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Compilation of bathymetric data for the South China Sea 2: High resolution dataset based on multiple sources

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New grid bathymetry dataset covering the whole South China Sea with a spatial resolution of 1 min (1/60 degrees) has been developed by compiling sounding data derived from various sources including recent multi-beam sounding records. This dataset was found to resolve more realistic bottom features than existing global DTMs (etopo1, gebco08, gebco2014) especially at shallow regions such as Spratly Islands and the Java Sea.

Key words: *bathymetry, South China Sea, tidal model, Spratly and Paracel Islands, DTM*

1. Introduction

The performance of ocean models, especially those predicting tides, rely greatly on the quality of bathymetric data used. For example, root-mean-square (RMS) differences between observed and predicted M_2 tides in the East China Sea were 17 cm and 15 degrees for amplitudes and phases, respectively[1], whereas corresponding values were 5.6 cm and 6.5 degrees in the case of the Northwest European Shelf seas[2]. As both studies used a same numerical model and the target seas were similar in size, the smaller RMS values found in the latter case may be ascribed to the difference in the availability of well-managed bathymetric data.

As for the case of the South China Sea (SCS), Uehara[3] verified three existing digital terrain models (DTMs), i.e., etopo5, etopo1 and gebco08, and found errors especially in coastal regions shallower than 200 m, which were caused by misinterpretation of units, inclusion of erroneous records and interpolation made over sparsely-distributed data.

Uehara[3] revised the shallow along-shore portion of gebco08 dataset by using depth information obtained from nautical charts and single-beam sounding data and compiled a new bathymetric dataset with a resolution of 1/12 degrees. Usage of the new dataset reduced the RMS difference of M_2 amplitudes from 13.4 cm (etopo5 case) to 8.9 cm.

In late 2014, gebco08 dataset was superseded by a new version, gebco2014. As presented later in this article, this new dataset has eliminated many errors existed in the former version. While spatial smoothing applied to the dataset assures overall quality over a wide area and makes the data suitable for large-scale studies, the procedure also seems to have suppressed small-scale features important for coastal studies. In addition, the dataset still does not represent gigantic coral reefs specific to SCS such as Spratly and Paracel Islands correctly.

As an extension of Uehara[3], this study develops a gridded bathymetry covering the whole SCS in a best-effort basis, i.e., compiling an unfiltered dataset which may resolve features having 5-10 km scale at regions where sounding data are fully available. The compilation of the 1/60-degree dataset was accomplished by collecting as many sounding data as possible from various sources including recent multi-beam survey products.

The next section describes the procedure to compile the dataset which is followed by the verification of the data.

2. Materials and methods

2.1 Existing bathymetry datasets

The final product of this study is compared with three existing global DTMs, i.e., etopo1, gebco08 and gebco2014, which all represent land altitudes or water depths on a longitude-latitude grid.

Etopo1 is 1 min resolution data developed in 2009 by U.S. National Geophysical Data Center (NGDC; now National Centers for Environmental Information, NCEI). The oceanic part of etopo1 is based on satellite altimetry technology which has greatly improved the

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accuracy of water depths at deep oceans.

Gebco08 (General Bathymetric Chart of the Oceans) gridded bathymetric dataset has been published in 2010 by British Oceanographic Data Centre (BODC), which was superseded by gebco2014 dataset in late 2014. Both gebco08 and gebco2014 have a spatial resolution of 1/2 min. Though they are based on the satellite altimetry products, as in the case of etopo1, depths in shallow areas were modified by referring to in-situ sounding data. Differences between gebco08 and gebco2014 will be discussed later.

2.2 Tscs bathymetry

The regional bathymetry dataset compiled in this study, tscs, is a successor of gbscs5 dataset developed by Uehara[3]. Tscs covers the whole SCS as well as adjacent waters such as Java, Flores, Celebes and Sulu seas.

While gbscs5 used depth of gebco08 at region deeper than 200 m, all depths in tscs were newly compiled from sounding data, except at an area south of the Sumatra Island west of 103°E where depths were obtained from gebco2014 because the sounding data were extremely sparse.

Tscs has higher spatial resolution (1 min) and larger latitudinal extent (10°S-27°N) than gbscs5 (5min, 0°-23°N). On the other hand, both tscs and gbscs5 cover same longitudinal extent (99°E--125°E) and uses land altitudes derived from gebco products: either gebco08 (gbscs5) or gebco2014 (tscs).

2.3 Data source

2.3.1 Navigational charts

The primary source of the sounding data was navigational charts: paper and electronic charts issued by local countries/regions other than Brunei, Cambodia, Macao and Taiwan (for Hong Kong, Indonesia and Singapore, electronic charts only), paper charts by U.S. and Russia, and electronic charts by U.K.

2.3.2 Bathymetric survey records

Raw sounding records derived from single-beam and multi-beam surveys were also used for the compilation, which provide information along ship tracks in high spatial density.

Single-beam surveys have been taken place mainly in the eastern part of the central SCS. Data have been obtained from NCEI and Japan Oceanographic Data Center (JODC).

In the last decade, increasing number of multi-beam surveys have been conducted at regions such as the Manila Strait and the Sulu Sea. The current study used multi-beam sounding data measured at 1995-2013 (mostly at 2005-2013), which were available from NCEI and Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

2.3.3 Reference data

In this study, electronic charts by East Asia Hydrographic Commission (EAHC-SCSenc) and Navionics were used only for reference because they contain errors which seem to have generated on data processing phase.

Gridded bathymetry data called JEGG500 issued by JODC were also used as reference for region around Japanese waters. Though their overall quality seems to be high, they are spatially filtered and were not conformable with other raw sounding data used.

2.4 Data processing

2.4.1 Navigational charts

Paper charts were scanned, tagged with geographic position and converted into WGS84 coordinates if necessary.

Depths indicated in rasterized paper charts and electronic charts were displayed altogether on a computer display by using a GIS software and were digitized into xyz (longitude, latitude, depth) format. Depth contours were not digitized unless contours (1) define the edge of the large coral reefs where water depth may change for more than 2,000 m or (2) represent the extent of elongated shoals or trenches where depths vary in anisotropic manner.

It should be noticed that using all the spot sounding data contained in electronic charts may often cause underestimation of depth in the final product, especially when reading from small-scale charts. It is because navigational charts tend to indicate depths over a shoal or an obstacle rather than those representing the region in concern.

Quality checks have been conducted before and after the digitizing process. Pre-digitizing check verifies the quality of the depth indicated on charts by overlaying different charts and compare each other on the screen, which may help excluding erroneous values and extreme values which may not represent the depth around the sounding spot. Post-digitizing check sorts out duplications and input errors.

In areas where depths are expected to change largely with time, we tried to use data originated from a single source to retain the consistency of the depth field. In cases of the northern part of the upper Gulf of Thailand and the area south of the Mekong River Delta, we adopted data measured at comprehensive surveys conducted in 1960s. For the Tonkin Gulf west of 108°E, we followed depths found in recent Vietnamese charts.

2.4.2 Bathymetric survey records

Sounding information obtained by single- and multi-beam surveys were displayed and compared with other data for verification.

As for the single-beam data, depths obtained by some cruises, mainly those conducted before 1980s, were excluded because water depths were inconsistent with others and also because old sounding records at offshore location tend to contain positioning errors.

The multi-beam data derived from several cruises conducted at a same area were merged and converted to a grid data having a spacing of 0.2 min, because the original data resolution was too high for the current purpose. While multi-beam soundings provide detailed two-dimensional information, the obtained product requires careful verification because it often include unrealistic values at shallow waters and at along the edge of swath bands.

2.4.3 Final sounding data

The sounding data created from various sources have been merged to a single file. It is relatively easy to reflect the modification or addition of the source data to this final file because individual files to be merged could be replaced by changing the file name listed in a fortran code used for the merging process.

Figure 1 denotes the distribution of the sounding data contained in the final file. The color represents the number of the data that falls into a 5 min bin. It is found that the sounding data is sparse in the Celebes Sea, the Gulf of Thailand, the Java Sea and an area off central Vietnam (ca. 11.5°N, 110°E), showing that the final product of this study, which rely solely on the sounding data, should be treated with care for these areas.

In addition to the seafloor depths based on the sounding data, land altitudes derived from 1/2 min resolution gebco2014 dataset were incorporated into the final data to obtain plausible water depth at around the coast and to avoid unnecessary overshooting at areas devoid of data when the interpolation is made. The maximum height of the altitude data used in the interpolation was limited to 10 m, to obtain realistic nearshore water depth even when sea is surrounded by high mountains.

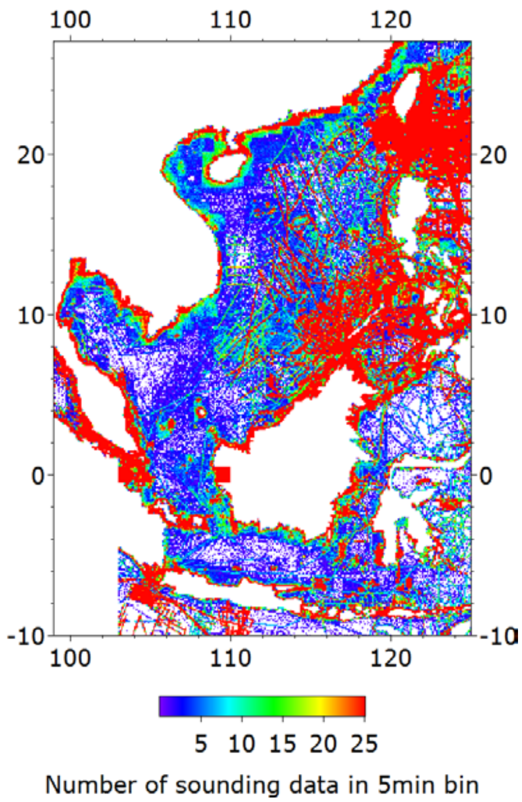


Fig.1 Histogram showing the number of sounding data used to compile the bathymetry dataset in grid bins having the size of 5 min. White shadings denote area without any depth data. Note that the actual number ranges up to ca.10,000.

2.4.4 Grid data generation

The sounding data were converted into a gridded format with a spacing of 1min by using Natural Neighbor Interpolation scheme of Surfer 13 application (Golden Software) which does not generate values beyond the range of the actual dataset. In this study, we have chosen this conservative interpolation scheme to avoid generating spurious depth values, with the cost of losing some information contained in the original sounding data.

3. Results

3.1 Data comparison

3.1.1 Overall features

Fig. 2 illustrates the depth pattern of etopo1, gebco08, gebco2014 and tscs datasets. To make the datasets comparable, gebco bathymetries were converted into 1 min resolution and etopo1 was transformed from grid-registered (data point is defined on the cell boundary) to cell-registered format (defined on cell center).

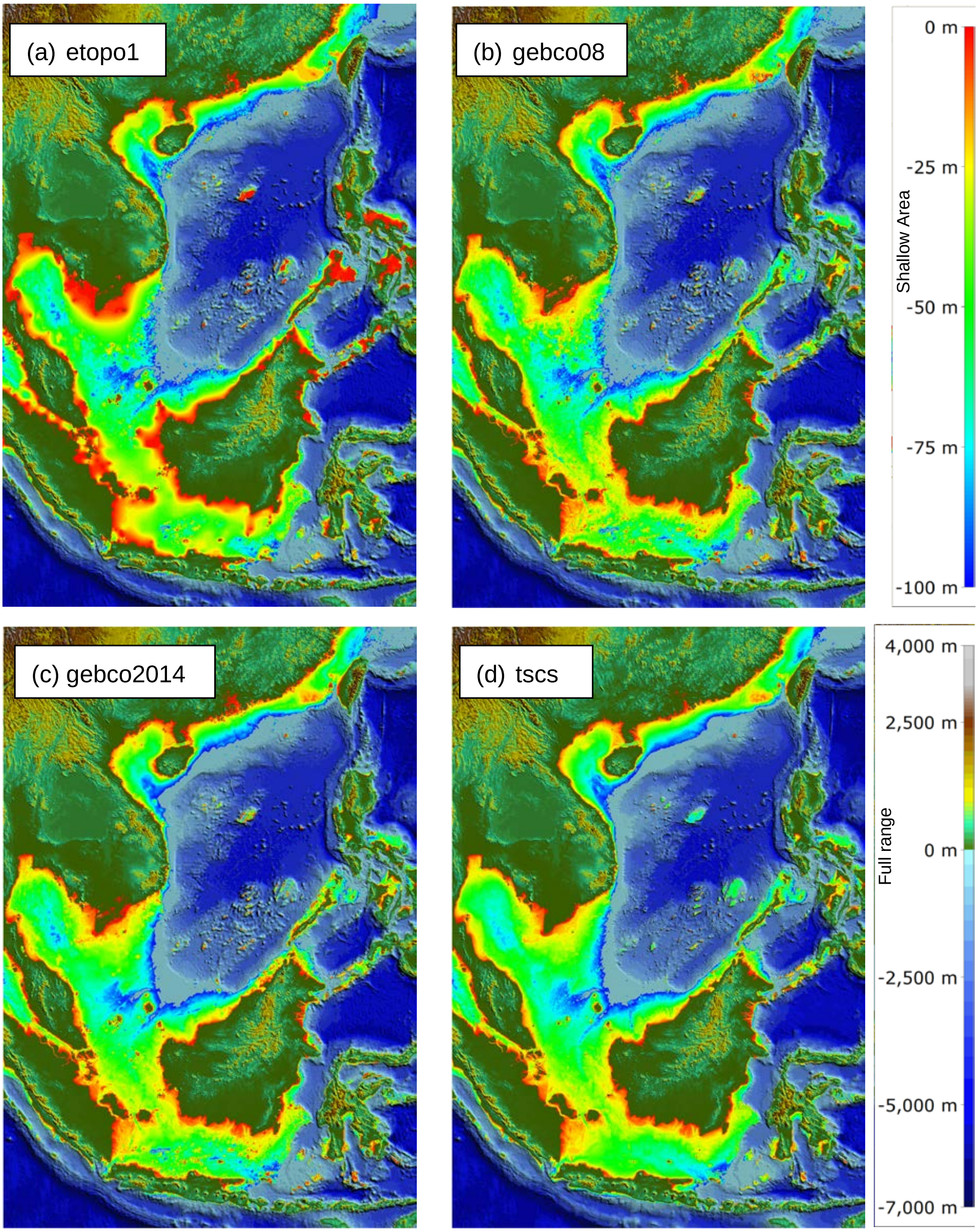


Fig.2 Depth distribution of four bathymetric datasets: (a) etopo1, (b) gebco08, (c) gebco2014 and (d) newly formed tscs. All figures use two color scales shown in the right: (upper row) depth scale applicable to seas shallower than 100 m and (lower row) scale for other depth/altitude ranges.

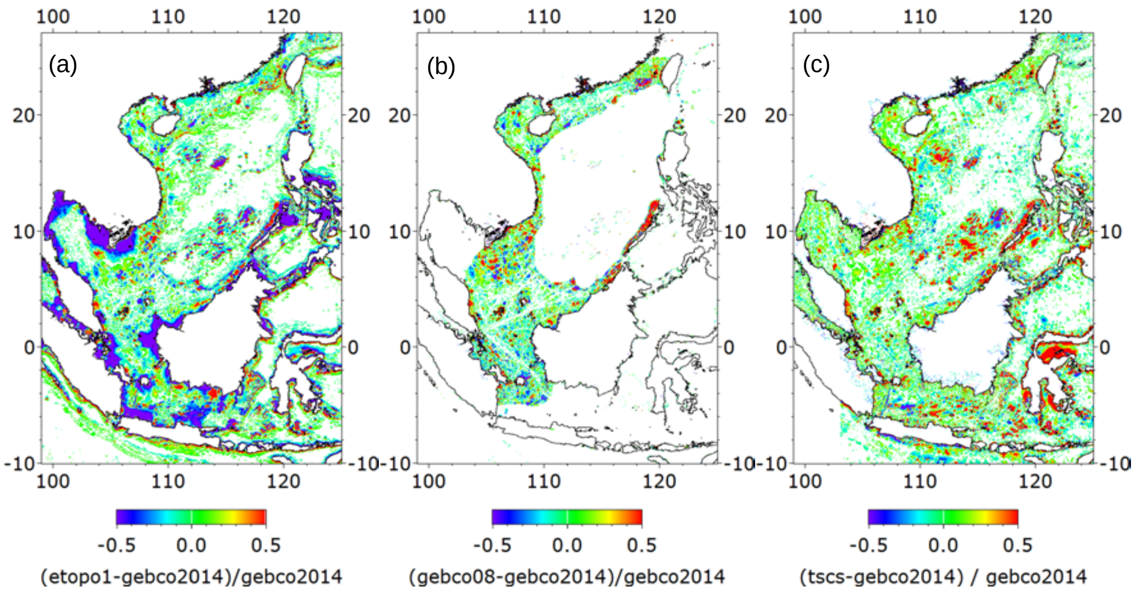


Fig.3 Relative difference between gebco2014 and (a) etopo1, (b) gebco08, (c) tscs bathymetries. Areas where the absolute difference is less than 0.05 are drawn in white. Note a positive value stands for the situation that the dataset in concern was deeper than gebco2014.

The most notable features found in Fig. 2 is extensive shallow regions observed in etopo1 (Fig. 2a), which seems to have caused because depths shallower than 50 m in etopo1 were obtained by interpolation. Shallow areas around Paracel and Philippine islands were padded with 1 m depth and the whole depth within the upper Gulf of Thailand was less than 10 m, less than one half of the observed depth.

The relative difference between etopo1 (Fig. 2a) and gebco2014 (Fig. 2c) are shown in Fig.3a. Judging from the distribution of the area where the difference is small, it is speculated that gebco2014 used satellite altimetry products at depth deeper than ca. 1,000 m and that some of them were modified by referring to the bathymetric survey records. On the other hand, depths shallower than 1000 m in gebco2014 seem to have based mainly on the in-situ sounding data.

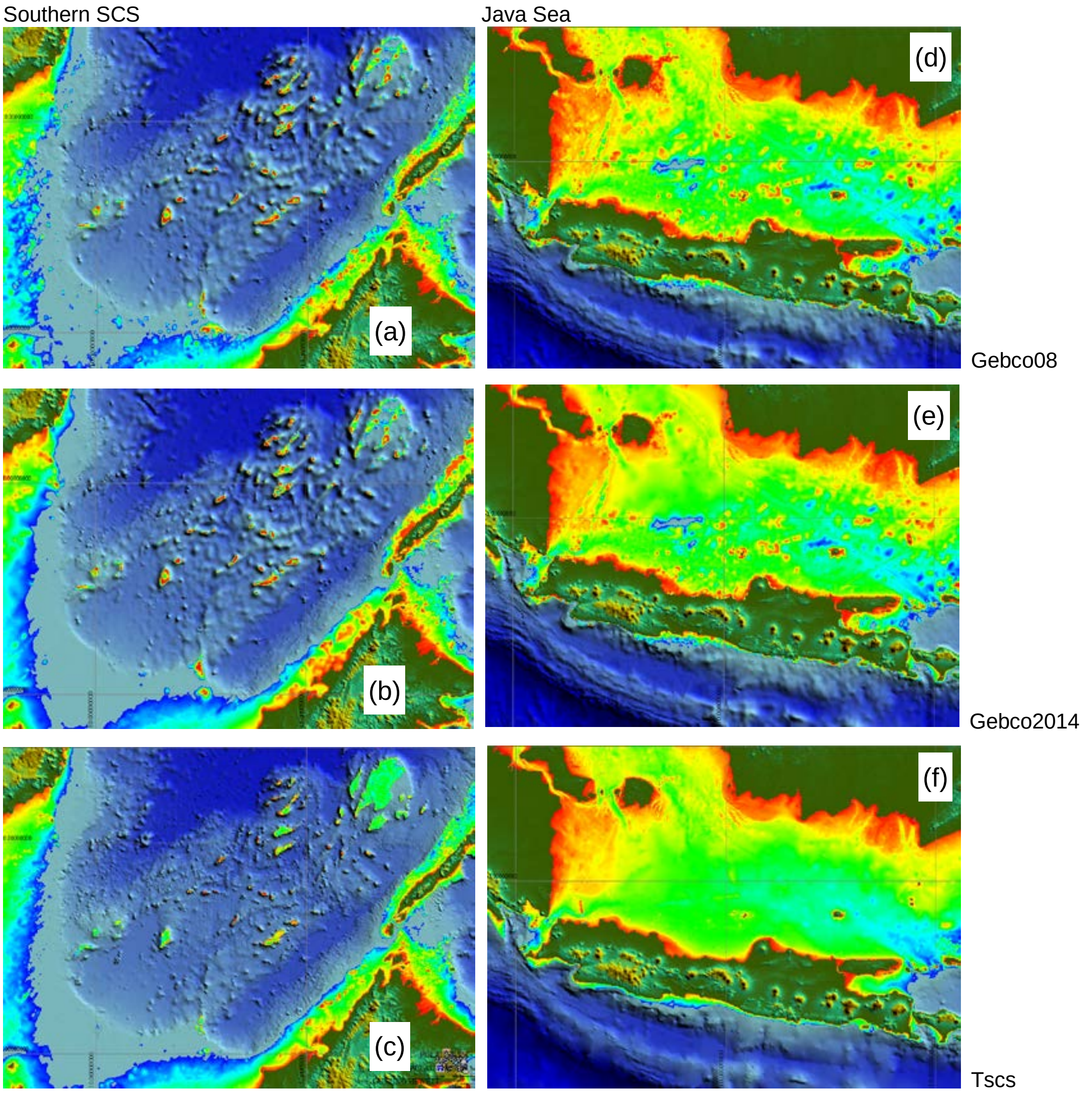
As mentioned in Uehara[3)], gebco08 dataset tends to show spurious bumps and hollows in shallow regions (Fig. 2b), which seems to have suppressed in newly introduced gebco2014 (Fig. 2c). Map showing relative difference between gebco08 and gebco2014 (Fig. 3b) indicates that the modification was made mostly at coastal region shallower than 200 m at longitudes 105°E-120°E. Fig. 3b suggests that the bathymetry of the gigantic reefs was not revised in gebco2014.

3.1.2 Southern SCS

To verify the difference among the datasets more in detail, enlarged bathymetric maps of two specific areas, the Southern SCS and the Java Sea, are shown in Fig. 4. Here, we will compare gebco08, gebco2014 and tscs datasets because basic features of etopo1 in deep seas were similar to those of gebco topographies while shallow features in etopo1 were not realistic.

In the southern SCS, the bathymetric map of gebco08 (Fig. 4a) again shows spurious features in the shallow shelf area (left and bottom edge of the figure) whereas they were less apparent in gebco2014 (Fig. 4b). Though the spatial smoothing applied to gebco2014 has improved the quality of the data in general, there were some cases when the smoothing seems to have given rise to spurious features. In the eastern side of the southern SCS, for example, the spatial pattern of shallow features such as offshore coral reefs near the shelf edge in gebco08 (Fig. 4a) resemble more with those in tscs (Fig. 4c) than in gebco2014 (Fig. 4b), while their width in gebco2014 (Fig. 4b) were much larger than those found in nautical charts.

As found in the northeastern edge of Fig. 4c (tscs case), Spratly Islands is a large shoal having a size of ca. 100 nautical miles (ca. 180 km). Though the interior of this shoal is typically about 50 m deep, majority of the area



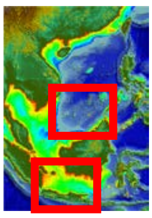


Fig.4 Enlarged bathymetric image of Fig. 2 for (a & d) gebco08, (b & e) gebco2014 and (c & f) tscs datasets at (a, b & c) southern SCS and (e, f & g) Java Sea, the locations of which are indicated as two red frames in the right figure. All six figures are shown in a same scale. Note zonal and meridional extent of the Spratly Islands (a large shoal near the NE corner indicated in light green, most apparent in Fig. 4c) are approximately 160 km and 190 km, respectively.

was shown as area deeper than 200 m in gebco bathymetries (Figs. 4a and 4b).

These results suggest that the high-resolution dataset does not necessarily resolve small-scale depth feature.

3.1.2 Java Sea

Another close-up area illustrated in Fig. 4 is the Java Sea, a marginal sea surrounded by Java, Sumatra and Kalimantan Islands. Difference between gebco08 (Fig. 4d) and gebco2014 (Fig. 4e) bathymetry is found only in the northwestern Java Sea north of 2°S (Fig. 3b), where gebco2014 represents more smooth bottom features and resembles more to tscs (Fig. 4f) than to gebco08. In the eastern Java Sea, both gebco08 and gebco2014 show many bumpy features in contrast to relatively smooth bathymetry found in the tscs case. A linear elongated trench feature observed at around 2°S coincides with the route of a sounding survey track which was not adopted in tscs as depths obtained by the cruise did not match with those shown in recently published Indonesian electronic charts. These results suggest higher performance of tscs compared to the gebco bathymetry in the Java Sea, even though the available sounding data is not sufficient.

On the other hand, comparison between gebco and tscs datasets suggest two potential issues reside in tscs. One is that the bathymetry along the northern Java coast seems to be too smooth. Taking into account that many rivers in the Java Island discharges a large amount of freshwater and sediments to the Java Sea, the actual bottom features might have been more complex than presented in tscs. The smooth nearshore bathymetry is due to relatively smooth features found in electronic charts, in which depth points are densely allocated. Spatial smoothing might have applied to the charts on their production. Similar smooth feature was observed at along Guangxi coast in southern China.

Another issue is that tscs, which rely solely on sounding data, does not represent detailed features observed in gebco datasets at regions south of the Java Island where the sounding data is sparse. Large discrepancy off Sulawesi Island (0° 122°E in Fig. 3c) may also be ascribed to the lack of sounding data.

In summary, tscs dataset seems to represent realistic small scale features in the shallow region in SCS, while a care must be taken when analyzing the bathymetry at regions where the sounding data was sparse.

3.2 Preliminary tidal-modeling test

A series of tidal simulations have been conducted to infer the performance of the bathymetric data by following the setting of Uehara[3] except that the spatial resolution was improved to 2 min.

A preliminary result show that the RMS differences between the model and tide-gauge data were (12.2 cm, 8.0 cm, 7.8 cm, 6.3 cm) for M_2 amplitudes in (etopo1, gebco08, gebco2014, tscs), respectively. Though tscs give rise to a best result among all cases including those found in Uehara[3], further validation is necessary to confirm this output.

4. Summary and Conclusion

Bathymetry data covering the whole SCS, aimed to resolve features having 5-10 km scale, was developed by compiling sounding data derived from various sources. The procedure to compile the bathymetry considers future replacement or addition of the source data. The data was found to represent more realistic features than existing global DTMs at regions such as Spratly Islands, the Java Sea, and northwest Borneo coasts, which was accomplished by multiple-step quality check and introduction of latest sounding data and usage of modest interpolation scheme. On the other hand, the source sounding data were less available in regions such as the Gulf of Thailand, the Java Sea and off central Vietnam, where the dataset may potentially contain some uncertainties.

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