Article



METHODOLOGY FOR QUALITY ANALYSIS OF REGIONAL BATHYMETRIC SURFACES

From Brazilian South Coast to Hunter Channel

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Abstract

There are several projects looking for a better way to represent large areas of seabed mapping using Digital Terrain Models (DTMs). Nonetheless, the selection of a DTM becomes a challenge in which the result should reflect the model with the highest quality. Thus, this paper aims to promote the development of a methodology in order to apply a set of graphical and statistical tools capable of supporting quantitative and qualitative analysis by the comparison of one surface (called LEPLAC Sul) against other DTMs available (as ETOPO1 and GEBCO_2014) and against a bathymetric control data derived from hydrographic surveys. The outcomes show that LEPLAC Sul has achieved the highest index of quality, presenting itself as an efficient reference for further national scientific researches of middle scale, like those related to oceanographic and geomorphological modeling.

Résumé

Il y a plusieurs projets qui visent la cartographie des fonds marins et sa représentation adéquate par les modèles de terrain numériques (MTN). Cependant, parmi les différentes options de surfaces marines disponibles, il est connu que le choix du MTN doit être basé sur la recherche du modèle de meilleure qualité. Ce travail a pour but de promouvoir le développement d’une méthodologie qui vise à l’application d’un ensemble d’outils graphiques et statistiques capables d’aider aux analyses quantitatives et qualitatives en comparant les surfaces d’intérêt (LEPLAC Sul) à d'autres dont l'accès est libre (ETOPO1 et GEBCO_2014) et aux données bathymétriques de contrôle dérivés des levés hydrographiques. Les résultats montrent que LEPLAC Sul a atteint l'indice de qualité le plus élevé et s'est présenté comme référence pour de futures analyses et études brésiliennes à moyenne échelle, telles que la modélisation océanographique et géomorphologiques.

Resumen

Hay varios proyectos dedicados a investigar la mejor forma de mapear grandes regiones del fondo del mar y su representación a través de Modelos Digitales de Terreno (MDT). Sin embargo, al elegir el MDT se debe tener en cuenta el modelo de mayor calidad. Por lo tanto, este trabajo pretende promover el desarrollo de una metodología que utiliza un conjunto de herramientas gráficas y estadísticas las cuales auxilian en los análisis cuantitativos y cualitativos, por medio de la comparación de una superficie (LEPLAC Sul) con otros MDT disponibles (ETOPO1 y GEBCO_2014) y con un dato batimétrico de control recogido de los levantamientos hidrográficos. El resultado de las pruebas demuestra que la superficie batimétrica LEPLAC Sul alcanzó los mayores índices de calidad. Así, puede considerarse una referencia eficiente para los futuros análisis e investigaciones brasileñas de mediana escala, como el caso de los modelos oceanográficos o geomorfológicos submarinos.

1. Introduction

In recent years bathymetric data has presented potential use beyond those restricted to safety of navigation. It has implied the development of many initiatives focused on seabed mapping according to different purposes and scales: global (IHO, 2014; Jakobsson et al., 2017), regional (EMODnet, 2018; 2017) and local (LINZ, 2015; NOAA and USGS, 2018), providing more than one product for the same geographic area.

Regarding scientific researches, the availability of accurate bathymetric surface models capable of representing underwater features details can be easily observed in numerical models dedicated to climate and ocean predictions (Gabioux et al., 2013; Lacasce, 2017) or those concerning to marine geomorphological analysis (Fernandes, 2010; IBGE, 2011; CPRM, 2003; Szatmari and Milani, 2016). Moreover, it is also possible to highlight the relevance of bathymetric Digital Terrain Model (DTM) in studies of geological hazards and the extension of national maritime boundaries (Chiocci; Cattaneo and Urgeles, 2011; Galvão, 2017; Mohriak and Torres, 2017; Torres et al., 2008; Lecours et al., 2016; Zimmermann and Prescott, 2018).

It is, therefore, possible to realize the benefits of the existence of some public DTMs able to nearly represent the marine relief in almost a worldwide coverage. Global DTMs examples, such as ETOPO1 – 1 arc-minute Global Relief Model (Amante and Eakins, 2009) and GEBCO_2014 – 30 arc-second Bathymetric Grid (Weatherall et al., 2015) are widely used for geoscientific studies over large unmapped features and regional tectonic investigations.

However, owing to intrinsic characteristics of their construction based on satellite measurements with significant imprecision (Macnab and Varma, 2008), those DTMs may not be suitable for some purposes, in special those regarding the description of environmental phenomena of large scales (Gabioux et al., 2013) or operations involving search and rescue (Mayer et al., 2018). These global DTMs usually have datasets with a small number of conventional soundings in contrast to the huge contribution of synthetic bathymetry derived from satellite radar (Becker et al., 2009).

Nowadays, this is changing with the support of renowned projects like Seabed 2030 (Mayer et al., 2018) and products as GEBCO_2019 Grid (GEBCO, 2019); although it still requires some steps until the complete reversion of this scenario.

In this context, this paper looks forward to give a special contribution with the selection process between bathymetric grid surfaces already available in overlapped areas. The establishment of an analytical method helps the definition of which DTM can represent more successfully the marine seafloor reality. Based on that, the selected bathymetric surface can be considered as a reliable reference for future studies, respecting their projected purposes and assuring their unbiased results (Chiocci; Cattaneo and Urgeles, 2011; FAPESP, 2012).

2. Study Area

The research was developed over a large area of the South Atlantic Ocean, covering 2,826,385.52km^2 inside NAVAREA V/METAREA V. All information in this region regarding the safety of navigation remains under the Brazilian responsibility with the International Hydrographic Organization (IHO), International Maritime Organization (IMO) and the World Meteorological Organization (WMO). This region extends from the national baseline to latitudes from 27°S to 37°S and longitudes from 025°W to 054°W, as presented by ***Figure 1a***.

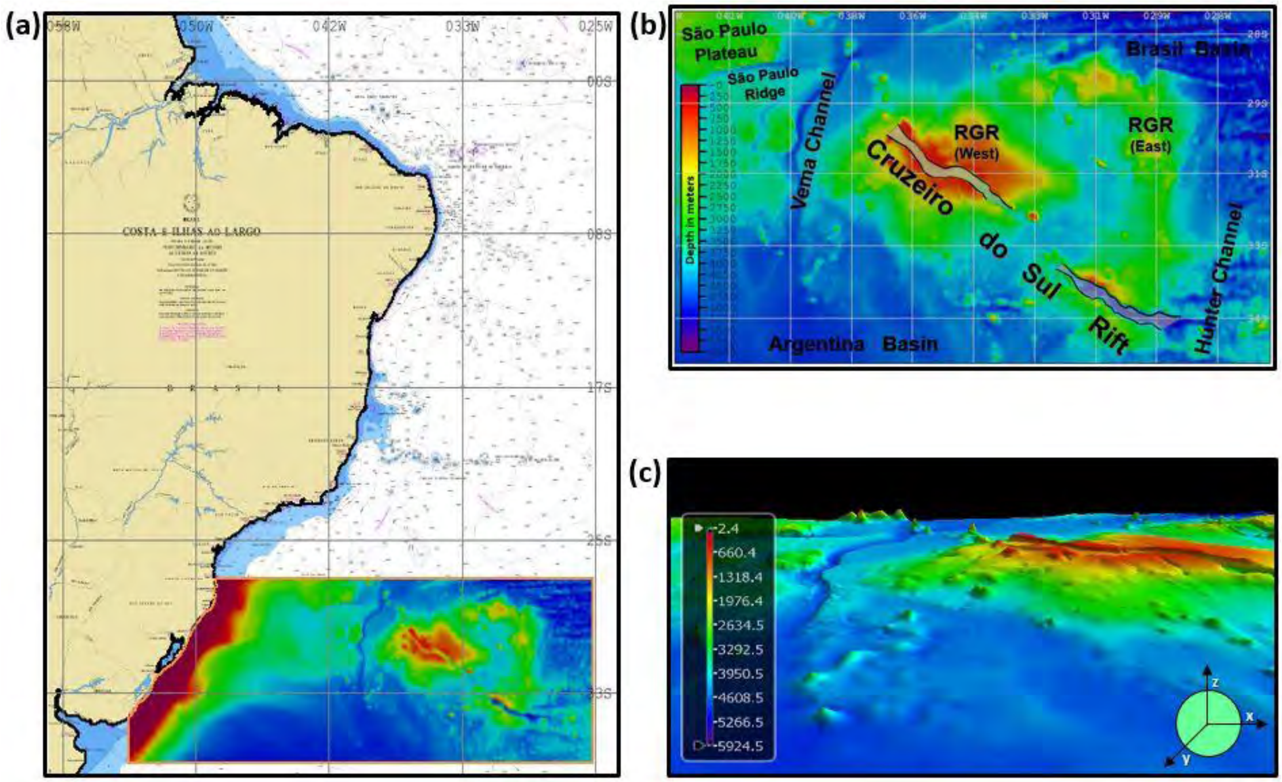


Figure 1– ***(a)*** *Location of the study area over the Brazilian nautical chart n°1.* ***(b)*** *Representation of main geomorphological features in the region.* ***(c)*** *3D visualization of seabed. Source: Made by authors.*

The bathymetry in this region reaches a significant range of depth (from 0 to 5,900m), with seabed characteristics varying from smooth to complex features (***Figure 1c***).

Among their geomorphological components, it is important to highlight the Rio Grande Rise (RGR) and the São Paulo Plateau (SPP). ***Figure 1b*** shows the RGR, one of the biggest morphological expressions of the South Atlantic Ocean, reaching 4,000m above the conventional depths and more than 3,000km^2. It is whittled by the Cruzeiro do Sul Rift (~1,500km), in which the central valley is surrounded by 3,500-m high cliffs. This structure is 1,500km offshore the Brazilian South Coast, being delimited by the Brazil and Argentina Basins and the Vema and Hunter Channels (Galvão, 2017; IBGE, 2011; LEPLAC, 2015).

3. Background

3.1 THE DIGITAL TERRAIN MODELS FOR MARINE REGIONS

According to Quadros (2012), a great part of interactions by users of bathymetric data deals with contour lines and 3D models. The marine Digital Terrain Model (DTM) is a special type of Digital Elevation Model (DEM), that can also include some features like breaklines or land mass points irregularly spaced which provide a better characterization of the bare terrain (Wilson, 2012; DSG, 2016).

Activities related to environmental management frequently demand an entire comprehension of the region of interest, and the use of spatially continuous products, such as the bathymetric grids, assumes great relevance (Li and Heap, 2014; IHO, 2017). Thus, Macnab and Varma (2008) and IHO&IOC (2018), recommend that marine DTMs must encompass the maximum number of qualified bathymetric data available and preferably those collected through acoustics methods, like the multibeam or singlebeam echosounders used in hydrographic surveys (IHO, 2008; DHN, 2017). The "EMODnet High Resolution Seabed Mapping" (EMODnet, 2018) and the "Seabed 2030

Project" (Mayer et al., 2018) are some examples of practices involving the enhancement of marine DTMs.

3.2 COMPARATIVE AND EVALUATION TOOLS FOR REGULAR BATHYMETRIC SURFACES

In general, the quality assurance of something is related to the attendance level of planned/ required parameters for some task or purpose. Regarding the DTMs, the EMODnet "Guidelines for Metadata, Data and DTM QA/QC" (EMODnet, 2017), made alongside with GEBCO, describes that for compatibility of different bathymetric data sources, the usage of quality controls can be made by visual analysis over the DTM (only qualitative aspects); by comparisons between the original soundings and the DTM created by them; by using the contrast between the DTM and external soundings (providing quantitative analysis by residual variances) and also by performing vertical and horizontal checks on a specific zone of the DTM.

Basically, there is no well-established method of quality analysis for small and medium-scale marine DTMs. Despite of that, there are many studies related to this subject (Marks and Smith, 2006; Abramova, 2012). It has been verified that comparison and evaluation methods can be divided into two approaches: qualitative (Weatherall et al., 2015; Becker et al., 2009; Amante and Eakins, 2009) and quantitative (Wlodarczyk-Sielicka and Stateczny, 2016; Yang et al., 2004), even though it is almost impossible to define a comparative tool exclusively by one or another. In any of these examinations, it is recommended that the data resulted by the interpolation are not trialed against the control data used in the construction of a DTM (IHO&IOC, 2018). Moreover, in the beginning, both procedures usually try to classify the bathymetric grid according to the magnitude of the measured errors and then compare one surface against the others to verify where the major distortions are found.

3.2.1 Control Data

For the purposes of evaluating the quality of bathymetric surfaces, soundings from hydrographic surveys conducted using qualified singlebeam and multibeam echosounders (IHO, 2008; DHN, 2017) can be adopted as representatives of the seabed reality and assumed as the control data.

Šiljeg; Lozić; Radoš (2015) pointed out some difficulties for establishing the enough amount of control data or the way they have to be exactly distributed. However, it is well known that this data should be spatially well distributed and in a consistent amount to deliver reliable statistics (Li and Heap, 2014; Olea, 2009).

3.2.2 General Statistics

The parameters related to the accuracy and precision of the measurements involved in the analytical process enhances the knowledge about the dataset (Olea, 2009). The validation process could be described mainly through the calculation of the Root Mean Square Error (RMSE) and the Mean Error (ME). The RMSE represents, on average, how far the observed values differ from the assumed true value, while the ME shows if a set of values were underestimated (negative ME) or overestimate (positive ME) in regard to the true value (Mukherjee et al., 2012; Patel et al., 2016).

Moreover, De Silveira et al. (2014) and Olea (2009) demonstrate that side by side comparisons of statistical parameters from each bathymetric surface is an alternative method to describe some population's characteristics using the measures of location (such as mean, median, and mode) or dispersion (standard deviation, variance, extreme values, and other metrics). The maximum and minimum dataset values (depths) are also important references to demonstrate trends or correlations among the surfaces (Wlodarczyk-Sielicka and Stateczny, 2016).

3.2.3 Histogram

In order to use this tool in spatial analysis, it is important to consider the connection between the frequency in which some values occur and its geographical distribution along the study area. Sometimes, only the statistics illustrated by the histogram is not enough to describe the general situation (De Silveira et al., 2014; IHO&IOC, 2018; Yang et al., 2004).

3.2.4 Correlation coefficient and linear regression

Normally, the comparison between the control data and the DTMs can be done using linear regression and correlation coefficient (R). In this case, it is possible to verify where the parameters were estimated by minimizing the mean square error (R^2), associated to a linear model (Olea, 2009). The results represent the proportion of the analytical dependency or the relationship that exists between both variables or studied surfaces. The highest R^2 value will point out the most successful DTM to represent the marine terrain (Khalid et al., 2016; Mukherjee et al., 2012).

3.2.5 Profile Graphics

It is also possible to compare different overlapped surfaces by using bathymetric profiles generated from control data and their respective representation on the DTMs. This kind of graphics may reveal some spatial behavior of the dataset relative to the characteristics of the marine terrain or some intrinsic issue of the DTM product (Khalid et al., 2016; Patel et. al., 2016).

In order to present a parameter for the comparisons in this paper, threshold values (maximum and minimum limits) were established from the control data. This tolerance was determined according to ***Equation 1***, using the Total Vertical Uncertainty (TVU) for Order 2 within a confidence level of 95% (IHO, 2008).

$$Limits = Z_i \pm \sqrt[2]{1 + (0.023 * Z_i)^2}$$

In which: Z_i is data control depths.

(***Equation* 1**)

3.2.6 Surfaces Difference

This mathematical instrument provides the detection of spatial discrepancies among the products. Although the results are taken from a reference surface, it is possible to observe the importance of cross-checking the techniques to create a wider comprehension of the variations within the study area. For instance, the connection between the maximum and minimum statistical errors or the mean and the standard variation values could provide additional information for analysis about the existence of residual obstacles in the bathymetric surface (Wlodarczyk-Sielicka and Stateczny, 2016).

Another way to express the differences between any of two bathymetric surfaces considered as the original (as LEPLAC Sul for example) and its new version, updated by a cluster of new dataset of soundings (like LEPLAC Sul*), can be calculated through adjustment with Weatherall et al. (2015) equation (***Equation 2***):

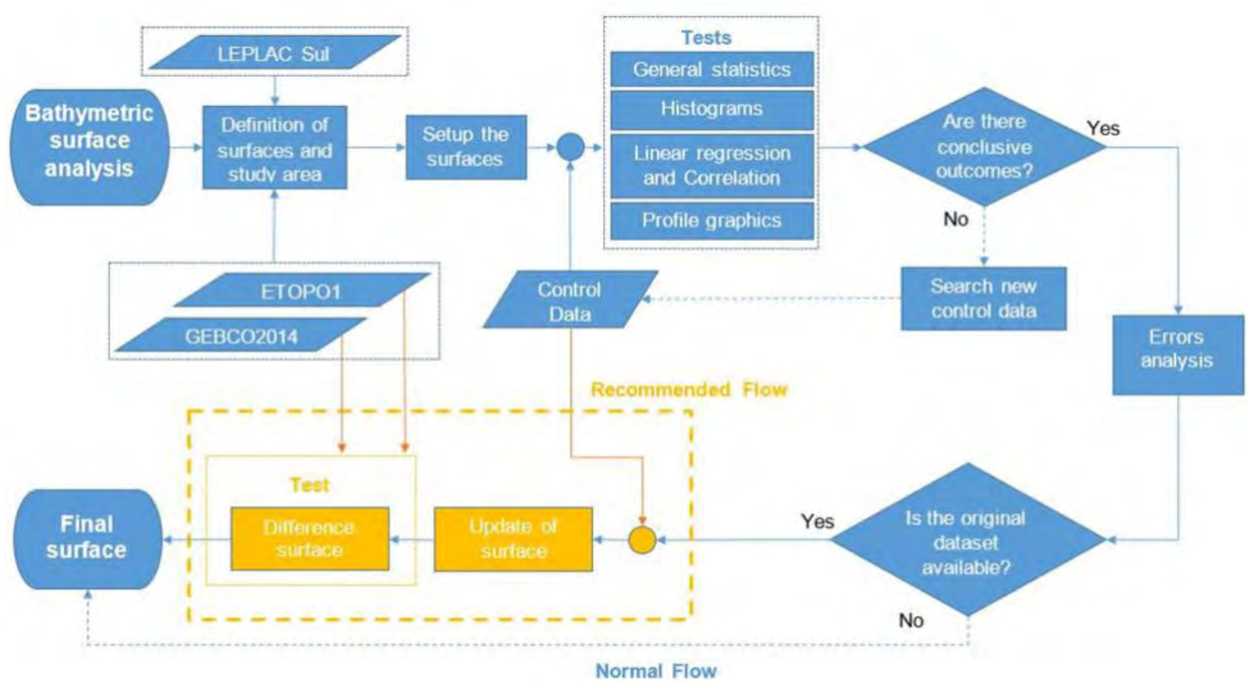
$$\frac{Abs(Sup.LEPLACSul - Sup.LEPLACSul*)}{Sup.LEPLACSul} * 100$$

(***Equation 2***)

4. Methodology

The diagram below (***Figure 2***) shows the main process applied in this research, which has adopted the "Recommended Flow".

Figure 2*: Analysis flowchart used in the present study. (*Source: Made by authors).



The process of "Bathymetric Surface Analysis" starts by the "Definition of Surfaces and the Study Area" (***Figure 2***). The DTMs used for comparison were GEBCO_2014 and ETOPO1', available in the GEBCO website (GEBCO, 2019) and in the NOAA website (NOAA, 2019), respectively. Meanwhile, the LEPLAC Sul surface was provided by the Brazilian Continental Shelf surveying Project (LEPLAC) only for this study. It remains integrated into the Partial Revised Submission made by Brazil to the UN Commission on the Limits of the Continental Shelf (CLCS), in respect of the Brazilian Southern Region (LEPLAC, 2015).

The LEPLAC Sul surface assembles a huge amount of bathymetric data from hydrographic surveys executed in order to map the Brazilian coastal region, the Brazilian continental shelf and the deep-sea bottom (***Figure 3***).

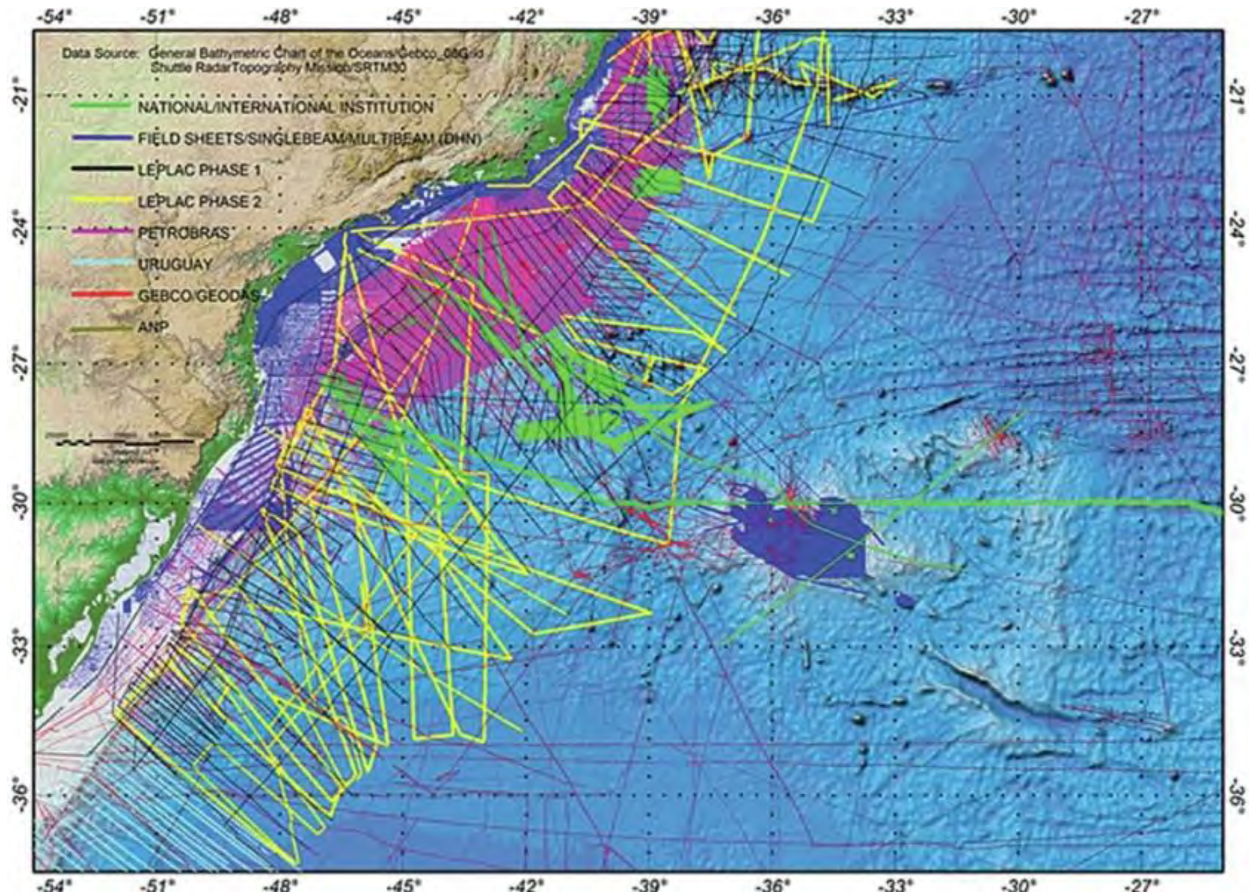


Figure 3: *Bathymetric dataset applied in the construction of LEPLAC Sul surface (except the information of SRTM30_Plus). Source: LEPLAC, 2015.*

The Table 1 shows the elementary characteristics of DTMs mentioned above.

Table 1: *Main bathymetric grid attributes.(Organized by authors).*

Parameter	GEBCO_2014	ETOPO1	LEPLAC Sul
Spatial resolution	Arc of 1/2' or 30''; 926m	Arc of 1'; 1,852m	Arc of 1.8898'; 3,500m
Coverage	Global	Global	Regional
DTM coverage	90°N to 90°S; 180°E to 180°W	90°N to 90°S; 180°E to 180°W	27°S to 37°S; 025°W to 054°W
Projection	Geographic; WGS84	Geographic; WGS84	Mercator; WGS84
Data released	December 2014	August 2008	April 2015
Data acquisition period	From 80' to 2014	From 1993 to 2008	From 1988 to 2014
Generation by	GEBCO	NGDC/NOAA	DHN
Interpolation methods	Algo-rithm"surface"derived of *Spline* and *scripts "remove-restore"* of *Generic Mapping Tools System* (GMT)	Algorithm "mbgrid" derived of *Spline* of MB-System and *"rdsample"* of GMT	Algorithm "rangrid" derived of *Spline* of GX/Oasis Montaj v8.1 of Geosoft

Source: AMANTE and EAKINS, 2009; LEPLAC, 2015; WEATHERALL et al., 2015

In order to “Setup the Surfaces” for comparisons through a specific application platform, the same reconstruction method was adopted in all surfaces (***Figure 2***). Focusing on the maintenance of the data values and the different resolution cells, the reconstruction of grids was made by the *nearest neighbor* interpolation method. Besides that, it was important to define the same geographic limits for all overlapped surfaces. These operations were performed though the CARIS BATHY DataBASE system, which is widely used by Hydrographic Offices, including the Directorate of Hydrography and Navigation (DHN). And among its applications, the BASE Editor provided most of the tools used in the steps that involve matchings between grids and control data.

Because of DHN’s participation in the Crowdsourced Bathymetry - CSB initiative (IHO, 2014, 2018), the metadata and the raw data of the “Control dataset” remain available in the IHO Data Center for Digital Bathymetry (DCDB) (IHO, 2019), as demonstrated in ***Figure 4***.

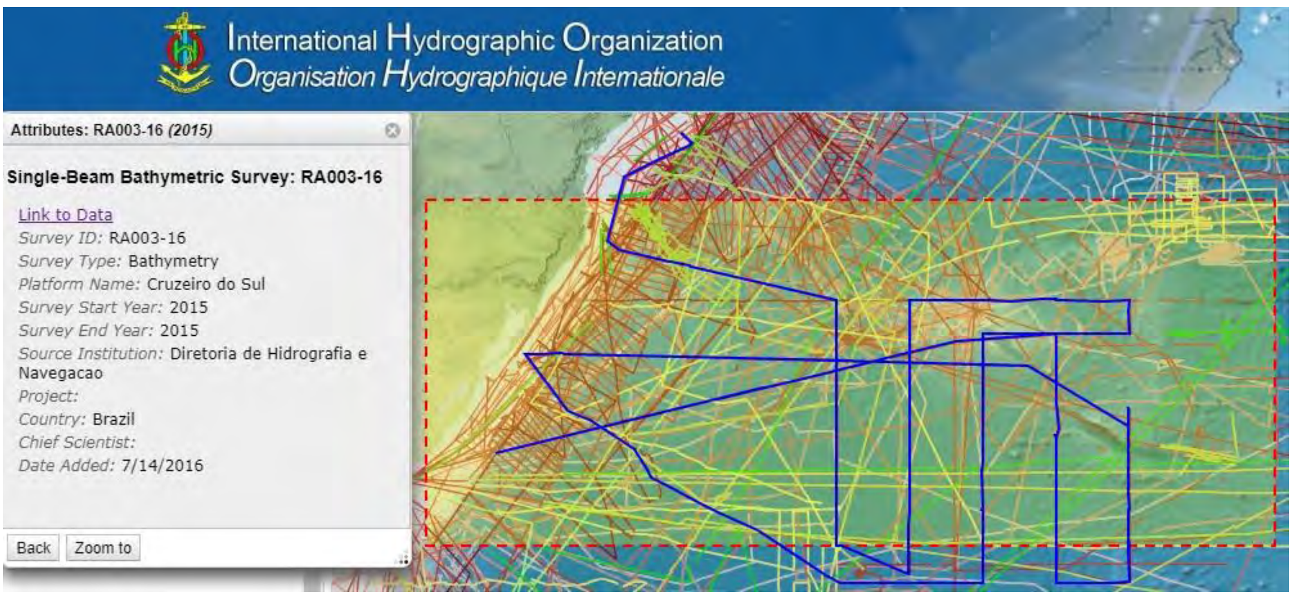


Figure 4: *Bathymetric control dataset (in blue) collected by DHN and provided to IHO for international distribution. Tracking line of “Cruzeiro do Sul”, 2015. Source: IHO, 2019.*

The hydrographic survey in ***Figure 4*** was conducted by the Brazilian Navy Ship “Cruzeiro do Sul” from 26 March to 27 May 27 2015. The bathymetry collected with a singlebeam EA600 (Kongsberg) echosounder was processed and the hydrographic survey was classified as Order 2, according to IHO Publication S-44 5th edition. The resulting bathymetric surface was named RA003-2016. The spatial distribution over the study area, with 5 vertical lines of sounding regularly spaced (222km) and long bathymetric profiles (2,100km) covering from the coast to the deep ocean, was also considered for the selection as a control data.

As soon as the surfaces and the control data were established, the flow diagram leaded to their own “Tests” (***Figure 2***). This step consisted in performing the test tools described on the theoretical background (***items 3.2.2 to 3.2.5***), as follow: computing general statistics, calculating histograms, making linear regression and verifying the correlation and the determination index, and building the profile graphics.

From the “Sample outcomes" (***Figure 2***) capable to lead to reliable conclusions about the behavior or trends of the dataset, the next step consisted in verifying the “Errors Analysis” (***Figure 2***). The IHO-IOC GEBCO Cook Book (IHO&IOC, 2018) describes the quality control as a set of procedures used to assure that the products are in accordance with the required standards and specifications. Then, one approach over this subject was designed through the establishment of limits or tolerances from the control data. Although the IHO Publication S-44 5th edition does not addresses the application of the TUV in DTM analysis, these metrics were applied as presented in this publication in order to define some comparison parameters between the DTMs (***Equation 1***).

The aim of this process consists in finding the bathymetric surface that is able to describe the main geomorphological features of the region and presents the lowest values of discrepancy from the control data. Achieving this "Final Surface" by "Normal Flow" (***Figure 2***) would already satisfy the objective of this research. However, focusing on continuous improvement of survey techniques and bathymetric process capacity, the DTM can still be enhanced through the “Recommended Flow” (***Figure 2***). In this case, the original data can be “Regridded” with the control data, making the new surface able to incorporate more qualified information, as well as making the interpolation more realistic. Therefore, the "Surface Difference" among the DTMs may be used to provide the amount of the main residuals between the products and its spatial location.

5. Results

5.1 GENERAL STATISTICS

Table 2 presents the global statistics of each marine DTM from this study. The difference among the bathymetric grids is verified through the different number of cells of each DTM as the result of their spatial resolutions and the negative depths observed in GEBCO_2014 and ETOPO1 surfaces, which reached -383m and -281m, respectively. According to the convention applied during the process, only positive values were supposed to be found. However, the GEBCO_2014 had 994 negative cells and ETOPO1 had 239 negative cells. The LEPLAC Sul surface was the only one in which this behavior could not be seen.

Table 2: *Global statistics from bathymetric surfaces.(Organized by authors).*

Parameter	GEBCO_2014	ETOPO1	LEPLAC Sul
Total number of cells (N)	3,831,187	956,108	317,092
Minimum depth (m)	-383	-281	2
Maximum depth (m)	5,968	5,967	5,911.7
Range (m)	6,351	6,248	5,909.7
Mean depth: μ (m)	3,665.6	3,668.8	3,676.6
Standard deviation:σ (m)	1,313.9	1,309.3	1,305.5

In sequence, ***Table 3*** shows the statistical outcomes from the relationship between the bathymetric surfaces and the control data. It is noticeable that the number of samples presents a small variation due to the influence of spatial resolution of the grids when in contact with the control data. The values of extreme error determine the possible amplitude of errors, indicating the DTM LEPLAC Sul as the one showing the highest variation (3,979.2m). The Mean Error (ME) indicates that ETOPO1 was deeper on average than the control data, while the LEPLAC Sul was shallower on average. The RMSE shows that LEPLAC Sul model was the nearest to the values considered as true, while the ETOPO1 was the farthest on average from the control data.

Table 3: *Statistical analysis of bathymetric grids and the control data.(Organized by authors).*

Parameter	RA003-2016 x GEBCO_2014	RA003-2016 x ETOPO1	RA003-2016 x LEPLAC Sul
Number of cells of sample (n)	272,184	271,357	271,234
Minor error of sample (m)	-1,726.8	-1,712.8	-1,750.2
Maximum error of sample (m)	2,230.2	2,221.2	2,229
Error range (m)	3,957.1	3,934.1	3,979.2
ME (m)	0.539	-14.716	8.714
RMSE (m)	143.971	145.338	140.125

5.2 HISTOGRAMS

The use of histograms allows the comparison of the distribution curves among the different surfaces, as well as the detection of extreme values in each product. The graphs in ***Figure 5a*** illustrate variations of up to 10 times in frequency, with 2,500 occurrences of a same value in GEBCO_2014 while the maximum frequency in LEPLAC Sul were 250 events. This difference is due to the variation in the number of cells of each DTM under analysis (see ***Table 2***, index "N"). ***Figure 5b*** demonstrates that bathymetric models GEBCO_2014 (in green) and ETOPO1 (in blue) show negative values in depths, while the LEPLAC Sul (black) distribution does not indicate depths below 0m.

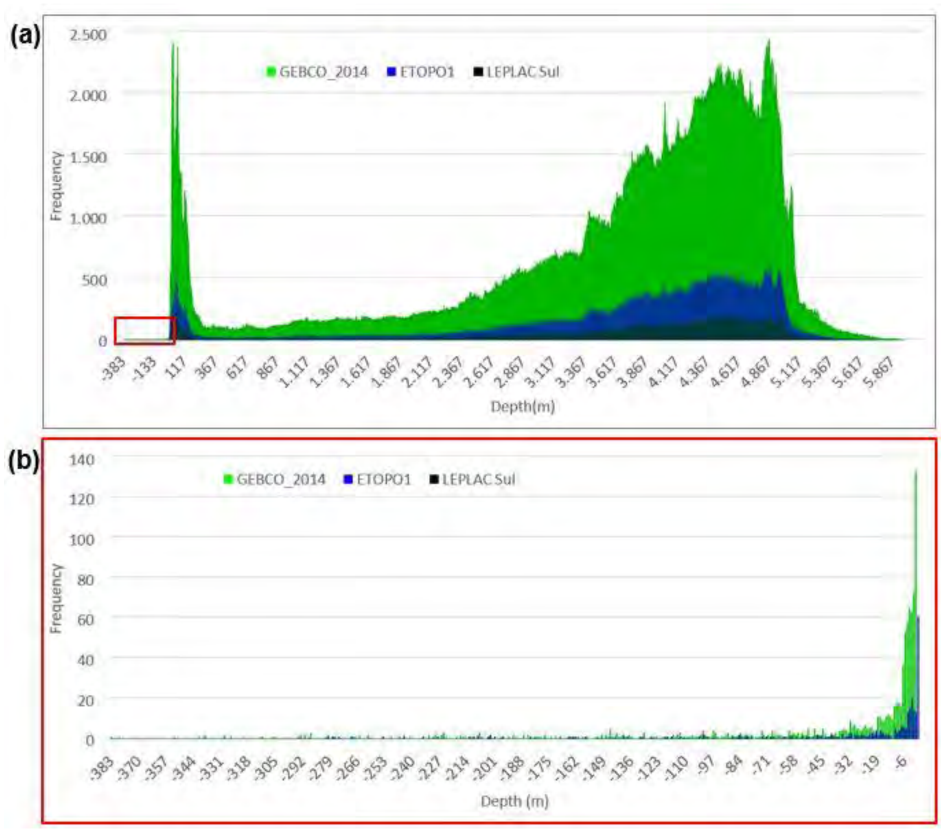


***Figure 5**: **(a)** Depth frequency distribution from the analyzed DTMs. **(b)** Detail of the frequency distribution of negative values found in DTMs GEBCO_2014 and ETOPO1. Source: Made by authors.*

Figure 6 presents the histogram of contrast between the depths derived from the DTMs and those obtained from the control data (RA003-2016). ***Figures 6a, 6b, and 6c*** show the histograms with the distribution of errors between the difference of the depths modeled by the DTMs and those derived from the control data (RA003-2016). Thus, the greater the occurrences of error values equal to 0m, the more precise the DTM will be. ***Figure 6b*** shows the maximum frequency range for the LEPLAC Sul with 5,885 occurrences of 1.90m, followed by ETOPO1 (***Figure 6c***) with 4,469 events of 1.20m and finally the GEBCO_2014 which obtained 4,179 measurements of 3.15m (***Figure 6a***). In addition, the ***Figure 6d*** presents these three overlapping curves, pointing out a concentration of events around 0m (errors close to zero meter) according to ME values previously obtained (***Table 3***), with the dispersion form of a Normal Distribution. A brief analysis of asymmetry and kurtosis of these curves demonstrates a leptokurtic behavior, which is a more vertically concentrated distribution (Olea, 2009). In this sense, it is understood that the higher the vertical concentration, the more the DTM will be similar to the control data.

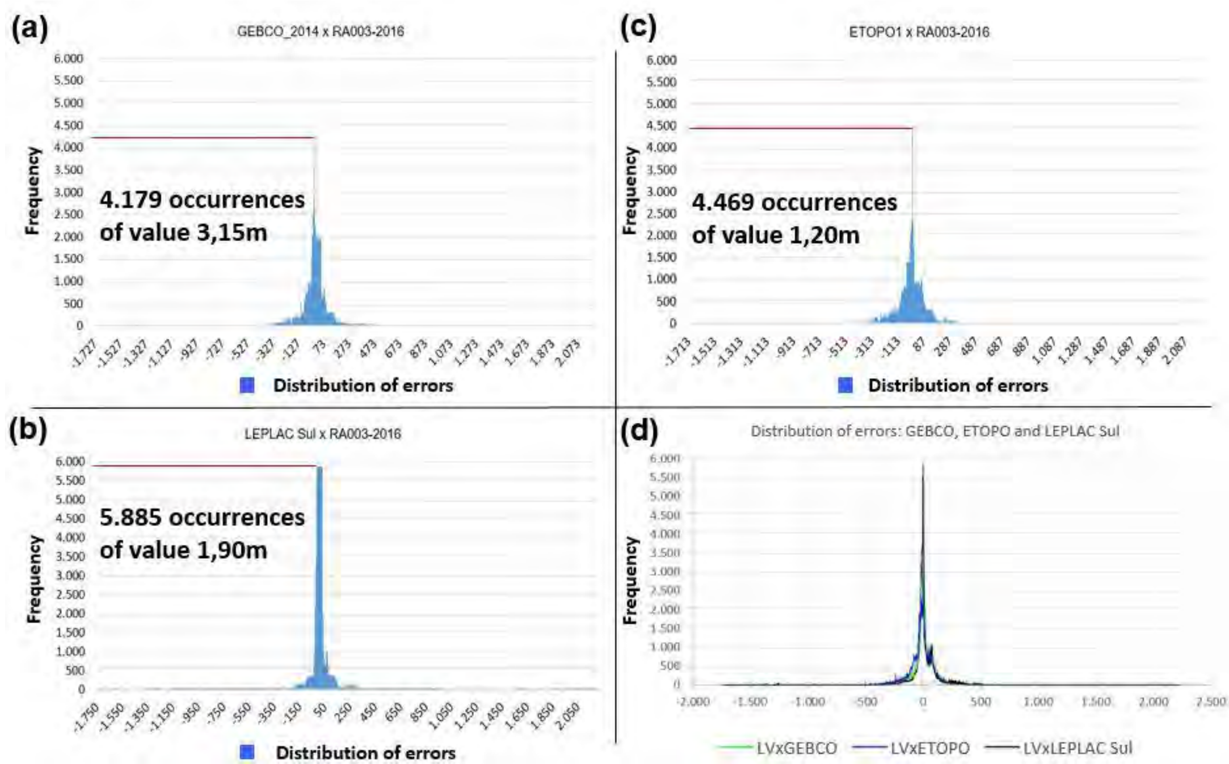


Figure 6*: Histograms of discrepancies between* ***(a)*** *GEBCO_2014,* ***(b)*** *ETOPO1,* ***(c)*** *LEPLAC Sul and the control dataset.* ***(d)*** *Overlapping of three curves of error distributions. Made by authors*

5.3 LINEAR REGRESSION AND CORRELATION COEFFICIENT

The graphics in ***Figure 7*** introduce the correlation between the depths calculated from the bathymetric DTMs (GEBCO_2014, ETOPO1 and LEPLAC Sul) and the control data (RA003-2016). They demonstrate the distribution trend of values and the associated linear regression provided the correlation coefficient (*or Pearson*) and the determination coefficient (R^2).

The correlation presented by all was considered high, as follow: GEBCO_2014xRA003-2016, 99.519%; ETOPO1xRA003-2016, 99.514% and LEPLAC SulxRA003-2016, 99.544%. The proximity of these values confirms the need to apply additional tools to improve the analysis.

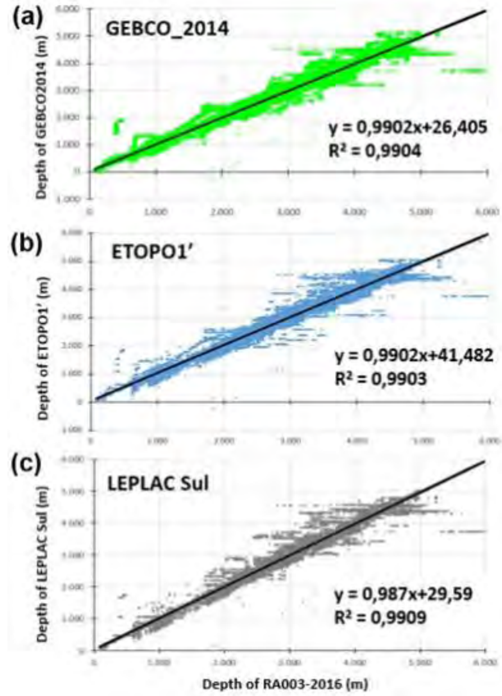


***Figure 7**: Correlation and linear regression between the depths of **(a)** GEBCO_2014, **(b)** ETOPO1', **(c)** LEPLAC Sul and the control dataset (RA003-2016). Source: Made by authors.*

5.4 PROFILE GRAPHICS

This profile was plotted from the extreme south of the Brazilian continental shelf (750m deep) eastwards offshore, to the deep waters of the Atlantic Ocean (4,500m) over a bathymetric line of control data (***Figure 8a***). ***Figure 8c*** details a section of approximately 500km long of the profile.

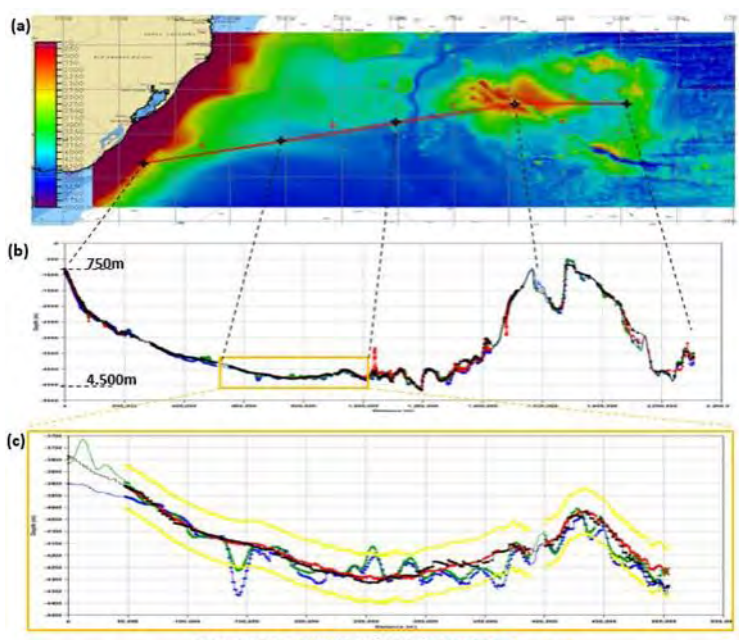


***Figure 8**: **(a)** Trackline (in red) and its segments (A, B, C, D) plotted over one line of the control dataset and the match of marine DTMs. **(b)** Bathymetric profiles of three DTMs and the control dataset (in red); **(c)** The detailed analysis in Sector B control data "RA003-2016" (in red), GEBCO_2014 (in green), ETOPO1 (in blue), LEPLAC Sul (in black) and the threshold (in yellow). Source: Made by authors.*

The LEPLAC Sul surface proved to have a smooth tendency in comparison to the other DTMs. Moreover, due to the application of parameters of Order 2 from IHO Publication S-44 (IHO, 2008) onto ***Equation 1***, it was possible to build the threshold (yellow limits in ***Figure 8c***) from control data and realize that LEPLAC Sul owned 71.2% into the tolerance, while the GEBCO_2014 and ETOPO1 had 62.4% and 57.4%, respectively.

5.5 DIFFERENCE SURFACE

Based on the domain of the construction parameters of DTM LEPLAC Sul, in the access to its original dataset and the new bathymetry from hydrographic surveys acquired in the region (such as RA003-2016), it was possible to use all of the information available to update the bathymetric grid.

Therefore, the "Recommended Flow" presented on ***Figure 2*** was performed by LEPLAC Project Team for the construction of a new version of the LEPLAC Sul surface. During this update, the addition of new qualified soundings in its interpolation process filled some geographic gaps, improving the spatial resolution of this model from 3,500km to 2,500km, now named LEPLAC Sul*. Besides that, it is possible to notice through the application of ***Equation 2*** that the updating process resulted in a new grid with approximately twice the number of cells (620,858 units). From the number of cells of LEPLAC Sul*, 460,027 cells (74%) remained within the tolerance range of 1% of the maximum observed difference (18m). Similarly, 595,722 cells are contained onto the limit of 5% of the maximum discrepancy, reaching about 95% of total variations.

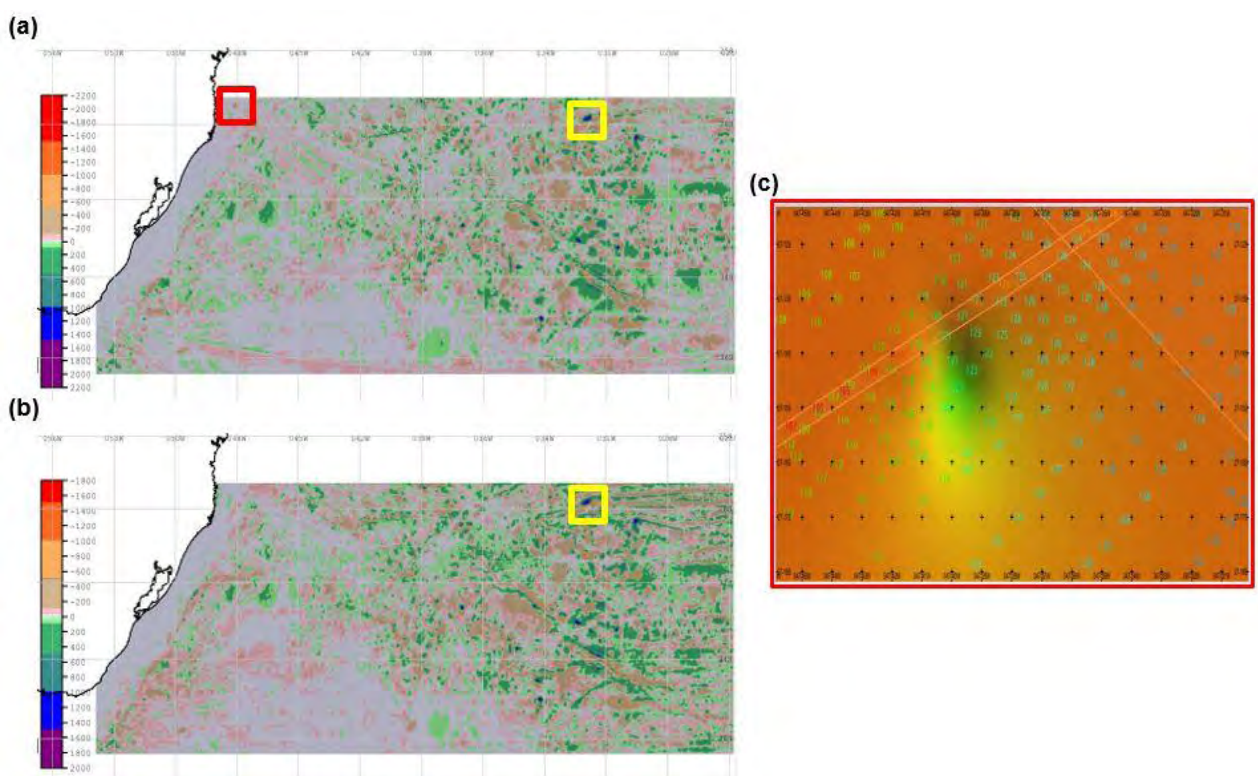


***Figure 9**: **(a)** Difference surface between LEPLAC Sul* and GEBCO_2014. The rectangles (in red and yellow) reveal the occurrence of extreme values. **(b)** Difference surface between LEPLAC Sul* and ETOPO1. The yellow rectangle highlights the maintenance of only that extreme value. **(c)** Artefact detected in GEBCO_2014 (red rectangle in Fig.9a). Source: Made by authors.*

The ***Figure 9a*** indicates the existence of some points of extreme values located near the 28°S parallel and the longitudes 032°W (yellow rectangle) and 048°W (red rectangle). Unlike the first feature mentioned, the event near the coast (coordinates 28°S, 048°W) is only detected on GEBCO_2014 surface (red rectangle). This situation was a warning call to a detailed investigation in this sector, which is presented by the magnified image (***Figure 9c***). Being an area located close to the Brazilian coast, it was possible to verify the bathymetry records from hydrographic surveys performed near this site. In this situation, the existence of a conspicuous element (green) - which has a vertical discrepancy of more than 1,500m relative to the surveys taken in this region - was not detected. This attested the existence of an artifact in the GEBCO_2014 surface.

6. Discussion

The adoption of statistical tools capable of describing (graphically and analytically) attributes of the behavior of bathymetric surfaces provided an integrated analysis of the results as illustrated by ***Table 4***.

Table 4: Summary of characteristics among the bathymetric grids evaluated.(Organized by authors).

Parameter	GEBCO_2014	ETOPO1	LEPLAC Sul*
Spatial resolution	926m	1,852m	Starts with 3,500m (in 2015) toward to 2,500m (in 2017) with improvement trend
Source data information and its construction's description	SID** and technical report is available to public	Don't have SID**, however its technical report is available to public	Contain SID** and a technical report, however due to CLPC process it is not available to public
Match of errors and uncertainty checked over the study area	A median result for its profile values (62.4%) into the tolerance of TUV order 2. However, even showing the smallest value of ME, this model has the highest standard deviation(σ) of its dataset.	Reaches the lowest number of values (54.7%) within the threshold TUV order 2.Presents the lowest index of R, R^2 and the greaters absolut values of ME and RMSE.	This profile achieved the best adjustment (71.2%) regarding the tolerance limits stablished from TUV order 2. It also presented the highests index of R, R^2 and the lowest value of RMSE.
Issues regarding source data accuracy	Contain a sparse number of soundings data over the study area, and the most part of altimetry values were estimated by satellite-derived gravity data. Its quality control wasn't capable to detect and remove all spurious data over this region.	It has the lowest number of soundings data in the study area. It was basically calculated from satellite-derived bathymetry dataset. Its quality control wasn't capable to detect and remove all spurious data over this region.	With the greatest number of soundings over the study area, has a good performance of internal consistency. It was capable to detected and represented the new geomorphologic features. Its robust quality control was able to identify and remove the spurious data over the region.
About artifacts	Possess some artificial elements of high magnitude.	The spurious spots are present in general smooth due to satellite data.	No spurious data was detected.

**SID - *Source Identifier Grid.*

The outcomes show that LEPLAC Sul surface reached the highest R (99.544%) and R^2 (0.9909), as well as the lowest RMSE (140.125m) while the ETOPO1 grid showed the highest RMSE (145.338m). The histograms demonstrated the dispersed behavior of GEBCO_2014 and ETOPO1 models, reaching the highest values of standard deviation in their bathymetric datasets (1,313.9m and 1,309.3m, respectively). The comparison of the bathymetric profiles along with the control data proves that the LEPLAC Sul surface reached the highest percentage of its depths within the established tolerance (71.2%), higher than GEBCO_2014 and ETOPO1 models. In addition, it is noteworthy that the GEBCO_2014 and ETOPO1 bathymetric models registered unexpected depths for the study area (presence of artifacts and negative depths), while LEPLAC Sul surface was the only one without this kind of behavior. Therefore, although LEPLAC Sul surface does not have the highest spatial resolution grid, it stands out for the highest number of arguments to support its superior quality when compared to other DTM assessed in this study.

7. Conclusion

The DTM quality analysis will always be connected to its purpose. In this study, the processed data was evaluated under a qualitative and quantitative perspective focusing on the definition of a bathymetric surface as consistent as possible with the objective of making it able to be used as a reference to future regional research, in the scope of ocean modeling and marine geomorphology.

Although some global seabed DTMs, such as GEBCO_2014 and ETOPO1 models, have spatial resolutions greater than 1km, it is possible to notice the demands of several countries for more detailed DTM, as well as the need for a greater reliability on the measurements. Thus, it is not a rule that the greater spatial resolution will result in a surface with best quality. This analysis shall consider as many parameters as possible in order to completely understand the relationship between the mathematical modeling and the reality of the represented terrain.

Therefore, in this study we developed a methodology applying a series of comparative analysis allowing the assessment of the main characteristics of each DTM. In addition, such methodology stands out for the capacity of adopting multiple tools, allowing a conjugated and robust approach over the subject. This method can be improved and applied in other areas of interest, expanding the evaluation procedure to other DTMs and other regions of the world.

Finally, among the verified models, the LEPLAC Sul surface demonstrated its precision by achieving good quality index and its detection and delimitation capacity of new submarine features. In this way, it is expected that it will be useful as a reference for further scientific researches, as well as tasks focusing on the delimitation of maritime boundaries and on the definition of the outer limits of the continental shelf, according to Art.76 of UNCLOS.

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