CLIMATE CHANGE

How fast are the oceans warming?

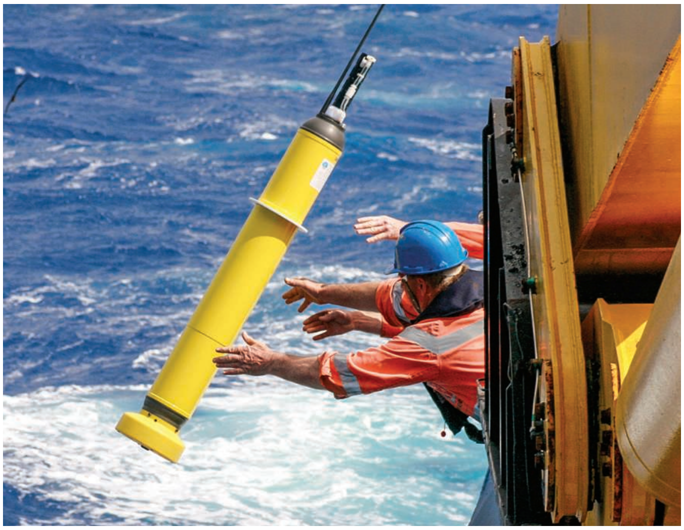
Observational records of ocean heat content show that ocean warming is accelerating

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).

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.

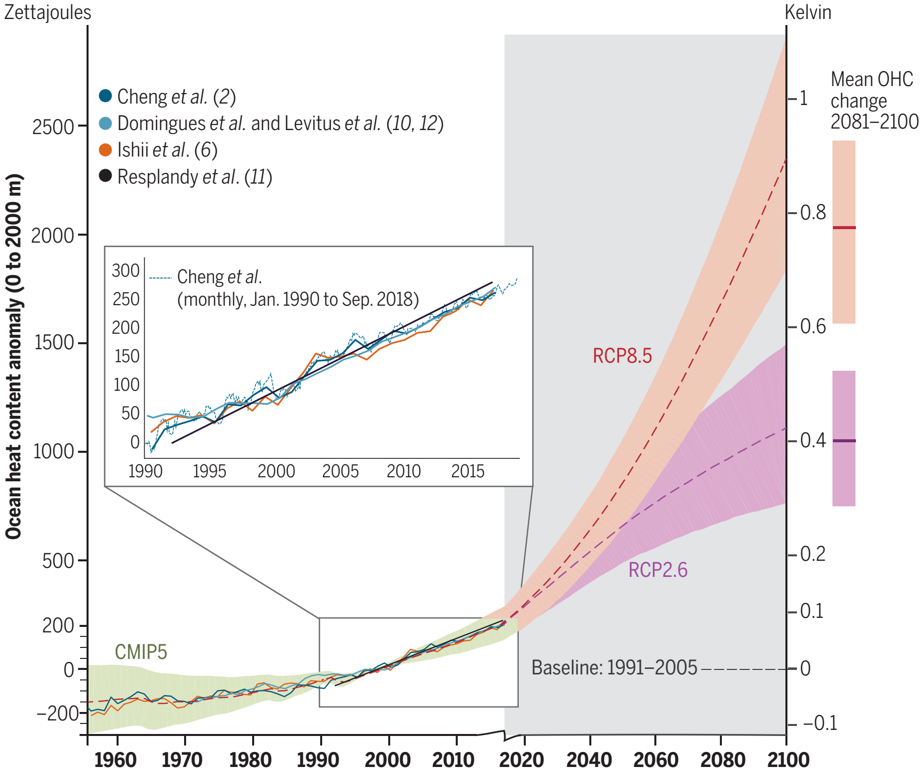
These recent observation-based OHC estimates show highly consistent changes since the late 1950s (see the figure). The warming is larger over the 1971–2010 period than reported in AR5. The OHC trend for the upper 2000 m in AR5 ranged from 0.20 to 0.32 W m^{-2} during this period (*4*). The three more 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).

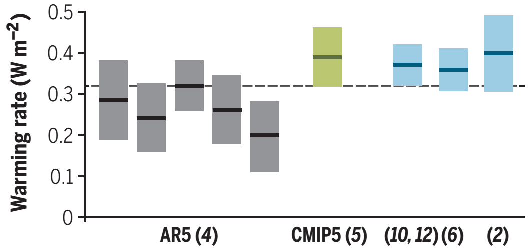
Multiple lines of evidence from four independent groups thus now suggest a stronger observed OHC warming. Although climate model results (see the supplementary materials) have been criticized during debates about a "hiatus" or "slowdown" of global mean surface temperature, it is increasingly clear that 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

[1]International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China. [2]School of Engineering, University of St. Thomas, 2115 Summit Avenue, St. Paul, MN, USA. [3]Energy and Resources Group, University of California, Berkeley, 310 Barrows Hall, Berkeley, CA 94720, USA. [4]National Center for Atmospheric Research, Post Office Box 3000, Boulder, CO 80307, USA. Email: chenglij@mail.iap.ac.cn

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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