CLIMATE CHANGE

How fast are the oceans warming?

Observational records of ocean heat content show that ocean warming is accelerating

By **Lijing Cheng[1], John Abraham[2], Zeke Hausfather[3], Kevin E. Trenberth[4]**

Climate change from human activities mainly results from the energy imbalance in Earth's climate system caused by rising concentrations of heat-trapping gases. About 93% of the energy imbalance accumulates in the ocean as increased ocean heat content (OHC). The ocean record of this imbalance is much less affected by internal variability and is thus better suited for detecting and attributing human influences (*1*) than more commonly used surface temperature records. Recent observation-based estimates show rapid warming of Earth's oceans over the past few decades (see the figure) (*1*, *2*). This warming has contributed to increases in rainfall intensity, rising sea levels, the destruction of coral reefs, declining ocean oxygen levels, and declines in ice sheets; glaciers; and ice caps in the polar regions (*3*, *4*). Recent estimates of observed warming resemble those seen in models, indicating that models reliably project changes in OHC.

The Intergovernmental Panel on Climate Change's Fifth Assessment Report (AR5), published in 2013 (*4*), featured five different time series of historical global OHC for the upper 700 m of the ocean. These time series are based on different choices for data processing (see the supplementary materials). Interpretation of the results is complicated by the fact that there are large differences among the series. Furthermore, the OHC changes that they showed were smaller than those projected by most climate models in the Coupled Model Intercomparison Project 5 (CMIP5) (*5*) over the period from 1971 to 2010 (see the figure).

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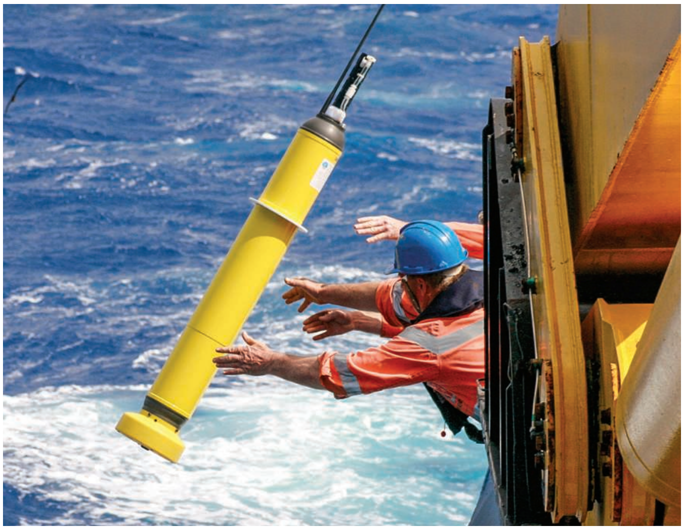
Since then, the research community has made substantial progress in improving long-term OHC records and has identified several sources of uncertainty in prior measurements and analyses (*2*, *6*–*8*). In AR5, all OHC time series were corrected for biases in expendable bathythermograph (XBT) data that had not been accounted for in the previous report (AR4). But these correction methods relied on very different assumptions of the error sources and led to substantial differences among correction schemes. Since AR5, the main factors influencing the errors have been identified (*2*), helping to better account for systematic errors in XBT data and their analysis.



Scientists deploy an Argo float. For over a decade, more than 3000 floats have provided near-global data coverage for the upper 2000 m of the ocean.

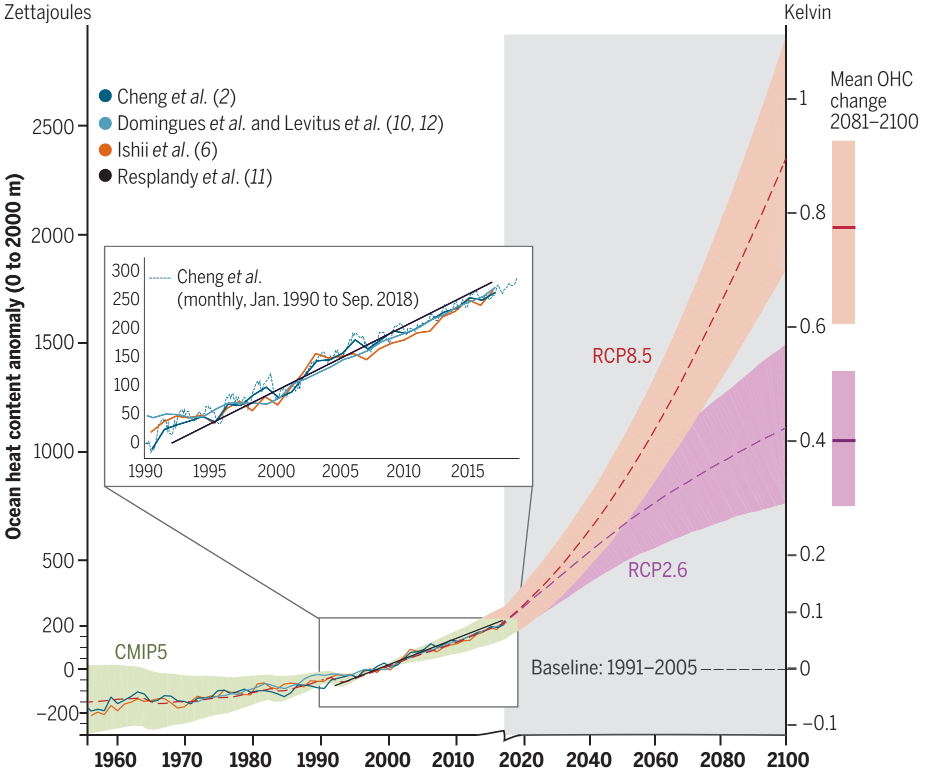
Several studies have attempted to improve the methods used to account for spatial and temporal gaps in ocean temperature measurements. Many traditional gap-filling strategies introduced a conservative bias toward low-magnitude changes (*9*). To reduce this bias, Domingues *et al.* (*10*) used satellite altimeter observations to complement the sparseness of in situ ocean observations and update their global OHC time series since 1970 for the upper 700 m. Cheng *et al.* (*2*) proposed a new gap-filling method that used multimodel simulations to provide an improved prior estimate and error covariance. This method allowed propagation of information from data-rich regions to the data gaps (data are available for the upper 2000 m since 1940). Ishii *et al.* (*6*) completed a major revision of their estimate in 2017 to account for the previous underestimation and also extended the analysis down to 2000 m and back to 1955. Resplandy *et al.* (*11*) used ocean warming outgassing of O_2 and CO_2, which can be isolated from the direct effects of anthropogenic emissions and CO_2 sinks, to independently estimate changes in OHC over time after 1991.

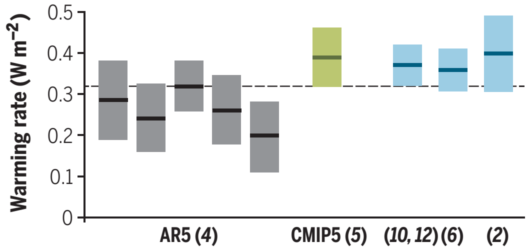
These recent observation-based OHC estimates show highly consistent changes since the late 1950s (see the figure). The warming is larger over the 1971–2010 period than reported in AR5. The OHC trend for the upper 2000 m in AR5 ranged from 0.20 to 0.32 W m^{-2} during this period (*4*). The three more contemporary estimates that cover the same time period suggest a warming rate of 0.36 ± 0.05 (*6*), 0.37 ± 0.04 (*10*), and 0.39 ± 0.09 (*2*) W m^{-2}. [Note that the analysis in Domingues *et al.* (*10*) is combined with that in Levitus *et al.* (*12*) for 700 to 2000 m to produce a 0 to 2000 m time series.] All four recent studies (*2*, *6*, *10*, *11*) show that the rate of ocean warming for the upper 2000 m has accelerated in the decades after 1991 to 0.55 to 0.68 W m^{-2} (calculations provided in the supplementary materials).

Multiple lines of evidence from four independent groups thus now suggest a stronger observed OHC warming. Although climate model results (see the supplementary materials) have been criticized during debates about a "hiatus" or "slowdown" of global mean surface temperature, it is increasingly clear that the pause in surface warming was at least in part due to the redistribution of heat within the climate system from Earth surface into the ocean interiors (*13*). The recent OHC warming estimates (*2*, *6*, *10*, *11*) are quite similar to the average of CMIP5 models, both for the late 1950s until present and during the 1971–2010 period highlighted in AR5 (see the figure). The ensemble average of the models has a linear ocean warming trend of 0.39 ± 0.07 W m^{-2} for the upper 2000 m

Past and future ocean heat content changes

Annual observational OHC changes are consistent with each other and consistent with the ensemble means of the CMIP5 models for historical simulations pre-2005 and projections from 2005–2017, giving confidence in future projections to 2100 (RCP2.6 and RCP8.5) (see the supplementary materials). The mean projected OHC changes and their 90% confidence intervals between 2081 and 2100 are shown in bars at the right. The inset depicts the detailed OHC changes after January 1990, using the monthly OHC changes updated to September 2018 [Cheng *et al*. (*2*)], along with the other annual observed values superposed.





Updated OHC estimates compared with AR5. The three most recent observation-based OHC analyses give ocean warming rates (depths from 0 to 2000 m) for 1971 to 2010 that are closer to model results than those reported in AR5. This increases confidence in the model projections (see the supplementary materials for more detail). The error bars are 90% confidence intervals.

from 1971–2010 compared with recent observations ranging from 0.36 to 0.39 W m^{-2} (see the figure).

The relatively short period after the deployment of the Argo network (see the photo) in the early 2000s has resulted in superior observational coverage and reduced uncertainties compared to earlier times. Over this period (2005–2017) for the top 2000 m, the linear warming rate for the ensemble mean of the CMIP5 models is 0.68 ± 0.02 W m^{-2}, whereas observations give rates of 0.54 ± 0.02 (*2*), 0.64 ± 0.02 (*10*), and 0.68 ± 0.60 (*11*) W m^{-2}. These new estimates suggest that models as a whole are reliably projecting OHC changes.

However, some uncertainties remain, particularly for deep and coastal ocean regions and in the period before the deployment of the Argo network. It is important to establish a deep ocean observation system to monitor changes below 2000 m (*14*). It is also essential to improve the historical record, for example, by recovering undigitized OHC observations.

Simulations of future climate use a set of scenarios or plausible radiative forcing pathways based on assumptions about demographic and socioeconomic development and technological changes (*5*). Two scenarios shown in the figure project a substantial warming in the 21st century. For the Representative Concentration Pathways (RCP) 2.6 scenario, the models project an ocean warming (0 to 2000 m) of 1037 zettajoules (ZJ) (~0.40 K) at the end of the 21st century (mean of 2081–2100 relative to 1991–2005); this pathway is close to the Paris Agreement goal of limiting global warming to well below 2°C. For the RCP8.5 scenario, a business-as-usual scenario with high greenhouse gas emissions, the models project a warming of 2020 ZJ (~0.78 K). This level of warming would have major impacts on ocean ecosystems and sea level rise through thermal expansion; 0.78 K warming at 2100 is roughly equal to a sea level rise of 30 cm. This is in addition to increased sea level rise caused by land ice melt.

The fairly steady rise in OHC shows that the planet is clearly warming. The prospects for much higher OHC, sea level, and sea-surface temperatures should be of concerngiven the abundant evidence of effects on storms, hurricanes, and the hydrological cycle, including extreme precipitation events (*3*, *15*). There is a clear need to continue to improve the ocean observation and analysis system to provide better estimates of OHC, because it will enable more refined regional projections of the future. In addition, the need to slow or stop the rates of climate change and prepare for the expected impacts is increasingly evident. ■

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SUPPLEMENTARY MATERIALS

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Supplementary Materials for

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This PDF file includes:

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.

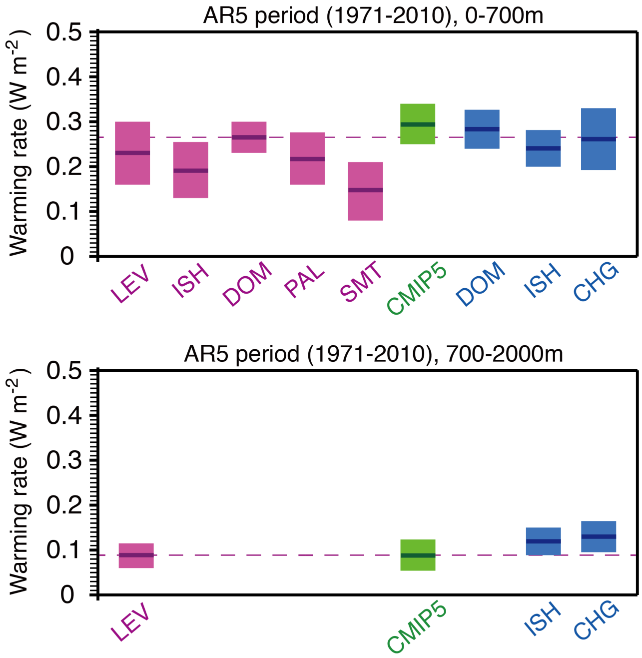
For OHC within 0-700m, the new CHG and ISH estimates are consistent with DOM (Figure S1, top). The three estimates are collectively higher than LEV/ISH/PAL/SMT featured in AR5 (Figure S1, top). Therefore, the progress after AR5 justifies the choice of DOM in AR5 for OHC 0-700m.

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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