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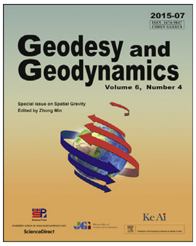

Global sea level variations from altimetry, GRACE and Argo data over 2005–2014

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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

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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:

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

where $\mathrm{SLV_{total}}$ is the total SLV observed by altimetry, $\mathrm{SLV_{steric}}$ is the steric component of sea level observed by Argo, and $\mathrm{SLV_{mass}}$ 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