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Sea Level Budget with Deep Ocean Warming Included

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Satellite altimeters have observed a global sea level rise of 3.3±0.4 mm/year from 1993 to 2008. The estimated rise includes contributions from steric effects due to ocean warming and mass changes due to mainly freshwater addition. In-situ CDT/XBT/Argo measurements can be used to estimate the steric component of the sea level, giving a warming trend of 1.2 mm/year in the upper 700 m for the same period. Recently, GRACE (Gravity Recovery and Climate Experiment) satellite mission data have been used to infer the mass changes, showing a rate of 0.8±0.5 mm/year over 2002-2008. The difficulty to close the sea level budget is the lack of deep ocean data, in addition to the uncertainty of glacial isostatic adjustment (GIA) models whose correction increases GRACE mass trend estimates by 1∼2 mm/year. Here, we use a non-Boussinesq (mass-conserving) ocean general circulation model (OGCM) to diagnose the total steric height of the ocean. Forced by NCEP heat flux and corrected by SST data, the model is shown consistent with the upper ocean heat content and satellite-derived sea-ice extensions. The model steric height plus GRACE-inferred ocean mass matches the altimetry data well, in which a significant contribution is from the deep ocean bellow 700 m with a rate of 1.7 mm/year, much higher than previously thought. The abyssal warming is closely related to ocean dynamics with the Atlantic and Indian Ocean warmed the most, and the Pacific Ocean warmed the least, consistent with available deep ocean measurements.