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Long-term mean sea level measurements along the Brazilian coast: a preliminary assessment

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Abstract. The main objective of this work is to present a brief historic review focused on sea level measurements along the Brazilian coast. Furthermore, it aims to describe the protocols as well as the state-of-the-art and future challenges regarding the mean sea level (MSL) estimates along the Brazilian coast. The Brazilian initiative of measuring the sea level can be grouped into two distinct periods. The first period basically involved the setup and maintenance of tide gauges, focusing on obtaining information for navigation and harbor applications, elaboration of nautical charts and altimetric surveys, which did not require accurate estimates. The second phase, from the 1990s to date, is marked by an improvement in the establishment of reference levels (either local or the Vertical Datum) and the creation of PTNG (permanent tide network for geodesy) along with more precise and accurate estimates using continuous GPS (CGPS), gravimeters and altimetry. In conclusion, it is believed that continuation of current efforts to improve MSL measurements, implementation and maintenance of a geocentric datum, use of altimetric information and incorporation of geodesic measures as well as crustal movements control, are technical approaches that allow for the development of long time-series data appropriate for application in studies regarding effects of climate change on MSL.

Keywords: Mean sea level, mean sea level measurement, tide, Brazilian coast, tide gauge

Resumo. Medições a longo prazo do nível média do mar ao longo da costa Brasileira: uma avaliação preliminar. O objetivo deste trabalho é apresentar uma breve revisão histórica focada nas medições do nível do mar ao longo da costa brasileira, além de descrever os protocolos, o estado-da-arte e os desafios futuros em relação a estimativa do nível médio do mar (NMM) ao longo da costa brasileira. A iniciativa brasileira de medição do nível do mar pode ser agrupada em dois períodos distintos. O primeiro período, envolvendo basicamente a instalação e manutenção dos medidores de maré, com foco na obtenção de informações para navegação e atividades portuárias, elaboração de cartas náuticas e levantamentos altimétricos, que não requerem estimativas precisas. A segunda fase, a partir da década de 1990 até à data atual é marcado por uma melhoria no estabelecimento dos níveis de referência (local ou Datum vertical) e a criação da RMPG (rede maregráfica permanente para geodésia), juntamente com estimativas mais precisas e exatas usando medidas contínuas de GPS (CGPS), gravímetros e altimetria. Conclui-se, então, que a continuidade dos esforços atuais voltados para a melhoria das medições do NMM, isto é, a implementação e manutenção de um datum geocêntrico, o uso de informações altimétricas e a incorporação de medidas geodésicas, bem como o controle de movimentos da crosta terrestre, se constituem em abordagens técnicas necessárias que permitirão o desenvolvimento de longas séries temporais de dados adequadas para aplicação em estudos sobre os efeitos das alterações climáticas no NMM.

Palavras-chave: Nível médio do mar, medida de nível médio do mar, maré, costa brasileira, marégrafo.

Introduction

The mean sea level (MSL) is defined as the average of the daily oscillating processes of rise and fall of tides and all the disturbing processes associated with the meteorological effects and seasonal cycles (Pugh 2004). Understanding the factors that influence MSL are important owing to the impact an eventual rise or fall of sea level may have on human activities, especially on continental borders. To evaluate MSL, a multidisciplinary approach comprising several oceanic and atmospheric processes of different spatial and temporal scales like termohaline processes, currents, long waves, meteorology, atmospheric pressure, wind curl, evaporation, precipitation, river discharge, crustal movements, tides, glaciology and eustatic changes, is required (Lisitzin 1974). Any possible change in one or more of these processes has the ability to deform the marine surface and thus, change the sea level (Dalazoana 2005).

According to the 4º Report of Assessment of the Intergovernmental Panel on Climate Change (IPCC 2007), the main processes affecting the oceans in a scenario of global warming are seawater thermal expansion and melting of ice caps. According to the report, the MSL derived from tide gauge records on a global scale during the last century points toward a gradual rise in sea level, and the projections for the current century indicate an average elevation of approximately 1.7 mm year^{-1}. Despite being one of the main causes of MSL elevation, thermal expansion of oceans is too complicated to be measured. Different features respond in different ways to thermal expansion in an eventual warming. For example, when tropical sea surface water is heated, it will expand more easily than the deep cold waters (Pugh 2004). According to Houghton (2004), if the first 100 m of the ocean, with an average original temperature of 25ºC, show a temperature increase of 1°C, then the local depth will increase by 3 cm. However, the first 100 m of the ocean include the mixing layer, a stratum susceptible to atmospheric changes, which makes it difficult to estimate thermal expansion. Thus, to calculate the increase in MSL, it is necessary to use oceanic-atmospheric coupled models. Some results from these models show a gradual increase in ocean volume as a consequence of the observed increase in atmospheric temperature since the last century (Pugh 2004). The sea level rose at a rate of approximately 0.3-0.7 mm year^{-1} in the last century (IPCC 2007), and has increased from 0.6 to 1.1 mm year^{-1} during the last decade.

Accurate measurement of sea level to the order of millimeters is a challenging task, mainly due to the technological dependence of instruments and techniques used over the years. There are two methods for measuring sea level: direct and indirect. Direct measurement is performed *in situ* using metric ruler, tide gauges, reference levels, etc. In contrast, indirect measurement involves the estimation of sea level from altimetry using satellites.

In Brazil, the first measurements of sea level using tide gauges started toward the end of the 19th and the beginning of the 20th century, under the responsibility of the Navigation and Hydrographic Bureau (DHN). These estimates were reserved for use on harbor applications to obtain tidal components, and/or for the elaboration of nautical charts. Majority of the *in situ* measurements lasted for no longer than a lunar month, covering one spring and neap tide.

The main objective of this work is to present a brief historic review focused on the sea level along the Brazilian coast. In addition, it is intended to describe the protocols as well as the state-of-the-art and future challenges regarding MSL estimates along the Brazilian coast. It is important to point out that this work is focused on the long-term absolute sea level measurements, and not on the relative sea level within the scale of decades, which is used in engineering surveys with local application.

Materials and Methods

Equipment and protocols for measuring MSL

Sea level mensuration can be carried out directly and indirectly. The method is considered to be direct when the equipment is installed *in situ*, like the tide stakes and tide gauges. As these methods are relatively cheap, easy to handle and do not require sophisticated technology, they were initially used to assess the MSL. Indirect method of sea level measurement makes use of altimetry satellite estimates and represents a new technology (in use since the 1990s) as well as a more accurate technique than the direct estimates. Nevertheless, both the methods have their advantages and disadvantages, and the readers are referred to the reports by UNESCO (1985, 1994, 2002, 2006) for further information.

In Brazil, direct estimates are generally used to measure sea level. Nowadays, the two most common and recommended tide gauges are the float tide gauge and the radar tide gauge. The float tide gauge is basically a weight floating inside a tube immersed partially in water. The tube prevents the float from moving under the action of winds and waves for short periods. The float keeps itself linked to a cable and one pulley. When the cable is displaced on the pulley, an encoder transforms this movement into a measurement of sea level oscillation. Despite the equipment being simple to install and widely used, it is susceptible to many errors, such as sedimentation in the installation site, biological encrustations and crustal movements. The radar tide gauge is a new technology recently applied in Brazil. The main advantage of this system is its installation (it is located outside the water) and thus, is not susceptible to temperature and density oscillations. It measures the distance between the air–sea interface and the equipment through an acoustic signal. However, a major disadvantage of this system is the energy demand in case of use in long-term research.

Protocols for measuring MSL using tide gauges

Since tide gauges are being currently used in Brazil to measure MSL, we will further discuss the protocols associated with this technique.

The choice of system to measure sea level depends mostly on the purpose for which the data is to be used. Aspects such as costs, accuracy, location and duration of measurements must be taken into account to make the best decision possible. For example, harbor operations demand an accuracy of about 0.1 m (Pugh 2004). Hence, there is no need of the equipment to be sophisticated and a low cost tide gauge may be used accordingly.

Scientific studies focusing on MSL, on the other hand, require a more accurate estimate of about 0.01 m. In this case, the installation must have an adequate number of reference levels (RRNNs) to monitor possible changes in the ruler(s) position, to carry out a topographic–geodesic monitoring of the reference levels and tide gauges, besides a digital data record (Fig. 1). These items will be discussed later.

Nevertheless, once the choice is made, it is essential to follow its basic recommendations accordingly to obtain a valid and useful measurement.

The use of metric ruler is the simplest way to measure sea level. Despite being quite susceptible to positioning mistakes, it is still used as a calibration reference to verify and/or correct eventual vertical displacements of already installed tide gauges.

Tide gauges are relatively simple to install, widely known and do not require sophisticated technology to operate. However, there are many errors and some disadvantages associated with them. For example, they are for local use (i.e., the information is restricted to the point being sampled), are subject to operational errors (e.g., biological incrustation), crustal movements, meteorological factors, geographic positioning of the levels' references, etc.

There are many types of tide gauges. They can be classified, for example, according to the physics employed to obtain the information. The readers can refer to UNESCO (2002) for a complete list of tide gauges and their operating systems. To ensure accuracy of results, all of them commonly follow the same basic installation requirements. Any measurements of height should have a reference level relative to that plane. A reference plane is well defined locally on a stable surface, free of any influence of vertical and horizontal movements,

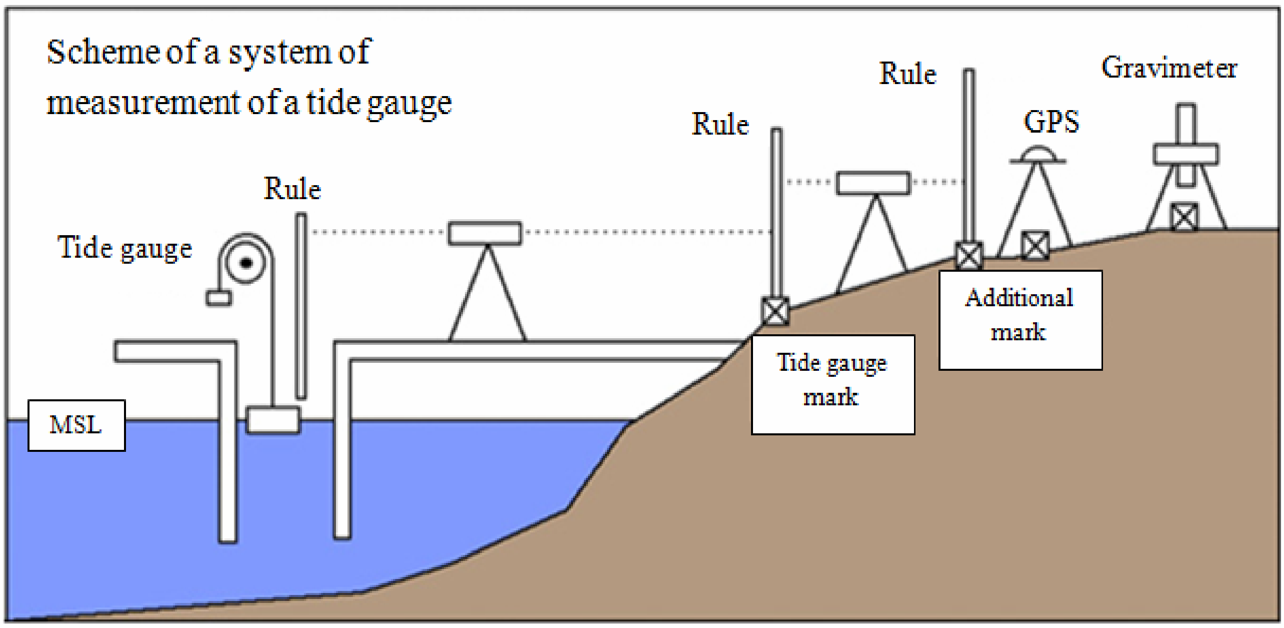

Figure 1. Scheme of the system of measurement using a tide gauge. Adapted from UNESCO (2002).

erosion, sedimentation, weathering, etc. Usually, a rock is used as a stable surface. When greater accuracy is required, or even for safety reasons in case one or more of them are destroyed, it is strongly recommended to use more than one reference plane (three, at least; UNESCO 1985). These local RRNNs are called Local Fixed Datum. Having more than one reference level guarantees the long term stability of a sea level time-series. In Brazil, the majority of tide gauges in operation are located in the harbor zones that are currently expanding their installation areas, and hence, it is quite possible to have some of the RRNNs destroyed during this process. The main disadvantage of this system (having multiple RRNNs) is that it is susceptible to crustal movements that may cause errors to the order of millimeters. Such errors must be removed using continuous GPS (CGPS) and gravimeter information if the data is to be used in studies regarding MSL variation due to climate change. CGPS is a GPS that records information continuously so that one can infer horizontal and vertical crustal movements.

The local datum RRNN should also be referenced to the Vertical Datum. The Vertical Datum can be defined as a standard mark to which any height measurement over the national territory is referenced.

According to UNESCO (1985), the local-depth tide gauge installation site should be at least 2 m below the surface in a low-tide regime. Estuaries, promontories, straits, and low-tide impoundment zones should, if possible, be avoided. Besides the RRNNs, the tide gauges should also have their own reference surface level, the so-called zero tide gauge (ZTG). The ZTG is a horizontal surface that indicates the mark zero. This mark can be any point located below the equipment. Table I summarizes the basic procedures that must be taken into account when a sea level measurement system based on tide gauges is set up. The readers are referred to the reports by UNESCO (1985, 1994, 2002) for more detailed information.

Results

The Brazilian initiative of measuring MSL

The first sea level measurements date back to the beginning of the last century, between 1910 and 1920, under the responsibility of DHN and INPH (National Institute of Hydrologic Research). Initially, the focus was toward navigation and harbor applications, elaboration of nautical charts and altimetric surveys (Neves 2005). After the creation of Portobras (Brazilian Harbor, or 'Portos Brasileiros'), the INPH became responsible for the installation and maintenance of all the equipment installed in harbors.

Over the decades, a total of 281 sites throughout the Brazilian coast, and a few offshore ones, were sampled (Fig. 2). Most of the sampling did not last for more than a month and were carried out during the 1970s. As described earlier, the data were used on specific applications, mainly harbor activities, and determination of tide components and amplitude.

Almost simultaneously, another set of information about the MSL was used to establish the Brazil Vertical Datum. Between 1919 and 1920, the extinct Brazilian General Chart Commission operated a tide gauge in the city of Torres in the Rio Grande do Sul state.

Despite the fact that such information no longer exists, those observations were referenced to a geodetic mark of the Geographic Service Board (or

Table I. Basic procedures to be considered when a tide-gauge sea level measurement scheme is set up. Adapted from UNESCO (1985, 1994, 2002).

Characteristic	**Description**
Installation	Locals of strong erosion, sedimentation, and hydrodynamics must be avoided
Reference levels	At least 3, arranged radially
Rules	Should be used for calibration and operational control purpose
Vertical Datum	All the RRNNs should be referenced to the Datum
CGPS	The equipment should be used for continuous monitoring of tide gauges' positions
Topographic–gravimetric control	It should be used to monitor the gravitational field of the installation site
Data records	Must be digital
Sampling	At least hourly, although high-frequency sampling is recommended
Physical protection	Built around the tide gauge to prevent damages
Accuracy	Minimum 0.01 m (Scientific studies)

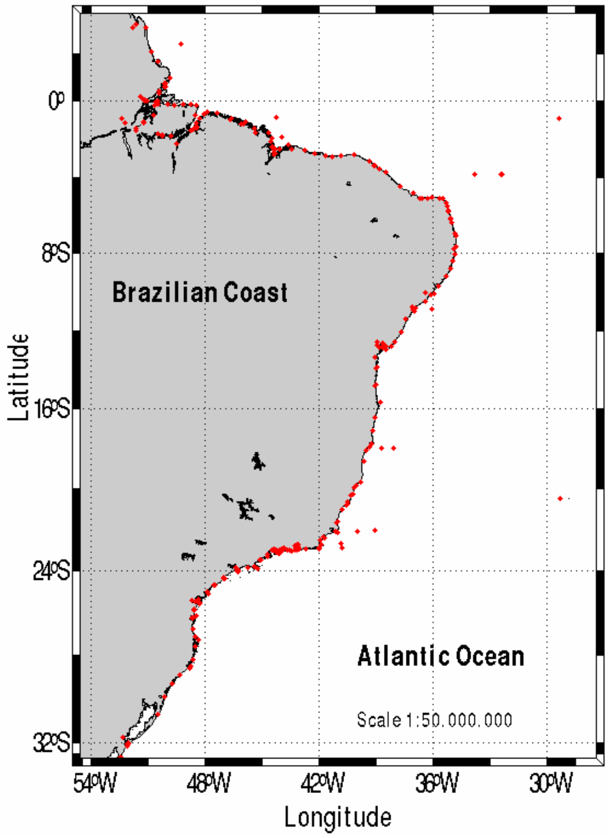

Figure 2. Geographic distribution of sites where tide-gauges measurements were carried out during the last century (red dots). Adapted from FEMAR (2000).

'Diretoria do Serviço Geográfico – DSG'), which was included in a new research leveling line between the city of Criciuma (Santa Catarina state) and Torres. As a result, a provisory Vertical Datum, called Torres Datum, was established. The determination of Vertical Datum had already attracted the attention of the Brazilian Geodesy System (SGB). Consequently, the Altimetry High Precision Net (or 'Rede Altimétrica de Alta Precisão – RAAP'), created in 1945, opted to establish the Datum of Torres, which marks the origin of all altimetric measurements. Thereafter, the Geographic National Council (presently, Brazilian Statistic and Geography Institute – IBGE) began proceedings to connect the RAAP datum with the several tide gauges spread along the Brazilian coast. In 1952, the first geographic readjustment of the Datum of Torres was established. By that time, more than 5000 RRNNs had been set near the Brazilian tide gauges. In 1959, the last readjustment of the Datum took place when it was moved definitely to the city of Imbituba (Santa Catarina state). The new Vertical Datum – Imbituba Datum – was carried out by the Inter-American Geodetic Survey after 9 years of observations, extending from 1949 to 1957. According to Franco (1988), the minimum recommended duration is 19 years. In the following decades (especially after 1970), there was a northward and mainland expansion regarding the establishment of RRNNs referenced to the Datum of Imbituba.

By the year 1960, a number of important tide-gauge stations with long data set records began to be deactivated. Recognizing the importance of having continuous and detailed records of sea level, in 1976, the IBGE considered the possibility of reactivating the tide gauge stations that were previously under the responsibility of IAGS. Between 1980 and 1986, the IBGE realized some re-evaluation of the Imbituba Datum. In 1993, the IBGE began to monitor sea level using tide gauges. This was done experimentally at the 'Estação Maregráfica Experimental de Copacabana', and lasted for one year when the gauge was destroyed by a storm surge. After a year of observation, it was concluded that sea level variation could be biased owing to instrumental deviation and vertical motions of the RRNNs.

In 1994, the IBGE took over the conventional tide gauge located at Porto de Imbetiba in the city of Macaé (Rio de Janeiro state) from Petrobras. Based on previous experience, IBGE upgraded the station, that is, employed measurement redundancy by operating two tide gauges with distinct principles of functioning, to avoid lack of information due to instrument failure. In addition, by upgrading the method of data storage, it was possible to make the information available in real time. As a result, the Macaé station has become a pilot station for the future Permanent Tide Network for Geodesy (PTNG) (or 'Rede Maregráfica Permanente para Geodésia – RMPG').

The PTNG was created in 1997 with a clear picture regarding the location of tide gauges. The locations chosen were in the following cities: Imbituba (Santa Catarina), Macaé (Rio de Janeiro), Salvador (Bahia), Fortaleza (Ceará), and Santana (Pará). The network became operational effectively from 2001, after the installation of digital equipment in Macaé and Imbituba.

The main goal of this network is to provide information to correlate the Datum of Imbituba with other sea level (tidal) references. The demand for such information was made clear in a study carried out by Alencar (1990). In his study, the author compared the local MSL with that referenced to the Datum of Imbituba (Table II).

Table II. MSL discrepancies between that measured locally and the reference level transported mechanically by geometric operations from Imbituba (SC). Adapted from Alencar (1990).

Tide gauge stations	Gap
Torres (Rio Grande do Sul)	+0.0584
Itajaí (Santa Catarina)	+0.1399
Paranaguá (Paraná)	+0.0010
Rio de Janeiro (Rio de Janeiro)	+0.1237
Vitória (Espírito Santo)	+0.2840
Fortaleza (Ceará)	+0.2923
Belém (Pará)	+0.8808

Positive values indicate that the local MSL is above the MSL referenced to Imbituba. According to Alencar (1990), the differences were accounted for by the errors in measuring sea level locally as well as by the instrumental, operational and gravimetric errors associated with the procedure of transporting the reference from Imbituba. Other causes may be due to meteorological and oceanographic factors, such as sea-surface temperature and salinity, and the lack of accurate information about MSL.

To achieve the main PTNG goal, it is necessary to repeat the leveling operations between stations using gravimetric information, and control the horizontal and vertical movements using CGPS estimates. These procedures will allow for a meticulous determination of the tide-gauge RRNN altitude as well as help in identifying the crustal movements, because any movement introduces error in the MSL estimates.

The PTNG is also a part of the SIRGAS Project (Reference System to the Americas (‘Sistema de Referência para as Américas’), a study that began in 1993. The project aims to define a unique reference system for the whole of South America, to establish and maintain a reference network among the South American countries, as well as to define a geocentric Datum. The readers can refer to SIRGAS (1997) for more details about the project.

Until 1993, every measurement assigned to the Datum and to the RRNN were (and most, or all, of them still are) topocentric. According to Freitas *et al.* (2002), the geocentric positions of the tide gauges serve as an initial condition to associate the MSL with global geoids. Thus, the contribution of SIRGAS to the studies on MSL comprises producing accurate positioning of the tide gauges and RRNNs, and their respective referencing to the new geocentric Vertical Datum.

The MSL topography, defined as the distance between the MSL and the geoid, should always be used to correct the tide gauge observations (Luz *et al.* 2008). The MSL topography results from the almost continuous action of many meteorological and oceanographic factors active on the sea surface, mainly on the shallow coastal regions. Thus, it is necessary for each tide gauge station to determine a specific value for the MSL topography, which was not possible until after 1995, making it difficult to correlate the MSL of the Vertical Datum region with that measured by the tide gauge stations along the coast. The technology that enables accurate estimates of MSL topography is altimetry satellite. The altimetry information was available since after the launch of a Franco-American mission carrying the TOPEX/Poseidon (T/P) sensor in 1992 (Dunbar & Hardin 1992). In 2005, the T/P mission finished its operations, when it was substituted by the Jason-1 satellite, launched in 2001. Despite the importance of the altimetry satellite in determining MSL topography, the estimates along the coastal regions are subject to some atmospheric and geophysical corrections of low accuracy. Nevertheless, Bosch & Savcenko (2007) used T/P and Jason-1 observations between 2002 and 2005 to estimate MSL topography in global coastal areas, using one-dimensional spectral filtering. Luz *et al.* (2008) applied the same methodology to the south-southeast Brazilian coast, with the purpose of solving the problem of integrating the RMPG results with the RRNNs. The results obtained showed some problems in estimating the MSL topography, mainly due to the spatial extension of the filter used to make the satellite and geoid model estimates compatible. However, the authors suggested a further study using the EGM-2008 (Earth Gravitational Model – US – National Geospatial-Intelligence Agency – NGA) model, which allows for a better spatial resolution of the geoid model in shallow waters. Matching deep-water sea level estimates and in situ tide gauge measurements, obtained along the satellite tracks, is also one of the objectives of the PTNG.

Present state of sea level measurements along the Brazilian coast

During the last century, some effort has been made to collect sea level information along the Brazilian coast. This aspect has been briefly reviewed in the previous section. Unfortunately, the majority (if not all) of the tide gauges, once active, are either not operational or have been destroyed. An exception is the Cananéia station, where the time-series is more than 50 years long. According to Pirazzoli (1986), who analyzed the data of long-term variations of MSL measurement from a data set available in the Permanente Mean Sea Level Institute (PMSLI), the rate of variation of the MSL followed a period of 20 years. Hence, the studies on long-term tendency should have at least 50 years of data.

Presently, according to their own needs for such information, universities, private institutions (industries), and public institutions or agencies (e.g., IBGE, INPE – Space Research National Institute, CHM – Navy Hydrographic Center) are (or are starting to) conducting long-term in situ sea level measurements. As a result, the effort of measuring sea level seems to be pulverized and uncoordinated, and it is not uncommon to observe gaps or discontinuity in the sea level time-series. Table III presents the active or planned (yet to install) tide gauges along the Brazilian coast and oceanic islands, and Figure 3 shows their spatial distribution. It is important to point out that a majority of the already-active stations shown in Figure 3 have not been planned for sea level change studies owing to climate change.

Table III. GLOSS-Brazil stations (Global Sea Level Observing System). Adapted from CHN (2009). Stations marked by * are part of the PTNG program.

Station	Responsible	Situation	Expected situation in 2010	Observations
Rio Grande (Rio Grande do Sul)	FURG-CHM	To be installed	Yet to be installed	Radar tide gauge
*Imbituba (Santa Catarina)	IBGE	Operating	Operational	Pressure tide gauge since 2001, CGPS from Dec 2006
Cananéia (Santa Catarina)	IOUSP	Operating	Operational	Radar tide gauge
Ilha Fiscal (Rio de Janeiro)	CHM	Operating	Operational	Radar tide gauge, conventional tide gauge (backup)
*Macaé (Rio de Janeiro)	IBGE	Operating	Operational	Pressure tide gauge, since July 2001, no CGPS station
Barra do Riacho (Espírito Santo) / Transfering to Vitória (Espírito Santo)	PORTOCEL/ VALE	Under test	Operational	Pressure tide gauge
*Salvador (Bahia)	IBGE (CHM)	Operating (under evaluation)	Operational	Radar tide gauge since Apr 2008; CGPS from Apr 2007; data transmitting in real time through satellite
*Fortaleza (Ceará)	IBGE	Operating (under evaluation)	Operational	Radar tide gauge since Apr 2008; CGPS from Oct 2008; data transmitting in real time through satellite
Ponta da Madeira (Maranhão)	Vale	Operating	Operational near real-time automatic data transmission	Conventional tide gauge, radar to be installed
Ilha da Trindade (Espírito Santo)	INPE-CHM	To be installed	Under evaluation	Radar tide gauge to be installed in 2010
Fernando de Noronha (Pernambuco)	INPE-CHM	To be installed	Under evaluation	Radar tide gauge to be installed in 2010
Arquipélago de São Pedro e São Paulo (Rio Grande do Norte)	INPE-CHM	Installed in 2008 (under test)	Operational	Radar tide gauge; data transmitting in real-time through satellite
*Santana (Pará)	IBGE	Operating	Operational	Radar tide gauge since Dec 2007; CGPS from July 2008

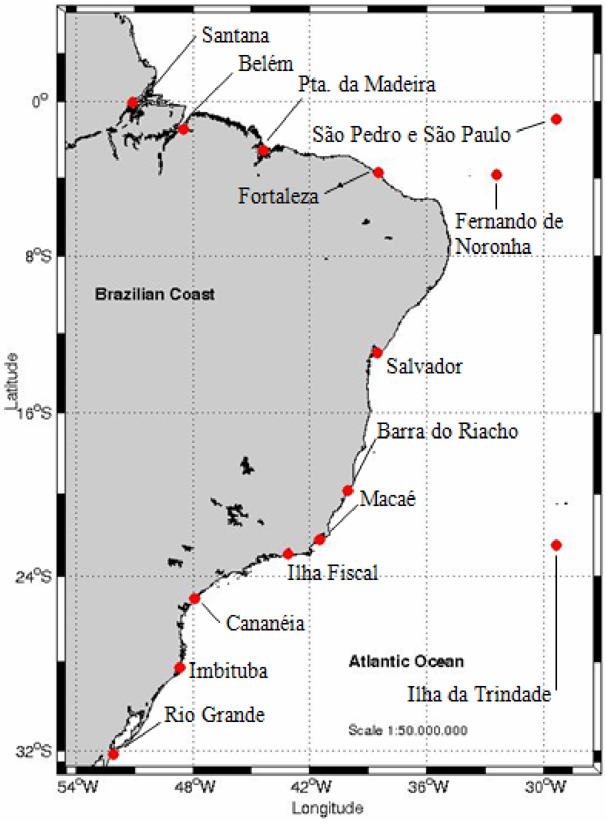

Figure 3. Location of the tide gauge stations along the Brazilian coast (red dots) included in the GLOSS-Brazil Program.

Discussion

In the Brazilian context of sea level measurements, two distinct periods can be established. The first basically comprised the setup and maintenance of tide gauges, focusing on obtaining information for harbor purposes, which did not require accurate estimates. This period ended by the late 1980s. The second phase that spans to date is marked by an improvement in the establishment of reference levels (either local or Vertical Datum) and the creation of PTNG for more precise and accurate estimates using CGPS, gravimeters and altimetry.

Although there are many tide gauge stations distributed along the Brazilian coast, a majority of them do not have an associated time-series of more than 10 years. Time-series longer than 30 years are restricted to the stations of Cananéia (São Paulo state) and Ilha Fiscal (Rio de Janeiro state). From the 1990s, these stations started implementing a topographic–geodesic control and installed digital equipment like the CGPS, covering a relatively short period of accurate data compared with the period when tide gauges were operational. The available time-series is shorter than that stipulated to study the impact of climate change on MSL. Douglas (1991) and Pirazzoli (1986) affirmed that the time-series should be of at least 50 years duration, to draw any specific conclusion regarding the sea level change.

Despite the results obtained by Douglas (1991), there have been some studies focused on evaluating the tendency of MSL along the Brazilian coast. França (1995) used tide gauge information from 1950 to 1990 from some Brazilians stations (Belém-Pará, Salinópolis- Pará,, Fortaleza-Ceará, Recife-Pernambuco, Salvador-Bahia, Canavieiras-Bahia, Rio de Janeiro-Rio de Janeiro, Ubatuba-São Paulo, Cananéia-Santa Catarina, and Imbituba-Santa Catarina) to verify the trend of MSL elevations. He found the tendency of elevation to be approximately 4 mm year^{-1} or about 50 cm century^{-1}.

Furthermore, the work carried out by Aubrey *et al.* (1988) also used the information from tide gauges to estimate MSL oscillations on the Brazilian coast, and concluded that the national tendency is of elevation. Both studies represent the first attempt to estimate the MSL changes along the coast. However, as stated previously, the information used in these studies had neither topographic–geodesic control nor correction from CGPS to eliminate the possible vertical and horizontal displacements of the crust.

Two problems can be associated with the current implemented system of using tide gauges for measuring sea level based on climate changes. The first problem is the use of different tide gauges along the coast (distinct physical principles of measurement); they might have different sampling rate and/or methods of digital record. Furthermore, the use of CGPS and gravimeter, the errors associated with the leveling using different techniques and the incompatibility of data from different types of equipment (cannot be used statistically) also pose a problem. Neves (2005) reported that to maintain a long-term MSL measurement, a rigorous assessment of the internal monitoring network, identification of the operation and its responsibilities, and a solid organization to maintain the network operation to continue data assimilation along the years are necessary.

The second problem is related to the maintenance of the station (which demands long-term financial support to maintain the functioning of the network), the control and processing of the data collected and its availability to the general public. These two aspects may be the cause of gaps in the historic time-series and the lack of sufficiently long sea level time-series to be used in studies regarding the impact of climate change on MSL.

Despite the efforts made by IBGE, CHN and other universities since the 1990's to obtain sea level data, Brazil is still in the early stages of developing a safe, precise, accurate and long-term sea-level time-series according to the standard protocols. An important initiative to create a realistic network for monitoring MSL is the Fluminense Tide Gauge Network (or 'Rede Maregráfica Fluminense – RMFlu'). This network was created in 1995 to control and support MSL measurements in Rio de Janeiro state. Currently, several organizations and institutions, like COPPE/UFRJ (Federal University of Rio de Janeiro), IBGE, Petrobras, DHN, CHM, IEAPM (Marine Research Institution Almirante Paulo Moreira) and Electronuclear S.A., constitute the RMFlu.

Nevertheless, the most recent and complete collection of MSL information and observations is included in the GLOSS-Brazil Program and PTMG project. According to the Marine Hydrographic Center (CHM-DHN), currently, only the tide gauge station of Imbituba (since December 2006), Cananéia (since January 2006), Salvador (since April 2007) and Fortaleza (since October 2008) have the CGPS installed and none of the GLOSS-Brazil stations have a gravimeter installed (Table III). In addition, they are mostly of the conventional (float) and pressure type. However, some stations like the stations of Ilha Fiscal, Cananéia, Vitória, Salvador, and Fortaleza, use the radar technology. Only two of the sites shown in Figure 3, Salvador and Fortaleza, have their measurements available online (data can be accessed on www.vliz.be/gauges). Most of the other stations have their information supposedly continuously uploaded (gaps in the records are common) to the international data centers like UHSLC (University of Hawaii Sea Level Center) and PSMSL. Finally, the application of altimetry technology on coastal regions is fundamental to studies regarding MSL changes since a geocentric Datum has to be used as the reference for MSL measurement.

Conclusion

Owing to the inconsistency of the local data distributed along the coast in relation to the Brazilian Vertical Datum, most of the tide gauge measurements carried out along the coast are not strictly accurate. This is because of the absence of accurate MSL topography estimates in shallow water regions. In addition, the fact that most of the MSL time-series do not have CGPS and gravimeter measurements (only recently, some stations have installed a CGPS) and the absence of a central organ responsible for managing the implementation, control and maintenance of the tide gauges, contribute to the current scenario where Brazil is still not able to precisely inform the impact of global warming on MSL. Hence, it can be concluded from the present work that these two aspects are the primordial issues that should be addressed. Nevertheless, it is believed that the continuity of the current efforts to improve MSL measurements, the implementation and maintenance of a geocentric Datum, the use of altimetric information, the incorporation of geodesic measures, as well as the control of crustal movements are approaches that allow for the development of long time-series data that can be applied to studies on the effects of climate changes on MSL.

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