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Antarctic circumpolar current from satellite gravimetric models ITG-GRACE2010, GOCE-TIM3 and satellite altimetry

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ABSTRACT

The Antarctic circumpolar current (ACC) is a clockwise ocean flow from west to east around Antarctica, connecting the Pacific, Indian and Atlantic oceans, and plays a key role in the heat transport and climate change. The geostrophic surface currents can be derived from the ocean dynamic height as the deviation of the actual sea level from satellite altimetry and the Earth's geoid. Although the gravity recovery and climate experiment (GRACE) and gravity field and steady-state ocean circulation explorer (GOCE) mission provided an initial estimate of global geostrophic currents, a more detailed Antarctic circumpolar current is still not well estimated. In this paper, the detailed ACC is estimated from the newest ITG-Grace2010 gravity model based on 7-years of GRACE data, and GO_CONS_GCF_2_TIM_R3 gravity model (hereafter referred to GOCE-TIM3) based on 12 months of GOCE data, with the mean sea surface height model MSS_CNES_CLS_11 from satellite altimetry, respectively. The evaluation and comparisons are performed with oceanographic models, the GOCO03S gravity model as well as in situ drifter's measurements. Results show that the Antarctic circumpolar current based on GOCE gravity field model depicts more details and transport characteristics with high accuracy and spatial resolution, e.g., Agulhas currents and Brazil-Malvinas Confluence regions, which are more consistent with the in situ drifter's results. The ACC based on ITG-Grace2010 model is similar with the result of the GOCE-TIM3 model with RMS of 8.39 cm/s and 7.85 cm/s, respectively, while the accuracy of GOCE-TIM3 is still higher. The correlation coefficients of the estimated velocities, compared to drifter results, are 0.70 and 0.76 for ITG-Grace2010 and GOCE-TIM3. ITG-Grace2010 model has more noise in the higher spherical harmonic coefficients and some better performances in the geostrophic currents are able to be obtained if the degrees are truncated to 160 for ITG-Grace2010, while the GOCE-TIM3 and GOCO03S model do not have this phenomenon. The gravity model GOCO03S with combined CHAMP, GRACE and GOCE observations almost have no improvement in ACC estimate when compared with GOCE-TIM3 results, while the RMS of GOCO03S is a little larger than the GOCE-TIM3 results.

1. Introduction

The Antarctic circumpolar current (ACC) connects the Atlantic, Pacific and Indian Oceans and transports the heat and salinity in the overall regulation of the ocean's energy budget around the Antarctica, which significantly influences the global climate system and ocean circulation (Zlotnicki et al., 2007; Barker and Thomas, 2004). Therefore, it is important to monitor and understand the transport and variability of ACC with high accuracy and resolution. Due to complex winds, sea ice, and topography, the ACC has not been well observed and understood (Griesel et al., 2012). The ocean's geostrophic currents are closely related to the ocean's mean dynamic topography (MDT), which is the difference between the mean sea surface height (MSSH) and the geoid (N). With the development of satellite altimetry since mid 1980s, satellite altimeters provide quasi-global sea level variations with unprecedented accuracy. Satellite altimetric observations (Topex/Poseidon, GEOSAT Follow-On (GFO), ERS-2, Jason-1/2, and Envisat) can provide the mean sea surface height (MSSH) at centimeter accuracy at almost global scales. However, the accuracy of previous global gravity models has largely restricted the precise estimation of the ocean's mean dynamic topography (MDT) and the geostrophic currents (Losch and Schröter, 2004).

Satellite gravimetry provides a new opportunity to determine with high-precision the Earth's gravitational field up to wavelengths of ~100–120 km. The Gravity Recovery and Climate Experiment (GRACE) mission with a pair of Low Earth Orbit (LEO)

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satellites launched in March 2002 determined the time-variable gravity field with high-accuracy (Wahr et al., 1998; Jin et al., 2010, 2011; Jin and Feng, 2013). In 2009, the European Space Agency launched the Earth's gravity and ocean circulation explorer (GOCE) satellite carrying a highly sensitive gravitational gradiometer to detect fine gravity gradient differences. GOCE could determine the 1–2 cm geoid at a spatial resolution lower than 100 km (Drinkwater et al., 2007). These satellite gravimetric missions provide a new opportunity in determining the ocean's MDT (e.g., Tapley et al., 2003; Vossepoel, 2007; Griesel et al., 2012; Albertella et al., 2012) and the initial ocean's geostrophic currents (e.g., Sanchez-Reales et al., 2012). For example, Maximenko et al. (2009) found that the locations of the velocity concentrations in the Antarctic Circumpolar Current are well defined based on GRACE gravity model. Knudsen et al. (2011) showed improvements in the global MDT and geostrophic surface currents from GOCE gravity model. Griesel et al. (2012) showed that four recent Southern Ocean MDT products differ in some locations by more than the nominal error bars. However, the estimate of Antarctic circumpolar current still has large uncertainties. In this paper, the detailed ACC is estimated from the newest GRACE-derived gravity field model ITG-Grace2010 with 7 years of observations, and 12 months of GOCE-derived gravity field model GOCE-TIM3 with the mean sea surface height model MSS_CNES_CLS_11 from satellite altimetry. These sets of ACC velocities are then evaluated using data from in situ drifter buoys, and compared with other oceanographic models and the GOCO03S gravity model with combined CHAMP, GRACE and GOCE observations. Some of the transport characteristics of the ACC are presented in the following sections.

2. Observation data and models

2.1. Geoid determination

The gravity field is normally described by expansions in spherical harmonic coefficients. The geoid height (N) can be expressed by Stokes coefficients (C_{nm},S_{nm}), (Chao and Gross, 1987):

$$N(\phi,\lambda)=R\sum_{n=0}^{\infty}\sum_{m=0}^{n}P_{nm}(\sin\phi)(C_{nm}\cos m\lambda+S_{nm}\sin m\lambda) \tag{1}$$

where ϕ is the geographic latitude, λ is the longitude, R is the mean radius of the Earth, P_{nm} is the fully-normalized Associated Legendre functions of degree n and order m, and C_{nm},S_{nm}, are dimensionless Stokes coefficients.

With the high-precision gravity field models, the geoid height can be accurately determined, e.g., from GRACE or GOCE. Here the geoid height was computed from the newest ITG-Grace2010 (Mayer-Gürr et al., 2010) and GOCE-TIM3 (Pail et al., 2011) gravity field models. The ITG-Grace2010 is a static gravity filed model, calculated from the GRACE-only observations covering the time span from August 2002 to August 2009, complete up to spherical harmonic degree/order 180. The processing details are presented in Mayer-Gürr et al. (2010). The GOCE-TIM3 is a GOCE-only solution based on measurements of GOCE orbit and gradiometer data from November 2009 to April 2011 (the effective GOCE data time span is about 12 months), and a least squares solution using full normal equations for GPS-GOCE satellite to satellite tracking (SST) and 4 components of gradiometry. The processing details are presented in Pail et al. (2011). In order to evaluate and check the ITG-Grace2010 and GOCE-TIM3 gravity models, we also use the GOCO03S and EGM2008 gravity models. GOCO03S gravity model is a combined solution based on 12 months of GOCE data (same data period as for GOCE-TIM3), 7 years of GRACE data, 8 years of CHAMP data and 5 years of laser ranging observations to 5 satellites (LAGEOS 1 and 2, Ajisai, Stella, Starlette) (Mayer-Gurr et al., 2012). The EGM2008 gravity model developed by the USA National Geospatial-Intelligence Agency (NGA) combined gravitational information from GRACE and addtioanl gravity and terrain data (Pavlis et al., 2012). EGM2008 is developed up to degree/order 2160 with some additional terms up to degree/order 2190.

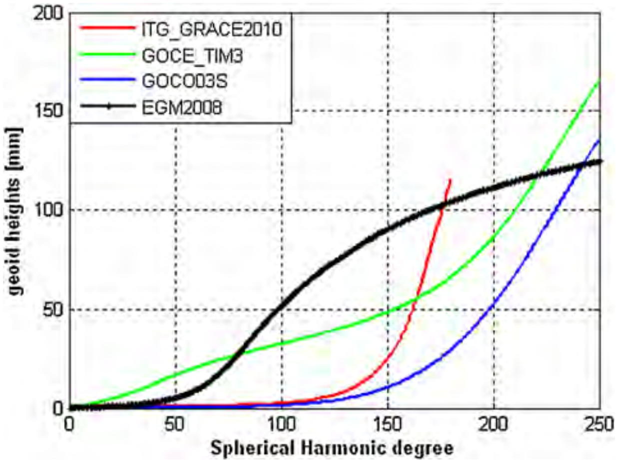

Fig. 1. Cumulative geoid errors (in millimeters) for the ITG-Grace2010 model (red), the GOCE-TIM3 model (green), the GOCO03S model (blue) and EGM2008 model (black). (For interpretation of the references to color in figure legend, the reader is referred to the web version of the article.)

Fig. 1 shows the cumulated geoid errors based on the 4 gravity field models. We can find that for ITG-Grace2010 and GOCE-TIM3 models, in the low degrees, the accuracy of ITG-Grace2010 is higher than GOCE-TIM3, while the GOCE-TIM3 is better above degree 160. With the accumulation of more data, combining with different gravity satellites' data, the accuracy of the gravity models is improved especially in the high degrees, e.g., GOCO03S. Since the GOCO03S uses the ITG-Grace2010 gravity model as a priori information, their coincidence is up to degree/order 110. Evidently, above degree 110 the contribution of GOCE data in GOCO03S is much more. However, for the EGM2008, it does not have too much advantage in the low degrees (less than 200). The larger degree variances above degree/order 50 for the EGM2008, is due to the influence of land gravity data in the geoid spectrum. Furthermore, the EGM2008 is based on ITG-GRACE03S model, using only 4.5 years of GRACE data. The difference between the ITG-Grace2010 and GOCE-TIM3 geoids can be up to 0.60 meter over the Southern Ocean region (Fig. 2).

2.2. Mean sea surface height (MSSH)

Altimetric satellites can provide precise and quasi-global measurements of sea surface heights. In this paper, we use the updated mean sea surface model MSS_CNES_CLS_11 produced by CLS Space Oceanographic Division and distributed by Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) in July 2011 (http://www.aviso.oceanobs.com). The model represented a mean sea surface for the period 1993–2010, which was derived from 10 years of Topex/Poseidon data, 3 years of Topex/Poseidon tandem, 8 years of ERS-2 data, 2 168-day non repeat cycle data of the ERS-1 geodetic phase, 7 years of GFO, 7 years of Envisat and 7 years of Jason-1 data (Schaeffer et al., 2012). All these altimetric data have been preprocessed in order to eliminate seasonal variations and be more homogeneous. Topex/Poseidon is chosen as the reference mission and other missions are adjusted to it. The MSS heights have been estimated at a regular 1/30° × 1/30° geographical grid using a local inverse method, corresponding to a grid spacing of 3.7 km, while the geographic coverage is from 80°S to 84°N.

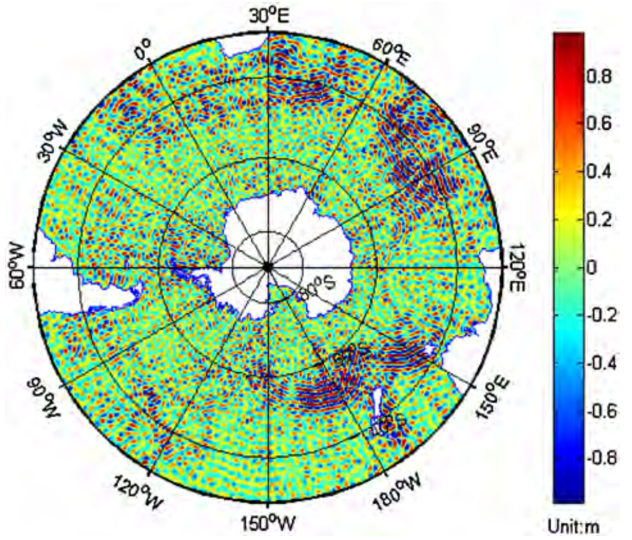

Fig. 2. Difference between the GOCE geoid (GOCE-TIM3) and GRACE geoid (ITG-Grace2010) over the Southern Ocean region.

2.3. *Oceanographic model*

In order to validate the mean dynamic topography (MDT) and Antarctic circumpolar currents based on GRACE and GOCE models, a comparison with other MDT model was performed. In this paper, we choose the CNES-CLS09 Mean Dynamic Topography (v1.1 release) model with a global 1/4° resolution, which used a recent geoid model, updated dataset, improved Ekman model, and improved processing method when compared to the previous RIO05 MDT field (Rio et al., 2009, 2011). The CNES-CLS09 MDT model is a combined solution based on 4.5 years of GRACE data and 15 years of altimetry and in situ data (hydrographic and Argo data) as well. We also used the Southern Ocean State Estimate (SOSE) model. The SOSE model is fit by constrained least squares to a large observational dataset during 2005–2007, including Argo float profiles, CTD synoptic sections, instrument-mounted seal profiles, XBTs, altimetric observations, sea surface temperature (Mazloff et al., 2010). The SOSE model is configured with 1/6° horizontal resolution, 42 vertical levels of varying thickness.

2.4. *Drifter observations*

The geostrophic velocities from the geodetic MDT are further validated by comparing with independent in situ measurements. The Global Drifter Program of the National Oceanic and Atmospheric Administration (NOAA) and Atlantic Oceanographic and Meteorological Laboratory (AOML) release near-surface currents and sea surface temperatures around the world from 73°S to 85°N, at one degree resolution, which are derived from satellite-tracked surface drifting buoy observations (Lumpkin and Garraffo, 2005; Lumpkin and Pazos, 2007). The drifter field used in this paper is the mean annual observation from January 2003 to December 2011. Since the drifter observations include geostrophic currents, tide currents, Ekman currents, inertial currents and high-frequency ageostrophic currents, the drifter data must be corrected in order to perform a consistent comparison with the geostrophic velocities derived from the geodetic MDT. In this study, the slip component is estimated from daily winds provided by the NCEP/NCAR (National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR)) (Niiler and Paduan, 1995; Pazan and Niiler, 2000). The Ekman component is estimated from the wind stress and local Coriolis parameter (Ralph and Niiler, 1999). At last, a 5-day low pass filter was applied to remove inertial and tidal currents as well as residual high frequency ageostrophic currents.

Table 1
RMS of the different MDT products in the Southern Ocean (cm).

EGM08	GRACE	GOCE	CNES-CLS09	DTU10	MN05	SOSE	
0	3.36	3.02	4.13	6.35	6.01	8.64	EGM08
	0	2.29	4.98	7.15	5.43	9.33	GRACE
		0	4.17	6.42	6.39	9.38	GOCE
			0	3.92	6.77	7.36	CNES-CLS09
				0	7.94	8.01	DTU10
					0	9.60	MN05
						0	SOSE

3. Data processing and method

3.1. *Mean dynamic ocean topography (MDT)*

The geodetic mean dynamic ocean topography (MDT) is defined as the difference between the mean sea surface height (MSSH) obtained from satellite altimetry and the geoid height (N) derived from global gravity models

$$\mathrm{MDT} = \mathrm{MSSH} - N \tag{2}$$

In order to compute a consistent geodetic MDT, the geoid and the MSSH must refer to the same coordinate system and reference ellipsoid while the permanent tide should be treated consistently (Hughes and Bingham, 2008; Bingham et al., 2008; Haines et al., 2011). Here, the geoid and MSSH are referred to the Topex/Poseidon ellipsoid and defined in the mean tide system. The mean sea surface height contain information with significantly higher spatial resolution than the gravity models, so these short scale features involved in the mean dynamic topography should be removed. For this purpose, the MSSH was extended to land areas using the gravity model, and in an iteration process, expanded into spherical harmonics, then translated to grid format (Albertella and Rummel, 2009; Bingham et al., 2008). A resolution with up to spherical harmonic degree 180 is used in this study. And spectral consistency between the mean sea surface and the geoid is achieved by applying a Gauss filter (Jekeli, 1981; Wahr et al., 1998). The half-weight radius r of the filter is defined by the empirical relation with the harmonic degree L of the spectrum ($r = 20{,}000/L$).We should also notice that the derived MDT model contains the geoid commission error, due to the limited expansion of the gravity models. For $N_{\max}$ to 180, the omission error is 35.6 cm and 46.7 cm (based on Kaula's rule and the Tscherning/Rapp model, respectively) (Vergos et al., 2013).

In order to validate the MDT results, a comparison with other 4 MDT models was performed, e.g., EGM08 (Pavlis et al., 2012), DTU10 (Andersen and Knudsen, 2009), MN05 (Maximenko and Niiler, 2005) and SOSE (Mazloff et al., 2010) models. The grid resolution of the four MDT models is different, e.g., the EGM08 is $1/60° \times 1/60°$, the DTU10 is $1/30° \times 1/30°$, the MN05 is $1/2° \times 1/2°$ and the SOSE is $1/6° \times 1/6°$. In order to carry out detailed comparisons, all MDT models are interpolated to the $1/4° \times 1/4°$ grid. The root-mean-square (RMS) in the Southern Ocean [90°S 30°S] × [0°E 360°E] between the 7 products is shown in Table 1. The RMS of the 7 MDT models is less than 10 cm, showing a good agreement between the 7 MDT models. If the SOSE model is excluded, the RMS of remaining 6 MDT models is less than 8 cm. The GRACE, GOCE and EGM08 MDT models are much closer, with the RMS less than 4 cm. The reason is that these three MDT models just combine the gravity model and satellite altimeter observations. In order to obtain higher resolution of MDT models, the CNES-CLS09, DTU10 and MN05 MDT models are based on a hybrid approach, which augment available altimetry and gravity observations with in situ oceanographic

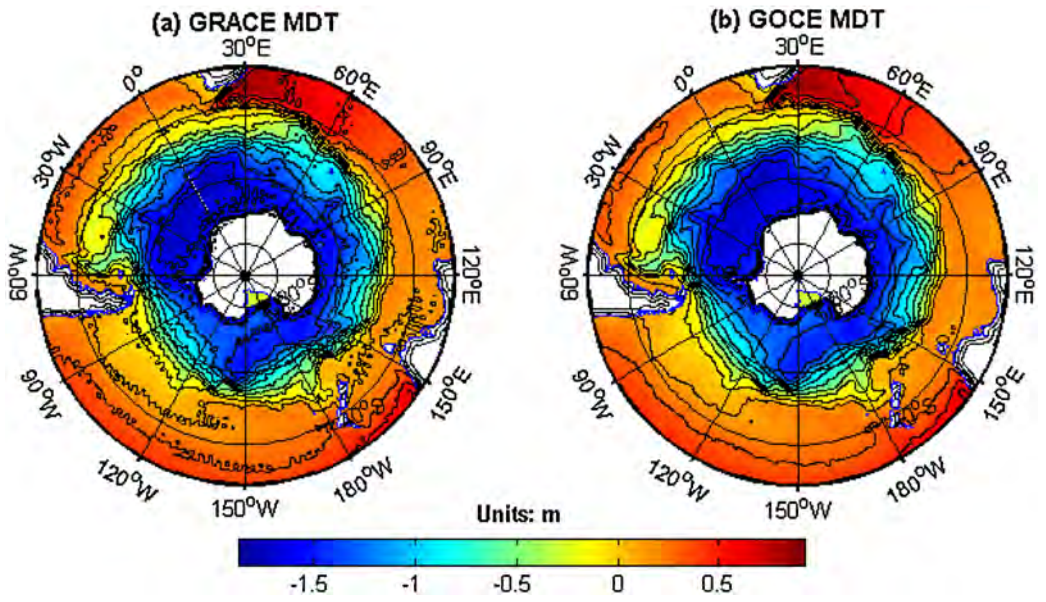

Fig. 3. MDT in the Southern Ocean based on GRACE model (ITG-Grace2010) (a) and GOCE model (GOCE-TIM3) (b).

observations (e.g., ocean drifters, hydrographic profiles, and ocean winds), and so made them disagree with the others by 6–7 cm. The use of different filtering techniques is another reason for these variations, since CNES-CLS09 uses the optimal filter; DTU10 uses an isotropic truncated Gaussian filter with a half-width at half-maximum of 0.75 spherical degrees. The smallest RMS is between the GOCE and GRACE results, and the largest RMS is between the SOSE and MN05. The SOSE has larger differences with the other 6 MDT models, which is due to the different time periods of observations; for the SOSE MDT model the time span is from 2005 to 2007, and it resolves mesoscale eddies (<50 km resolution), whereas the others do not.

Fig. 3 shows the MDT in the Southern Ocean based on GRACE model (ITG-Grace2010) (a) and GOCE model (GOCE-TIM3) (b). When compared with each other, the GRACE MDT results have some errors indicated by contour lines that are not very smooth. Fig. 4 shows the differences between the synthesized MDT, (a) based on GRACE model (ITG-Grace2010) with CNES-CLS09 model, (b) based on GOCE model (GOCE-TIM3) with CNES-CLS09 model, (c) based on GRACE model (ITG-Grace2010) with GOCO03S model and (d) based on GOCE model (GOCE-TIM3) with GOCO03S model. It can be seen that GRACE results have more noise that we can't distinguish the details of ocean topography (Fig. 4(a)), while the GOCE results show clearly visible ocean topography, such as Agulhas current and the Brazil-Malvinas Confluence Region. Compared Fig. 4(c) with (d), the differences between ITG-Grace2010 and GOCO03S model are larger than GOCE-TIM3 results, which is due to errors in ITG-Grace2010 (tesseral harmonics) and remaining geoid errors in the higher-frequencies (due to the filter characteristics).

3.2. Geostrophic velocities

The geostrophic currents are directly related to the gradient of MDT. The geostrophic velocities of the ocean circulation in longitude (east) and in latitude (north) direction are expressed as

$$
\begin{aligned}
u_s &= -\frac{g}{f}\frac{\partial MDT}{\partial y} = -\frac{g}{f}\frac{\partial MDT}{R\partial \phi} \\
v_s &= \frac{g}{f}\frac{\partial MDT}{\partial x} = \frac{g}{f}\frac{\partial MDT}{R\cos\phi \cdot \partial \lambda}
\end{aligned}
\tag{3}
$$

where g is the gravitational acceleration, $f = 2\Omega\sin\phi$ is the Coriolis parameter which is dependent on latitude ϕ, Ω is the angular velocity of the earth, R is the mean earth radius, and (ϕ, λ) is the latitude and longitude. The direction (azimuth) of the geostrophic currents vectors is $A = \arctan(u_s/v_s)$, and their length is $V = \sqrt{u_s{}^2 + v_s{}^2}$ (Elema, 1993).

4. Results and discussion

The detailed ACC is estimated from the newest GRACE ITG-Grace2010 and GOCE-TIM3 gravity models. In order to check the capabilities of GRACE and GOCE to observe Antarctic circumpolar currents, the oceanographic model and in situ drifters' measurements are also used. Fig. 5 shows the magnitude of geostrophic velocities in the Southern Ocean. The velocities estimated from (a) GRACE-derived geoid (ITG-Grace2010), (b) GOCE-derived geoid (GOCE-TIM3), (c) the CNES-CLS09 model, and (d) the in situ drifters' measurements. The geostrophic currents based on GOCE-derived geoid (GOCE-TIM3) agree well with the GRACE-derived geoid (ITG-Grace2010), but better with drifters. The GOCE-based results clearly describe the general circulation pattern of the region. As we can see from Fig. 5 (b) the ACC flows across the Atlantic, the Indian Ocean and clearly extends northward and across the South Pacific weakened southward due to the influence of Drake Passage. The RMS between GOCE results and drifters is 7.85 cm/s, and the RMS between GRACE results and drifters is 8.39 cm/s. The GRACE results have more noise (Fig. 5(a)), while the CNES-CLS09 velocities are smaller when compared to the other three models. The CNES-CLS09 results imply quite weak currents in the South Indian Ocean and South Pacific when compared to the other estimates, including drifters. It is mainly that because the CNES-CLS09 MDT model used hydrographic data with assuming a zero velocity at depth.

In order to analyze the transport characteristics of ACC, two major currents areas are further analyzed, Agulhas currents and Brazil-Malvinas Confluence regions.

The Agulhas Current (Fig. 6) flows around the southern horn of Africa, which is importantly connecting the global overturning circulation and provides a route for warm water out of the Indian Ocean and into the Atlantic Ocean (Knudsen et al., 2011). At first, the southward Agulhas Current is a continuous boundary current flowing south along the African continental slope. Four locations

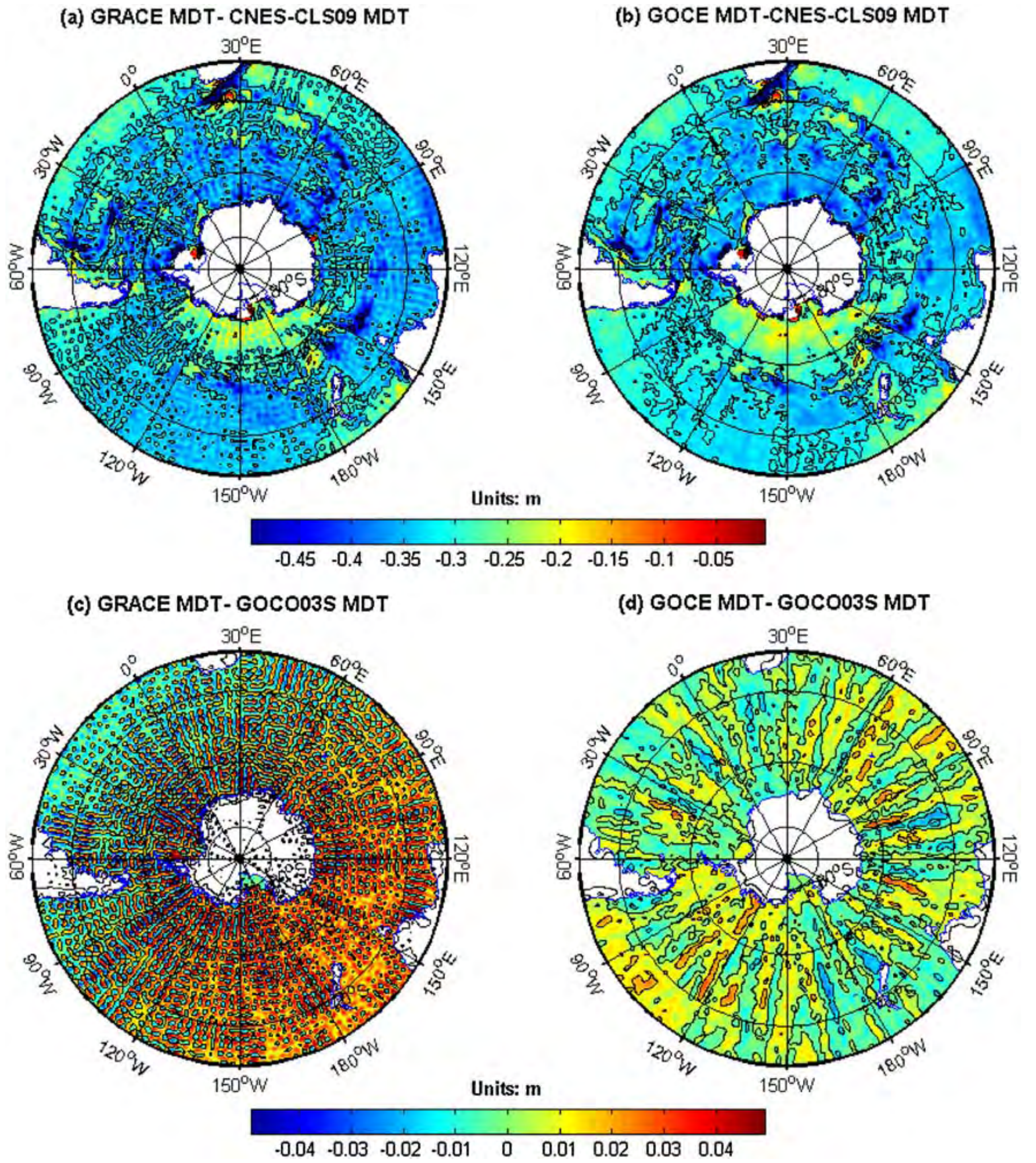

Fig. 4. Differences between the synthesized MDT based on GRACE model (ITG-Grace2010) with CNES-CLS09 model (a), GOCE model (GOCE-TIM3) with CNES-CLS09 model (b), GRACE model (ITG-Grace2010) with GOCO03S model (c) and GOCE model (GOCE-TIM3) with GOCO03S model (d).

(black dots surrounded by white circles) have been selected in this area in order to show the details of the Agulhas Current, and velocities are provided in Table 2. At location A (Fig. 6) the current geostrophic speed is 53.83 cm/s from drifters, 55.04 cm/s from GOCE and 61.99 cm/s from GRACE, respectively. When the Agulhas Current arrives at the tip of Africa, shear interaction with the strong ACC causes the current to retroflex (turn back on itself), and become the Agulhas Return Current. This retroflection made the mean geostrophic current speeds of the Agulhas Current maximum. For the CNES-CLS09 model estimates, maximum current velocities are around 65 cm/s at location B (Fig. 6). The current velocities from GOCE are about 66 cm/s, while GRACE results are about 69 cm/s. Then, the Agulhas Current becomes the meanders in the boundary of MDT between high (red) and low (yellow) values. These meanders are clearly seen in GOCE, GRACE and drifter results but not obvious from CNES-CLS09 model (e.g. location C and D in Fig. 6). At location C, the current velocities are about 43 cm/s from GOCE, about 37 cm/s for GRACE and about 43 cm/s for drifters. At location D, the current velocities are about 40 cm/s from GOCE, about 45 cm/s from GRACE and about 37 cm/s from drifters (Table 2). The GOCE results are closer to the drifters' results than the GRACE results in the Agulhas Current. We also calculate the RMS of differences in geostrophic current speeds and the two components (Table 3). The GOCE RMS is less than GRACE results not only in total velocities, but also in the two components. Therefore, the GOCE results are in a better agreement with drifters' results than the GRACE results in the Agulhas Current.

The Brazil-Malvinas Confluence Region is a very energetic zone with water just off the coast of Argentina and Uruguay. The Antarctic coastal current flows westward along the coast of Antarctica and meets the eastward-flowing ACC at the Drake Passage, emerging as the Malvinas current (Sanchez-Reales et al., 2012). Again

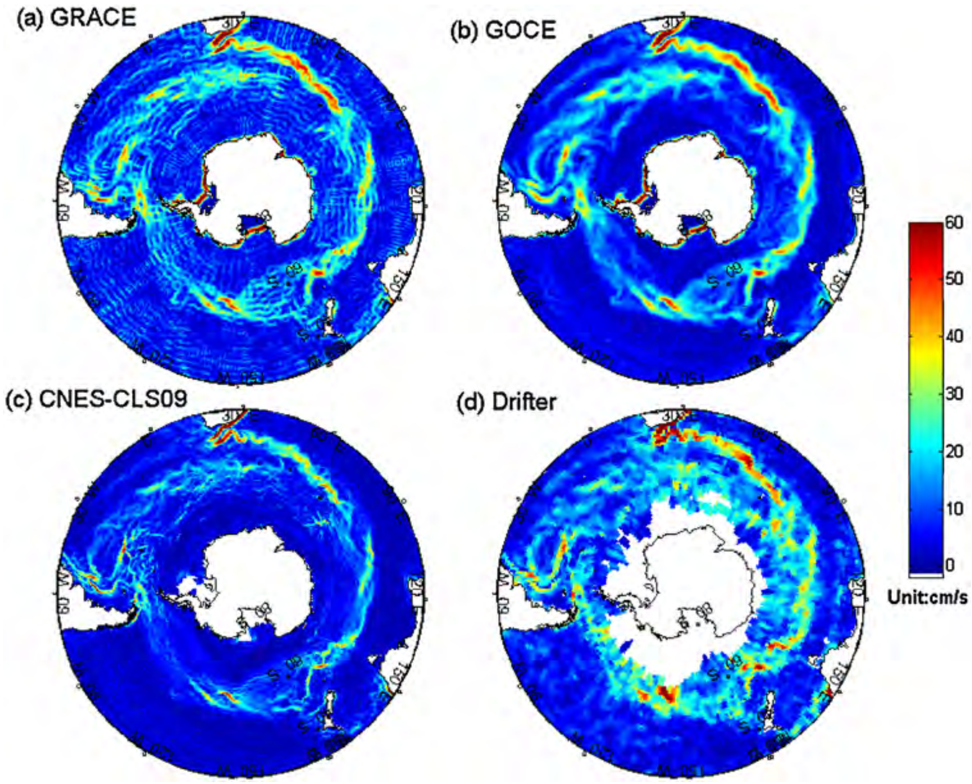

Fig. 5. Magnitude of the geostrophic velocities in the Antarctic circumpolar area. The velocity estimates from GRACE-derived geoid (ITG-Grace2010) (a), GOCE-derived geoid (GOCE-TIM3) (b), the CNES-CLS09 model (c) and the in situ drifters' measurements (d).

four locations have been strategically selected in order to show the details of the currents in the Brazil-Malvinas confluence region and velocities are provided in Table 2. The peak current speed along the path of the Malvinas Current (location A in Fig. 7) is 41 cm/s from GOCE, 28 cm/s from drifter's results and 46 cm/s from GRACE. The Brazil Current branches off into two pieces at around 22°S, and one portion continues the poleward march flowing along the South American continental shelf, which converges with the

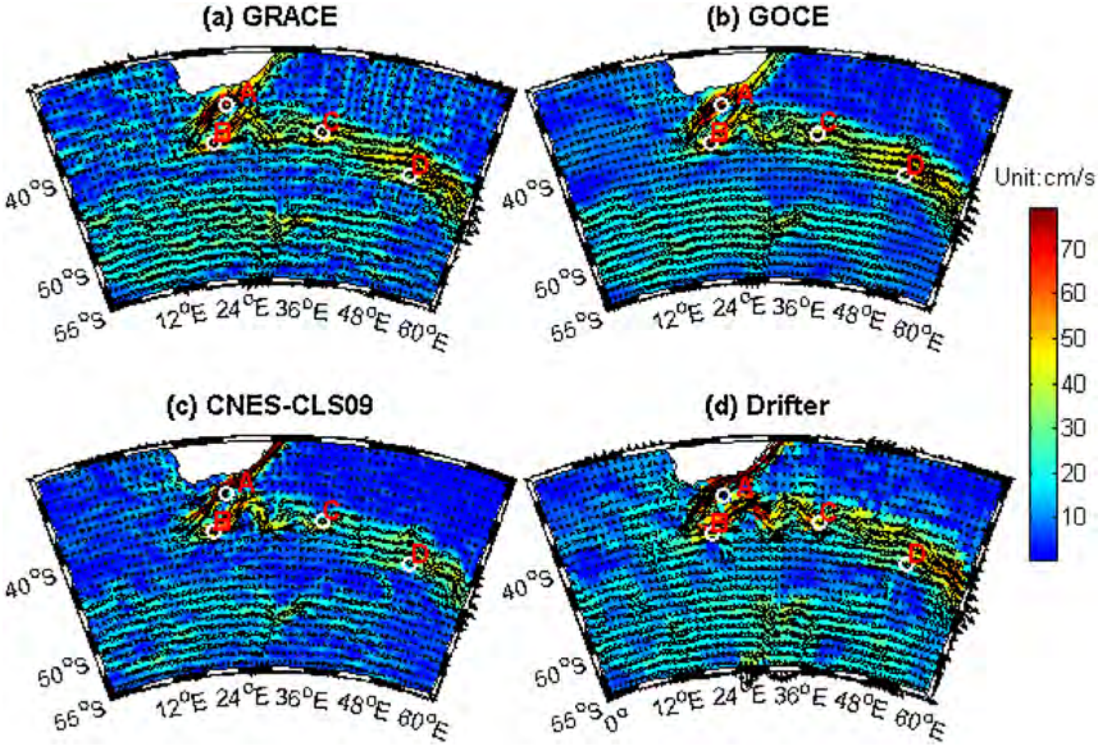

Fig. 6. Agulhas currents estimate from GRACE-derived geoid (ITG-Grace2010) (a), GOCE-derived geoid (GOCE-TIM3) (b), the CNES-CLS09 model (c) and the in situ drifters' measurements (d).

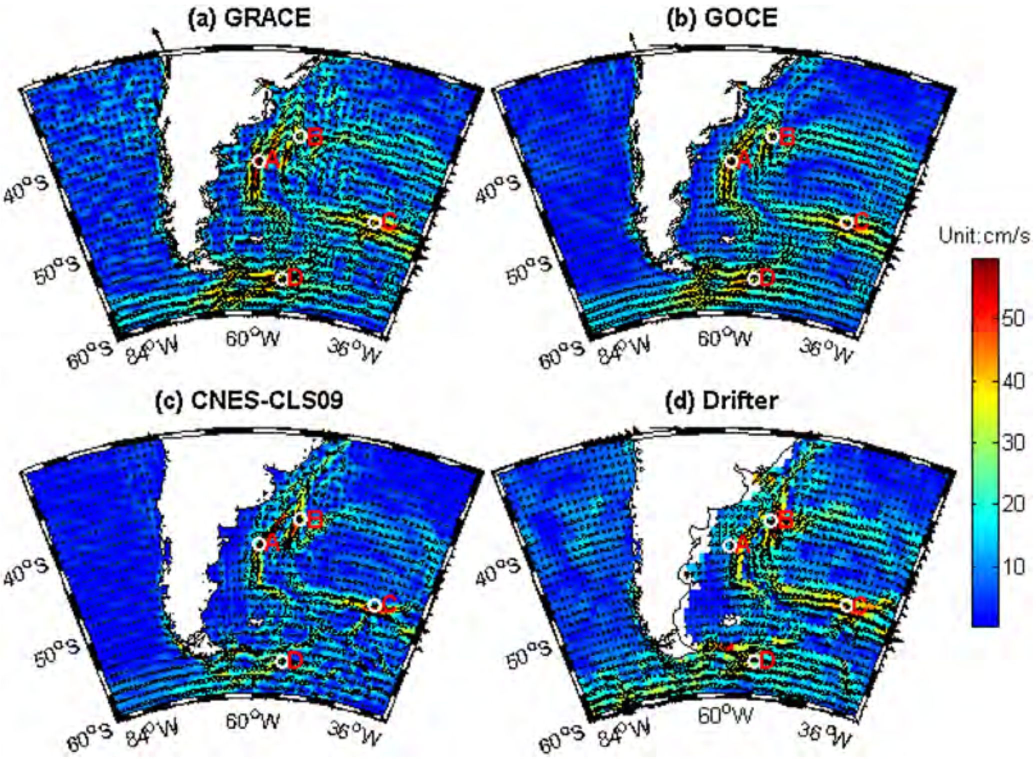

Fig. 7. Geostrophic current speeds in the Brazil-Malvinas Confluence regions estimated from GRACE-derived geoid (ITG-Grace2010) (a), GOCE-derived geoid (GOCE-TIM3) (b), the CNES-CLS09 model (c) and the in situ drifters' measurements (d).

Table 2
Geostrophic current speeds at eight locations of two regions from the GRACE, GOCE, CNES-CLS09 model and drifters' results. Each location is marked in the corresponding regional maps (Figs. 6 and 7).

	Location		Geostrophic current speeds (cm/s)			
Agulhas current	Lat	Lon	GRACE	GOCE	CNES-CLS09	Drifters
A	−36	24	61.99	55.04	32.61	53.83
B	−40	22	68.97	65.64	65.21	68.10
C	−39	37	37.03	43.03	30.73	43.50
D	−42	50	44.87	40.54	24.08	36.99
Brazil-Malvinas Confluence regions						
A	−43	301	45.55	40.86	59.14	21.08
B	−40	307	32.04	37.63	40.09	37.41
C	−48	321	45.95	38.27	20.08	38.48
D	−56	306	33.57	30.94	35.65	29.21

Malvinas Current at location B, with geostrophic speed is 37.41 cm/s from drifters, 37.63 cm/s from GOCE and 32.04 cm/s from GRACE. The ACC sub-Antarctic front is proved to be the maximum current speeds of this region at about 48°S and 39°W (location C in Fig. 7).

Table 3
Comparison of geostrophic current speeds (cm/s) from GRACE, GOCE and CNES-CLS09 model with the drifters' results in Agulhas current and Brazil-Malvinas Confluence regions.

Global Gravity Field Models	Agulhas current					
	ΔV		Δu_s		Δv_s	
	Mean	RMS	Mean	RMS	Mean	RMS
GRACE	−1.32	8.52	−0.76	8.37	4.23	8.49
GOCE	−2.55	8.05	−0.83	7.52	4.14	7.13
CNES-CLS09	−6.24	8.49	−4.36	9.29	4.16	7.62
	Brazil-Malvinas Confluence regions					
GRACE	−0.79	8.82	−1.02	7.56	3.83	10.64
GOCE	−1.31	7.67	−1.12	6.31	3.79	7.07
CNES-CLS09	−4.43	8.34	−3.79	7.57	2.18	7.89

It is relatively good agreement between the GOCE and drifters' current fields in terms of both the location and magnitude, while GRACE derived currents are larger. In order to assess the accuracy of geostrophic current speeds in the Brazil-Malvinas Confluence Region, we also calculate the total RMS and the RMS in the two different directions' components (Table 3). In total velocities, the GOCE RMS is just 7.67 cm/s, while the GRACE RMS is 8.82 cm/s. In east direction, the GOCE RMS is 6.31 cm/s, while GRACE RMS is 7.56 cm/s. In north direction, the GOCE RMS is 7.07 cm/s, while GRACE RMS is 10.64 cm/s. The RMS of CNES-CLS09 is almost located between the GOCE and GRACE results in the Brazil-Malvinas Confluence Region. The GOCE results are much closer with drifters' results than the GRACE in the Brazil-Malvinas Confluence region.

In order to check the ability of satellite gravimetry to obtain the Antarctic circumpolar current, the GOCO03S gravity model with combined CHAMP, GRACE and GOCE observations is further used to estimate geostrophic currents in the Southern Ocean. The correlation analysis and RMS are calculated in Table 4. The gravity field model ITG-Grace2010 from 7 years of GRACE observation data has the RMS of 8.39 cm/s, while the GOCE-TIM3 gravity field model from 12 months of GOCE observations has the RMS of only 7.85 cm/s, and the accuracy is higher than ITG-Grace2010 results. For the correlation coefficients, ITG-Grace2010 result is 0.70 in total velocities, 0.65 in east direction, and 0.51 in north direction, while

Table 4
Comparison of the geostrophic velocities from GOCE and GRACE with drifter results in the ACC (units are cm/s).

Global gravity field models	ΔV		Δu_s		Δv_s	
	Cor	RMS	Cor	RMS	Cor	RMS
ITG-Grace2010	0.70	8.39	0.65	8.38	0.51	8.35
GOCE-TIM3	0.76	7.85	0.73	7.41	0.63	7.10
GOCO03S	0.76	7.89	0.73	7.42	0.63	7.08

Note: cor is correlation coefficient.

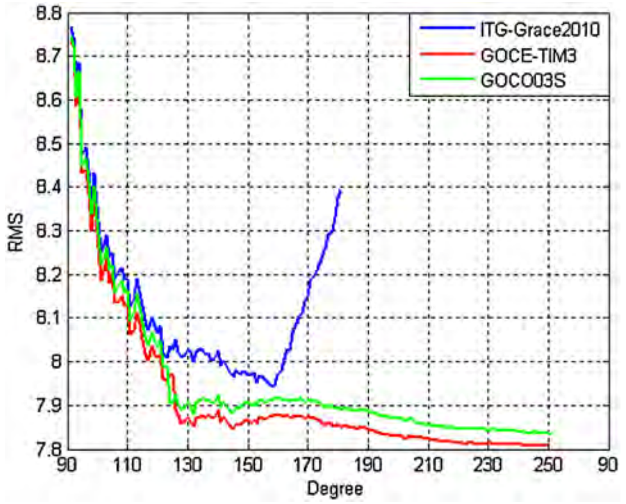

Fig. 8. RMS between the geostrophic currents based on GRACE/GOCE models and drifters' results with the truncated degrees.

GOCE-TIM3 result is 0.76 in total velocities, 0.73 in east direction, and 0.63 in north direction. In addition, the RMS and correlation coefficients of GOCO3S gravity model almost have no improvement when compared with GOCE-TIM3 results. In the contrary, the RMS of GOCO03S is a little larger than the GOCE-TIM3 results. The reason is that when combined CHAMP, GRACE and GOCE data, the relatively lower accuracy of CHAMP and GRACE data will influence the accuracy of GOCE data.

In order to know the influence of gravity model's truncated degree on the accuracy of Antarctic circumpolar current estimate, we further calculate the RMS between geostrophic currents based on GRACE and GOCE models and drifters' results as a function of truncated degree (Fig. 8). It can be seen that the RMS decreases from 8.77 cm/s to 7.95 cm/s until the truncated degree with 160 based on ITG-Grace2010 model, however, when the truncated degree is larger than 160, the RMS increases rapidly to the 8.39 cm/s. While for the GOCE-TIM3 model, the RMS decreases gradually from 8.73 cm/s to 7.80 cm/s, and the RMS is less than the ITG-Grace2010 RMS. In addition, for the GOCO03S model, the RMS also decreases gradually from 8.74 cm/s to 7.83 cm/s, and is larger than the GOCE-TIM3 results in most degrees. The RMS of GOCO03S has the similar trend with GOCE-TIM3 model, when the truncated degree is smaller than 130. The RMS between GOCO03S and GOCE-TIM3 model is almost the same. However, when the truncated degree is larger than 130, the RMS of GOCO03S is larger than that of GOCE-TIM3 and the difference is about 0.03 cm/s. The largest RMS difference between ITG-Grace2010 and GOCE-TIM3 model is 0.54 cm/s at degree 180. Unlike GOCE-TIM3 and GOCO03S model, ITG-Grace2010 model has more noise in the higher spherical harmonic coefficients and better performance in the geostrophic currents can be obtained if truncated at the right degree (e.g., ~ d/o 160 for ITG-Grace2010).

5. Conclusion

In this paper, the detailed Antarctic circumpolar currents are estimated from satellite altimetry, GOCE and GRACE and compared with in situ drifter buoys measurements and oceanographic models. The geostrophic currents based on the GOCE-derived geoid (GOCE-TIM3) agree well with the GRACE-derived geoid (ITG-Grace2010), but better with drifters. The gravity field model ITG-Grace2010 from 7 years of GRACE observations is similar with the GOCE-TIM3 gravity field model from 12 months of GOCE observations with RMS of 8.39 cm/s and 7.85 cm/s, respectively, but the GOCE-TIM3 gravity field model is better. The correlation coefficients are 0.70 in total velocities between ITG-Grace2010 and drifters, and 0.76 in total velocities between GOCE-TIM3 and drifters. GOCE better determines the details and transport characteristics of Antarctic circumpolar current than the GRACE results with more noises, particularly two major currents areas in the Southern Ocean, i.e., Agulhas currents and Brazil-Malvinas Confluence regions, while the CNES-CLS09 model's results are a little less than other three observation results. In addition, the gravity model GOCO03S with combined CHAMP, GRACE and GOCE observations almost has no improvement in ACC estimate when compared with GOCE-TIM3 results. In the contrary, the RMS of GOCO03S is a little larger than the GOCE-TIM3 results. Unlike GOCE-TIM3 and GOCO03S model, ITG-Grace2010 model has more noise in the higher spherical harmonic coefficients and better performance in the geostrophic currents can be obtained for ITG-Grace2010 with the truncated degree 160.

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