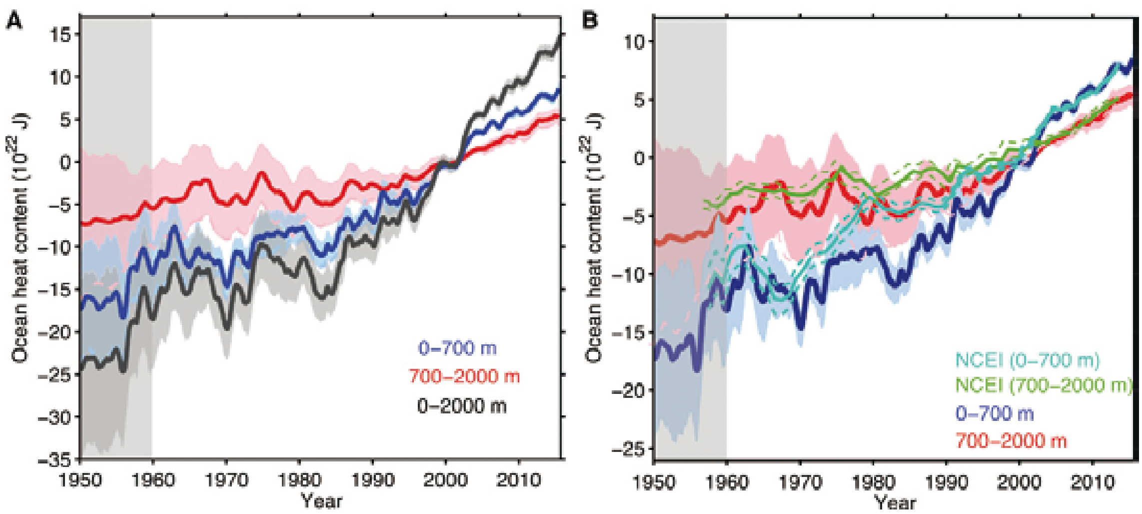
New Study Provides Solid Evidence for Global Warming

Global warming is driven by the Earth's energy imbalance (EEI): our planet traps more and more heat due to continuous increasing greenhouse gases. From the energy perspective, the global warming is actually ocean warming, since ocean stores more than 90% of the trapped heat. Therefore, ocean heat content (OHC) change is a fundamental indicator of global warming, and direct measurement of OHC will provide a direct evidence for climate change.

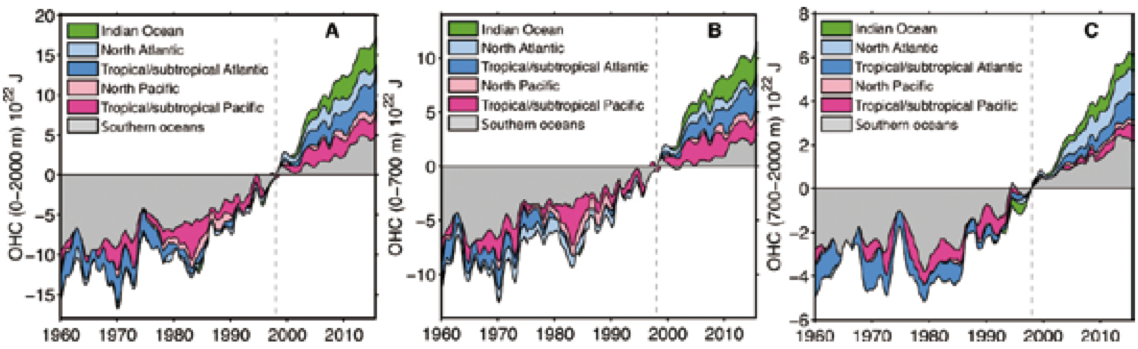
Reliable assessment of historical OHC change is a key task in climate studies. OHC time series provided by independent international groups show large discrepancies for long-term trend, intra-seasonal, inter-annual and decadal variability, because there are many challenges in estimating historical OHC change.

"Firstly, one of the major ocean subsurface observations (i.e. XBT) contains systematic bias", said Dr. CHENG Lijing from the Institute of Atmospheric Physics, Chinese Academy of Science, who is also lead author of a recent study published in *Science Advances*. "Secondly, temperature observations at ocean subsurface are extremely sparse, especially before 2005, since they were mainly distributed along the major shipping routes in the Northern Hemisphere."

During the recent decade, a new type of sensing device called the Argo float system has been deployed, which significantly increases the coverage of ocean data. However, there are still more than 60% of the ocean grids without any observations (if the global ocean is divided into 1 degree and 1 month grids). So a gap-filling method is required to make a "guess" for the temperature change in the ocean grids without observations. This "guess" is based on the spatial and temporal covariance of ocean temperature changes. In



Global OHC change time series. (A) OHC from 0 to 700 m (blue), 700 to 2000 m (red), and 0 to 2000 m (dark gray) from 1955 to 2015 as obtained by this study, with the uncertainty of the ±2σ interval shown in shading. All time series of the new analysis are smoothed by a 12-month running mean filter, relative to the 1997–2005 base period. **(B)** The new estimate is compared with an independent estimate from NCEI with its SE as dashed lines. Both OHC 0 to 700 m and OHC 700 to 2000 m are shown from 1957 to 2014. The baseline of the time series from NCEI is adjusted to the values of the current analysis within 2005–2014.

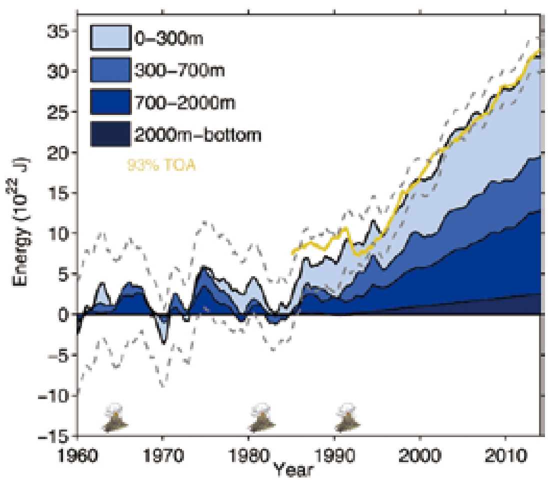


OHC changes from 1960 to 2015 for different ocean basins. (A) For 0 to 2000 m, **(B)** 0 to 700 m, and **(C)** 700 to 2000 m. All the time series are relative to the 1997-1999 base period and smoothed by a 12-month running filter. The curves are additive, and the OHC changes in different ocean basins are shaded in different colors.

other words, the ocean changes at two locations are not completely independent; instead, they are correlated under specific physical rules. The gap-filling method aims to utilize the correlation to reconstruct the missed information. The choice of different gap-filling methods is the major error source in global OHC calculation.

The new study, led by researchers at IAP in collaboration with the National Center for Atmospheric Research, Boulder, the National Oceanic and Atmospheric Administration and the University of St. Thomas, has made a major step to estimate historical OHC change. It applied an advanced XBT bias correction method, which is recommended according to an XBT community paper published in 2016 in the *Bulletin of the American Meteorological Society*. This ensures that the observation bias is minimized. A key step made by the new study is the application of an advanced gap-filling method and a careful evaluation on the results. It is highlighted that the study not only used the knowledge of recent well-observed ocean states, but also sub-sampled it using the sparse distribution of observations in the more distant past. Such a method turned out to show startling good results since the late 1950s.

This new work allows a more accurate assessment of how much heat has accumulated in the ocean (and Earth) system. The inferred ocean energy accumulation is higher than previous estimates, such as from the last IPCC-AR5 in 2013. But it is consistent with the direct observations of Earth's energy imbalance at top of atmosphere since the late 1980s. This new look at OHC and EEI changes over time provides greater confidence



Estimate of the ocean energy budget. The three major volcanic eruptions are marked. The energy budgets are relative to the 1958–1962 base period. The integrated net radiative imbalance from Allan et al. (65) estimated from the TOA is included in yellow and is multiplied by 0.93 to be comparable with the ocean energy budget. The TOA radiation is adjusted to the value of OHC within 2013–2014. The dashed gray lines encompass the 95% confidence interval.

than previously possible, and the data sets produced are a valuable resource for further climate change study.

Prof. WANG Fan, deputy director of the CAS Institute of Oceanography in Qingdao, said that "the study provided a new reconstruction on ocean subsurface temperature change since 1960 for the 0-2000m depths, and assessed historical ocean energy budget more accurately. It will be a valuable resource for future studies of oceanic variability and its climatic impacts on both regional and global scales".