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# Improved ocean-warming estimates: implications for climate models and sea-level rise

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Changes in the climate system's energy budget are predominantly revealed in ocean temperatures and the associated thermal expansion contribution to sea-level rise. However, climate models do not reproduce the large decadal variability in globally-averaged ocean heat content inferred from the sparse hydrographic data set, even when volcanic and other variable climate forcings are included. Also, the sum of the observed contributions to sea-level rise has not adequately explained the historical rise. Here, we report improved estimates of near-global ocean heat content and thermal expansion for the upper 700 m of the ocean for 1950 to 2003, using a reconstruction method that allows for sparse data coverage and applying recent corrections to reduce systematic errors in the most common ocean temperature observations. Our linear trend in ocean heat content (thermal expansion) corresponds to an air-sea flux of $0.35 \pm 0.08$ W m$^{-2}$ ($0.52 \pm 0.10$ mm yr$^{-1}$) for 1961 to 2003, and $0.37 \pm 0.28$ W m$^{-2}$ ($0.80 \pm 0.39$ mm yr$^{-1}$) for 1993 to 2003, over the ocean surface area considered ($3.3 \times 10^{14}$ m$^2$). Compared to earlier estimates, our rates are about 50% larger for the historical period but about 40% smaller for the recent period, consistent with the recognition that previously estimated rates for the 1990s were biased high by instru-

mental errors. On average, the decadal variability of the climate models with volcanic forcing now agrees approximately with the observations but the multidecadal trends are smaller than observed. We add our observational estimates of upper ocean thermal expansion to other contributions to sea-level rise and find that the sum of contributions from 1961 to 2003 is about $1.5 \pm 0.4$ mm yr$^{-1}$, in good agreement with our updated estimate of near-global mean sea level of $1.6 \pm 0.2$ mm yr$^{-1}$.