SEA LEVEL PROJECTIONS (BP HORTON, SECTION EDITOR)

The Balancing of the Sea-Level Budget

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Abstract The last 5 years have seen continued progress in closing the sea-level budget, the accounting for the contributions of sea-level change, during the late twentieth and early twenty-first centuries. Balancing the sea-level budget is critical to understanding recent and future climate change as well as balancing the Earth's energy budget and water budget. During the last decade, advancements in the ocean observing system—satellite altimeters, hydrographic profiling floats, and space-based gravity missions—have allowed the sea-level budget to be assessed with unprecedented accuracy from direct, rather than inferred, estimates. In particular, several recent studies have used the sea-level budget to bound the rate of deep-ocean warming. Despite the fact that much of the observing system in place before the satellite era was not intended for global climate monitoring, new analyses of the historical record suggest that the twentieth century sea-level budget may be understood.

Keywords Sea level · Argo · GRACE · Altimetry

Introduction

Among the many measurements of the Earth's climate, sea-level change is prominent both for its direct impact on human

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activities and as an indicator of climatic change. The ocean is overwhelmingly the major reservoir for the storage of extra heat that has been added to the climate system as well as the water mass lost from melting ice sheets and glaciers. Worldwide, hundreds of millions of people live in coastal zones, and rising seas and their accompanying impacts—flooding, saltwater intrusion, and habitat loss—will increasingly burden the affected societies [1]. With the expectation that sea-level rise will continue to accelerate over the next century, a robust system for monitoring sea-level rise, as well as measuring its causes, is vital.

Instrumental to demonstrating the integrity of climate monitoring is the concept of an observational budget. Because of the conservation of energy or mass, it should be possible to completely account for the exchange of heat, water, or other matter by fluxes from one reservoir to another in the climate system. In the case of sea level, the budget is often accounted in units of global mean sea level, a reflection of incremental increases or decreases of the volume of water in the global ocean. Changes in the volume of the ocean are inferred by observing variations in globally averaged sea level and by modeling the changes in the shape of the ocean basin that are caused by geophysical processes. One millimeter of global mean sea-level change is equivalent to 361 km^3 of volume change. The goal, therefore, in the exercise of determining the sea-level budget is to confirm that observations of changes in sea level during a particular time period match the sum of the measurements of the component causes of sea-level change [2].

On decadal time scales, the individual causes of volume change in the ocean are two processes, density (steric) changes and the water exchange between the ocean and continents [2]. Changes in ocean temperature and salinity produce density changes, which are inversely proportional to volume changes. When expressed as a component of mean sea level, this effect

is termed steric sea level. Temperature changes are equivalent to ocean heat content changes. The exchange of water between the ocean and reservoirs of continental hydrology (ice sheets, glaciers, ice caps, groundwater, and inland surface waters) results in variations in the ocean's total mass. This component is sometimes called barystatic sea level [3•].

To meaningfully interpret the causes of sea-level change during a particular period, the budget must be closed. In other words, changes in observed sea level should be equal to the sum of the changes attributable to density changes and water mass exchange, or observed total sea-level changes should be the sum of steric and barystatic sea level. This closure implies that the observations are complete and accurate.

The sea-level budget is intimately related to other important climate system budgets (Fig. 1). The conservation of water mass in the hydrological cycle requires that all water exchanged between the land (and to a much lesser extent the atmosphere) and the ocean should be accounted for by observations. Similarly, the oceans play a dominant role in accounting for the Earth's energy budget (also known as the Earth's radiation balance), which describes the net flow of energy into the Earth in the form of shortwave radiation and outgoing infrared long-wave radiation. The ocean accounts for over 90 % of the changes in global heat storage, with terrestrial and atmospheric reservoirs of heat being far less important [4, 5]. Arguably, closing the sea-level budget to within appropriate confidence intervals is essential to the closing of the global energy and the hydrological budgets.

## Observations of Sea Level and Its Components

International collaborations in recent years have implemented a global ocean observing system that monitors the variability of not only total sea level but also the major contributions to sea-level change. The combination of contemporaneous

measurements from this observing system—satellite altimeters, hydrographic profiling floats, and space-based gravity missions—allows the observational sea-level budget to be assessed from direct, rather than inferred, estimates. Sea-level datasets from earlier eras are from measuring systems not designed for global climate monitoring. Reconstructing the sea-level record for at least the entire twentieth century is critical to understanding multidecadal variability. The sea-level budget has been a valuable metric in assessing the completeness and accuracy of these historical reanalyses of steric, barystatic, and total sea levels.

Total Sea Level

The sea level observing system has evolved from intermittent records of sea level at four sites in Northern Europe starting in the 1700s to nearly complete and regular coverage by satellite altimeters and a geodetically monitored network of tide gauges in the 1990s. By the late 1800s, tide gauges were in operation in Northern Europe, on both North American coasts, and in Australia and New Zealand in the Southern Hemisphere. In the early twentieth century, tide gauges began to be installed on islands far from continental coasts. Not until the 1970s did a majority of deep-ocean islands have an operating tide gauge suitable. Analyses of twentieth century global mean sea level (GMSL) using tide gauge records have employed different methods to accommodate the spatially sparse, temporally incomplete sampling of global sea level by gauges, which potentially introduces significant biases into estimates of GMSL. Most of these have concluded that GMSL rose over the twentieth century at a mean rate of 1.6 to 1.9 mm/year [6–12]. However, two recent studies suggest a somewhat slower trend. Woppelmann et al. [13] extrapolated contemporary land motion corrections at gauges into the past [14] and found a rate of 1.5±0.5 mm/year after area-weighting trends in the northern and southern hemispheres. Hay et al. [15•] use a Kalman smoothing reconstruction [16] that uses the spatial patterns inherent to the individual physical processes driving sea-level change to infer weights for the gauges. They find a significant rate of GMSL rise from 1901 to 1990, 1.2±0.2 mm/year (90 % CI) slower than the rate in the IPCC Fifth Assessment Report for the same period, 1.5±0.2 mm/year [39].

Sea level has been continuously monitored since 1992 by satellite radar altimeters (e.g., TOPEX/Poseidon, Jason-1, Jason-2, and Envisat) with sufficient accuracy and stability to monitor regional and global trends. Estimates of the straight-line trend in GMSL from 1992 to 2013 are higher than the pre-satellite twentieth century rate, 3.1±0.4 mm/year (90 % CI) [17, 18]. Different studies of trends in the GMSL record from altimetry show close agreement despite differences in interannual variability resulting from processing choices [19, 20]. Monthly, the global mean sea-level change can be monitored
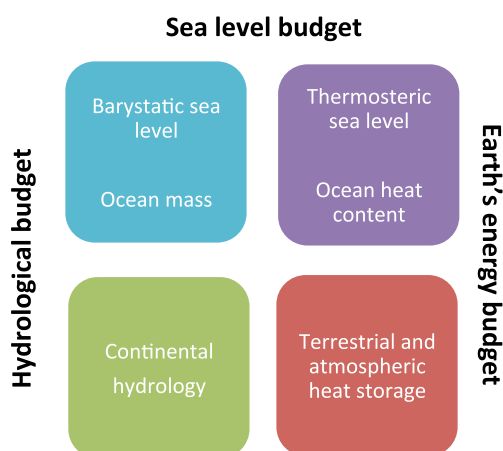
Sea level budget

Fig. 1 The relationship between the sea-level budget, the Earth's energy budget, and the hydrological cycle

with errors around 2 mm. Drifts in sea-level estimates from altimetry can be detected using a network of tide gauges [21, 22]. Reported tide gauge comparisons for the combined record from TOPEX/Poseidon, Jason-1, and Jason-2 are consistent with no significant drift [22–26]. The comparison technique is limited mainly by the availability and accuracy of land motion corrections at the gauges and may be capable of detecting drifts >0.4 mm/year.

Steric Sea Level

Steric (density) sea-level changes are largely a response to changes in temperature with local contributions from salinity. Much of the historical record of the subsurface prior to 2000 is from bathythermographs, measuring only heat content or, equivalently, the thermosteric component of sea level due to thermal expansion of sea water. Routine observations beginning in the 1960s gradually transitioned from mechanical to more precise electronic instruments. By the late 1960s expendable bathythermographs (XBTs) released from ships of opportunity contributed the majority of subsurface temperature measurements. However, XBTs were not designed for climate measurements. XBT sampling depths are not measured from pressure, but are inferred from the estimated fall rate, and uncertainties in the fall rate, manufacturing variations, and other issues caused some reported XBT temperatures to be biased.

More recently, estimates of steric sea-level variations in the upper ocean are obtained from the global array of the Argo project [2, 27–34]. Argo deployments of autonomous hydrographic profiling floats that measure both temperature and salinity began in 2000. In November 2007, the array surpassed 3000 active floats, achieving a sampling of approximately every three degrees of latitude and longitude over 10 days [35]. Now, with more than 3500 active floats, Argo creates a more uniform distribution than historical observations, providing dramatically improved coverage of the upper 700 m and increasingly the upper 2000 m of the global ocean, particularly in the Southern Hemisphere [36]. On a monthly basis, the global mean steric sea-level change from Argo in the upper ocean can be found with errors around 3 mm, with the error decreasing over time as more floats sample to 2000 m with fewer biases [28, 37]. Some studies have suggested that Argo data are best suited for global analyses of upper ocean steric changes only after 2005 due to a combination of inter-annual variability and significant biases when using earlier data due to sparser and shallower sampling [28, 34].

The fifth assessment report of the IPCC [38, 39] concluded that upper ocean measurements were too sparse before 1971 to estimate trends in thermosteric sea level. The warming of the upper 700 m from 1971 to 2010 caused an estimated mean thermosteric rate of rise of 0.6±0.2 mm/year (90 % CI), 50 % higher than previous estimates [27, 40•, 41]. Observations of

the contribution to sea-level rise from warming below 700 m are more uncertain due to limited historical data and are usually based on 5-year averages to 2000-m depth [33]. From 1971 to 2010, the estimated trend for the contribution between 700 and 2000 m is 0.1±0.1 mm/year (90 % CI) [33]. To measure the contribution of warming below 2000 m, much sparser but very accurate temperature profiles along repeat hydrographic sections are used [42–44]. The studies have found a significant warming trend between 1000 and 4000 m within and south of the Sub-Antarctic Front. The estimated total contribution of warming below 2000 m to global mean sea-level rise between circa 1992 and 2005 is 0.1±0.1 mm/year (95 % CI) [44].

Ocean Mass/Barystatic Sea Level

Broadly speaking, four approaches have been used to infer or directly measure changes in barystatic sea level. In one approach, all changes in continental water storage is estimated [4], including the melting of the Greenland and Antarctic ice sheets, mountain glaciers and ice caps, changes in dam retention, the depletion of groundwater, and natural variability of terrestrial surface waters [45, 46]. Any net change in the sum of these reservoirs is assumed to be an exchange of freshwater with the ocean. In another approach, the rate of barystatic sea level is inferred from freshening of the ocean (i.e., decreases in mean salinity), if the contribution from melting of sea ice, which affects freshening but not sea level, can be estimated [47–49]. A more recent approach exploits so-called sea-level fingerprints, which are regional patterns in sea-level change that result from the deformation of the solid Earth and the changes in the Earth's gravitational field in response to ice sheets gaining or losing mass and water exchange between the continents and the ocean [50]. For example, sea-level measurements from tide gauges can be used to solve for "fingerprints" and infer the individual contributions to sea level [16]. Lastly, changes in time-varying gravity observed from space missions such as the Gravity Recovery and Climate Experiment (GRACE) are used to observe changes in ocean mass after using models to remove the variations of atmospheric mass and the effects of glacial isostatic adjustment (see below) [15•]. Additionally, GRACE can be used to measure changes in continental hydrology and can potentially close the hydrological cycle by tracking the exchange of freshwater between the continents and ocean.

The Role of Geodesy and Geophysics

Geophysical processes of the solid Earth affect several measurements from the observing system related to sea level. At the most basic level, to close the sea-level budget, all measurements must be made in a common terrestrial reference frame,

Table 1 Global mean sea-level budget over different time intervals from observations, adapted from [39], Table 13.1, except where noted

Source	1901–1990	1971–2010	1993–2010	2005–2013 [64•, 65]
Observed contributions to global mean sea-level (GMSL) rise in millimeter/year (95 % CI)				
Thermal expansion	–	0.8±0.3	1.1±0.3	1.0±0.5
Glaciers except in Greenland and Antarctica	0.54±0.07	0.62±0.37	0.76±0.37	–
Glaciers in Greenland	0.15±0.05	0.06±0.03	0.10±0.03	–
Greenland ice sheet	–	–	0.33±0.08	–
Antarctic ice sheet	–	–	0.27±0.11	–
Land water storage	−0.11±0.05	0.12±0.10	0.38±0.12	–
Ocean mass/barystatic from GRACE	–	–	–	2.0±0.2
Total of contributions	–	–	**2.8±0.6**	**3.0±0.5**
Observed GMSL rise	**1.5±0.21** 1.2±0.2 [15]	**2.0±0.3**	**3.2±0.4**	**3.0±0.4**

The bold entries were meant to highlight the lines for total sea level to aid comparison

the International Terrestrial Reference System (ITRS). The global networks for the four major precise positioning systems—satellite laser ranging, GNSS, VLBI, and DORIS—form the backbone of the observing system by providing continuous monitoring of the International Terrestrial Reference Frame (ITRF).

Terrestrial land motion in the vertical must be removed from tide gauge levels to translate relative sea level measured with respect to the continental crust into a volume or mass change needed for sea-level budget. In addition, land motion effects must be removed from elevation changes in the cryosphere to compute land ice changes from ice sheets and glaciers [51]. These land motions include tectonic deformations from earthquakes and plate motion, subsidence from water or resource extraction, and the responses to the removal of ice and liquid water loads. The responses to load changes are particularly important when estimating the sea-level budget. The first is a nearly instantaneous, elastic response of the Earth due to contemporary load changes (e.g., melting ice sheets). The second is the time-delayed, viscous response due to past load changes from the last ice age, glacial isostatic adjustment (GIA). After some confusion about the appropriate methodology necessary to compute the GIA effect on ocean mass estimates from GRACE [52–55], model predictions of the GIA effects on tide gauges (relative sea level), altimetry (geocentric sea level or the sea surface), the time-varying geoid as measured by GRACE, and crustal motion are available for sea-level budget studies [51, 56, 57].

In the global mean, GIA produces a small net sinking of the ocean floor relative to the Earth's center, which, if the sea surface did not change, would imply a small secular increase in volume, which geophysical modeling suggests is 75 to 180 km^3/year. Therefore, the rate of GMSL observed by altimeters is higher by +0.3 mm/year when GMSL is expressed as a change in ocean volume [58]. Similarly, GIA effects must be removed from GRACE observations of changes in the geoid in order to isolate ocean mass variations [52]. While

the GIA signal for altimetry reflects changes in ocean volume, the GIA correction for ocean mass variations from GRACE accounts for mass redistribution from crustal motion, which produces significantly larger apparent changes in terms of equivalent water height, roughly 1 mm/year.

Recent Progress in Sea-Level Budget Closure

The current state of knowledge of the sea-level budget is summarized in Table 1, adapted largely from [39], Table 13.1. Surprisingly, sea-level rise since the early 1990s has progressed at a relatively constant rate, despite evidence of acceleration in the melting of mountain glaciers and ice sheets in Greenland and Antarctica. The resulting acceleration in the rate of ocean mass increase appears to have been somewhat compensated by a decrease in the rate of steric rise due to thermal expansion [2]. There have been departures from a straight-line trend, associated mainly with ENSO variability [59, 60]. The sea-level budget and GRACE observations were able to confirm that the significant decrease in mean sea level from 2010 to the middle of 2011 was due to a large increase in
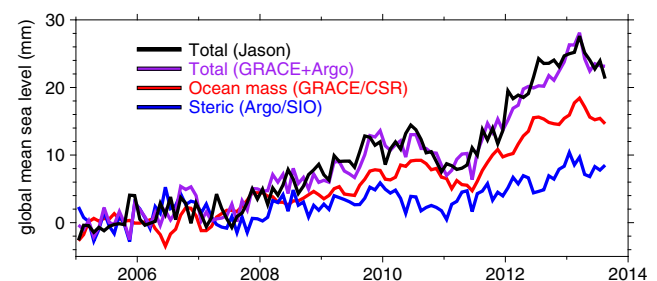
Fig. 2 Monthly estimates from Jason-1 and Jason-2 of global mean sea level (*black*), which are in general agreement with the sum (*purple*) of the ocean mass component from the Gravity Recovery and Climate Experiment, GRACE (*red*), and the steric component of the upper 2000 m from Argo (*blue*) from Leuliette [65]. Seasonal signals have been removed

water storage in northern South America and Australia [61]. Further study indicated that the longevity of the anomaly could be attributed to water storage in closed drainage basins in Australia [62].

On a monthly basis, the sum of the steric component estimated from Argo and the barystatic component from GRACE agree with total sea level from Jason within the estimated uncertainties (Fig. 2), with the residual difference having less than 4 mm [65]. Direct measurements of ocean warming above 2000-m depth during January 2005 and December 2013 explain about one third of the observed annual rate of global mean sea-level rise. While some recent budget studies infer a significant contribution to recent global sea-level rise from deep-ocean warming [63], direct observations accounting for systematic uncertainties find that the deep ocean (below 2000 m) contributes only -0.13 ± 0.72 mm/year to global sea-level rise [64•].

Purkey et al. [43] use the sea-level budget to estimate regional and global trends of sea level due to ocean mass changes using a residual method (the difference between altimetry and full-depth in situ ocean data) between 1996 and 2006 and directly estimated from the GRACE during 2003 to 2013. Both methods capture the same large-scale mass addition trend patterns, including higher rates of mass addition in the North Pacific, South Atlantic, and the Indo-Atlantic sector of the Southern Ocean, and lower ocean mass trends in the Indian, North Atlantic, South Pacific, and the Pacific sector of the Southern Ocean.

Conclusion

As the climate continues to warm, sustained observations to monitor changes in global sea level and its causes will remain as important priorities. While warming of the ocean over the century will continue to cause sea-level rise from thermal expansion, loss of ice from Greenland and Antarctica, already the dominant contribution to total rise, is expected to accelerate. Over the last decade, the spatial pattern of sea-level change has been dominated by steric changes and wind-driven redistribution, but as the contribution from ocean mass becomes larger, very different patterns are expected.

The sea-level climate data record from altimetry will continue with new reference missions with sufficient stability to monitor sea-level rise: Jason-3 and Jason-CS/Sentinel-6, which are planned for launches in 2015 and 2020, respectively. The instruments on the GRACE satellites have operated several years beyond their nominal mission design. In order to prevent or shorten a significant gap in observations, a follow-on mission is planned for late 2017. The Argo array will need continual replacement of floats to maintain the network, as well as the development and deployment of Deep Argo floats capable of monitoring changes in the abyssal ocean.

Extending the understanding of the historical budget from global mean sea level to regional patterns of sea-level change will require interdisciplinary research. For example, we do not yet have a thorough understanding of past and future changes in low-frequency spatial redistribution of water [66, 67]. Until ocean reanalyses begin assimilating tide gauge observations and the geophysical response of the solid Earth along with historical ocean databases, we will lack a fuller understanding of twentieth century sea-level rise [68].

Compliance with Ethics Guidelines

Conflict of Interest   On behalf of all authors, the corresponding author states that there is no conflict of interest.

Human and Animal Rights and Informed Consent   This article does not contain any studies with human or animal subjects performed by any of the authors.

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