The use of satellite derived sea surface temperature in Guanabara Bay, Brazil

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Abstract. In this work, we show for the first time the applicability of a recently available high-resolution satellite derived sea surface temperature G1SST to the Guanabara Bay by setting comparisons with two independent *in situ* datasets. Considering the costs of data acquisition in a regular basis with sufficient space/time coverage, and the economical crisis the State of Rio de Janeiro is facing, the possible use of a freely available remote sensing product for monitoring the Guanabara Bay is of extreme importance.

Keywords. Guanabara Bay, SST, Salinity, G1SST, Remote sensing

1. Introduction

The Guanabara Bay (GB) is located in the state of Rio de Janeiro along the southeastern Brazilian coast. The GB displays an area 384 km² surrounded by the second most densely populated region of Brazil, with approximately 16 million inhabitants (SEMADS, 2001). The bay has a mean depth of 5.7 m with a complex bathymetry. From the entrance to the middle of the bay, the predominant feature is a channel with depths ranging from 30-40 m reaching over 50 m in some depressions. In the northwestern sector depths as low as 0.5 m are observed (SEMADS, 2001).

In addition to the large resident population, the occupation of the GB margins is diverse with a variety of industry facilities, shipyards, naval bases and ports, causing significant impacts to the ecosystem. Due to the rapid degradation of the ecosystem, the bay is a major focus of environmental interest (Carreira et al., 2002). Recently, the GB was in the focus of international media, since it was the place of aquatic competitions during Rio 2016 Olympic games.

The GB is part of a large ecosystem that forms the Guanabara Bay drainage basin receiving waters from 45 rivers, six of which are responsible for 85% of the mean annual runoff of 100 ± 59 $m^3 s^{-1}$. The runoff ranges from 33 m³/s in the dry austral winter to 186 m³/s in the rainy austral summer (Kjerfve et al., 1997). Due to ocean versus riverine contributions to bay waters, vertical gradients of temperature and salinity can be up to 20 ^oC and 18, respectively (Paranhos et al., 1998). Density stratification of the water column is most pronounced in the shallow inner parts near stream discharges, and is correlated to the rainy and dry seasons: during the rainy period (October to April) temperatures are higher and salinities are lower, with the presence of thermoclines and haloclines, while during the dry season (May to September) temperatures are lower, salinities are higher and there is no stratification (Paranhos and Mayr, 1993; Paranhos et al., 1993).

Along the estuarine channel highest salinity values occur at the GB entrance up to 36 and less salty waters are found near the rivers mouths and wetlands in the northern portion, i.e, estuarine bay head, reaching values below 8 (Eichler et al., 2003). According to Melo (2004), mostly in the summer, relatively saltier /colder waters (S>35.5 and T<20 °C) associated to the South Atlantic Central Waters (ACAS) are observed in the deeper areas of the GB channel. Tides of semidiurnal period are the dominant forcing mechanism controlling currents at the GB promoting water renewal, mainly in the deeper areas, and mixture of riverine and ocean waters (Mayr et al., 1989; Paranhos et al., 1998). The hydrographic heterogeneity between different parts of the bay shows that it cannot be considered as a homogeneous environment, and sub-regional dissimilarities should always be considered in its assessments and monitoring (Mayr et al., 1989; Fistarol et al., 2015).

Monitoring environmental conditions is mandatory for coastal bays under high anthropogenic impacts. Once capable of providing data at proper resolutions, remote sensing products are one of the most powerful sources to help improving the understanding on space and low frequency variabilities of coastal water bodies resulting on reliable diagnostic and monitoring. In this study, for the first time the applicability of a recently available high resolution Sea Surface Temperature (SST) data product is tested in the GB. Considering the costs of data acquisition in a regular basis with sufficient space/time coverage, and the economical crisis the State of Rio de Janeiro is facing, the possible use of a freely available remote sensing product for monitoring the GB is of extreme importance. We analyze the data and validate it against *in situ* SST in the period 2011-2014. Short-term trends were also computed and their potential impacts are discussed.

2. Data and Methods

2.1 High resolution remote sensing derived sea surface temperature data

In this work we use the Group for High Resolution Sea Surface Temperature (GHRSST) Level 4 G1SST sea surface temperature analysis produced daily on an operational basis by the JPL Ocean group using a multi-scale two-dimensional variational (MS-2DVAR) blending algorithm on a global 0.009 degree grid. This Global 1 km SST (G1SST) analysis (Chao et al. 2009) uses satellite data from sensors that include the Advanced Very High Resolution Radiometer (AVHRR), the Advanced Along Track Scanning Radiometer (AATSR), the Spinning Enhanced Visible and Infrared Imager (SEVIRI), the Advanced Microwave Scanning Radiometer-EOS (AMSRE), the Tropical Rainfall Measuring Mission Microwave Imager (TMI), the Moderate Resolution Imaging Spectroradiometer (MODIS), the Geostationary Operational Environmental Satellite (GOES) Imager, the Multi-Functional Transport Satellite 1R (MTSAT-1R) radiometer, and *in situ* data from drifting and moored buoys.

2.1 *In situ* temperature data

The two *in situ* datasets used in this work were available thanks to two exceptional monitoring initiatives. Since 1997, the *Hydrobiology Lab* from the *Biology Institute of the Federal University of Rio de Janeiro* (IB-UFRJ) measures temperature and other variables at surface and bottom of the Guanabara Bay at many locations in a regular basis. We use data collected from January 2011 to December 2015 using an YSI 556 Multiparameter, which provides temperature measurements with 0.1°C accuracy. In addition, the *Guanabara Bay Project* from 2011 to 2014 conducted weekly campaigns profiling temperature and salinity

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through the water column. The data were sampled at 5Hz using the Sontenk Castway CTD with temperatures being measured with 0.05 °C accuracy. This dataset is freely available at *http://www.projetobaiadeguanabara.com.br.*

2.3 Methods

In Figure 1a we represent three regions inside the Guanabara Bay: North Region (NR), Central Region (CR), and the Entrance Region (ER). Each one has different oceanographic characteristics. The NR is the shallowest with depths ranging approximately from 10 to 25 m, within the main central channel. The CR is located around the Rio-Niteroi bridge with depths ranging from 10 to 35 m and the ER, where the exchange of oceanic and bay waters take place, displays depths ranging from 10 to 60 m also within the main channel. Elsewhere the main central channel, that is, in the shallowest areas, all regions display depths varying from 0 to 10 m.

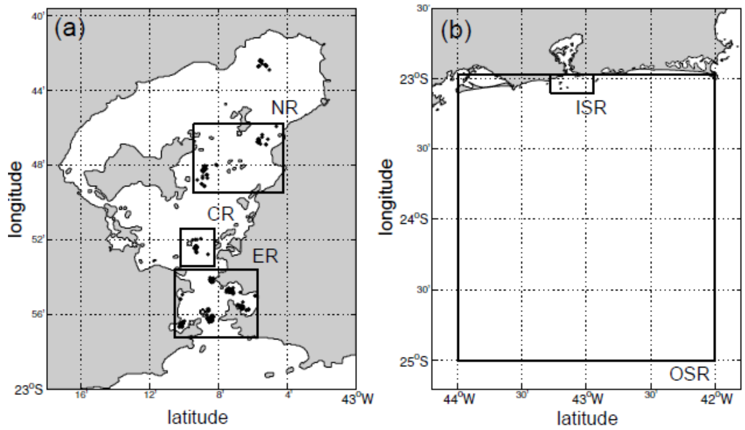

Figure 1. Schematic map indicating the regions where SST data is averaged: (a) North Region (NR), Central Region (CR), and Entrance Region; (b) Inner Shelf Region (ISR), and Outer Shelf Region (OSR). In panel (a) the black dots and squares indicate the CTD collection sites of *Guanabara Bay Project* and *IB-UFRJ-Hydrobiology Lab*, respectively.

In Figure 1b we indicate two shelf regions: the Inner Shelf Region (ISR), and the Outer Shelf Region (OSR). The ISR is the portion of the shelf with direct interaction with GB through the ER, so that it is presumably the region with waters with closer characteristics of the ER. The OSR is a larger area most influenced by the mesoscale circulation and oceanic water masses.

In order to compare the G1SST with *in situ* SST, and address its temporal and spatial variability, we daily averaged for each region in Figure 1 all available data. After this averaging process, we build time series of G1SST and *in situ* SST for each GB region (NR, CR, and ER) and time series of G1SST for each shelf region (ISR, and OSR).

3. Results and Discussion

In Figure 2 we plot the time series of G1SST (solid line), and *in situ* SST (circles) for NR (Figure 2a), CR (Figure 2b), and ER (Figure 2c). Red circles correspond to *Guanabara Bay Project* and green circles to *Hydrobiology Lab* campaigns. The dominant seasonal variability is evident on both G1SST and *in situ* time series with highest temperatures observed during the rainy period (October to April) and lowest temperatures during the dry period (May to September) as described in the literature (Paranhos and Mayr, 1993; Paranhos et al., 1993; Fistarol et al., 2015). The G1SST time series also exhibits variability on higher frequencies. For the three GB sub-regions, both time series seem to agree on displaying lower maximum temperature values on 2012 than observed on the years of 2011 and 2013. Short-term trends

(Table 1) were also calculated revealing an increase in temperature for both G1SST (black dashed line) and *in situ* (red dashed line). The positive SST trends are verified for the entire GB as well as for each sub-region (NR, CR, ER).

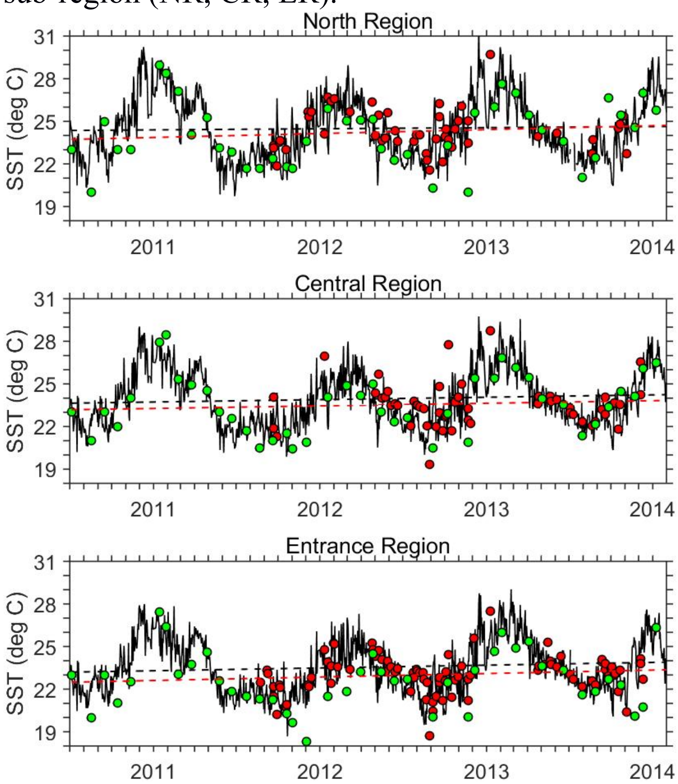

Figure 2. The solid lines are daily averages of G1SST at each region indicated in Figure 2a. The circles are daily averages of all in situ SST falling into each region in Figure 2a. Green dots are days where thermometer data is available. In each plot the dotted black line is the best linear fit to the G1SST data, and the dotted red line is the best linear fit to *in situ* data.

In Figure 3, we plot the dispersion diagrams and linear regression lines between G1SST and *in situ* SST for NR (Figure 3a), CR (Figure 3b), ER (Figure 3c), and all regions combined (Figure 3d). The Pearson correlation coefficient (r) is higher than 0.52 for all regions indicating a fair correlation between G1SST and *in situ* SST. When we combine all regions together (Figure 3d) the correlation increases to 0.59. Also, most of the points in each dispersion diagram are inside the 95% confidence interval for the linear regression. It is worth pointing out that the level of correlations between these two datasets is remarkable taking into account their differences in acquisition and processing. The G1SST is a hybrid product generated by the combination of multiple remote sensing sensors mounted in satellites with different tracks, orbits and periodicities. Also, the SST measured from space is the *skin temperature*, that is, the temperature at the top few millimeters of water column, whereas the *in situ* SST is the temperature of water a few centimeters below the ocean surface. Finally, we are comparing regional averages, where the space coverage of the G1SST is much higher than the *in situ* observations that, in general, there are only few points in each region at non-uniformly spaced days.

In Table 2 we list the SST annual means and its differences from year to year (ΔSST) for both datasets. It is clear that SST increased from 2011 to 2012 (ΔSST > 0) in the three regions inside the bay, and slightly decreased in the two shelf regions (ΔSST < 0). From 2012 to 2013 all regions presented warming with a vigorous increase in the two shelf regions. In most cases, the observed warming in the *in situ* SST is higher than in the G1SST. This is probably due to the non-uniform time sampling.

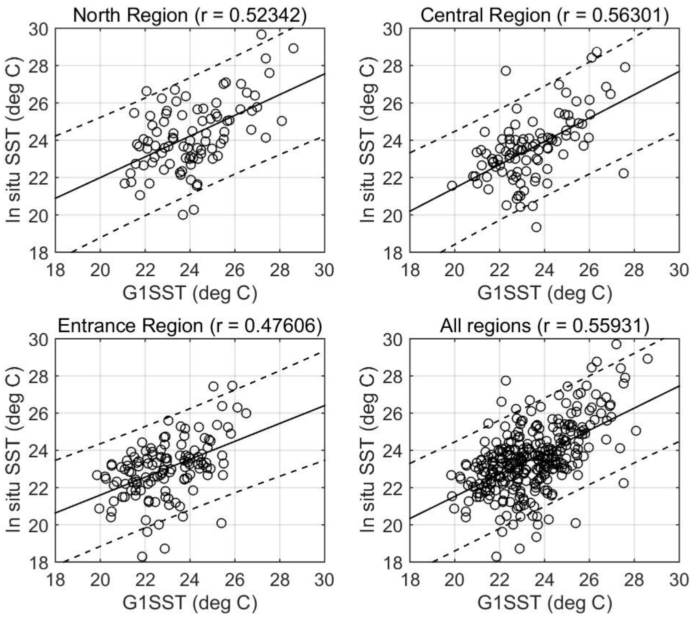

Figure 3. Dispersion diagrams of G1SST against *in situ* SST for each region indicated in Figure 1a. (panels (a), (b), and (c)), and for all regions combined (panel (d)). The straight lines are the linear regression lines and *r* is the correlation coefficient. The dotted lines bound the 95% confidence interval.

Table 1. Slopes (±95% confidence) of the straight lines in Figure 3 (NR, CR, and ER), and similarly for ISR, and OSR. Each line is best linear fit to the data in the least squares sense.

Region	Dataset	Slope (°C/year)
NR	G1SST	0.078 ± 0.113
	In situ	0.276 ± 0.449
CR	G1SST	0.167 ± 0.103
	In situ	0.182 ± 0.409
ER	G1SST	0.196 ± 0.099
	In situ	0.244 ± 0.322
ISR	G1SST	0.219 ± 0.106
OSR	G1SST	0.244 ± 0.096

The analyses of all datasets indicated that annual averaged surface temperatures decrease from NR to ER, that is, towards the Guanabara Bay mouth. Also, all sub-regions of GB presented averaged SST values higher than those found at the two shelf regions considered. A relatively cold subsurface ocean water named South Atlantic Central Water (SACW), defined by temperatures above 6 °C and below 20 °C and salinities between 34.6 and 36.2 (Miranda, 1985), is known to penetrate the GB through the central channel in the ER (Melo, 2004;

Bergamo, 2006). Persistent northeasterly winds that blow over the continental shelf, mostly intensified during austral spring and summer, force SACW to shallower depths at the inner continental shelf leading to the well know upwelling events observed off Cape Frio-RJ, about 100 km to the east of the GB entrance (Castro, et al., 2006; Castelão and Barth, 2006) and also to subsurface intrusions into the GB. Although the winds are intensified during austral spring and summer, many recent *in situ* measurements have shown the presence of SACW at other periods throughout the year within the GB. In fact, a surface TS diagram (not showed) computed using the temperature and salinity surface values from both *in situ* datasets described in this work revealed a larger influence of SACW on surface at the ER when compared to CR and, almost, no influence at NR.

Table 2. Annual means of SST for each region indicated in Figure 1 for 2011, 2012, and 2013. ΔSST is the difference between SST at the indicated years.

Regions	Dataset	SST (°C)			ΔSST (°C)		
		2011	2012	2013	2012 (2011)	2013 (2012)	2013 (2011)
NR	G1SST	24.14	24.55	24.59	0.41	0.04	0.45
	In situ	23.98	24.24	24.89	0.24	0.67	0.91
CR	G1SST	23.47	23.90	24.32	0.43	0.42	0.85
	In situ	23.13	23.49	23.95	0.36	0.46	0.82
ER	G1SST	23.03	23.38	24.14	0.35	0.76	1.11
	In situ	22.31	23.06	23.41	0.76	0.35	1.10
ISR	G1SST	22.48	22.37	23.73	-0.11	1.36	1.25
OSR	G1SST	22.65	22.56	23.73	-0.09	1.16	1.07

For all sub-regions considered in this pioneer work, the analyzed datasets show an increase of SST from 2011 to 2013. Although three years is a very short period for driving any long-term conclusions, at this first glance, the high-resolution G1SST dataset proved to be a valuable source for future diagnostic and monitoring of seasonal and climate effects on the GB. A long-term temperature increase would lead to an increase in water column stability and sea level within the GB. Both are matters of major concern, since vertical mixing driven by tidal currents, crucial for water quality conditions within the GB, would be potentially reduced while frequently observed flood events would be more dramatic under higher sea level conditions.

4. Conclusions

In this work, we showed for the first time the applicability of a recently available high resolution remote sensing G1SST product to the GB by setting comparisons with two independent *in situ* datasets. The GB was divided in three sub-regions (North Region, Center Region, and External Region) and SST time series were computed from 2011 to 2014. In addition, two sub-regions in the adjacent continental shelf were also defined for evaluation of bay versus oceanic conditions. For all sub-regions considered in this work, the analyzed datasets showed an increase of SST from 2011 to 2013. At this first glance, the high resolution G1SST dataset proved to be a valuable source for future diagnostic and monitoring of seasonal and climate effects on the GB. The analyses also indicate that annually averaged SST decreases from NR to ER, that is, towards the bay mouth. We conclude this should be expected since the ocean is the source of relatively very cold subsurface waters that penetrate into the GB.

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