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Supplementary Materials for

How fast are the oceans warming?

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Supplementary material

Materials and Methods

1. Calculation of OHC based on different estimates

IPCC-AR5 (*1*) featured five estimates for OHC within 0-700m including Levitus et al. (*2*) (LEV), Ishii et al. (*3*) (ISH), Domingues et al. (*4*) (DOM), Palmer et al. (*5*) (PAL), Smith and Murphy (*6*) (SMT), one estimate for 700-2000m: Levitus et al. (*2*) (LEV) and one estimate below 20000m: Purkey and Johnson (*7*) (PG). For the Earth's energy budget inventory (Box 3.1 in Ref. (*1*)) and other places, DOM, LEV and PG are used for 0-700m, 700-2000m, and below 2000m respectively. Among the five 0-700m OHC estimates in AR5, the minimum yields an ocean warming of 74 [43 to 105] TW (SMT) within 1971-2010, which is almost half of the maximum, with a rate of OHC change of 137 [120 to 154] TW (DOM). If all of five estimates are treated equally, a huge error bar has to be put in the final OHC estimate, downplaying the reliability of OHC records.

AR5 chose the DOM estimate to assess Earth's energy budget, rather than any others or an ensemble mean of the five featured estimates by stating "*Generally the smaller trends are for estimates that assume zero anomalies in areas of sparse data, as expected for that choice, which will tend to reduce trends and variability. Hence the assessment of the Earth's energy uptake (Box 3.1) employs a global UOHC estimate (Domingues et al., 2008) chosen because it fills in sparsely sampled areas and estimates uncertainties using a statistical analysis of ocean variability patterns.*". In this way, the "conservative error" of many estimates has been identified in AR5 but not supported by the literature. Since AR5, many studies have been looked into this issue either directly or indirectly (*8-13*) and several new/revised estimates are available, and are chosen by our study.

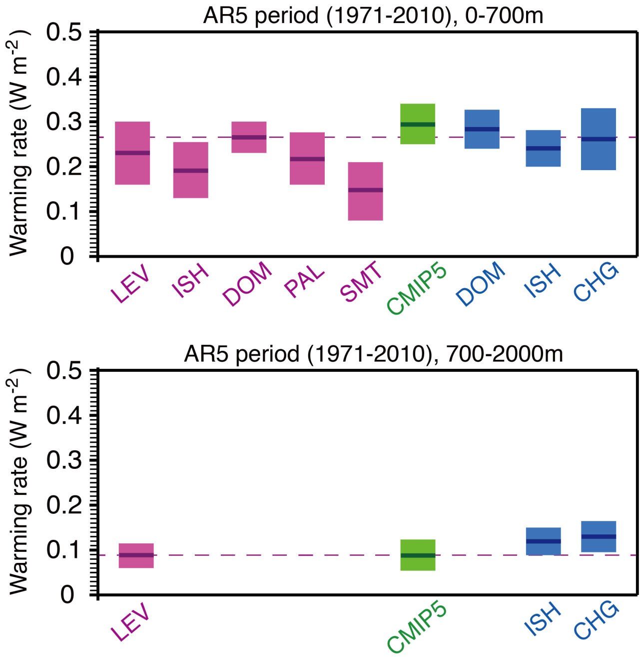
For OHC within 0-700m, the new CHG and ISH estimates are consistent with DOM (Figure S1, top). The three estimates are collectively higher than LEV/ISH/PAL/SMT featured in AR5 (Figure S1, top). Therefore, the progress after AR5 justifies the choice of DOM in AR5 for OHC 0-700m.

For 700-2000m, only LEV is available in AR5, and their mapping method likely underestimates the long-term trend (Figure S1, bottom). The new available data are stronger than the AR5 estimate for OHC700-2000m.

For 0-2000m OHC in Fig.2 of the main text, DOM is combined with LEV following AR5, but LEV potentially underestimates the 700-2000m change. Using other estimates such as ISH or CHG will result in larger warming than DOM+LEV.

We show in the main text that over the period of 2005-2017, the linear warming rate for the ensemble mean of the CMIP5 models is 0.68 ± 0.02 W m^{-2}, slightly larger than the observations (ranging from 0.54 ± 0.02 to 0.64 ± 0.02). Many studies, including Gleckler et al. (*13*) and Santer et al. (*14*) have shown that the volcanic eruptions after 2000 have not been taken into account in CMIP5 models. Taking this into account, the Multi-Model-Average of CMIP5 simulations will be more consistent with observations (*13*).

In this study, all error bars are calculated as 90% confidence intervals for an ordinary least squares fit, taking into account the reduction in the degrees of freedom implied by the temporal correlation of the residuals following Foster and Rahmstorf (*15*), which is similar to AR5.



Supplementary Figure S1. Updated OHC estimates within 0-700m (top) and 700-2000m (bottom) compared with IPCC-AR5. Linear rates of 0-700m/700-2000m ocean warming for 1971-2010 featured in the AR5 (*1*) are shown in purple bars. CMIP5 results (historical runs from 1971 to 2005 and RCP4.5 from 2006 to 2010) are indicated by the green bar, and the latest observational estimates by blue bars. The error bars are 90% confidence intervals.

2. CMIP5 models

The CMIP5 experiments used in our analyses include: pre-industrial control (piControl) runs, Historical simulations (Hist), and RCP2.6, 4.5, 8.5 projections (Supplementary Table S1). All of these data are available from the Earth System Grid Federation (ESFG; http://pcmdi9.llnl.gov/esgf-web-fe). Not all models are available for all experiments, we find a total of 25 models for piControl+Hist+RCP26, 33 models for piControl+Hist+RCP45, and 42 models for piControl+Hist+RCP85.

The piControl is used for removing the "model drift", which is associated with many possible errors: (i). Incomplete model spin-up, as deep ocean requires at least hundreds of years to stabilize. (ii). Errors in models (*16*). There are alternative ways of treating "model drift": fitting "linear" or "quadratic" or "cubic" polynomial regression to the piControl global time series. For historical simulations, studies have found that Multi-Model-Average of OHC changes is not sensitive to the choice of the drift correction (*13, 17-19*). However, for future projections, some models show too much correction if a higher order "quadratic" or "cubic" polynomial fit is used. Therefore, to be conservative, the "model drift" is assessed by fitting a linear trend to the piControl time series.

Supplementary Table S1. A list of CMIP5 models used in this analysis. The marks "√" indicate all the three experiments are available for a model, which are then used in our analyses.

CMIP5 models	piControl+Hist +RCP26	piControl+Hist +RCP85	piControl+Hist +RCP45
ACCESS1-0_r1i1p1		√	√
ACCESS1-3_r1i1p1		√	√
BNU-ESM_r1i1p1	√	√	√
CCSM4_r1i1p1	√	√	√
CESM1-BGC_r1i1p1		√	√
CESM1-CAM5_r1i1p1	√	√	√
CMCC-CESM_r1i1p1		√	
CMCC-CMS_r1i1p1		√	√
CMCC-CM_r1i1p1		√	√
CNRM-CM5_r1i1p1	√	√	√
CSIRO-Mk3-6-0_r1i1p1	√	√	√
CanESM2_r1i1p1	√	√	√
FGOALS-g2_r1i1p1	√	√	√
GFDL-CM3_r1i1p1	√	√	√
GFDL-ESM2G_r1i1p1	√	√	√
GFDL-ESM2M_r1i1p1	√	√	√
GISS-E2-H-CC_r1i1p1		√	√
GISS-E2-H_r1i1p1	√	√	√
GISS-E2-R-CC_r1i1p1		√	√
GISS-E2-R_r1i1p1	√	√	√
HadGEM2-AO_r1i1p1	√	√	√
HadGEM2-CC_r1i1p1		√	√
HadGEM2-ES_r1i1p1	√		√
IPSL-CM5A-LR_r1i1p1	√	√	√
IPSL-CM5A-MR_r1i1p1	√	√	√
IPSL-CM5B-LR_r1i1p1		√	√

MIROC-ESM-CHEM_r1i1p1	√	√	√
MIROC-ESM_r1i1p1	√	√	√
MIROC5_r1i1p1	√	√	√
MPI-ESM-LR_r1i1p1	√	√	√
MPI-ESM-MR_r1i1p1	√	√	√
MRI-CGCM3_r1i1p1	√	√	√
NorESM1-ME_r1i1p1	√	√	√
NorESM1-M_r1i1p1	√	√	√
bcc-csm1-1-m_r1i1p1		√	
bcc-csm1-1_r1i1p1	√	√	

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