The Volume of Earth's Ocean

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ABSTRACT. Despite playing a significant role in the global water cycle, ocean volume has not been re-examined in over 25 years. The main uncertainty associated with ocean volume is the mean ocean depth. The earliest studies tended to overestimate ocean depth due to undersampling of seamounts and ocean ridges. The advent of the echosounder in the 1920s and subsequent ship-borne technologies rapidly increased aerial coverage of the ocean; hence, over time there has been a gradual decrease in calculated mean ocean depth. Today, however, in situ measurements span only ~ 10% of the ocean's surface area. Here, we use satellite altimetry data to estimate the ocean's volume, which is lower by a volume equivalent to 500 times the Great Lakes or five times the Gulf of Mexico when compared to the most recent published estimates.

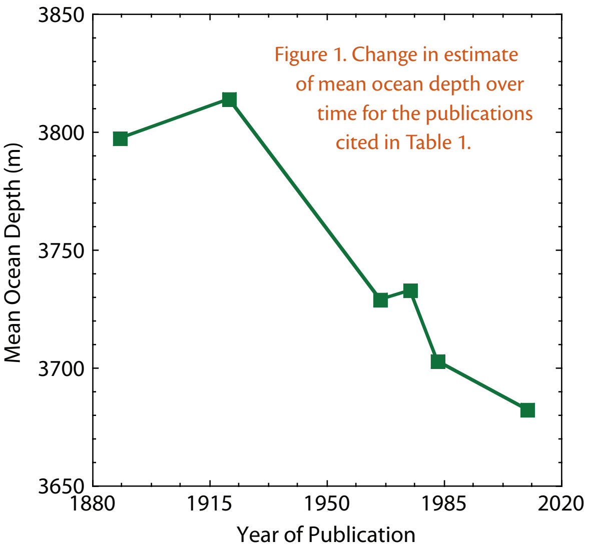

Figure 1. Change in estimate of mean ocean depth over time for the publications cited in Table 1.

Approximately 97% of the world's water reserves exist in the ocean. In addition, 82% of water exchange occurs over the ocean, making it the major player in the world water balance (Baumgartner and Reichel, 1975). Geochemical budgets and climate models depend on accurate estimates of ocean volume. Despite having a significant role in the global water cycle, ocean volume has not been re-examined in over 25 years, and thus the most recent estimates are based on dated technology and databases for ocean area and, most importantly, depth.

Historically, ocean volume has been calculated as the product of ocean area and mean ocean depth. Most early estimates were based on soundings with line or wire reported by various ships of opportunity (Murray, 1888; Kossinna, 1921). Data compilations based on such methods tended to overestimate ocean depth due to undersampling of seamounts and ocean ridges. Remarkably, Bache (1855), using tsunami-driven excursions in a tide gauge, estimated the mean depth of the Pacific Ocean between Shimoda, Japan, and San Francisco, California, to within 10%. The advent of the echosounder led to increased ocean bottom coverage and therefore greatly improved estimates. Since Kossinna (1921), the trend has been a gradual decrease in estimated mean ocean depth (Figure 1; Table 1). Given that estimates of ocean area have generally varied by less than 0.25% over time, the main driver in ocean volume estimate deviation has been depth, which decreased ~ 3% between the Kossinna (1921) and Shiklomanov and Sokolov (1983) approximations. Surprisingly, this key component of the global water budget had not been recalculated using the latest satellite-derived ocean bathymetry.

How can satellite data be used to improve the accuracy of the ocean's volume? Despite great advances in ocean exploration over the past 50 years, less than 10% of the seafloor has been mapped with ship-borne instrumentation. Smith and Sandwell (1997) combined satellite data, which determines ocean depth from gravity anomalies, with quality-controlled ship depth soundings to derive a high-resolution grid of seafloor topography. For this effort, we relied on the SRTM30PLUS V5 bathymetry database (Becker et al., 2009), which is derived following the method of Smith and Sandwell (1997), but includes the Arctic Ocean and incorporates retracked altimetry (Sandwell and Smith, 2009) and new single- and multi-beam echosounder data from US Navy, US National Geospatial Intelligence Agency, International Hydrographic Organization, US National Geophysical Data Center, and numerous other academic and industrial sources. This analysis resulted in a mean ocean depth value of 3682 m.

Table 1. Estimates of ocean depth, area, and volume.

Mean Depth (m)	Area (10^6 km^2)	Volume (10^9 km^3)	Reference
3797	355.3	1.349	Murray (1888)
3814	362.0	1.370	Kossinna (1921)
3729	362.0	1.350	Menard and Smith (1966)
3733	361.1	1.348	Baumgartner and Reichel (1975)
3703	361.3	1.338	Shiklomanov and Sokolov (1983)
3682.2	361.84	1.3324	This study

Remarkably, despite limited knowledge of seafloor topography and ocean area, Murray's ocean volume calculation is within ~ 1.2% of the value derived from this study. Compared with the most highly cited estimates of ocean volume (Baumgartner and Reichel, 1975; Shiklomanov and Sokolov, 1983; Menard and Smith, 1966), our estimate of 1.332 x 10^9 km^3 is 6–18 x 10^6 km^3 less (Table 1). This difference is primarily a result of a 21–51-m reduction in the mean ocean depth estimate. This difference, while only 0.45–1.4% of the total, represents a volume equivalent to 500 times the Great Lakes or five times the Gulf of Mexico. Although this reduction will not significantly affect, for example, oceanic geochemical budget calculations, ocean volume is a key constant in Earth science that should be reported accurately with the most current, state-of-the-art ocean area and mean depth estimates.

Interestingly, technical improvements in seafloor mapping are mainly improving the spatial resolution, that is, adding detail at certain wavelengths in the topography spectrum, while making little or no change in the grand mean. For example, satellite altimetry, in part limited by geophysics (isostasy) and more certainly limited by the algorithms used, can add information to topography only over a limited band of wavelengths, and this cannot change the overall mean. Therefore, the mean depth of the ocean changes only as more of the ocean is mapped by ships, a process that is, at present, happening very slowly. The fact that to date only 10% of the seafloor has been mapped, and that the measured area is not a random sample given that the majority of the soundings have taken place in coastal areas, argues for continued ocean exploration as well as development of new approaches and technologies over the coming decades. The new emphasis on ocean observing systems should provide an ideal opportunity to answer this call.

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SUPPORTING MATERIAL

For the bathymetry analysis, we worked from the SRTM30PLUS V5 dataset of September 16, 2008. The "pinged" and "estimated" values in Table 2 refer to 30 arc second pixels in the gridded data set that are flagged as having been measured by one or more echosoundings (pinged), or that were estimated (we had no direct in situ data so we filled them in with estimates from our satellite altimetry technique).

It is important to note that the pinged mean depth is shallower, on average, than the estimated mean depth (Table 2). This is not entirely unexpected, as surveys are more common and dense in shallow coastal areas, while the deep ocean is relatively unexplored. Hence, our conclusion about the ocean volume rests mostly on unsurveyed (in a direct sense) areas. It is possible that the volume may change by 7% if all the unsurveyed areas were found to be so shallow that the unmeasured mean depth converged upon the measured one. In order to put a bound on potential uncertainty in the ocean depth measurement, suppose that eventually the entire ocean is mapped with multi-beam echosounders to the standards for hydrographic surveys of the International Hydrographic Organization S-44 (5th edition; http://www.iho-ohi.net/iho_pubs/IHO_Download.htm), and suppose further that the depths reported by the ships give mean values in 30 arc second boxes that exactly match the estimates in Sandwell and Smith (2009). Even with these additional data, the expected 1-sigma uncertainty in depth measurements will be 1.2%.

The uncertainty associated with the ocean area estimate was derived in the following way: when we make a 30 arc second grid point estimate, the output is an elevation or depth value. If the value is less than zero, it was recorded as a depth (*Note*: We did not try to mask out land topography below sea level such as for Death Valley and the Dead Sea rift, which should make a negligible change in the results within the number of significant digits we report). Where a coastline crosses through a pixel and there is both land and sea within the box, the result ends up either land or sea but not both. We counted the number of times the land/sea state changed, and assumed that that many pixels could be ambiguous. The summed area of the "ambiguous" pixels is given as the possible error bar on ocean surface area. An additional complication not discussed here is the Antarctic ice shelves with open ocean water beneath them, and how they are represented in the grid. These are an inconsequential fraction of the ocean area and volume.

For the volumes, again, the measured volume is less than 10% of the total volume as it relies upon the new mean depth value, which is 90% estimated. Regardless, we conclude that the trend of a decrease in mean depth over time is real, and can be explained by better technology finding more shallow areas and seamounts. The uncertainty reported in Table 2 is propagated from the estimated depth and area uncertainties.

Table 2. Mean ocean depth, area, and volume derived for this study.

	Mean Depth (m)	Area (10^6 km^2)	Volume (10^9 km^3)
Mean or Total	3682.22	361.841	1.33238
Pinged	3504.49	32.4558	0.113741
Estimated	3699.73	329.385	1.21864
1-sigma Uncertainty (%)	1.2	0.14	1.2

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