

The construction of high precision geostrophic currents based on new gravity models of GOCE and satellite altimetry data

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Abstract

The new gravity field models of gravity field and steady-state ocean circulation explorer (GOCE), TIM_R6 and DIR_R6, were released by the European Space Agency (ESA) in June 2019. The sixth generation of gravity models have the highest possible signal and lowest error levels compared with other GOCE-only gravity models, and the accuracy is significantly improved. This is an opportunity to build high precision geostrophic currents. The mean dynamic topography and geostrophic currents have been calculated by the 5th (TIM_R5 and DIR_R5), 6th (TIM_R6 and DIR_R6) release of GOCE gravity field models and ITSG-Grace2018 of GRACE gravity field model in this study. By comparison with the drifter results, the optimal filtering lengths of them have been obtained (for DIR_R5, DIR_R6, TIM_R5 and TIM_R6 models are 1° and for ITSG-Grace2018 model is 1.1°). The filtered results show that the geostrophic currents obtained by the GOCE gravity field models can better reflect detailed characteristics of ocean currents. The total geostrophic speed based on the TIM_R6 model is similar to the result of the DIR_R6 model with standard deviation (STD) of 0.320 m/s and 0.321 m/s, respectively. The STD of the total velocities are 0.333 m/s and 0.325 m/s for DIR_R5 and TIM_R5. When compared with ITSG-Grace2018 results, the STD (0.344 m/s) of total geostrophic speeds is larger than GOCE results, and the accuracy of geostrophic currents obtained by ITSG-Grace2018 is lower. And the absolute errors are mainly distributed in the areas with faster speeds, such as the Antarctic circumpolar circulation, equatorial region, Kuroshio and Gulf Stream areas. After the remove-restore technique was applied to TIM_R6 MDT, the STD of total geostrophic speeds dropped to 0.162 m/s.

Key words: GOCE, gravity field model, mean dynamic topography, geostrophic current

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1 Introduction

The ocean circulation is the link between the global oceans, which provides dynamic conditions for material transport, heat transfer, sea-land exchange, and seawater quality change. Accurate ocean circulation has important implications for meteorology, oceanography, and geophysics. With the development of satellite altimetry technology and the launch of gravity satellites, the accuracy of the ocean circulation is getting higher, and it has become a hot spot in currents research with its large area and all-weather characteristics. The satellite GOCE (gravity field and steady-state ocean circulation explorer) was launched by the

European Space Agency (ESA) from the Plesetsk Space center in Russia on March 17, 2009. It is the first satellite in the world to adopt gravity gradient measurement technology (Pail et al., 2011). The implementation of Gravity satellite projects represented by GOCE, GRACE (Gravity Recovery and Climate Experiment) and GRACE-FO (follow-on) (launched in May 2018) created conditions for the construction of Gravity field models. The mass distribution of the earth is irregular. On the whole, the earth is very close to an ellipsoid, and the actual earth can be regularized. The regularized earth is called the normal earth, and its corresponding gravity field is called the normal gravity field. The difference

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between the gravity potential at any point and the normal gravity potential in the earth's gravity field is called disturbed potential (Pavlis et al., 2008). The earth's gravity field model is the coefficients of the spherical harmonic series expansion of the potentials, which is expressed as a set of potential coefficients truncated to a finite degree/order. The degree of the models has developed rapidly from the first 8-degree gravity field model in the 1950s to the present ultra-high degree 2 190, and the accuracy of geoid has been improved from several meters to several centimeters or even higher (Pavlis et al., 2008). However, EGM2008, EIGEN-6C4 or other ultra-high degree/order gravity field models are mainly calculated by satellite altimetry data, ground gravity data and satellite gravity data. So, the calculated geoid of the ocean area is related to satellite altimetry data (Förste et al., 2008). To get a more accurate MDT (mean dynamic topography), we need to use a satellite-only gravity model. Accurate geoid and MSS (mean sea surface) are the basis of accurate MDT, and accurate MDT is the key to obtain high precision geostrophic currents. Therefore, the high precision satellite-only gravity models are very important for geostrophic currents research.

After the launch of GOCE satellite, numerous scholars and institutions calculated the GOCE data and generated a series of satellite-only gravity field models (Brockmann et al., 2014; Bruinsma et al., 2013; Kvas et al., 2019; Pail et al., 2010). Geostrophic currents can be constructed by combining these satellite-only gravity models with satellite altimetry data, global or regional MDT, and the calculation principles of mean dynamic topography were discussed (Andersen et al., 2015; Haines et al., 2011; Knudsen et al., 2011a). Some scholars have compared the MDT accuracy obtained by GOCE, GRACE and other gravity models, and discussed the application results and prospects of GOCE data in oceanography (Bingham et al., 2011; Knudsen et al., 2011b). Some scholars discussed the geoid errors and tested a series of MDT with different filter parameters (Albertella et al., 2012; Bingham et al., 2015; Jin et al., 2014; Siegismund, 2013). Many papers have constructed precise Antarctic circumpolar currents and assess the performance of the GOCE and GRACE missions in detail (Bingham et al., 2015; Feng et al., 2013). Because of gravity data have a long lag, these analyses used older gravity models. The loss of high frequency information caused by noise removal by filtering was rarely discussed in the literature. In June 2019, ESA released the sixth generation of gravity field models in the GOCE Virtual Archive, which is 20% more accurate than the previous models (Brockmann et al., 2019; Förste et al., 2019). These help us to have a deeper understanding of ocean current changes.

In this paper, in Section 2 the calculation and comparison of geoid obtained by different gravity field models are described, the MSS and drifter data used in this paper are introduced and their errors are analyzed. We introduce the calculation of mean dynamic topography (MDT) and geostrophic velocities in Section 3. In Section 4, the filtering lengths and errors of different gravity fields are discussed. The latest GOCE's sixth generation gravity field models and MSS_CNES-CLS15 mean sea surface height are used to calculate MDT and geostrophic currents. And other gravity models are used to reflect the advantages of GOCE's new gravity field models. In Section 5, the Remove-restore technique is used to calculate the small-scale currents in the regions to solve the attenuation problem of high-frequency information caused by filtering. Section 6 contains the conclusions.

2 Data

2.1 Geoid

The official GOCE gravity field models published by ESA can

be solved by three methods: direct solution, time-wise solution, and space-wise solution. Except for the latest sixth generation models TIM_R6 (solved by time-wise solution) and DIR_R6 (solved by direct solution), the fifth generation of gravitational field models TIM_R5 (solved by time-wise solution) and DIR_R5 (solved by direct solution) are also adopted in this paper. In TIM_R6 and TIM_R5, the short-arc integral method applied to kinematic orbits, cascaded digital filters applied to the gravity gradients, Kaula-regularization applied to deal with data gaps. Besides, satellite attitude data and nonconservative acceleration data were used in TIM_R6 and TIM_R5. TIM_R5 and TIM_R6 have no priori gravity field information. TIM_R5 is a tide free system, and it is available up degree/order 280 (spatial resolution is about 71 km). TIM_R6 is the zero-tide system, and it is available up degree/order 300 (about 67 km) (Brockmann et al., 2019; Pail et al., 2011). About four years of GOCE gravity gradient data, satellite orbit data, satellite attitude data and a lot of other satellite data such as GRACE and LAGEOS applied in DIR_R5 and DIR_R6 gravity field models. DIR_R5 uses the DIR_R4 gravity model as a priori information and DIR_R6 uses the DIR_R5 gravity model as a priori information. DIR_R5 and DIR_R6 are tide free system, they are available up degree/order 300 (about 67 km) (Bruinsma et al., 2014; Förste et al., 2019).

In order to demonstrate the advantages of the new GOCE models, the latest GRACE gravity model ITSG-Grace2018 is used for comparison. ITSG-Grace2018 is calculated from GRACE L1B data of about 14 years (April 2002 to August 2016). The model is a zero-tide system, complete up to spherical harmonic degree/order 200, which corresponds to a spatial resolution of 100 km (Mayer-Gürr et al., 2018). The cutoff degree/order selected in the calculation of geoid is the maximum degree/order of the gravity field models. The geoid can be calculated by using the gravity field models:

$$N(\vartheta, \lambda) = R \sum_{\ell=0}^L \sum_{m=0}^{\ell} (C_{\ell m} \cos m\lambda + S_{\ell m} \sin m\lambda) P_{\ell m}(\cos \vartheta), \quad (1)$$

where ϑ is the geographic colatitude, λ is the longitude, R is the mean earth radius, L is the highest degree considered in the spherical harmonic expansion, $C_{\ell m}$ and $S_{\ell m}$ are the nondimensional regularized spherical harmonic coefficients, $P_{\ell m}$ are the fully normalized associated Legendre functions of degree ℓ and order m .

The geoid of each gravity field model is calculated by Eq. (1). The differences are shown in Figs 1, 2 and Table 1. Figure 1 depicts the difference among geoids determined by GOCE's four gravity field models. It can be seen from Figs 1c, e and f that the differences between TIM_R6 and other GOCE gravity models are mainly in the north and south poles, and the differences are smaller as close to the equator. Figures 1a, b and d show that the differences of DIR_R5, DIR_R6 and TIM_R5 are mainly distributed in north and south poles, southern Australia and northern North America regions.

Figure 2 shows that the differences between GRACE and GOCE geoid are very large. At the edge of the coastline, their differences can reach 1 m.

Table 1 shows that the RMS differences between ITSG-Grace2018 and other gravity models are relatively large (more than 0.30 m). However, the differences among geoids determined by the four GOCE models are small and their RMS values are within 0.30 m. The RMS of DIR_R5 and DIR_R6 is the minimum (0.147 m), and TIM_R5 and TIM_R6 have the largest RMS (0.284 m). The reas-

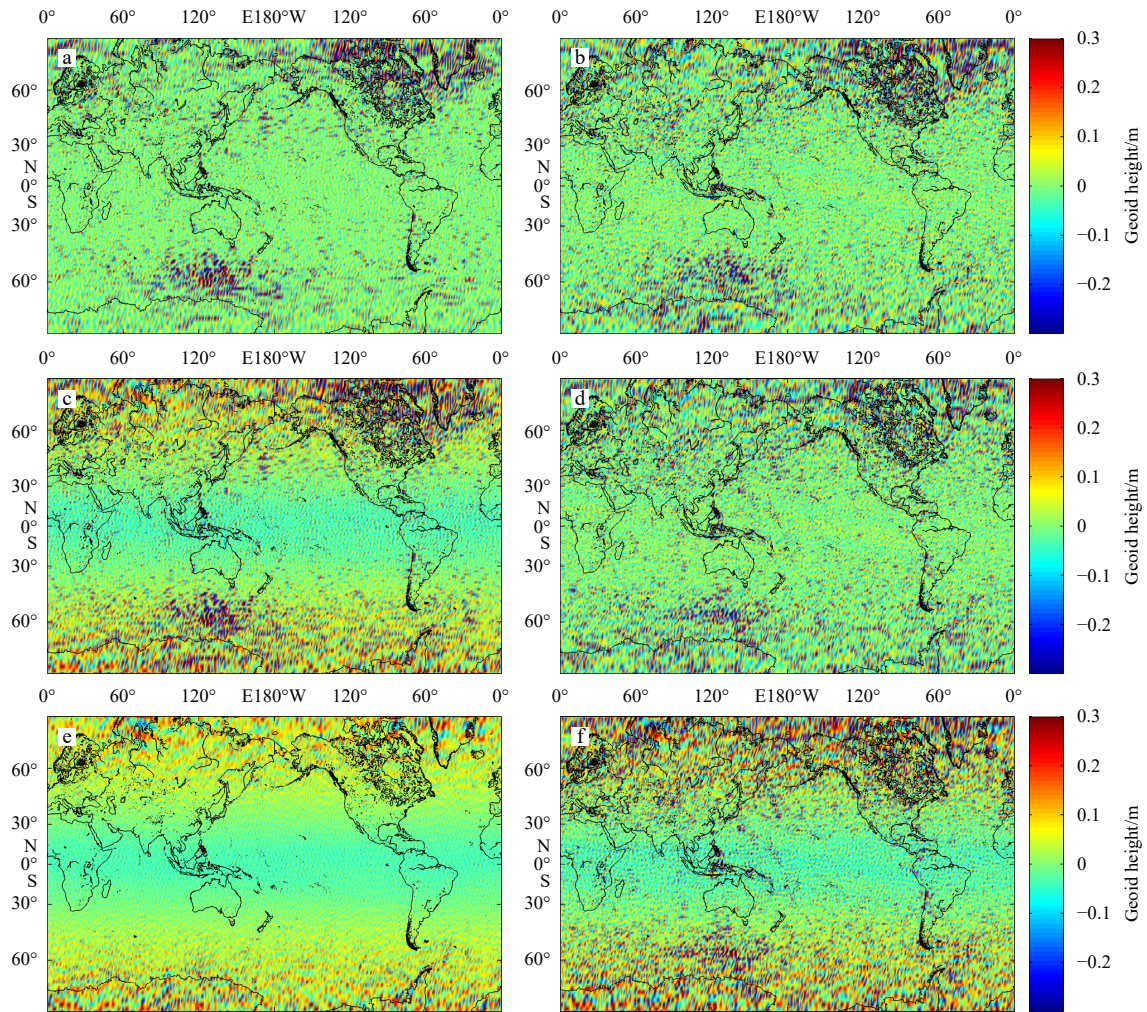


Fig. 1. Comparison of geoid heights from different GOCE gravity field models. a. DIR_R5-DIR_R6 model, b. DIR_R5-TIM_R5 model, c. DIR_R5-TIM_R6 model, d. DIR_R6-TIM_R5 model, e. DIR_R6-TIM_R6 model, and f. TIM_R5-TIM_R6 model.

ons for the differences are related to the data source and truncation degree/order of the models.

2.2 Mean sea surface (MSS)

Satellite altimeters provide accurate sea surface heights for the calculation of geostrophic currents. This paper adopts the latest mean sea surface height model MSS_CNES-CLS15 released by CNES (Centre National d'Etudes Spatiales). This data provide a global grid of 1' ((1/60)°) resolution between 80°S and 84°N, using altimeter data (TOPEX/Poseidon, ERS-2, GFO, JASON-1, JASON-2, ENVISAT mean profile and data of the ERS-1, Jason-1, and Cryosat-2 geodetic phase) for 20 years (1993–2012). The MSS is defined in the mean tide system and the TOPEX/POSEIDON reference ellipsoid (Schaeffer et al., 2012). Figure 3 shows the errors between MSS_CNES-CLS15 and the previous version MSS_CNES-CLS11. The errors of MSS_CNES-CLS15 are smaller than that of MSS_CNES-CLS11 in the coastal areas. In parts of the north and south polar regions (especially in northern North America), the errors of MSS_CNES-CLS15 increased slightly.

2.3 Drifter observations

On September 5, 2018, the Global Drifter Program of the National Oceanic and Atmospheric Administration (NOAA) and the Atlantic Oceanographic and Meteorological Laboratory (AOML)

release the version 3.03 of near-surface currents and sea surface temperatures around the world from 73°S to 85°N, at (1/4)° resolution, which are derived from satellite tracked buoys (Laurindo et al., 2017; Lumpkin et al., 2013; Lumpkin and Johnson, 2013). We will use this data to verify the accuracy of geostrophic currents obtained by satellite gravity models. Figure 4 shows that the standard errors of velocity from buoy data are small. The maximum standard errors are about 0.1 m/s, which distributed in coastal and equatorial areas.

3 Calculation of mean dynamic topography (MDT) and geostrophic velocities

The height of MDT (H) is defined as the difference between the MSS (h) and the geoid (N):

$$H = h - N. \quad (2)$$

The MSS and the geoid must adopt the uniform reference ellipsoid system and tide system. The MDT difference calculated by different reference ellipsoid and tide system is about 30 cm (Tsoulis and Patlakis, 2013). Here, the geoid and MSS are referred to the TOPEX/Poseidon ellipsoid and defined in the mean tide system.

The geoid is solved by a gravity field model and can only be

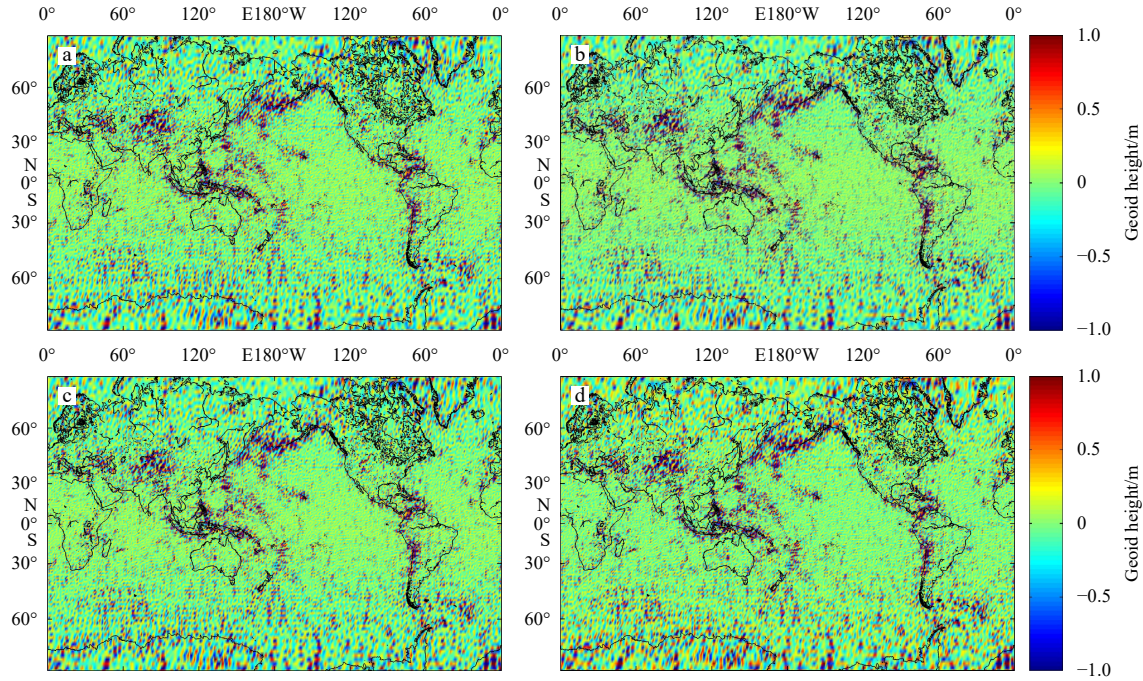


Fig. 2. Comparison of geoid heights from GRACE and GOCE gravity field models. a. ITSG-Grace2018-DIR_R5 model, b. ITSG-Grace2018-DIR_R6 model, c. ITSG-Grace2018-TIM_R5 model, and d. ITSG-Grace2018-TIM_R6 model.

Table 1. Statistics of the different geoid products

Gravity model	Mean geoid height/m	RMS/m	Minmum geoid height/m	Maximum geoid height/m
DIR_R5-DIR_R6	0.001	0.147	-1.878	1.853
DIR_R5-TIM_R5	0.006	0.246	-2.624	3.286
DIR_R5-TIM_R6	0.006	0.251	-2.812	2.580
DIR_R6-TIM_R5	0.005	0.209	-2.360	2.167
DIR_R6-TIM_R6	0.005	0.207	-2.785	2.461
TIM_R5-TIM_R6	0.000	0.284	-2.463	3.510
ITSG-Grace2018-DIR_R5	-0.014	0.349	-3.423	2.337
ITSG-Grace2018-DIR_R6	-0.013	0.323	-3.506	2.419
ITSG-Grace2018-TIM_R5	-0.008	0.373	-3.331	2.342
ITSG-Grace2018-TIM_R6	-0.007	0.383	-3.655	3.322

expanded to a finite degree/order. But MSS is derived from satellite altimetry, which can be expanded to an infinite degree/order by spherical harmonic expansion (Tsoulis and Patlakis, 2013). Their spatial resolution is inconsistent. The MSS and geoid must be unified to the same scale if we calculate the difference of them. There are two methods to do it: the spherical harmonic function method (solved in the spectral domain) and the geometric method (solved in the spatial domain) (Haines et al., 2011). The spherical harmonic function method will be used in this paper.

Since the resolution of geoid and mean sea surface is inconsistent, MSS is interpolated to the resolution consistent with geoid and the MSS of land areas need to be replaced by geoid heights (Albertella et al., 2012). The spherical harmonic form of the MSS is (Bingham et al., 2008):

$$h(\vartheta, \lambda) = R \sum_{\ell=0}^L \sum_{m=0}^{\ell} (C_{\ell m}^h \cos m\lambda + S_{\ell m}^h \sin m\lambda) P_{\ell m}(\cos \vartheta). \quad (3)$$

According to Eqs (1)–(3), the mean dynamic topography H

can be obtained, whose spherical harmonic form is (Bingham et al., 2008):

$$H(\vartheta, \lambda) = R \sum_{\ell=0}^L \sum_{m=0}^{\ell} (C_{\ell m}^H \cos m\lambda + S_{\ell m}^H \sin m\lambda) P_{\ell m}(\cos \vartheta), \quad (4)$$

where

$$\begin{cases} C_{\ell m}^H = C_{\ell m}^h - C_{\ell m} \\ S_{\ell m}^H = S_{\ell m}^h - S_{\ell m} \end{cases}.$$

The spherical harmonic coefficient $(C_{\ell m}^H, S_{\ell m}^H)$ is the difference between the spherical harmonic coefficient of MSS $(C_{\ell m}^h, S_{\ell m}^h)$ and geoid $(C_{\ell m}, S_{\ell m})$.

According to the MDT, the velocities of geostrophic currents in the east (u) and north (v) direction can be calculated (Knudsen et al., 2011b):

$$u = -\frac{g}{fR} \frac{\partial H}{\partial \vartheta}, \quad (5)$$

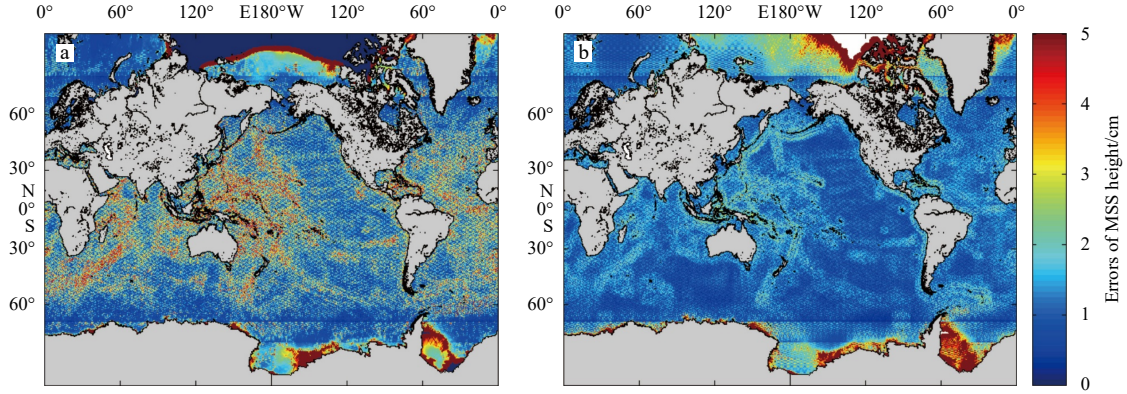


Fig. 3. The errors of CNES-CLS11 (a) and CNES-CLS15 (b).

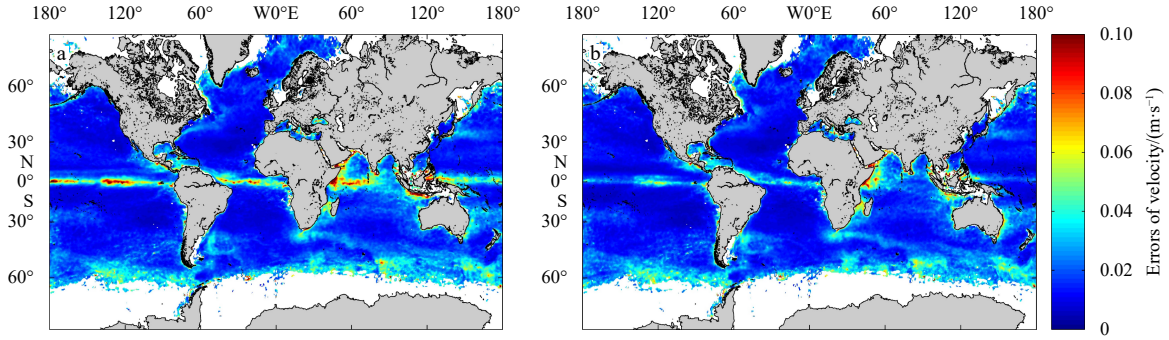


Fig. 4. Standard errors of drifters' eastward velocities (a) and northward velocities (b).

$$v = \frac{g}{fR} \frac{1}{\sin \vartheta} \frac{\partial H}{\partial \lambda}, \quad (6)$$

where g is gravity acceleration, $f = 2\Omega \cos \vartheta$ is the Coriolis parameter, ϑ is the residual latitude, and Ω is the angular velocity of the earth. Since the Coriolis force near the equator tends to 0, geostrophic velocities are replaced by 0 in the region of 3°S and 3°N. Its spherical harmonic form can be expressed as

$$u = -\frac{g}{fR} \sum_{\ell=0}^L \sum_{m=0}^{\ell} R (C_{\ell m}^H \cos m\lambda + S_{\ell m}^H \sin m\lambda) P'_{\ell m}(\cos \vartheta), \quad (7)$$

$$v = \frac{g}{fR} \frac{1}{\sin \vartheta} \sum_{\ell=0}^L \sum_{m=0}^{\ell} mR (-C_{\ell m}^H \sin m\lambda + S_{\ell m}^H \cos m\lambda) P_{\ell m}(\cos \vartheta), \quad (8)$$

where R is the average radius of the earth, and $P'_{\ell m}$ is the partial derivative with respect to ϑ of the associated Legendre function $P_{\ell m}$. The spatial resolution of the geostrophic current calculated by TIM_R5, TIM_R6, DIR_R5, DIR_R6 and ITSG-Grace2018 in this paper is $(1/2)^\circ$. The total speeds (V) and direction (A) of geostrophic currents are as follows (Albertella et al., 2012):

$$V = \sqrt{u^2 + v^2}, \quad (9)$$

$$A = \arctan\left(\frac{u}{v}\right). \quad (10)$$

4 Errors and optimization of geostrophic currents

High precision MDT is the basis of geostrophic currents. However, in addition to the omission error caused by the discrepancy of spatial resolution between the geoid and mean sea surface, there is a commission error defined by the spherical harmonic terms (Knudsen et al., 2011b). These two errors lead to small-scale noise when calculating the MDT. In order to obtain high precision geostrophic currents, it is necessary to filter the MDT to reduce noise before calculating geostrophic currents. Gauss filtering is performed on the MDT obtained from Eq. (4). The calculation formula of Gauss filtering is as follows (Siegismund, 2013):

$$\zeta_P = \frac{\sum_Q W_{P,Q_i} \zeta_{Q_i}}{\sum_Q W_{P,Q_i}}, \quad (11)$$

where P is the central mesh point to be filtered; Q is the grid dot within the filtering radius; ζ_P, ζ_{Q_i} are the MDT value of grid dot P, Q_i , respectively; W_{P,Q_i} is weight and its formulas are as follows (Siegismund, 2013):

$$\begin{cases} W_{P,Q_i} = \frac{1}{\beta \sqrt{2\pi\sigma}} e^{-\frac{d_i^2}{2\sigma^2}} \\ \sigma = \frac{\beta}{\sqrt{2 \ln 2}} \end{cases}, \quad (12)$$

where d_i is the spherical distance between points P and Q_i , and β is the filter radius. The spherical distance d_i can be derived from the spherical trigonometry formula:

$$d_i = 2R \sqrt{\sin^2 \frac{\vartheta - \vartheta_i}{2} + \sin^2 \frac{\lambda - \lambda_i}{2} \cos \vartheta \cos \vartheta_i}, \quad (13)$$

where R is the average radius of the earth; (λ, ϑ) and (λ_i, ϑ_i) are the geodetic longitude and latitude of P and Q_i , respectively.

Gauss filtering also filters out some ocean signals while removing noise. In order to minimize attenuation of MDT signals and fully suppress noise, it is necessary to select the optimal filtering length. Geostrophic currents are calculated by the Eqs (7)–(10) after MDT filtered with different filtering lengths (from 0.6° – 1.6° , with a step size of 0.1°). Because there is little drifter data in polar regions, the global regions considered for calculation are limited to 60°S – 70°N . Drifter data are replaced by 0 in the region of 3°S and 3°N , which is same as gravity models' results. Figure 5 shows that the STD (standard errors) results between gravity models results and drifter in the Kuroshio and Gulf Stream areas. When the filter length is 1° for GOCE models and 1.1° for GRACE model, the STD reaches the minimum value in the Kuroshio and Gulf Stream area. This indicates that beyond the filter length, the attenuation of the signal outweighs the benefits of noise reduction. Therefore, the filter length chosen for DIR_R5, DIR_R6, TIM_R5 and TIM_R6 in this paper is 1° , and the filter length chosen for the ITSG-Grace2018 model is 1.1° .

Table 2 shows that the filtered geostrophic currents have better consistency with the drifter results, indicating that the filtered geostrophic currents have higher precision. The accuracy of geostrophic currents from ITSG-Grace2018 is the lowest. The STD results of the four GOCE models showed little difference about 1 cm. The accuracy of geostrophic currents calculated by TIM_R6 and DIR_R6 is higher than that of TIM_R5 and DIR_R5, respectively.

Figure 6 is the absolute errors of total geostrophic speeds after using optimal filter length. We can see the error distributions and

range in the figures. The errors of total geostrophic speeds between gravity field models and drifter are mainly distributed in the areas with faster speed (such as the Antarctic circumpolar circulation, equatorial region, Kuroshio and Gulf Stream areas). The absolute errors difference between each gravity model results are small. We can see their difference more clearly from the STD in Table 2.

Figures 7 and 8 respectively show the filtered MDT and related geostrophic current results in the Kuroshio area and Gulf Stream area. The geostrophic velocities of ITSG-Grace2018 are relatively low. There is little difference among DIR_R5, DIR_R6, TIM_R5 and TIM_R6 results. In summary, the accuracy of ocean surface topography and geostrophic currents calculated by GOCE are better than those calculated by GRACE.

5 Geostrophic currents of high precision

Gauss filtering can effectively remove the noise, but also filter out the high frequency information. As a result, the detail features of currents in some areas are not obvious. In order to improve the accuracy of the calculation results, this paper adopts the Remove-restore technique to recover the small-scale details of geostrophic currents. The Remove-restore technique is to deduct the high frequency parts of MDT (remove), so as to facilitate the subsequent data processing. The high frequency parts are added to the MDT to get the desired result finally (restore) (Sjöberg, 2005). In this paper, MDT_CNES-CLS13, a short-scale MDT model published by CNES with a resolution of $(1/4)^\circ$, is used to complete satellite-only MDT. The MDT_CNES-CLS13 model is combined with satellite altimetry, temperature and salt, buoy and hydrological model data, and solved by direct method, comprehensive method and multivariate objective analysis method (Knudsen et al., 2019). Based on the satellite-only MDT calculated by previous method in Section 4, MDT_CNES-CLS13 is filtered by the same filter length and the residuals (MDT_CNES-

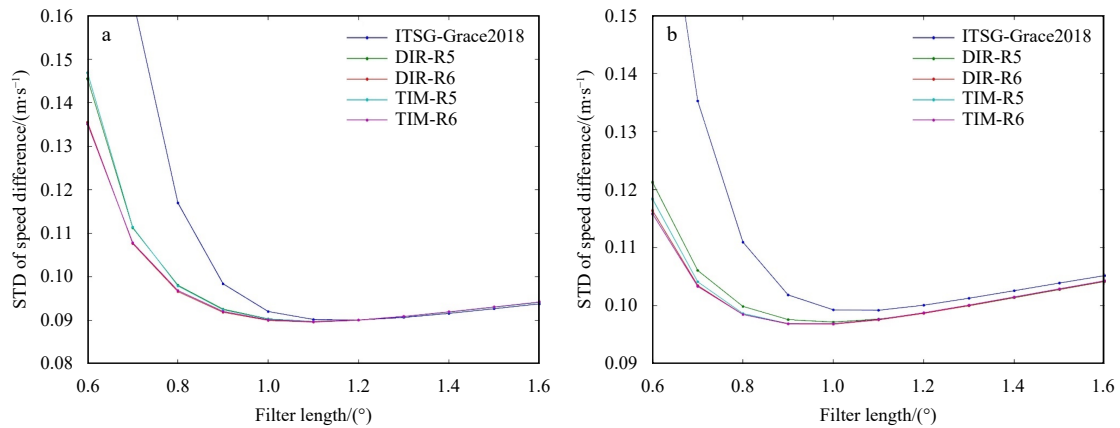


Fig. 5. Standard errors of the total geostrophic speed differences between gravity models and drifter in Kuroshio area (a) and Gulf Stream area (b).

Table 2. STD between the geostrophic currents based on GRACE/GOCE models and drifter results

Gravity field model	Unfiltered velocity			Filtered velocity		
	STD (u)/($\text{m}\cdot\text{s}^{-1}$)	STD (v)/($\text{m}\cdot\text{s}^{-1}$)	STD (V)/($\text{m}\cdot\text{s}^{-1}$)	STD (u)/($\text{m}\cdot\text{s}^{-1}$)	STD (v)/($\text{m}\cdot\text{s}^{-1}$)	STD (V)/($\text{m}\cdot\text{s}^{-1}$)
DIR_R5	0.771	7.830	12.375	0.091	0.367	0.333
DIR_R6	0.765	7.567	12.118	0.091	0.355	0.321
TIM_R5	0.786	7.706	12.251	0.091	0.359	0.325
TIM_R6	0.767	7.404	11.907	0.091	0.353	0.320
ITSG-Grace2018	1.293	11.702	16.186	0.097	0.377	0.344

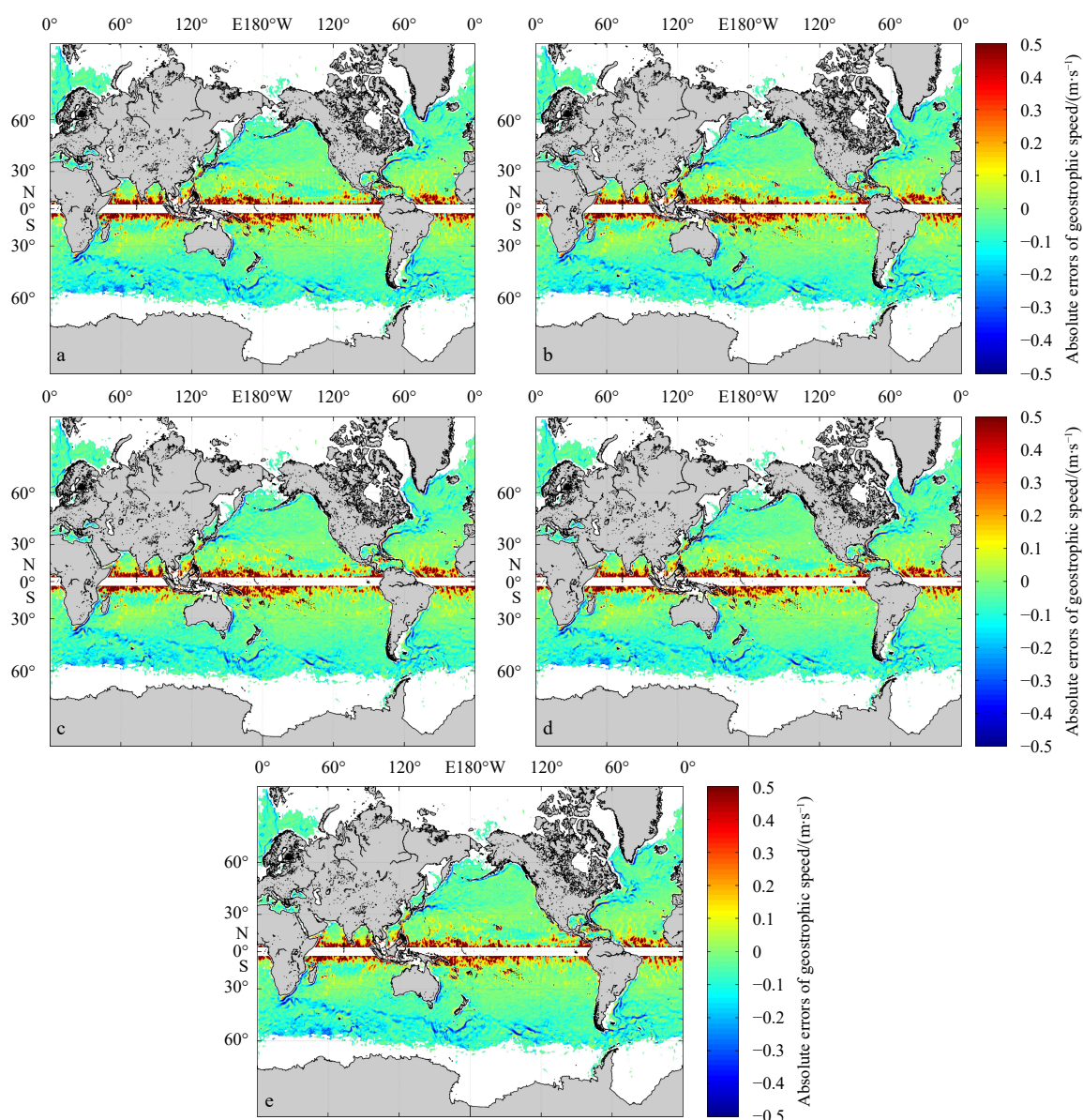


Fig. 6. The absolute errors of total geostrophic speeds calculated by different gravity field models. a. DIR_R5-drifter model, b. DIR_R6-drifter model, c. TIM_R5-drifter model, d. TIM_R6-drifter model, and e. ITSG-Grace2018-drifter model.

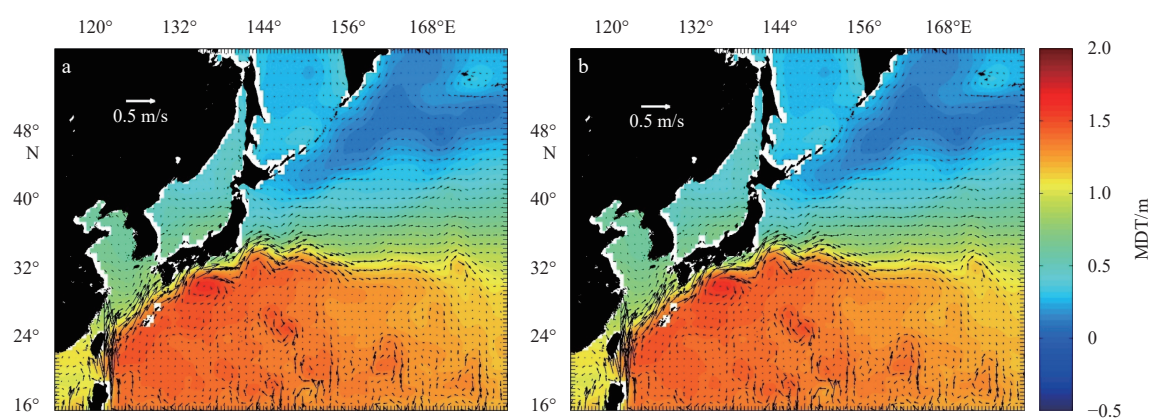


Fig. 7.

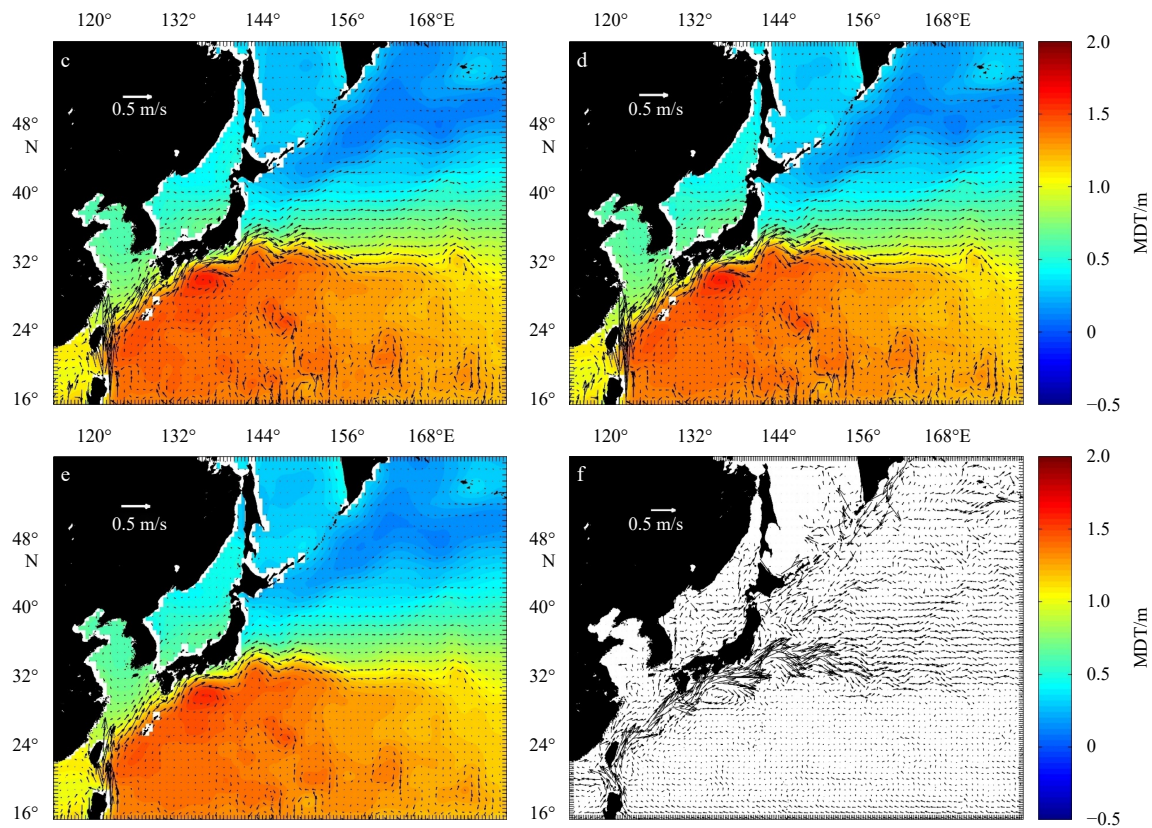


Fig. 7. Mean dynamic topography (shading) and corresponding geostrophic currents (black arrows) in the Kuroshio area. a. DIR_R5 model, b. DIR_R6 model, c. TIM_R5 model, d. TIM_R6 model, e. ITSG-Grace2018, and f. drifter.

CLS13 minus the filtered MDT_CNES-CLS13) are added to the satellite-only MDT (Rio et al., 2014).

The satellite-only MDT selected here is the MDT obtained by TIM_R6. It can be seen from Table 3 that the STD of the eastward, northward and total speeds of geostrophic currents calculated by TIM_R6 dropped to 0.077 m/s, 0.209 m/s and 0.162 m/s after the remove-restore technique. And the accuracy of geostrophic cur-

rents after remove-restore technique is higher than that of MDT_CNES-CLS13. It can be seen that the geostrophic current speeds after the remove-restore technique are closer to the drifter results in Fig. 9.

6 Conclusions

The geostrophic currents calculated by different filter lengths

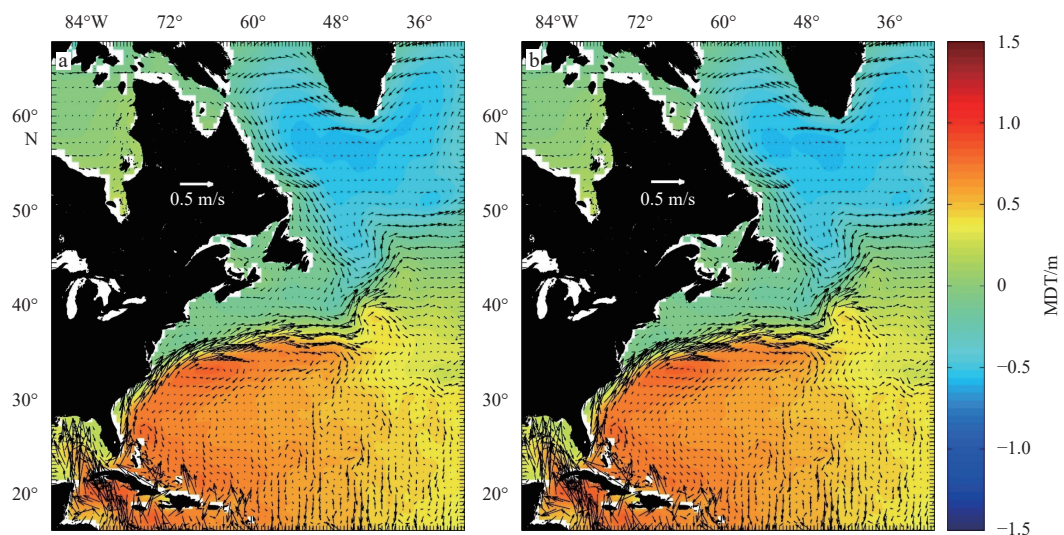


Fig. 8.

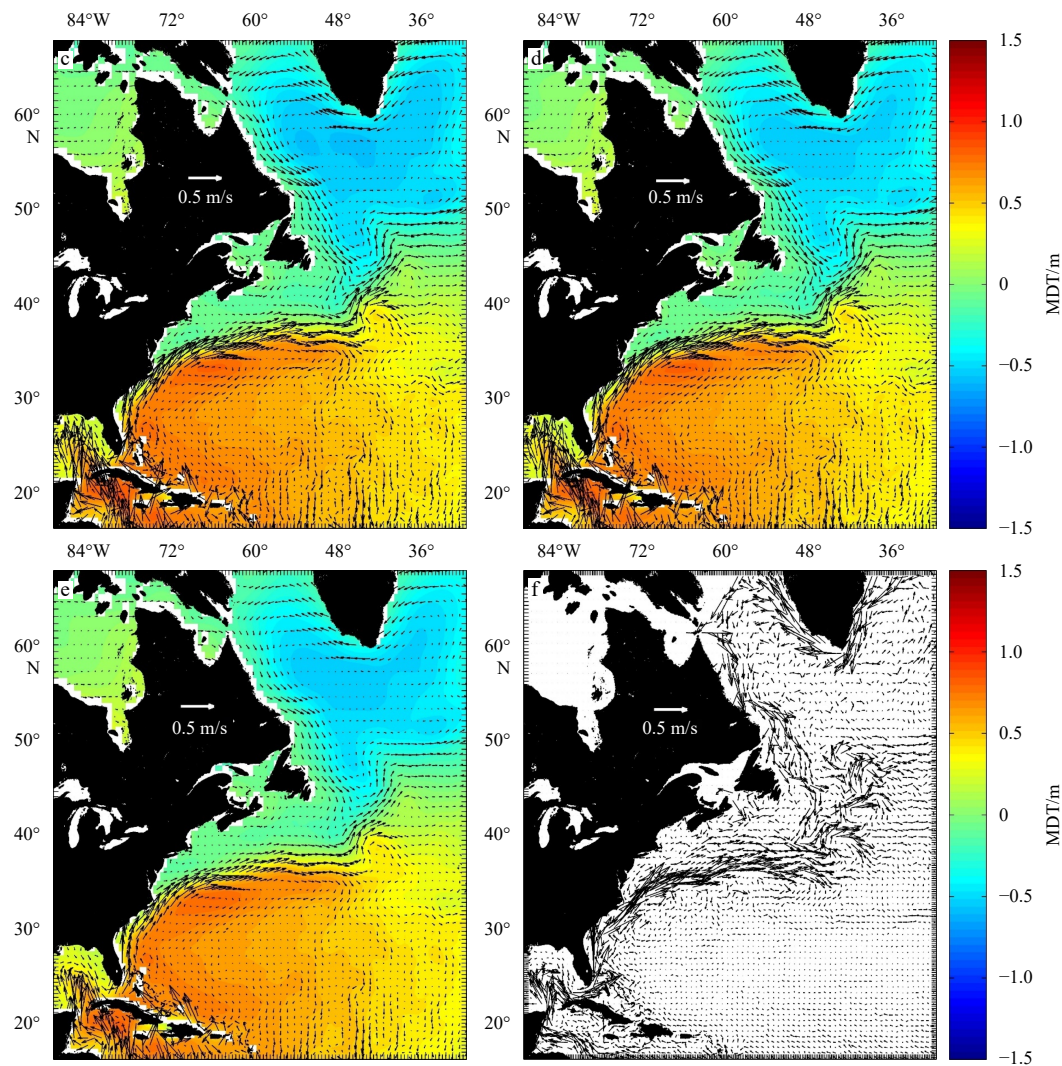


Fig. 8. Mean dynamic topography and corresponding geostrophic currents (velocities are displayed as black arrows) in the Gulf Stream area. a. DIR_R5 model, b. DIR_R6 model, c. TIM_R5 model, d. TIM_R6 model, e. ITSG-Grace2018 model, and f. drifter.

Table 3. STD of geostrophic currents between the different MDT and drifter results

MDT models	STD of geostrophic current/(m·s ⁻¹)		
	STD (<i>u</i>)	STD (<i>v</i>)	STD (<i>V</i>)
TIM_R6 before remove-restore	0.091	0.353	0.320
TIM_R6 after Remove-restore	0.077	0.209	0.162
MDT_CNES-CLS13	0.080	0.233	0.186

have been compared with the drifter results in this paper and the optimal filtering length of DIR_R5, DIR_R6, TIM_R5 and TIM_R6 is 1°, and that of ITSG-Grace2018 model is 1.1°. The STD of filtered total geostrophic speeds based on TIM_R6, DIR_R6, TIM_R5, DIR_R5 and ITSG-Grace2018 models are 0.320 m/s, 0.321 m/s, 0.325 m/s, 0.333 m/s and 0.344 m/s, respectively. And the absolute errors are mainly distributed in the areas with faster speed (such as the Antarctic circumpolar circulation, equatorial region, Kuroshio and Gulf Stream areas). It can be concluded that the accuracy of geostrophic currents calculated by GOCE gravity field model is higher than that of GRACE. This is due to GOCE's gravity gradient measurement technology can effectively detect gravity signals of medium-short wave and small-scale cur-

rents. However, due to the truncation of geoid and filtering, there is still a gap with drifter results. The accuracy of geostrophic currents is improved obviously and the high frequency information is recovered after using the Remove-restore technique.

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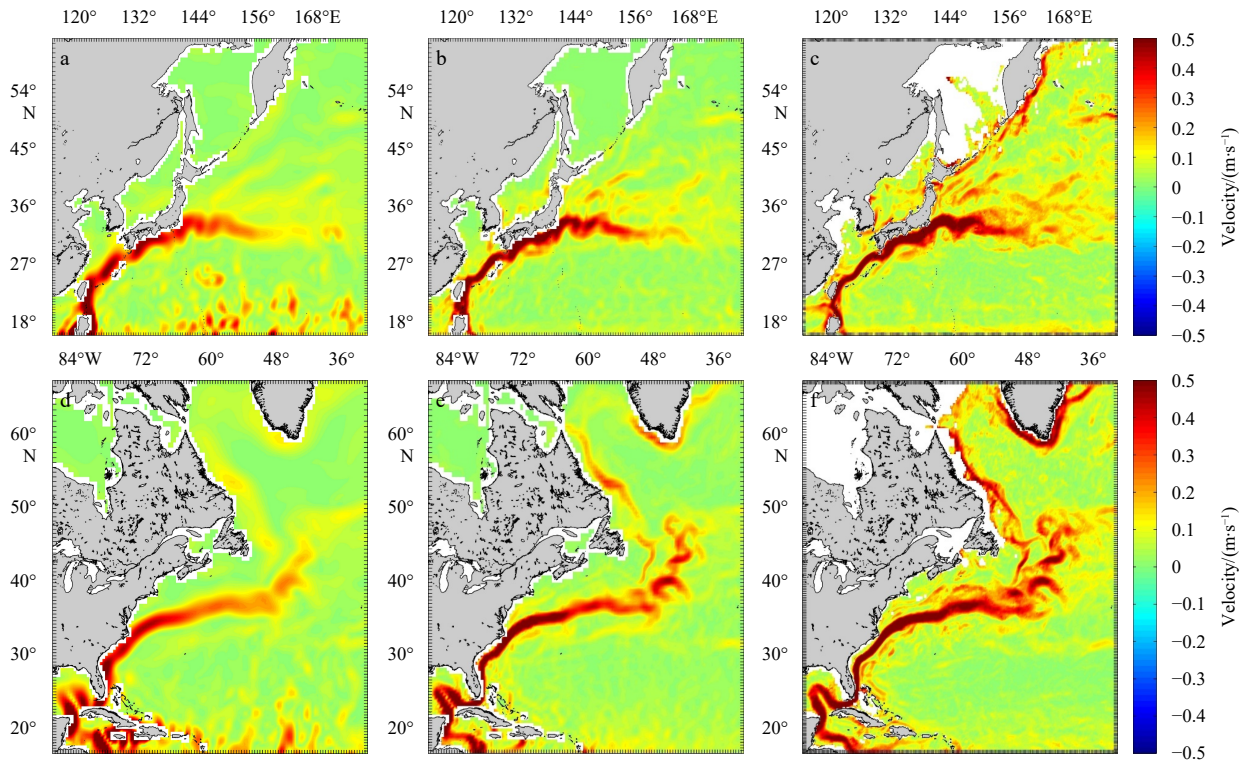


Fig. 9. Comparison of total geostrophic speeds before and after Remove-restore technique in the Kuroshio current area (a. before remove-restore, b. after remove-restore, and c. drifter) and Gulf Stream area (d. before remove-restore, e. after remove-restore, and f. drifter).

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