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Evaluating of the accuracy of the DTU22MDT mean dynamic topography model based on the tidal gauge data in Vietnam's coastal areas

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ABSTRACT

In this study, the accuracy of the latest mean dynamic topography model (MDT), DTU22MDT, is determined based on data collected from 14 tide gauge stations along the coast of Vietnam, from the North to the South. The process of assessing the accuracy of the DTU22MDT model is carried out carefully and precisely, involving determining the model's height at tide gauge stations, quality checks of the data, and evaluation of the model's accuracy. The research results indicate that, compared to the local sea surface in Vietnam, the DTU22MDT model has a higher height of approximately 0.7 meters. This model represents the global MDT with the highest accuracy in Vietnam, with a mean square error of about 9.0 cm. This information provides a basis for applying the model in scientific research and practical applications, such as constructing a national height system, planning the economic development of coastal areas, generating specialized maps, designing structures, and other activities in the maritime regions of Vietnam. The method used to evaluate the accuracy of the MDT in this study can be applied to other research areas and to different MDTs.

Keywords*:* MDT, sea level, DTU, tidal data.

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BACKGROUND

Since the first altitude-measuring satellites were launched in the 1970s, altitude data has been widely utilized to understand better the global ocean system and its evolution at various spatial and temporal scales [1]. One significant outcome of applying satellite altimetry is the creation of MDT models.

The mean dynamic topography is the average, undisturbed surface of the seas and oceans over many years [2]; it represents the difference between the sea surface height and the geoid.

Mean dynamic topography models are important data sources for comprehensive land-sea research, sea level variability, and climate change [3]. The static current velocity can be calculated using the gradient of the MDT. This current velocity significantly influences oceanic dynamic processes such as material transport, heat transfer, and exchange, and human activities. Accurating and modeling ocean currents is significant to meteorology, oceanography, and geophysics [4]. Mean dynamic topography models also provide data for geodetic work and mapping, such as unifying height systems and building local gravity field models in various regions.

Since the early 1990s, organizations worldwide have been establishing global MDT models. Some representative models are mentioned here, including:

The mean dynamic topography model DNSC08MDT

The DNSC08MDT model was established by the Danish National Space Center (DNSC) under the Technical University of Denmark (DTU). This model is based on high-precision satellite measurements from TOPEX/POSEIDON, JACSON-1, GEOSAT, GFO, ERS-1, ERS-2, ICESAT, and the Earth's gravity field model EGM2008 [5]. The accuracy of the DNSC08MDT model for sea and ocean elevations ranges from 9–12 cm.

The MDT model DTU10MDT

The MDT model DTU10MDT is developed by the Technical University of Denmark (DTU). This model is constructed based on the DTU10MSS model and the GOCE DIR model (Geoid determined from high-resolution and low-noise satellite GOCE data using the "direct" method over "2 months"). The DTU10MSS model is the result of upgrading the DNSC08MSS model with increased observational data from 8 years to 13 years in the North Pole region. This model incorporates corrected values for physical geography and distances, reprocesses data in icy areas, expands satellite coverage from ICESAT from 4 to 17 cycles per month, and enhances the editing of North Pole data according to MSS standards. A refined filtering process has been implemented throughout the model computation to detect short-wave features of gravity data. Adjustments to the coastal MSS values have also been included [6].

The quality of the DTU10MDT model is superior to previous MDT models because it better represents the distinct features and boundaries of ocean and sea currents. This model also significantly advantages the mean dynamic topography model built from the GOCE geoid model in the study of marine currents.

Table 1. Mean dynamic topography models

Mean dynamic topography model	Mean sea surface	Geoid model
DTU13MDT [7]	DTU13MSS	EIGEN-6C3stat
DTU15MDT [8]	DTU15MSS	GOCO05S-EIGEN-6C4 hybrid
DTU16MDT [9]	DTU15MSS	GOCO05S-EIGEN-6C4 hybrid
DTU17MDT [10, 11]	DTU15MSS	OGMOC hybrid
DTU18MDT [12]	DTU18MSS	OGMOC hybrid
DTU22MDT [13]	DTU21MSS	XGM2019e

Every year, new measurement data is constantly added, which is why MDT models are established and published. Some versions of MDT models are presented in Table 1.

The subsequent versions of MDT models are built upon previous versions, incorporating additional data such as satellite-based elevation data, gravity data, surface current velocities, and updated ocean tidal models. As a result, both mean sea surface models and geoid models are determined with higher accuracy, leading to more detailed representations in the later versions of MDT models. The accuracy of these newer versions is significantly improved compared to the earlier versions.

The MDT model DTU22MDT

This model originates from using the DTU21MSS mean sea surface model. The DTU21MSS model was constructed based on repeated measurements from the CRYOSAT-2 satellite altimetry data, thereby enhancing the model's resolution. Some issues in polar regions have also been addressed. The geoid model XGM2019e with a degree/order of 2160 was also used to construct the DTU22MDT model. The computation and processing involved in creating the DTU22MDT model are similar to previous DTU versions; however, the filtering techniques have been re-evaluated to optimize the model's fit with drift velocities. Furthermore, an optimal filtering scheme has been applied to coastal areas, with drift velocities integrated into the calculation process to improve the resolution of the constructed model. Weighting and constraint conditions have been incorporated into the computation to achieve a smoother MDT model with increased detail [13].

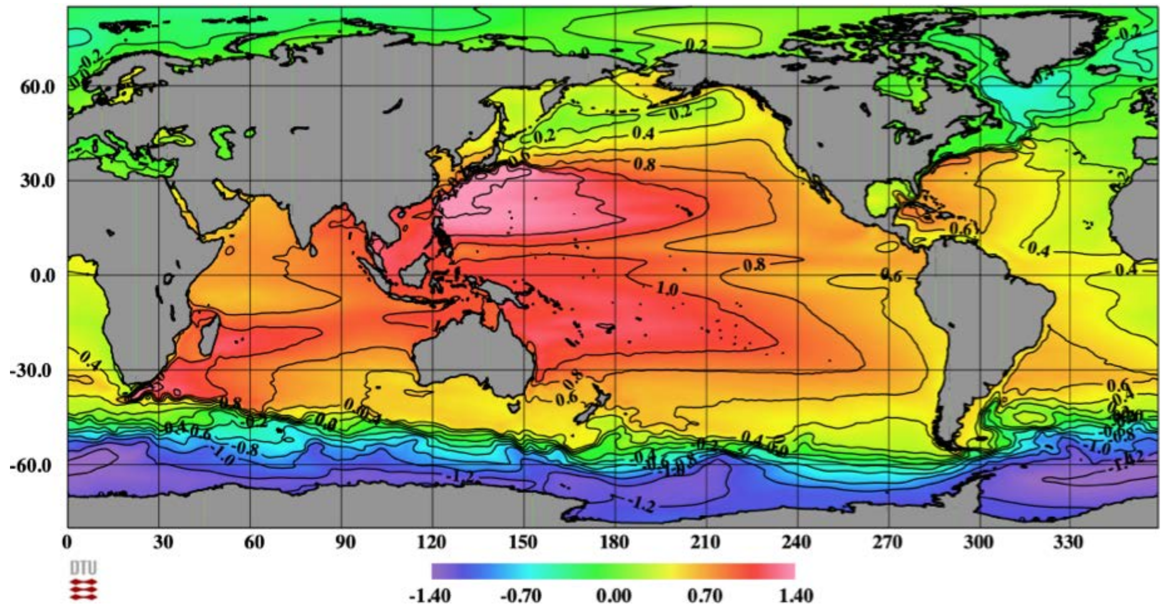

Figure 1. Mean dynamic topography from the geodetic DTU22MDT [13]

The DTU22MDT model is currently the latest model for mean dynamic topography. Hence, more information regarding its global application in research needs to be published. Scant details related to this model are presented in document [14], where the DTU22MDT was employed to study currents in the Chukchi Sea - an area situated in the northern part of the Atlantic Ocean, between the northern coast of Eastern Siberia and the northwest of Alaska. Information about the use of the DTU22MDT model in the East Vietnam Sea region needs to be published.

In Vietnam, MDT models have been researched and applied, as evidenced by various notable publications:

In 2015, the DNSC08MDT model was transformed into the national coordinate system, the national height system, to facilitate depth measurements of the seafloor terrain without needing coastal hydrographic stations [2]. During this time, the DTU10MDT model was also used to construct a mean dynamic topography model suitable for the mean sea surface in the sea of Vietnam, serving the construction of coastal infrastructure and regional planning in response to climate change trends [15].

In 2022, the MDT models DNSC08MDT, DTU10MDT, DTU13MDT, and DTU15MDT were assessed for their accuracy in order to select the most suitable model for improving the accuracy of anomalous gravity determination in the North Gulf of Tonkin region using satellite altimetry data [16].

As can be seen, MDT models have been studied in Vietnam. However, the models being studied are at earlier stages. Over time, newer versions of MDT models have been published. Therefore, to have a basis for applying these models in practice, it is necessary to have information about the model's accuracy on a local area. So, the newest MDT model DTU22MDT has been chosen to determine accuracy in this research.

Data on tidal elevation at observation stations will be utilized to determine the accuracy of the DTU22MDT model. From the 19th century to the present, tidal observation stations have been constructed along the coastline, determining the national height system and aiding in construction design, maritime activities, and national security. In this study, height data of tidal stations in the national height system serve as the original data to evaluate the accuracy of the DTU22MDT model.

METHODS AND DATA

Methods

The MDT model

The relationship between mean dynamic topography (MDT) and mean sea surface (MSS) height can be expressed by the following formula [4]:

$$MSS(\phi,\lambda) = Geoid(\phi,\lambda) + MDT(\phi,\lambda) \quad (1)$$

In equation (1), ϕ represents latitude, and λ represents longitude. The geoid model and the mean sea surface model used for MDT model need to be harmonized with the same resolution. The mean sea surface model and the geoid model must be harmonized within the GRS80 ellipsoid and the free tidal system.

The MDT model is represented through Lagrange basis functions with the following formula:

$$MDT(\phi,\lambda) = \sum_{k \in K} a_k b_k(\phi,\lambda) \quad (2)$$

where: b_k is the base function; K is the number of base functions; a_k is the mean dynamic topography at (ϕ, λ).

The choice of the Lagrange base function is crucial, as it significantly affects the construction of the mean dynamic topography model.

Evaluate the accuracy of the mean dynamic topography model

The difference in height between h_{nt} and h_{model} of the tidal point i, denoted as Δh^i, is determined by the following formula:

$$\Delta h^i = h^i_{model} - h^i_{nt} \quad (3)$$

where: h_{nt} is the height in the zero tidal system of the points determining from mean sea level; h_{model} is the height in the zero tidal system of the points determining from the global mean dynamic topography model.

The average value of height deviation is calculated using the following formula:

$$\Delta h_{aver} = \sum_{i=1}^{n} \Delta h^i / n \quad (4)$$

where: n is a number of points used to assess the accuracy of the mean dynamic topography model.

Let v_i be the correction value for the height difference between h_{nt} and h_{model} of the tidal point *i*. This value is calculated according to the following formula:

$$v_i = \Delta h^i - \Delta h_{aver} \quad (5)$$

The mean square error to evaluate the accuracy of the mean dynamic topography model is calculated according to the following formula:

$$m = \pm\sqrt{\frac{[\upsilon\upsilon]}{n-1}} \quad (6)$$

Points, whose values are not within the range from -3 m to +3 m are eliminated and cannot be used to evaluate the accuracy of the MDT model.

Data

There are two data sources used for evaluating the accuracy of the MDT model DTU22MDT:

(1) Height data of tidal gauge stations;

(2) Height data exploited from the DTU22MDT model.

Table 2 lists the average height data for the tide gauge stations of Cua Ong, Hon Dau, Tien Sa - Son Tra, Quy Nhon, Nha Trang, Vung Tau, Co To, Bach Long Vi, Hon Ngu, Con Co, Phu Quy, Con Dao, Phu Quoc, Tho Chu (Figure 2) in the national height system extracted from document [16].

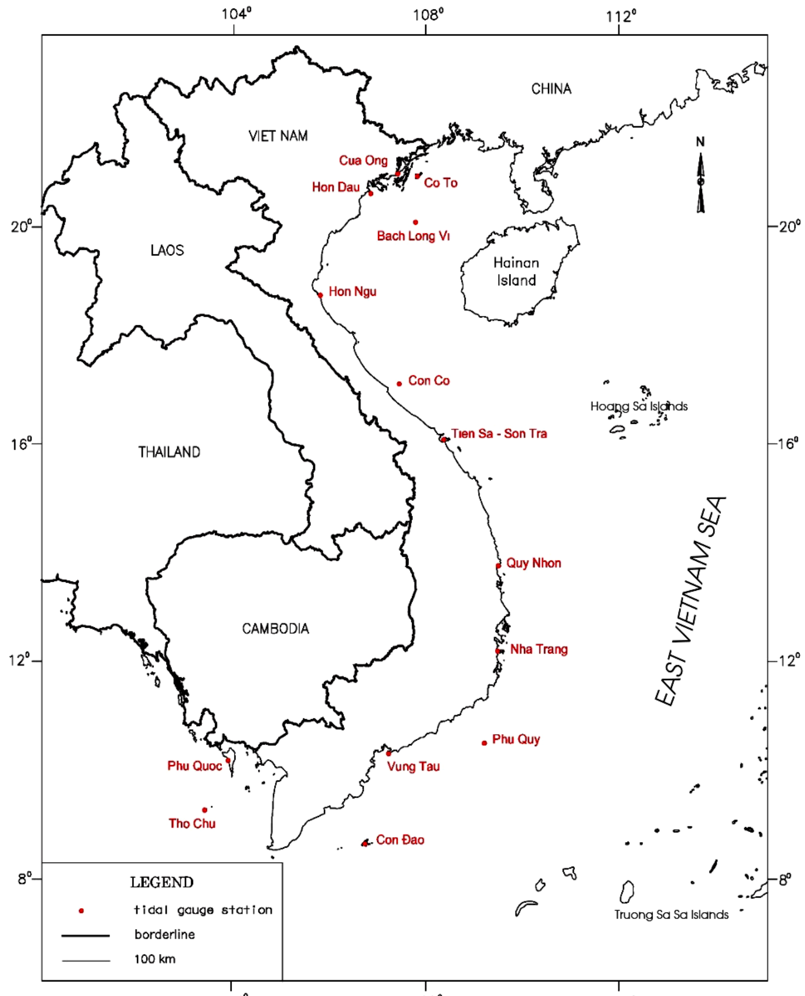

Figure 2. Diagram of tidal gauge stations

Table 2. Height data

No.	Tidal gauge station	Normal height of the mean sea surface in the national height system (m)	Height of the model DTU22MDT (m)
1	Cua Ong	0.056	1.135
2	Hon Dau	0.000	1.129
3	Tien Sa - Son Tra	0.103	1.136
4	Quy Nhon	0.076	1.030
5	Nha Trang	0.050	1.071
6	Vung Tau	-0.030	1.160
7	Co To	0.174	1.141
8	Bach Long Vi	0.004	1.150
9	Hon Ngu	0.085	1.182
10	Con Co	0.072	1.162
11	Phu Quy	0.101	1.126
12	Con Đao	0.044	1.146
13	Phu Quoc	-0.098	1.205
14	Tho Chu	0.114	1.207

The data of the DTU22MDT model is stored in the files dtu22mdt.xyz and dtu22mdt.grd, with a resolution of 7.5′ × 7.5′. The software Global Mapper is utilized to extract data from this model, detailing the height of 14 tide gauge stations, as shown in Table 2.

RESULTS AND DISCUSSION

The value of height deviation at tidal gauge stations is calculated according to formula (3) and the results are shown in Table 3.

These values are modeled as a histogram in Figure 3.

Figure 3 shows that the smallest height deviation is at Quy Nhon tidal station with a value of 0.574 m, the largest height deviation is at Phu Quoc tidal station with a value of 0.923 m.

The average of the height deviation is calculated according to formula (4):

$$\Delta h_{aver} = \frac{9.909}{14} = 0.708 \text{ (m)}$$

It can be seen that, based on data from 14 tidal gauge stations, the global MDT model DTU22MDT shows a higher than the average sea surface at tidal gauge stations in Vietnam by about 0.7 m.

The values of corrections for the height difference between h_{nt} and h_{model} of the tidal station, calculated according to formula (5) are shown in Table 4.

The mean square error to evaluate the accuracy of the MDT model is calculated according to the following formula:

$$m = \pm\sqrt{\frac{0.1061}{14-1}} = \pm 0.090 \text{ (m)}$$

There were no tidal gauge stations with values outside the range from -3 m to +3 m, so all tidal gauge stations are used to determine the accuracy of the the mean dynamic topography model DTU22MDT. The accuracy of this model is approximately 9.0 cm.

Subsequently, in 2022, Pham, V. T. employed 31 tide gauge stations along the coast of Vietnam to evaluate the accuracy of the models DNSC08MDT, DTU10MDT, DTU13MDT, and DTU15MDT [16]. The findings regarding the accuracy of the MDT models in these studies have been compiled in Table 5.

Based on Table 5, the DTU22MDT model in this study has demonstrated a higher level of accuracy compared to previous models. This progress accurately reflects the developmental trend of the MDT model series. Regarded as the latest iteration of the mean dynamic topography model, DTU22MDT provides additional data and incorporates significant improvements in data processing compared to its previous versions.

Table 3. Height deviation

No.	Tidal gauge station	Δ*h* (m)	No.	Tidal gauge station	Δ*h* (m)
1	Cua Ong	0.699	8	Bach Long Vi	0.766
2	Hon Dau	0.749	9	Hon Ngu	0.717
3	Tien Sa - Son Tra	0.653	10	Con Co	0.710
4	Quy Nhon	0.574	11	Phu Quy	0.645
5	Nha Trang	0.641	12	Con Đao	0.722
6	Vung Tau	0.810	13	Phu Quoc	0.923
7	Co To	0.587	14	Tho Chu	0.713

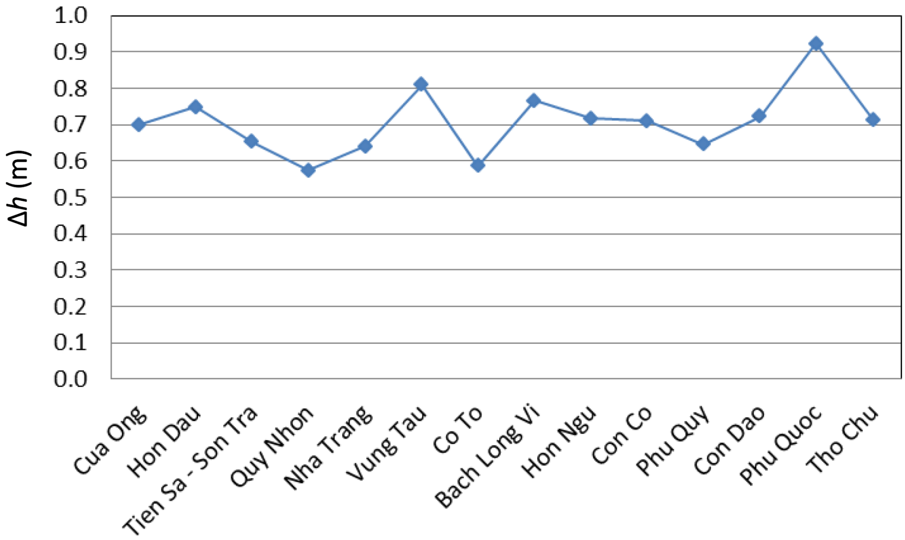

Figure 3. Height difference between h_{nt} and h_{model}

Table 4. Height deviation correction value

No.	Tidal gauge station	*v* (m)	No.	Tidal gauge station	*v* (m)
1	Cua Ong	-0.009	8	Bach Long Vi	0.058
2	Hon Dau	0.041	9	Hon Ngu	0.009
3	Tien Sa - Son Tra	-0.055	10	Con Co	0.002
4	Quy Nhon	-0.134	11	Phu Quy	-0.063
5	Nha Trang	-0.067	12	Con Dao	0.014
6	Vung Tau	0.102	13	Phu Quoc	0.215
7	Co To	-0.121	14	Tho Chu	0.005

Table 5. Accuracy statistics of MDT models

No.	The accuracy of the MDT (m)					Document
	DNSC08MDT	DTU10MDT	DTU13MDT	DTU15MDT	DTU22MDT	
1	±0.208	±0.172	±0.132	±0.131		[16]
2					±0.090	This study

CONCLUSION

Through the research process, several conclusions have been drawn as follows:

To support the research, data on the sea level heights of 14 coastal tide gauge stations in Vietnam, along with the data on the height from the DTU22MDT model, have been collected. Determining the accuracy of the MDT model DTU22MDT is conducted rigorously and precisely. The data quality assessment process was done by calculating the root mean square error. Since all data points met the requirements, the value of this error also represents the accuracy of the DTU22MDT model.

Research has indicated that the DTU22MDT model’s accuracy is approximately 9 centimeters. Therefore, this is the most precise mean dynamic topography model to date. Utilizing data from this model will support various studies and applications across multiple fields in Vietnam, such as establishing a national height system, climate change research, sea level rise, and managing resources and marine environments.

The height of the DTU22MDT model is approximately 0.7 meters higher than the local average sea surface. Consequently, when implementing the DTU22MDT model in Vietnam, correcting the model to align with the local average sea surface is necessary.

Data from 14 tide gauge stations are utilized in this study to assess the accuracy of the DTU22MDT model. Additional tide gauge data will enhance the model’s reliability to support accuracy assessment.

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