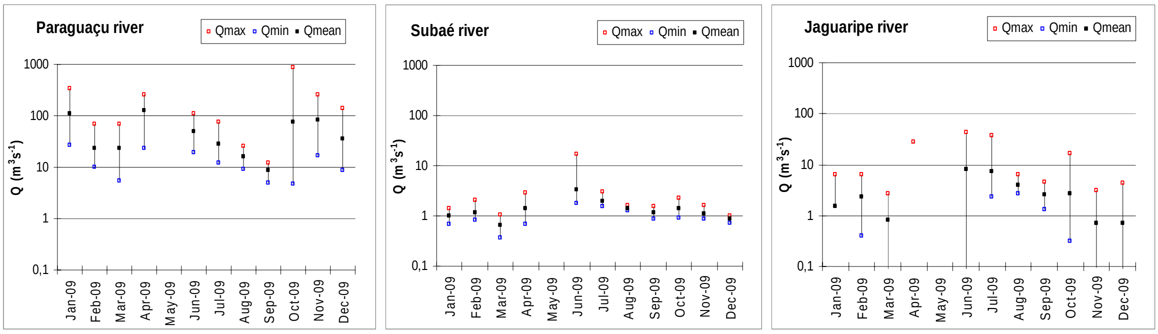

Figure 6- 2009 river discharges into TSB

On November, 6th, SCC remained high inside the TSB, especially between the Frades island and the northernmost point of Itaparica island. Concentration values for the western corner were superior to 4mgm^{-3}, reaching the highest values recorded for all CRA stations in #4 (15.7 mg.m^{-3}) at the entrance of the Paraguaçu channel. This high value might be a result of the high discharge rates of the Paraguaçu river during the months of October and November/2009, as showed on figure 6. The central part of the bay registered a maximum concentration of 1.9 mg.m^{-3}.

Monthly SCC data recorded for the coast of Bahia for the year 2009 shows high concentration values between April and July, with peak concentration in the month of June (figure 7). For the TSB selected area, SCC reached its minimum in October/2009 and maximum in June/2009. Still in June 2009, SCC reached the 3rd highest concentration value since July/2002 (figure 8).

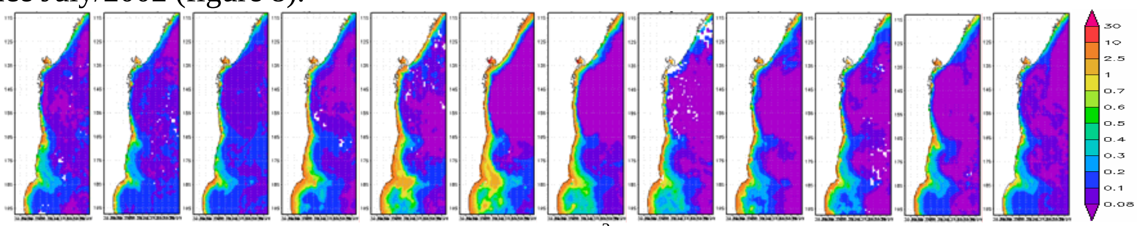

Figure 7- 2009' 12 month SCC (mg.m^{-3}) retrieved for the coast of Bahia

Although SST images do not show a visible surface gradient between coastal and offshore waters, the same cannot be said of the SCC images. It is surprising how the Brazil Current innermost branch and its interaction with coastal waters can be observed over this narrow shelf. This onshore limit is well marked by low SCC due to the Brazil Current's oligothropic waters.

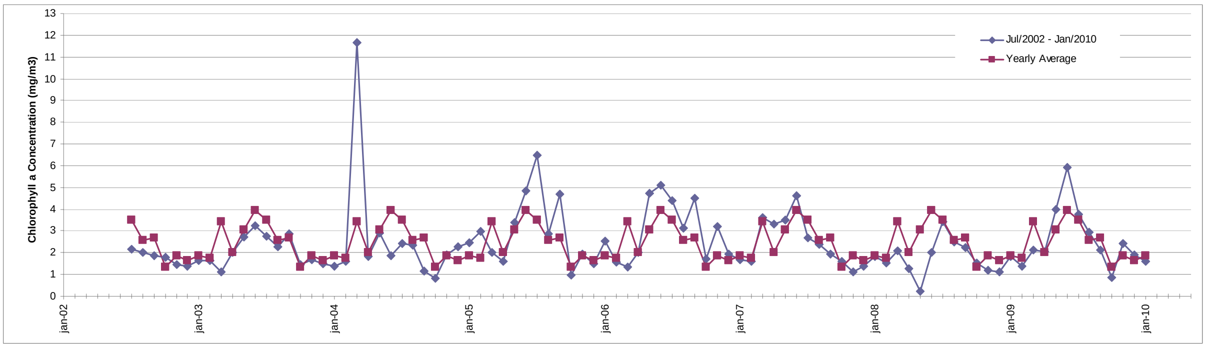

Figure 8- SCC Jul2002-Jan2010 TSB area-averaged time series

Table 2. SCC values retrieved on CRA stations

MODIS	*#1*	*#2*	*#3*	*#4*	*#5*	*#6*	*#7*	*#8*	*#9*	*#10*	*#11*	*#12*
15/01/2009	3,9	2,4		7,3	3,6	1,6		1,4	1,4	7,7	0,5	0,3
05/04/2009	4,0	2,6		4,3	2,5	2,3	3,4	0,9	0,5	1,1	0,3	0,2
12/07/2009	6,1	2,4		6,0	3,1	1,5	3,8	1,7	1,3	1,9	1,7	1,1
06/11/2009	4,3			15,7	3,2			1,2	1,7	3,2	1,3	0,4

4. Conclusion

SST in the TSB reaches its maximum peak in March and minimum peak in August, while SCC lowest (highest) observed values take place in October (June). In 2009, SST increased until April and then, decreased its surface temperature, reaching its minimum in August. SCC behaved exactly as expected with a low peak in October and a high peak in June.

Confined waters of TSB's northwestern part reached surface temperatures above 32°C in April 5th and chlorophyll concentrations of 12 mg.m^{-3} in July 12th. In the eastern part, colder waters occur and the SCC variability depends much more on the tidal penetration than on the freshwater input.

MODIS images, benefited from its high temporal resolution, has proven to be of importance in coastal, estuarine and ocean monitoring. Its high spatial resolution (up to 250m) allows the monitoring of physiographies off the Brazilian coastline, without the need of using multiple orbital platforms, costly data and delayed access to data. These particular characterists are crucial when dealing with spatially separated stations (hundreds of meters apart). Clouds and radiometric processing issues are still a big problem when dealing with MODIS data though.

5. References

Acker, J.G; McMahon, E; Shen, S.; Hearty, T.; Casey, N. Time-series analysis of remotely-sensed Seawifs Chlorophyll in river-influenced coastal regions. EARSel eProceedings 8, 2, p.114-139, 2009.

Bonfim, C.S.; Carvalho, R.C.; Lessa, G.C. Distribuição dos manguezais na Baia de Todos os Santos e seu impacto no balanço hídrico. In: Congresso sobre planejamento e gestão da zona costeira dos paises de expressão portuguesa, 9. Recife/PE, 2003.

Carvalho, R.C. Avaliação da adequabilidade da Baía de Todos os Santos para implantação de recifes artificiais – Exemplo de utilização de sistema de informação geográfica. Graduate thesis. UFBA. 39p. 2004

CRA – Centro de Recursos Ambientais. Saneamento ambiental da Baía de Todos os Santos. Modelamento e avaliação ambiental. Desenvolvimento de modelos computacionais de circulação hidrodinâmica, de transporte de contaminantes e de qualidade de água da BTS, e elaboração do seu diagnóstico. Relatório dos estudos básicos. Technical Report RT-257-03-GR-002-RF, 288p, 2000.

Cirano, M.; Lessa, G.C. Oceanographic characteristics of Baía de Todos os Santos, Brazil. Part I: circulation and seasonal variations described from *in situ* data. Revista Brasileira de Geofísica, v. 25, n. 4, p. 363-387, 2007.

Dias, K. Reavaliação da distribuição espacial das facies texturais do leito da Bahia de Todos os Santos. Monografia de conclusão de curso de graduação em Geologia/ UFBA. 50p, 2003.

FEMAR - Fundação de Estudos do Mar – Disponível em: <www.fundacaofemar.org.br>. Acesso em: 15 Jul 2009.

Finney, B. P,; Gregory-Eaves, I. ; Sweetman, J ; Douglas, M. S. V. & Smol, J. P. Impacts of Climatic Change and Fishing on Pacific Salmon Abundance over the Past 300 Years. Science, Vol. 290, no. 5492,795-799, DOI: 10.1126/science.290.5492.795, 2000.

Hu, C; Lin, I-I & Lien, C-C. Introduction to SeaWIFS/MODIS chlorophyll data products and data analysis tools. In: Carbon and nutrient fluxes in continental margins: A global synthesis. Eds. K.-K. Liu; Atkinson, L.; Quinones, R.; Talaue-McManus, IGBP Book series, Springer, Berlim, 744p, 2010.

IBGE- Instituto Brasileiro de Geografia e Estatística. Contagem da população 2007, Rio de Janeiro, 311p, 2007

INMET 1992 Normais climatológicas – 1961-1990. Ministério da agricultura, pecuária e abastecimento, 155p.

Knoppers, B; Ekau, W.; Figueiredo, A.G. The coast and shelf of east and northeast Brazil and material transporte. Geo-Marine Letters v.19, p. 171-178, 1999.

Krug, L.A. Um estudo diagnóstico e prognóstico do branqueamento de corais na plataforma leste do Brasil. Dissertação de Mestrado em Sensoriamento Remoto. INPE, São José dos Campos, 2008.

Leao, Z.M.A.N.; Kikuchi, R.K.P.; Oliveira, M.D.M. Branqueamento de corais nos recifes da Bahia e sua relação com eventos de anomalias termicas nas águas superficiais do oceano. Biota Neotropica, v. 8, n. 3, p. 1-14, 2008.

Lehodey, P.; Bertignac, M.; Hampton, J.; Lewis, A & Picaut, J. El Niño Southern Oscillation and tuna in the western Pacific. Nature, Vol. 389, 714-718, 1997.

Lessa, G.C; Bittencourt, A.C.S.P; Brichta, A.; Dominguez, J.M.L. A Reevaluation of the Late Quaternary Sedimentation in Todos os Santos Bay (BA), Brazil. Anais da academia Brasileira de Ciências. v. 72, n. 4, 2000.

Lessa, G.C; Dominguez, J.M.L.; Bittencourt, A.C.S.P; Brichta, A. The Tides and Tidal Circulation of Todos os Santos Bay. Northeast Brazil: a general characterization. Anais da Acadêmia Brasileira de Ciências, v. 73, n. 2, p. 245-261, 2001.

Lessa, G.C.; Cirano, M.; Genz, F.; Tanajura, C.A.S.; Silva, R.R.. Oceanografia Física. In: Hatje, V.; Andrade, J. B. (Org). Baía de Todos os Santos – Aspectos Oceanográficos. ed. Salvador: EDUFBA, 2009, v.1, p. 71-119.

Lima, G.M.P. & Lessa, G.C; The fresh-water discharge in Todos os Santos Bay (BA) and its significance to the general water circulation. Pesquisas em Geociências. 28 (2):85-97, 2001.

Medeiros, R.A.; Pontes, F.C. Roteiro Geológico da Bacia do Recôncavo, Bahia. Salvador. PETROBRAS/SEPES/DIVEN/Setor de Ensino na Bahia. 63p, 1983.

Reynolds, R. W.; Rayner, N. A.; Smith, T. M.;Stokes, D. C. & Wanh, W. An improved In Situ and Satellite SST Analysis for Climate. J. Climate, Vol 15, 1609-1625.

Soppa, M.A. Caracterização da variabilidade climatica nos ecossistemas recifais brasileiros e sua relação com a biodiversidade de corais. Master Thesis. INPE, 2008.

Winarso, G.; Hosotani, K.; Kikukawa, H. Chlorophyll-a distribution deduced from MODIS ocean color data and its characteristics around Hyuganada. Men. Fac. Fish. Kagoshima Univ. v. 55, p. 13-26, 2006.

Xavier, A.G. Análise hidrodinâmica da Baía de Todos os Santos. Doctor thesis. Graduate program in Engineering. UFRJ, p. 222, 2002.