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Historical ocean heat uptake in CMIP6 Earth System models: global and regional perspectives

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Ocean heat content is arguably one of the most relevant metrics for tracking global climate change and in particular the current global heating. Because of its enormous heat capacity, the global ocean stores about 93 percent of the excess heat in the Earth System. Time series of global ocean heat content (OHC) closely track Earth's energy imbalance as observed as the net radiative balance at the top of the atmosphere. For these reasons simulated OHC time series are a cornerstone for assessing the scientific performance of Earth System models (ESM) and global climate models. Here we present a detailed analysis of the OHC change in simulations of the historical climate (20th century up to 2014) performed with four of the current, state-of-the art generation of ESMs and climate models. These four models are UKESM1, HadGEM3-GC3.1-LL, CNRM-ESM2-1 and CNRM-CM6-1. All four share the same ocean component, NEMO3.6 in the shaconemo eORCA1 configuration, and they all take part in CMIP6, the current Phase 6 of the Coupled Model Intercomparison Project. Analysing a small number of models gives us the opportunity to analyse OHC change for the global ocean as well as for individual ocean basins. In addition to the ensemble means, we focus on some individual ensemble members for a more detailed process understanding. For the global ocean, the two CNRM models reproduce the observed OHC change since the 1960s closely, especially in the top 700 m of the ocean. The two UK models (UKESM1 and HadGEM3-GC3.1-LL) do not simulate the observed global ocean warming in the 1970s and 1980s, and they warm too fast after 1991. We analyse how this varied performance across the models relates to the simulated radiative forcing of the atmosphere. All four models show a smaller ocean heat uptake since 1971, and a larger transient climate response (TCR), than the CMIP5 ensemble mean. Close analysis of a few individual ensemble members indicates a dominant role of heat uptake and deep-water formation processes in the Southern Ocean for variability and change in global OHC. Evaluating OHC change in individual ocean basins reveals that the lack of warming in the UK models stems from the Pacific and Indian basins, while in the Atlantic the OHC change 1971-2014 is close to the observed value. Resolving the ocean warming in depth and time shows that regional ocean heat uptake in the North Atlantic plays a substantial role in compensating small warming rates elsewhere. An opposite picture emerges from the CNRM models. Here the simulated OHC change is close to observations in the Pacific and Indian basins, while tending to be

too small in the Atlantic, indicating a markedly different role for the Atlantic meridional overturning circulation (AMOC) and cross-equatorial heat transport in these models.