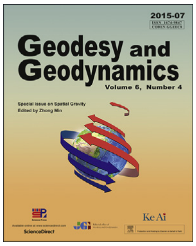
GEODESY AND GEODYNAMICS 2015, VOL 6 NO 4, 274–279

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.keaipublishing.com/en/journals/geog;
http://www.jgg09.com/jweb_ddcl_en/EN/volumn/home.shtml



Global sea level variations from altimetry, GRACE and Argo data over 2005–2014

Feng Wei*, Zhong Min

State Key Laboratory of Geodesy and Earth's Dynamics, Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan 430077, China

ARTICLE INFO

Article history:
Received 13 May 2015
Accepted 3 July 2015
Available online 15 July 2015

Keywords:
Sea level variations
Gravity Recovery and Climate Experiment (GRACE)
Altimetry
Argo
Ocean mass change
La Niña event
Steric sea level
Sea level budget

ABSTRACT

Total sea level variations (SLVs) are caused by two major components: steric variations due to thermal expansion of seawater, and mass-induced variations due to mass exchange between ocean and land. In this study, the global SLV and its steric and mass components were estimated by satellite altimetry, Argo float data and the Gravity Recovery and Climate Experiment (GRACE) data over 2005–2014. Space gravimetry observations from GRACE suggested that two-thirds of the global mean sea level rise rate observed by altimetry (i.e., 3.1 ± 0.3 mm/a from 2005 to 2014) could be explained by an increase in ocean mass. Furthermore, the global mean sea level was observed to drop significantly during the 2010/2011 La Niña event, which may be attributed to the decline of ocean mass and steric SLV. Since early 2011, the global mean sea level began to rise rapidly, which was attributed to an increase in ocean mass. The findings in this study suggested that the global mean sea-level budget was closed from 2005 to 2014 based on altimetry, GRACE, and Argo data.

1. Introduction

As human beings have begun to pay more attention to the consequences of global climate change in recent decades, an increasing number of studies have investigated the cause of global sea level variations (SLVs) as sea level rise is an important indicator of climate change. Rising sea levels will have a negative impact on the lives of millions of people living in coastal zones [1]. Two main factors are known to contribute to global SLVs: (i) steric SLVs, which are mainly caused by the thermal expansion of sea water due to ocean warming, and (ii) mass-induced SLVs due to mass exchange among the oceans, land, and atmosphere. Since the 1990s, the average global sea level has been measured continuously with an accuracy of a few millimeters by a series of altimetry satellites (e.g., TOPEX/Poseidon, Jason-1/2, and Envisat). The global mean sea level rise rate is approximately 3.3 mm/a since 1993 [2,3]. The steric SLVs can be estimated from oceanographic

---

* *Corresponding author.*
E-mail address: fengwei@whigg.ac.cn (Feng W.).
Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.geog.2015.07.001

temperature and salinity observations [4]. Since the 2000s, the global array of Argo floats can be used to measure temperature and salinity with a more uniform distribution compared to historical oceanographic observations [5]. Since its launch in 2002, the Gravity Recovery and Climate Experiment (GRACE) mission has been measuring temporal gravity fields that reveal the mass variations both on and in the Earth [6]. With an improvement in data processing methods, GRACE was the first experiment to observe global ocean mass change on seasonal time scales [7–12].

With the accumulation of altimetry, Argo, and GRACE data, numerous researchers have begun to focus their attention on the global sea-level budget, which states that the sum of the steric and mass-induced SLVs should be equal to the total SLV. Willis et al. [13] reported that the total sea level rise rate from altimetry data is 3.6 ± 0.8 mm/a from 2003 to 2007, which is significantly higher than the estimate from GRACE and Argo results of approximately 0.3 ± 0.6 mm/a. The findings indicated that the global sea-level budget was not closed. However, Leuliette and Miller [14] found a closed global sea-level budget with an observed rate of total SLV from GRACE and Argo data of 1.5 ± 1.0 mm/a, which agrees with the estimate from altimetry (i.e., 2.4 ± 1.1 mm/a) from 2004 to 2007. Leuliette and Miller [14] concluded that the differences between their results and those from Willis et al. [13] were caused by a different method used to fill the gaps in Argo data before 2004. Cazenave et al. [15] also found a closed global sea-level budget from 2003 to 2008. However, Willis et al. [13] and Leuliette and Miller [14] applied a near +1 mm/a glacial isostatic adjustment (GIA) correction based on the GIA model from Paulson et al. [16], while Cazenave et al. [15] used a correction of +2 mm/a based on the GIA model from Peltier [17]. A recent study by Chambers et al. [18] indicated that the GIA model reported by Paulson et al. [16] is more appropriate for the calculation of ocean mass from GRACE data. Recent studies have shown that the global sea-level budget can be closed by applying improved data processing methods [18]. On inter-annual time scales, the exceptionally strong 2010/2011 La Niña event caused the global mean sea level to drop by 5 mm [19]. Further studies showed that the hydrologic surface mass anomaly observed in Australia was a dominant contributor to the drop [20]. The purpose of this study is to isolate steric and mass components of global SLVs on seasonal, inter-annual, and long-term time scales over 2005–2014, and to quantify the contributions of these two components based on the three independent observation systems, i.e., altimetry, GRACE, and Argo.

2. Data and methods

2.1. *GRACE data*

Data from GRACE Release-05 ranging from 2005 to 2014 (provided by the Center for Space Research (CSR), University of Texas) were utilized to calculate the change in ocean mass. These data products were expressed in the form of spherical harmonic geopotential coefficients up to degree and order 96, and GRACE atmosphere and ocean de-aliasing products were subsequently added back to recover variations in ocean mass. To reduce the correlated north–south stripes and short-wavelength random noises in the coefficients, de-striping and 300-km Gaussian smoothing were applied [21,22]. The degree two and geocenter coefficients were replaced with more accurate estimates from satellite laser ranging [23,24]. The GRACE data were further corrected for GIA on the basis of the model of Geruo et al [25].

2.2. *Altimetry data*

Merged maps of sea level anomalies (MSLA) were used, as derived from TOPEX/Poseidon, Jason-1/2, ERS-1/2, and Envisat (provided by the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) data (http://www.aviso.oceanobs.com/). Gridded data of 0.25° × 0.25° were adopted from 2005 to 2014. All standard geophysical and environmental corrections were applied, including the ionospheric correction, dry and wet tropospheric corrections, solid Earth and ocean tides, ocean tide loading, pole tide, electromagnetic bias, inverted barometer corrections, and instrumental corrections. The GIA effect on sea bottom deformation was removed on the basis of the model of Geruo et al [25]. To be consistent with GRACE results in the spatial domain, gridded altimetry data were transferred to spherical harmonic coefficients and filtered with 300-km Gaussian smoothing.

2.3. *Argo data*

Steric SLVs were calculated on the basis of temperature and salinity observations from the Argo project. The project, which began in 2000, provides uniform distribution of observations after 2005. Gridded Argo products were used as provided by the Japan Agency for Marin-Earth Science and Technology (JAMSTEC), the International Pacific Research Center (IPRC) at the University of Hawaii, and the Scripps Institute of Oceanography (ISO) at the University of California at San Diego. The mean values of three products were used to estimate the steric SLV. To be consistent with GRACE and altimetry results, the Argo results were also expanded to spherical harmonic coefficients and filtered with 300-km Gaussian smoothing. Since the spatial coverage of Argo data was from 60°N to 60°S, the SLV from altimetry, GRACE and Argo data were calculated between ±60° to be consistent with each other.

3. Results

The global mean sea-level budget can be expressed as:

$$\mathrm{SLV}_{\mathrm{total}} = \mathrm{SLV}_{\mathrm{steric}} + \mathrm{SLV}_{\mathrm{mass}} \tag{1}$$

where $\mathrm{SLV}_{\mathrm{total}}$ is the total SLV observed by altimetry, $\mathrm{SLV}_{\mathrm{steric}}$ is the steric component of sea level observed by Argo, and $\mathrm{SLV}_{\mathrm{mass}}$ is the ocean mass component of sea level observed by GRACE. The sea-level budget will be closed if the three independent observations agree with each other, i.e., if the left term of equation (1) equals the sum of the two right terms within the error estimates of each term. The global mean sea-level budget was analyzed on seasonal and inter-annual time scales, and the spatial variations of sea level and its steric and mass component was further investigated.

3.1. *Seasonal SLVs*

On seasonal time scales, the three independent observations (i.e., altimetry, GRACE, and Argo) appeared to agree well with each other (Fig. 1). For example, seasonal, inter-annual, and long-term fluctuations of global mean sea level from altimetry agree well with the results from GRACE + Argo (Fig. 1a). Table 1 further shows the annual amplitudes and phases of global mean SLV and the mass and steric components. The annual amplitude of global mean SLV from altimetry was 4.0 ± 1.2 mm, which reached the maximum in mid-October. The annual amplitudes of the mass component from GRACE and the steric component from Argo were 10.2 ± 1.0 mm and 4.7 ± 1.6 mm, respectively, which peaked in late-September and late-March. The good agreement shown in Fig. 1 indicates that the global mean sea-level budget was closed on seasonal time scales.

Table 1 – Annual amplitudes, annual phases, and trends of global mean SLV and the mass and steric components estimated from altimetry, Argo, and GRACE from 2005 to 2014. Uncertainties were estimated as two standard deviations after propagation of monthly value errors in the least squares fit procedure, which represent the 95% confidence interval.

	Annual amplitude (mm)	Annual phase (°)	Trend (mm/a)
Altimetry	4.0 ± 1.2	289 ± 17	3.1 ± 0.3
GRACE + Argo	5.6 ± 1.9	281 ± 19	2.8 ± 0.5
GRACE	10.2 ± 1.0	274 ± 6	1.9 ± 0.3
Altimetry-Argo	8.5 ± 2.0	276 ± 14	2.2 ± 0.5
Argo	4.7 ± 1.6	86 ± 19	0.9 ± 0.4
Altimetry-GRACE	6.5 ± 1.6	86 ± 14	1.2 ± 0.4

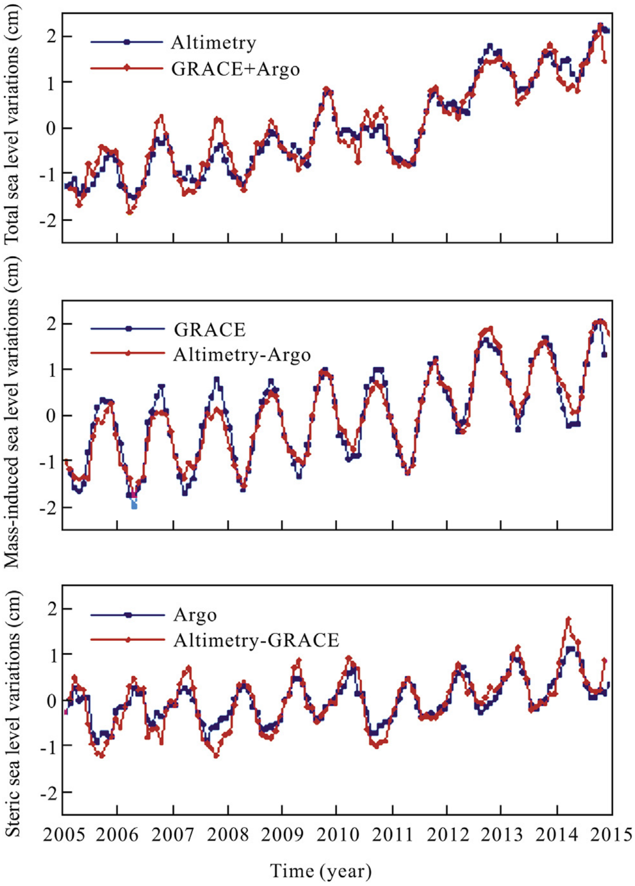


Fig. 1 – Global mean SLVs and the mass and steric components. Blue lines represent observed (a) total SLV from altimetry, (b) mass-induced SLV from GRACE, and (c) steric SLV from Argo. Red lines show the inferred estimates calculated by adding or subtracting the other two estimates in equation (1).

3.2. *Inter-annual and long-term SLVs*

Seasonal cycles were removed from the global mean SLV time series, and three-month moving averages were calculated to show the inter-annual and long-term SLVs. As shown in Fig. 2 and Table 1, the altimetry-observed global mean sea level rise rate was 3.1 ± 0.3 mm/a from 2005 to 2014, which is consistent with the estimate from GRACE + Argo (2.8 ± 0.5 mm/a). This indicates that the long-term global mean sea-level budget was closed, based on these three independent observations. The correlation between global mean SLV from altimetry and GRACE + Argo reached 0.98 (95% confidence level), which also indicates the good agreement among the three independent observations. The ocean mass increase rate estimated from GRACE was 1.9 ± 0.3 mm/a over 2005–2014, which is approximately two-thirds of the total sea level rise rate estimated from

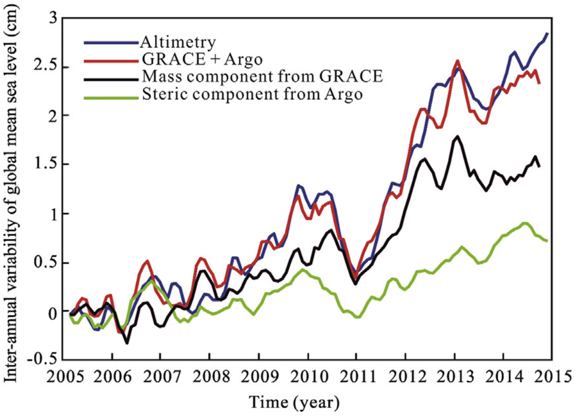
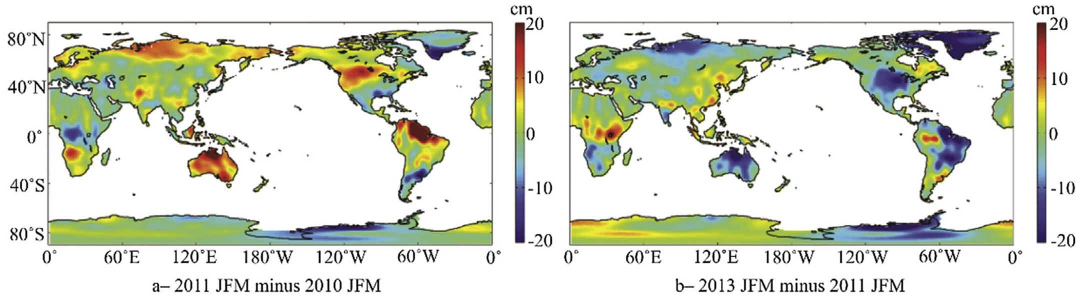


Fig. 2 – Inter-annual variability of global mean sea level from altimetry (blue) and from GRACE + Argo (red). Steric component from Argo (green) and mass component from GRACE (black) are also shown. Seasonal cycles were removed and a three-month moving window was applied.



a– 2011 JFM minus 2010 JFM

b– 2013 JFM minus 2011 JFM

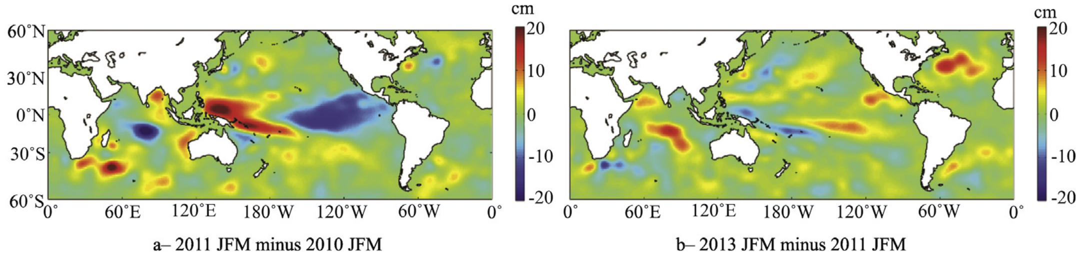
Fig. 3 – Change in water mass (a) from beginning of 2010 (JFM average) to beginning of 2011 (JFM average), and (b) from beginning of 2011 (JFM average) to beginning of 2013 (JFM average).

altimetry. For the same time period, the steric sea level rise rate from Argo was 0.9 ± 0.4 mm/a, which accounts for the remaining one-third of total sea level rise rate.

In addition to the obvious trend signals in the global mean SLV time series, significant inter-annual fluctuations were also observed (Fig. 2). These were particularly noticeable from early 2010 to early 2011, where the global mean sea level from altimetry dropped nearly 1 cm on inter-annual time scales. These results were also confirmed by GRACE + Argo. For the same time period, the ocean mass and steric SLVs were also observed to drop. Furthermore, the global mean sea level recovered rapidly from early 2011 to early 2013 (Fig. 2), which may be explained by ocean mass increase observed by GRACE.

Given that the total mass over the surface of the Earth is conserved and the contribution from the atmosphere is negligible, the mass increase in the ocean represents the mass loss on land, and vice versa. Therefore, the study further focused on the water mass differences and steric SLV differences in the spatial domain among three different time spans representing the averages of January, February, and March (JFM) for 2010, 2011, and 2013. The terrestrial water storage (TWS) over Australia and the Amazon Basin substantially increased by early 2011 compared to early 2010 (Fig. 3a), which may explain the ocean mass loss and global mean sea level drop over this period. This finding is consistent with those of Boening et al. [19] and Fasullo et al. [20], who concluded that the exceptionally strong 2010/2011 La Niña, which affected worldwide precipitation patterns, caused the sea level drop over this period. Over the same period, the global mean steric sea level also dropped significantly (Fig. 2). The decrease of steric sea level mainly occurred over the eastern equatorial Pacific Ocean and the central region of the Indian Ocean (Fig. 4a). From early 2011 to early 2013, the mass loss over Australia, the Amazon Basin, and Greenland contributed to rapid global mean sea level rise (Fig. 3b). Over the same time period, the steric sea level rise mainly occurred in the Northern Atlantic Ocean and the Indian Ocean (Fig. 4b). However, the magnitude of the trend signal from steric SLV was smaller than that of the mass-induced SLV from early 2011 to early 2013, indicating that the ocean mass change dominated most of altimetry-observed sea level rise (Fig. 2).

The trend maps of total SLVs and the mass and steric components were calculated from 2005 to 2014, which were estimated from direct observations and inferred estimates calculated by adding or subtracting the other two estimates in equation (1). The trend map of altimetry-observed total SLV showed significant spatial variability (Fig. 5a). In some regions, such as the mid-latitude regions of the Pacific and Indian Oceans, sea level rise rates are up to three times faster than the global mean, while the sea level near the point (120°W, 60°S) exhibited a drop. The trend map of total SLV from GRACE + Argo displayed good agreement with the altimetry data though some differences exist, especially in the Southern Hemisphere Ocean (Fig. 5b). An obvious discrepancy exists between the trend maps of mass-induced SLV from GRACE and from altimetry-Argo (Fig. 5c–d). Note that the trend signals in the Eastern Indian Ocean and in the Northwestern Pacific Ocean observed by GRACE were caused by the Earth crust readjustment after the 2004



a– 2011 JFM minus 2010 JFM

b– 2013 JFM minus 2011 JFM

Fig. 4 – Change in steric sea level (a) from beginning of 2010 (JFM average) to beginning of 2011 (JFM average), and (b) from beginning of 2011 (JFM average) to beginning of 2013 (JFM average).

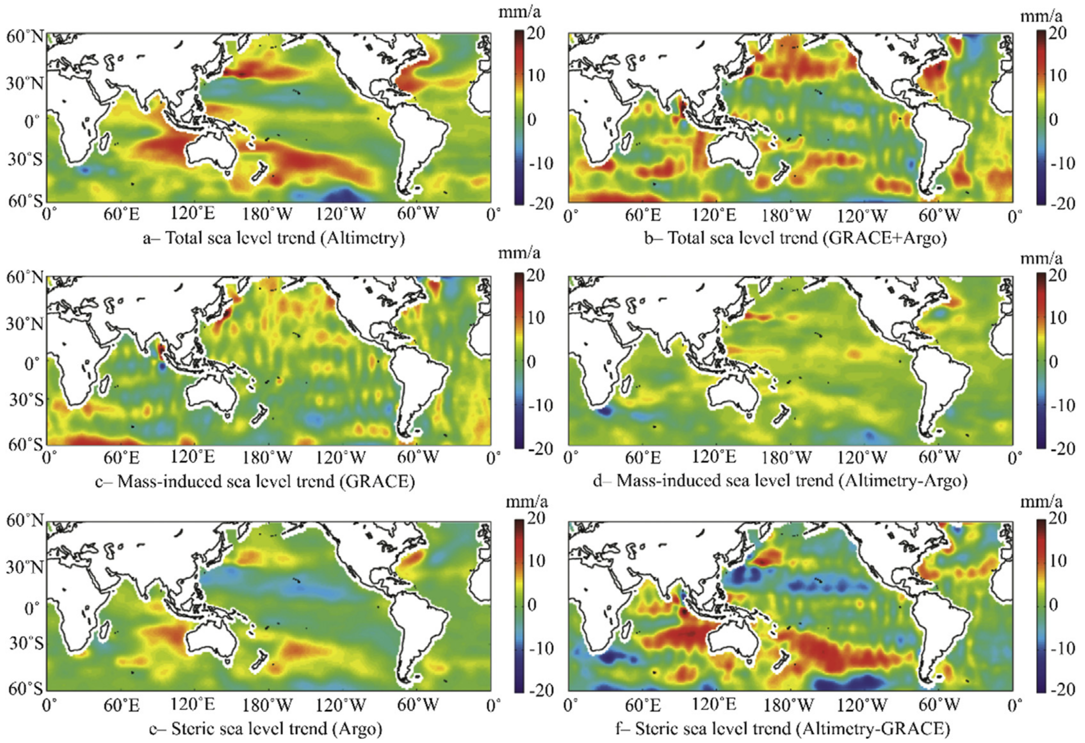


Fig. 5 – Trend maps of total SLV from (a) altimetry and (b) GRACE + Argo, mass-induced SLV from (c) GRACE and (d) altimetry-Argo, and steric SLV from (e) Argo and (f) altimetry-GRACE.

Sumatra–Andaman earthquake and 2011 Tohoku–Oki earthquake [26,27]. Nevertheless, the spatial trend pattern differences over 2005–2014 between GRACE and altimetry-Argo were still notable, and were possibly caused by the uncertainties of GRACE, altimetry, and Argo. For example, Quinn and Ponte [28] observed substantial trend uncertainties in GRACE results, which may have been caused by the different sources (e.g., different gravity inversion strategies and post-processing methods such as destriping and smoothing). On the basis of Fig. 5c–d and the study of Quinn and Ponte [28], it was concluded that it was not possible to obtain a reliable trend map of mass-induced SLV from GRACE or from altimetry-Argo, although the global mean time series of mass-induced SLV appear to be estimated accurately (Fig. 1b). The spatial pattern of steric SLV estimated from Argo agreed with that of total SLV from altimetry rather well (Fig. 5e), but its magnitude was smaller than that from altimetry. The spatial variance of steric SLV from altimetry-GRACE was larger than that from Argo (Fig. 5f). Differences between Argo and altimetry-GRACE also indicated the uncertainties of altimetry, GRACE, and Argo in the spatial domain.

4. Summary

In this study, global SLVs were estimated in temporal and spatial domains based on the three independent observations (altimetry, GRACE, and Argo), from 2005 to 2014. The global sea-level budget was closed both on seasonal and inter-annual time scales. On seasonal time scales, the annual amplitude and phase of altimetry-observed global mean SLVs were consistent with those obtained from the sum of the GRACE-derived mass-induced SLV and Argo-based steric SLV. The altimetry-observed global mean sea level rise rate from 2005 to 2014 was 3.1 ± 0.3 mm/a, which agreed well with the estimate from GRACE + Argo of 2.8 ± 0.5 mm/a. A total ocean mass contribution of approximately 2 mm/a over 2005–2014 was observed, which may account for two-thirds of the total sea level rise rate. On inter-annual time scales during the strong 2010/2011 La Niña event, the global mean sea level dropped nearly 1 cm, which coincided with the decline of ocean mass and steric sea level from GRACE and Argo. The decline of ocean mass was consistent with an equivalent increase of terrestrial water storage, which occurred primarily over Australia and the Amazon Basin. Since early 2011, the global mean sea level rose rapidly, which is likely attributed to the ocean mass increase observed by GRACE. It is worthwhile to notice the poor agreement in regional variability of ocean mass trend maps estimated from GRACE and from altimetry-Argo. This discrepancy might have resulted from the uncertainties in Argo data or the low signal-to-noise ratio of GRACE results. Nevertheless, for the global mean SLV, GRACE, Argo, and altimetry were consistent with each other both on seasonal and inter-annual time scales.

Acknowledgments

This work is supported by the National Key Basic Research Program of China (973 program, 2012CB957703 and 2013CB733305) and the National Natural Science Foundation of China (41431070, 41174066 and 41321063).

REFERENCES

[1] Nicholls R, Cazenave A. Sea-level rise and its impact on coastal zones. Science 2010;328(5985):1517–20.

[2] Cazenave A, Llovel W. Contemporary sea level rise. Annu Rev Mar Sci 2010;2:145–73.

[3] Leuliette EW, Scharroo R. Integrating Jason-2 into a multiple-altimeter climate data record. Mar Geod 2010;33(S1):504–17.

[4] Levitus S, Antonov JI, Boyer TP, Stephens C. Warming of the world ocean. Science 2000;287(5461):2225–9.

[5] Roemmich D, Owens WB. The Argo Project: global ocean observations for understanding and prediction of climate variability. Oceanography 2000;13(2):45–50.

[6] Tapley BD, Bettadpur S, Ries JC, Thompson PF, Watkins MM. GRACE measurements of mass variability in the Earth system. Science 2004;305:503–5. http://dx.doi.org/10.1126/science.1099192.

[7] Chambers DP. Evaluation of new GRACE time-variable gravity data over the ocean. Geophys Res Lett 2006;33:L17603. http://dx.doi.org/10.1029/2006GL027296.

[8] Wen Hanjing, Li Hongchao, Cai Yanhui, Cheng Pengfei, Zhu Guangbin. The study of global sea level change by combining Argo floats data, satellite altimetry and GRACE observation. Acta Geod Cartogr Sinica 2012;41(5):696–702 [in Chinese].

[9] Jin Taoyong, Li Jiancheng, Wang Zhengtao, Jiang Weiping. Global ocean mass variation in recent four years and its spatial and temporal characteristics. Chin J Geophys 2010;53(1):49–56 [in Chinese].

[10] Feng Wei, Zhong Min, Xu Houze. Sea level variations in the South China Sea inferred from satellite gravity, altimetry, and oceanographic data. Sci China Earth Sci 2012;55(10):1696–701.

[11] Feng Wei, Zhong Min, Xu Houze. Global sea level changes estimated from satellite altimetry, satellite gravimetry and Argo data during 2005–2013. Prog Geophys 2014;29(2):0471–7 [in Chinese].

[12] Yin Shuguang, Zhu Yaozhong, Zhong Min, Zhu Jiang. Study on seasonal variations of global ocean mass. J Geodesy Geodyn 2005;25(4):33–7 [in Chinese].

[13] Willis JK, Chambers DP, Nerem RS. Assessing the globally averaged sea level budget on seasonal to interannual time scales. J Geophys Res 2008;113:C06015. http://dx.doi.org/10.1029/2007JC004517.

[14] Leuliette EW, Miller L. Closing the sea level rise budget with altimetry, Argo, and GRACE. Geophys Res Lett 2009;36:L04608. http://dx.doi.org/10.1029/2008GL036010.

[15] Cazenave A, Dominh K, Guinehut S, Berthier E, Llovel W, Ramillien G, et al. Sea level budget over 2003–2008: a reevaluation from GRACE space gravimetry, satellite altimetry and Argo. Glob Planet Change 2009;65(1–2):83–8.

[16] Paulson A, Zhong SJ, Wahr J. Inference of mantle viscosity from GRACE and relative sea level data. Geophys J Int 2007;171(2):497–508. http://dx.doi.org/10.1111/j.1365-246X.2007.03556.x.

[17] Peltier W. Closure of the budget of global sea level rise over the GRACE era: the importance and magnitudes of the required corrections for global glacial isostatic adjustment. Quat Sci Rev 2009;28(17–18):1658–74.

[18] Chambers D, Wahr J, Tamisiea M, Nerem R. Ocean mass from GRACE and glacial isostatic adjustment. J Geophys Res 2010;115:B11415. http://dx.doi.org/10.1029/2010JB007530.

[19] Boening C, Willis JK, Landerer FW, Nerem RS, Fasullo J. The 2011 La Niña: so strong, the oceans fell. Geophys Res Lett 2012;39:L19602. http://dx.doi.org/10.1029/2012GL053055.

[20] Fasullo JT, Boening C, Landerer FW, Nerem RS. Australia's unique influence on global sea level in 2010–2011. Geophys Res Lett 2013;40(16):4368–73.

[21] Chambers D, Bonin J. Evaluation of Release-05 GRACE time-variable gravity coefficients over the ocean. Ocean Sci Discuss 2012;9:2187–214.

[22] Wahr J, Molenaar M, Bryan F. Time variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. J Geophys Res 1998;103(B12):30205–29.

[23] Cheng M, Ries JC, Tapley BD. Variations of the Earth's figure axis from satellite laser ranging and GRACE. J Geophys Res 2011;116(B1):B01409.

[24] Swenson S, Chambers D, Wahr J. Estimating geocenter variations from a combination of GRACE and ocean model output. J Geophys Res 2008;113:B08410. http://dx.doi.org/10.1029/2007JB005338.

[25] Geruo A, Wahr J, Zhong S. Computations of the viscoelastic response of a 3-D compressible Earth to surface loading: an application to glacial isostatic adjustment in Antarctica and Canada. Geophys J Int 2013;192(2):557–72.

[26] Matsuo K, Heki K. Coseismic gravity changes of the 2011 Tohoku-Oki earthquake from satellite gravimetry. Geophys Res Lett 2011;38:L00G12. http://dx.doi.org/10.1029/2011GL049018.

[27] Han SC, Shum CK, Bevis M, Ji C, Kuo CY. Crustal dilatation observed by GRACE after the 2004 Sumatra-Andaman earthquake. Science 2006;313(5787):658–62.

[28] Quinn K, Ponte R. Uncertainty in ocean mass trends from GRACE. Geophys J Int 2010;181:762–8.

Feng Wei, Assistant Research Fellow at the Institute of Geodesy and Geophysics, Chinese Academy of Sciences. He received the B.S degree in Surveying Engineering from Hohai University in 2007, and the Ph.D in Geophysics from Graduate University of Chinese Academy of Sciences and University of Toulouse III in France in 2013. His current research interests include the oceanic and hydrologic applications of satellite altimetry and gravimetry.