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The global mean sea surface model WHU2013

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ABSTRACT

The mean sea surface (MSS) model is an important reference for the study of charting datum and sea level change. A global MSS model named WHU2013, with 2′ × 2′ spatial resolution between 80°S and 84°N, is established in this paper by combining nearly 20 years of multi-satellite altimetric data that include Topex/Poseidon (T/P), Jason-1, Jason-2, ERS-2, ENVISAT and GFO Exact Repeat Mission (ERM) data, ERS-1/168, Jason-1/C geodetic mission data and Cryosat-2 low resolution mode (LRM) data. All the ERM data are adjusted by the collinear method to achieve the mean along-track sea surface height (SSH), and the combined dataset of T/P, Jason-1 and Jason-2 from 1993 to 2012 after collinear adjustment is used as the reference data. The sea level variations in the non-ERM data (geodetic mission data and LRM data) are mainly investigated, and a combined method is proposed to correct the sea level variations between 66°S and 66°N by along-track sea level variation time series and beyond 66°S or 66°N by seasonal sea level variations. In the crossover adjustment between multi-altimetric data, a stepwise method is used to solve the problem of inconsistency in the reference data between the high and low latitude regions. The proposed model is compared with the CNES-CLS2011 and DTU13 MSS models, and the standard derivation (STD) of the differences between the models is about 5 cm between 80°S and 84°N, less than 3 cm between 66°S and 66°N, and less than 4 cm in the China Sea and its adjacent sea. Furthermore, the three models exhibit a good agreement in the SSH differences and the along-track gradient of SSH following comparisons with satellite altimetry data.

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1. Introduction

Satellite altimetry has greatly improved the spatial and temporal resolution of sea surface height (SSH) observations. Since the first altimetric satellite Geos-3 observations were successfully achieved in the 1970s, a series of global and regional mean sea surface (MSS) models have been established [1,2], including OSU MSS95 [3], GSFC00.1 [4], WHU2000 [5], CLS01 [6], DNSC08 [7] and WHU2009 [8]. Currently, only two institutions — the Centre National d'Etudes Spatiales (CNES) and the Space Research Center of the Technical University of Denmark (DTU) — are still publishing MSS models. The latest MSS models are CNES-CLS11 MSS [9] and DTU13 MSS [10]. The altimetry data used in the CNES-CLS11 MSS spans the 16 years from 1993 to 2008 and includes 16-year combined observations of T/P and Jason-1 data, 14-year combined observations of ERS-2 and ENVISAT data from 1995 to 2008, 7-year GFO data from 2001 to 2007, 3-year T/P tandem data from 2003 to 2006, and two ERS-1 geodetic mission observations. Furthermore, the CNES-CLS11 MSS is referenced to the mean along-track SSH of T/P data between 1993 and 1999 after collinear adjustment, with spatial resolution of $2' \times 2'$ and coverage from 80°S to 84°N, and the EIGEN-GRACE-5C geoid height is used to fill the land area. The DTU13 MSS was established using altimetry data spanning the 20 years after 1993 and includes combined observations of T/P, Jason-1 and Jason-2 series data, combined observations of ERS-1, ERS-2 and ENVISAT data, the Jason-1 geodetic mission observations, the SAR observations of Cryosat-2 in the polar region with a reference of the mean along-track SSH of T/P, Jason-1 and Jason-2 data between 1993 and 2012 after collinear adjustment, global coverage and spatial resolution of $1' \times 1'$, and the EGM08 geoid height is used to fill the land area.

Usually, the Exact Repeat Mission (ERM) observations of altimetric satellites are collinearly adjusted to eliminate the sea level variation signals and achieve the mean along-track SSH in the observation period. The dataset of T/P, Jason-1 and Jason-2 ERM observations are usually collinearly adjusted for using as a high-precision reference datum. However, in order to improve the spatial resolution, the geodetic mission observations or the non-ERM observations must be involved in MSS determination. Historically, MSS models have used the Geosat and ERS-1 geodetic mission observations, but these observations have been gradually replaced by the Jason-1 geodetic missions and Cryosat-2 observations, which have better orbit precision and provide better accuracy of geophysical corrections.

When these multi-altimetric observations are combined to establish the MSS model, two issues should be carefully considered: the sea level variations correction in the non-ERM data and the consistency between data below 66° latitude and beyond 66° latitude. For the CNES-CLS11 MSS model, the sea level variations are corrected by grid sea level variation time series from multi-ERM observations. In this method, systematic bias would exist if the grid sea level variation time series data was not consistent with the data of the MSS model. For the DTU13 MSS model, the sea level variations were directly solved in crossover adjustment. This method is more commonly used, like in OSU MSS95, but considerable residuals would still exist. Since the multi-year average along-track SSH of the T/P satellite series is generally used as reference datum, but its orbit inclination is only 66°, it will lead to the absence of data in the high latitude region beyond 66°, which means that the European Remote-Sensing (ERS) satellite series and Cryosat-2 observations cannot be adjusted to the same data in the polar region with an early 20° latitude coverage. To address these two issues, this paper conducted a more detailed analysis, and a global MSS model with $2' \times 2'$ resolution was established using multi-altimetry data.

2. Selection and data processing of multi-satellite altimetry data

Currently, there are several 20-year observations of multi-satellite altimetry, and among them, the observations of T/P, Jason-1 and Jason-2 satellite series are well known with high accuracy. In order to obtain a global MSS model with high accuracy and high resolution, both ERM data with different accuracies and non-ERM data are needed. For ERM observations, full-year observations are selected to eliminate the seasonal and annual sea level variations in collinear adjustment. These observations include 20-year observations of T/P, Jason-1 and Jason-2 mission A between 1993 and 2012, which will be also used as the reference data for the MSS model, 3-year T/P and Jason-1 mission B observations, 8-year ERS-2 observations, 8-year ENVISAT observations, and 7-year GFO observations. For non-ERM observations, ERS-1 and Jason-1 geodetic mission, and Cryosat-2 LRM observations are selected to improve the spatial resolution (Table 1).

All these data were provided by Delft University, which has a radar altimetry data set (RADS) [11] that provides information about the latest orbits as well as some geophysical and environmental corrections, such as ocean tide model corrections, non-parameter sea state bias corrections, and smoothed dual-frequency ionosphere corrections. All the references of other satellites are adjusted to the T/P satellite, and the altimetry observations over oceans and lakes are obtained by strict criteria. Additionally, the ERM data are collinearly adjusted to eliminate seasonal, annual and part of the inter-annual sea level variations to obtain the mean along-track SSH within their observation

Table 1 – Satellite altimetry data used in the MSS model.

	Start cycle	Start date	End cycle	End date
Topex/A	11	1992-12-31	353	2002-04-24
Jason-1/A	11	2002-04-24	249	2008-10-19
Jason-2/A	11	2008-10-19	165	2013-01-03
Topex/B	369	2002-09-20	479	2005-09-24
Jason-1/B	262	2009-02-10	372	2012-02-15
ERS-2	001	1995-05-15	084	2003-06-02
ENVISAT/B	010	2002-09-30	093	2010-10-18
GFO	037	2001-01-07	208	2008-01-18
ERS-1/168	Phase E	94.04–94.09	Phase F	94.10–95.03
Jaon-1/C	382	2012-05-07	425	2013-06-20
Cryosat-2/LRM	004	2010-07-14	048	2013-12-28

period. In the collinear adjustment, the sea surface gradients in the cross-track direction are calculated by the EGM08 geoid height and then corrected in the sea level observations.

The data in Table 2 show that the standard derivation (STD) of crossover difference of the T/P mission A series after collinear adjustment is only 8 mm, while the STDs of other data are better than 2 cm after adjustment. It can be inferred that the accuracy improves after adjustment, and the residuals basically reach the highest level of the satellite orbit's precision.

3. Sea level variation correction for non-ERM data

Two methods for correcting the sea level variations of non-ERM data were mentioned above. The method used in the CNES-CLS11 MSS model corrects the sea level variations by reference to a certain dataset, which eliminates both the sea level seasonal and long-term variations. However, the seasonal and long-term variations are only averaged in collinear adjustment. When a full year's ERM data are used, the seasonal variations can be eliminated, but the trend is still only averaged. So, the datum of corrected grid sea level variation time series data set should be the same as the datum used in the MSS model. The method used in the DTU13 MSS model directly incorporates the sea level variations into the fitting model of orbit error in the crossover adjustment. Since the fitting model is usually linear, the trend of sea level variation may be corrected. However, the seasonal signals should be fitted by trigonometric functions, which means they are not well handled. Therefore, the elimination of sea level seasonal variations should be primarily considered when the non-ERM data are involved in the MSS model.

Considering these issues, we propose two methods here. The first is based on the seasonal variations fitting from the grid sea level variation time series, while the second is directly based on the sea level variation time series. The two methods are described below, and the results they provide are compared to the crossover difference before and after correction.

3.1. *Correction based on seasonal signals fitting*

In this method, seasonal variations are extracted using grid sea level variation time series, interpolated to the non-ERM observations and corrected. The seasonal variations are extracted from the monthly averaged grid sea level variation time series between 1993 and 2012 provided by AVISO, with spatial resolution of $0.25° \times 0.25°$ [12,13]. Then, the bias, linear trend, seasonal and annual signals of sea level variations for each grid point are fitted by equation (1). Since the data of this grid dataset are also the average data from 1993 to 2012, which are the same as the reference data used in the MSS model, it is reasonable to calculate the sea level variations directly with the fitted parameters.

$$y = a + bt + c\cos(2\pi t) + d\sin(2\pi t) + e\cos(4\pi t) + f\sin(4\pi t) \tag{1}$$

where y is the sea level variation time series, t the time, a the bias, b the trend, c and d the coefficients of the annual signal, and e and f the coefficients of the semi-annual signal.

3.2. *Correction based on along-track sea level variation time series by collinear method*

Using the mean along-track SSH of T/P, Jason-1 and Jason-2 data between 1993 and 2012 as a reference, the corresponding along-track sea level variation time series are calculated to correct the ERS-1, Jason-1 and Cryosat-2 non-ERM observations. According to their observation period, the sea level variations of the ERS-1, Jason-1 and Cryosat-2 non-ERM observations can be corrected by the corresponding along-track sea level variation time series as shown in Table 3. In this

Table 2 — Statistics of the crossover differences before and after collinear adjustment of ERM observations.

Altimetry observations and their combinations	Before collinear adjustment (m)			After collinear adjustment (m)		
	Mean	RMS	STD	Mean	RMS	STD
Topex/A + Jason-1/A + Jason-2/A	−0.002	0.061	0.061	0.000	0.008	0.008
Topex/B + Jason-1/B	−0.008	0.062	0.061	−0.001	0.010	0.010
ERS-2	0.000	0.109	0.109	−0.001	0.018	0.018
ENVISAT/B	0.001	0.084	0.084	0.006	0.022	0.021
GFO	−0.006	0.080	0.079	0.000	0.010	0.010

Table 3 — Corresponding data used for sea level variation corrections of non-ERM data.

Non-ERM observations			Corresponding ERM data		
Satellite	Cycles	Observation period	Satellite	Cycles	Observation period
ERS-1	139—143	1994.04.10—1995.03.21	T/P	57—93	1994.04.01—1995.04.03
Jason-1	382—425	2012.05.07—2013.06.20	Jason-2	140—183	2012.04.20—2013.06.30
Cryosat-2	004—048	2010.07.14—2013.12.28	Jason-1	313—374	2010.06.30—2012.03.03
			Jason-2	74—202	2010.07.05—2014.01.05

method, the position and observation time of available ERM data must be close to that of the non-ERM observations; however, it can be seen from Table 3 that even when the observation times of the ERM observations are close to those of all the non-ERM data, some non-ERM observations in the high latitude can't be corrected because the corresponding ERM observations, such as the ERS-1 geodetic observations and the Cryosat-2 LRM observations in the latitude region beyond 66°S and 66°N, are unavailable.

3.3. *Comparison*

ERS-1 geodetic mission data and the test area (0°N–10°N, 90°E–180°E) are selected for the comparison. Combined with the ERM observations after collinear adjustment in Table 2, the crossover differences before and after applying sea level variation corrections by different methods are given. The test area is located around the corner of the South China and Philippine Sea near the equator, but the observations are not continuous, and their accuracy is also affected by many islands. Table 4 shows the root mean square (RMS) error of crossover difference related to ERS-1 geodetic mission data before and after applying three kinds of sea level variation corrections. The first correction is calculated by interpolated fitting of semi-annual and annual signals. The second correction is calculated by interpolated fitting of bias and trend together with semi-annual and annual signals. The third correction is calculated by interpolated mean along-track sea level variations. It can be seen that all these three corrections have decreased the RMS of crossover difference both before and after crossover adjustment. The most remarkable improvement is made by the third correction, which results in a 50% and 25% improvement before and after crossover adjustment respectively. The second correction resulted in a higher percentage improvement than the first correction before crossover adjustment, but their improvements are nearly the same after crossover adjustment, which shows that the linear trend of sea level variation can be corrected in the crossover adjustment if the seasonal signals are removed by the first correction.

In this paper, corrections of sea level variations are conducted as follows: for those observations with similar time and locations inside the coverage of the T/P satellite series data, the sea level variations are corrected by the along-track sea level variations, but for all other observations, the sea level variations are corrected by the interpolated fitting of seasonal sea level variations.

4. Establishment of the MSS model

Considering the data selected, the actual coverage of the MSS model is chosen from 80°S to 84°N, which is the largest coverage of Cryosat-2 LRM observations on oceans, and the spatial resolution is chosen as $2' \times 2'$, which is nearly the minimum spatial distance of 1 Hz non-ERM observations.

After the collinear adjustment of ERM observations, the long wave sea level variation signals, including part of radial orbit error and the seasonal sea level variations, can be greatly eliminated. However, many errors, such as the residual radial orbit error, low-frequency sea level signals and residual geophysical corrections, still exist. Theoretically, observations at the same crossover in an MSS model should have the same values over a long period; therefore, the observations with lower accuracy can be improved by the observations with higher accuracy through adjustment at their crossovers.

The crossover adjustment is a general method used to combine multi-altimetry data, including ERM and non-ERM observations. Since the mean along-track SSH of the T/P satellite series between 1993 and 2012 is used as reference data, there is a nearly 20° latitude coverage out of the data for the ERS satellite series and Cryosat-2 observations. Generally, this part of the observations was adjusted directly by only using the T/P satellite series data between 60° and 66°, which leads to a large band of missing data from 66° up to 84°. However, in this latitudinal band, the altimetry observations are much denser and their accuracy is even much lower. Thus, this kind of adjustment could deflect the reference constraint to one side, and the errors at the other side might become amplified. Since the latitudinal coverage of GFO and ERS satellites is about 72° and 82° respectively, step-by-step reference data is used. For instance, in the region from 60°S to 84°S, according to the accuracy from selected ERM observations after collinear adjustment shown in Table 2, the T/P satellite series data, the GFO data, the ENVISAT data are used as a reference and substituted step-by-step. This guarantees the consistency with reference to the T/P satellite series data and the accuracy of altimetry data in polar regions after adjustment.

The results in Table 4 show that the non-seasonal sea level variations in non-ERM data can be partly corrected in the crossover adjustment. Therefore, a smaller adjustment box could reduce more sea level variations in the non-ERM data. Taking the large quantity of non-ERM data and the calculation efficiency into account, the 6° band in latitude plus the 30° band in longitude are chosen to be the

Table 4 – Crossover difference related to ERS-1 geodetic mission data by applying different sea level variation corrections before and after crossover adjustment in test area.

Crossover difference		No correction		Correction (1)		Correction (2)		Correction (3)	
		Before	After	Before	After	Before	After	Before	After
ERS-1/168	ERS-1/168	0.127	0.086	0.100	0.072	0.101	0.072	0.085	0.068
TOPEX/B	ERS-1/168	0.133	0.064	0.121	0.056	0.100	0.054	0.061	0.048
ERS-1/168	ERS-2	0.111	0.065	0.095	0.056	0.081	0.055	0.068	0.049
ERS-1/168	GFO	0.126	0.062	0.114	0.053	0.095	0.053	0.061	0.047
ERS-1/168	ENVISAT	0.119	0.065	0.105	0.055	0.088	0.053	0.063	0.048
TOPEX/A	ERS-1/168	0.121	0.064	0.107	0.054	0.089	0.052	0.060	0.047

adjustment box. Furthermore, the adjustment boxes should be partly overlapped and averaged to conserve the consistency.

After crossover adjustment, the least square collocation (LSC) is chosen to generate the grid MSS model. Considering the calculation efficiency of the LSC method, the global ocean is divided into 144 blocks [3,14]. The region between latitudinal band of 60°N and 80°S is divided into 126 blocks, each with a resolution of 20° × 20°. The region between latitudinal band of 60°N and 84°N is divided into 18 blocks, each with a resolution of 22° × 20°. Among these 144 blocks, no observation is available in 2 blocks (40°N–60°N, 60°W–100°W) in Asia and 1 block (40°N–60°N, 240°W–260°W) in America. The geoid height calculated from the EGM2008 gravitation model is removed to get the residual SSH. Then, the residual SSH in 141 blocks is gridded in each block, and the average of the residual SSH is also subtracted to ensure its zero-mean property. The values at repeated longitude and latitude lines along the adjacent blocks are weighted and averaged based on error estimation. All the above blocks are merged through restoration of the geoid height of EGM2008 in each grid and the average in each block, and the global grid MSS is finally achieved.

Since the LSC method has both the function of interpolation and extrapolation, the grid values of all the 141 blocks can be estimated both on the land and in the ocean. Therefore, the Generic Mapping Tools (GMT) are used to generate a 2′ × 2′ land and ocean boundary mask [15]. Then, the WHU2013 MSS model is achieved over the ocean between 80°S and 84°N latitude with a resolution of 2′ × 2′ as shown in Fig. 1. The grid values in land are fulfilled with EGM08 geoid height.

5. Validations

It is difficult to estimate the accuracy of MSS models established by altimetry data. Satellite altimetry observations have the highest accuracy currently, and the most accurate altimetry data are already used in the model. Usually, the reliability and accuracy are validated through comparisons with mean along-track altimetry data and other models. Hence, the latest CNES-CLS11 and DTU13 MSS models, as well as several mean along-track altimetry datasets after collinear adjustment and some other altimetry data independent of the WHU2013 MSS model, are used.

5.1. *Validation with MSS models*

Since the altimetry data used beyond 66°S and 66°N are different for the three MSS models, the differences between them are given in three different latitudinal bands: the latitudinal band from 80°S to 84°N, the latitudinal band from 66°S to 66°N, and latitudinal band beyond 66°S and 66°N.

Outliers in the difference are rejected by three times STD to avoid contamination by the poor observations around coastal regions and islands. The results are shown in Table 5. It can be inferred that the differences between the three models are around 4–5 cm, and the WHU13 MSS and DTU13 MSS models have the best consistency. In addition, systematic biases are revealed between the CLS11 MSS model and the other two models since the period of its reference data is different from that of the others. In the latitudinal band from 66°S to 66°N, the difference between the WHU13 MSS and DTU13 MSS models is less than 2 cm, while the differences between all the three models are less than 3 cm. The differences between the models are relatively larger in the latitudinal band beyond 66°S and 66°N, because different data and processing methods are used.

Fig. 2 and Fig. 3 show the differences of the WHU13 MSS model relative to the DTU13 MSS and CLS11 MSS models respectively. The figures show that all the larger differences are located in regions where the sea level variations are also relatively larger, e.g. the western boundary currents that include the Kuroshio Current, the Mexican Gulf and Agulhas Current, and the region affected by El Nino lies in the equatorial Pacific Ocean. This is quite common because

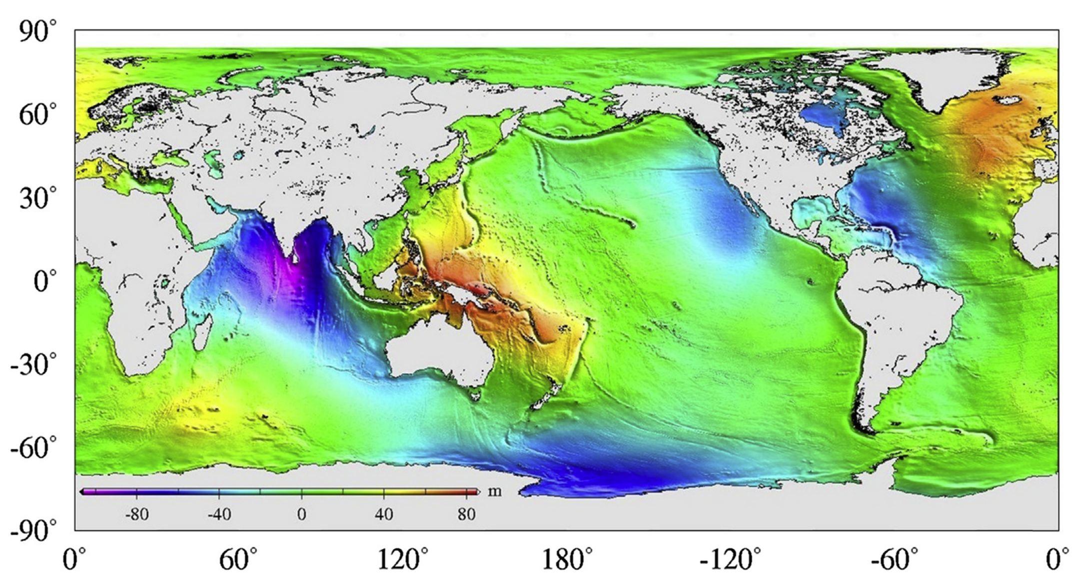

Fig. 1 — Global MSS model WHU2013.

Table 5 – Comparisons of different global MSS models.

Latitudinal coverage	Difference	Mean (m)	RMS (m)	STD (m)	Number of point
[−80°, 84°]	WHU13 – DTU13	0.012	0.046	0.045	35684891
	WHU13 – CLS11	0.038	0.065	0.053	35551655
	CLS11 – DTU13	−0.026	0.054	0.047	35732892
[−66°, 66°]	WHU13 – DTU13	0.012	0.023	0.019	30706100
	WHU13 – CLS11	0.037	0.046	0.027	30716865
	CLS11 – DTU13	−0.025	0.036	0.026	30713163
[−80°, −66°]	WHU13 – DTU13	0.018	0.176	0.175	5478700
[66°, 84°]	WHU13 – CLS11	0.033	0.231	0.228	5476998
	CLS11 – DTU13	−0.015	0.174	0.174	5487775

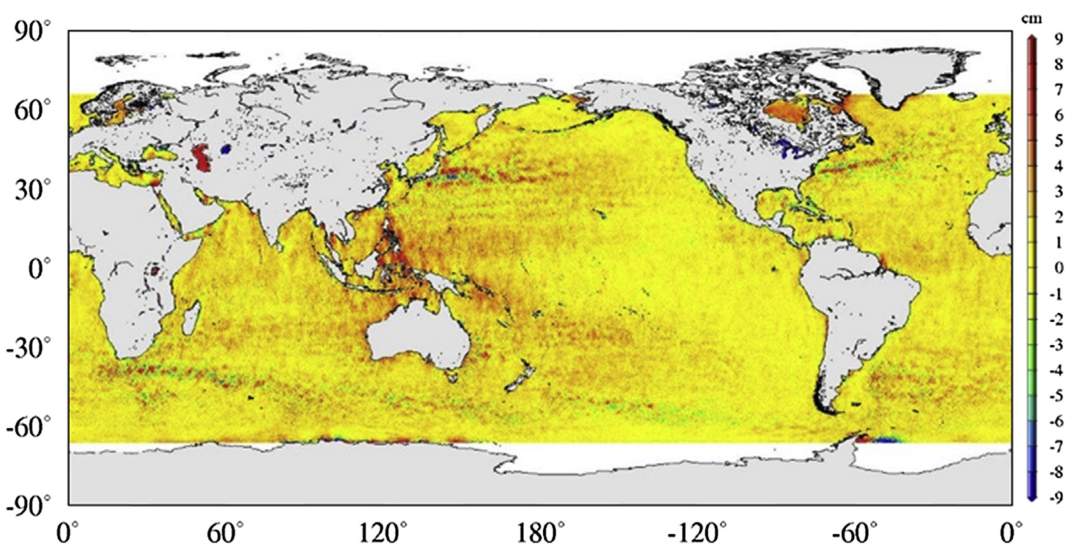

Fig. 2 – Difference between WHU13 MSS and DTU13 MSS between 66°S and 66°N.

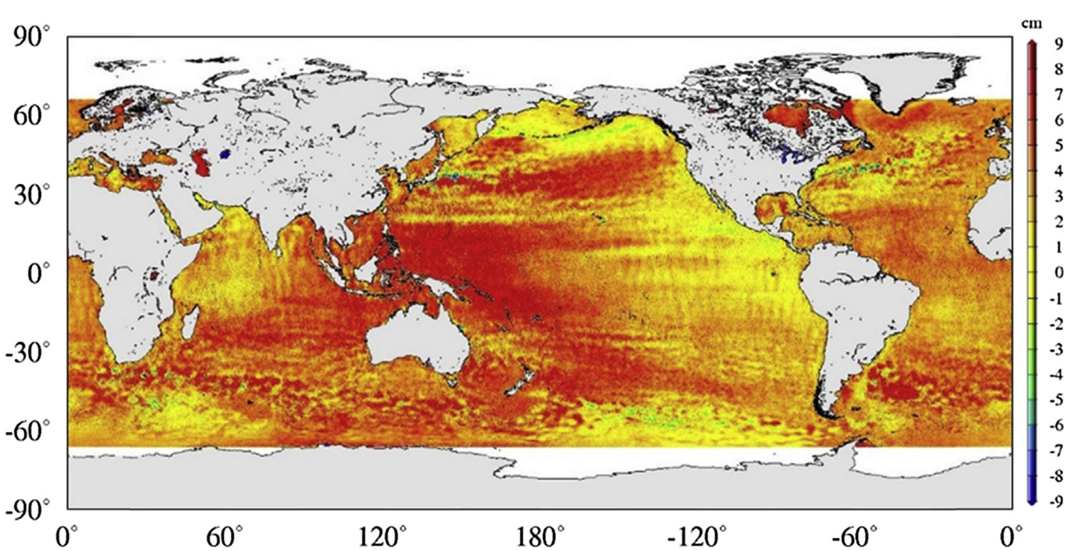

Fig. 3 – Difference between WHU13 MSS and CLS11 MSS between 66°S and 66°N.

different altimetry data with different time spans are used. Furthermore, the bias of the CLS11 MSS model can be seen clearly in Fig. 3.

Moreover, the differences between the three models in the China Sea and its adjacent sea are shown in Table 6. The WHU13 MSS and DTU13 MSS models again have the best consistency, with a STD less than 4 cm.

5.2. *Validation with altimetry observations*

The altimetry observations are another highly effective way of validating the MSS model. Several datasets are chosen, including the mean along-track SSH of 20-year T/P satellite series data, 8-year ENVISAT data and 7-year GFO data after collinear adjustment, which are involved in the WHU13 MSS model, together with the mean along-track SSH of 1-year ENVISAT data after collinear adjustment, one cycle of Jason-2 data and one cycle of Cryosat-2 data, which are not involved in the WHU13 MSS model. One important application of MSS is that it serves as the reference data for sea level variations. Therefore, it will be focused on the variability of the STDs of difference between the models, with a smaller STD meaning more reliable data for the MSS.

According to the results in Table 7, the differences of along-track SSH of the former three groups for the WHU13 MSS model are definitely smaller than those of the other models because they are involved in the model. These groups are similar to those of the CLS11 MSS model, but different time spans are used, namely the 4-year T/P satellite series data, 2-year ENVISAT data and 1-year GFO data. These differences lead mainly to inter-annual sea level variations; however, the results of along-track SSH gradients fit the altimetry datasets quite well for both WHU13 and CLS11 MSS models. The latter three groups of data are not involved in the three models, and among them, the differences of along-track SSH of 1-year ENVISAT data are much smaller than those of the single cycle observations of Jason-2 and Cryosat-2. Furthermore, the results of the WHU13 MSS model are better than those of the other two models. The differences between the along-track SSH gradients are very close to each other for the three models, which show the short-term accuracies of the three models are quite consistent. In summary, the WHU13 MSS model fits quite well with the DTU13 and CLS11 MSS models both on along-track SSH and its gradients.

6. Conclusion

In this paper, multi-satellite altimetry observations are combined to establish a global MSS model named WHU2013, using the mean along-track SSH of T/P satellite series observations spanning the 20 years between 1993 and 2012 after collinear adjustment for reference datum. The corrections for sea level variations of non-ERM observations are compared and analyzed in detail. A method that uses seasonal variations to fit and correct the sea level variations in high latitude regions is proposed and verified. Compared with the CNES-CLS11 and DTU13 MSS models, the WHU13 MSS model has an accuracy of about 5 cm around the global ocean and better than 3 cm between 66°S and 66°N. The three models show similar accuracies after comparisons to satellite altimetry data, which also verifies their reliabilities.

MSS is an important reference for sea level variation. The WHU13 MSS model has a relatively high overall accuracy, but

Table 6 – Accuracy comparisons of different mean sea surface models in China Seas and recent seas.

Coverage	Model discrepancy	Mean (m)	RMS (m)	STD (m)	Number of point
[102°–160°]	WHU13 – DTU13	0.020	0.039	0.034	1731619
[0°–45°]	WHU13 – CLS11	0.054	0.068	0.040	1726381
	CLS11 – DTU13	−0.034	0.056	0.043	1729603

Table 7 – STD of the difference of along-track SSH and its gradients between MSS models and altimetry datasets.

Observations (period)	WHU13		DTU13		CLS11	
	Along-track SSH (mm)	Along-track gradient (mm/km)	Along-track SSH (mm)	Along-track gradient (mm/km)	Along-track SSH (mm)	Along-track gradient (mm/km)
Topex + J1 + J2 (199301–201212)	6.5	0.87	17.1	1.24	20.8	0.82
ENVISAT/B (200210–201010)	23.4	1.14	24.1	1.50	34.0	1.24
GFO (200001–200701)	16.3	1.04	24.0	1.53	33.6	0.84
ENVISAT/C (201101–201201)	55.0	1.68	56.5	1.65	65.0	1.78
Jason-2 (cyc200, 201312)	99.6	6.60	100.6	6.64	104.2	6.59
Cryosat-2 (cyc050, 201402)	110.8	5.55	113.0	5.56	114.9	5.58

no special processes are carried out in coastal areas and polar regions of ice-covered seas, and sea level variation is strong in these areas. Thus, an improvement in coverage and reliability of altimetry data for coastal areas and polar region will be the next focus.

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