Climate chronicles

https://doi.org/10.1038/s43017-024-00539-9

Ocean heat content in 2023

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In 2023, global full-depth ocean heat content (OHC) reached a record increase of 464 ± 55 ZJ since 1960, with strong heat gain observed in the Southern and Atlantic Oceans. OHC was 16 ± 10 ZJ higher than in 2022, continuing the long-term increasing trend that started in 1960.

Improved integrated ocean observation systems since the 1960s have made estimates of ocean heat content (OHC) possible[1]. These observations indicate that approximately 90% of extra heat stored in the climate system is taken up by the ocean[2], resulting in marked OHC increases[3]. Indeed, from 1958 to 2019, it is estimated that the top 2,000 m of the global ocean gained 351 ± 59.8 ZJ (1 ZJ = 10^{21} J) heat, with most heat stored in the Atlantic and Southern Oceans (ocean area south of 35 °S)[1].

On longer timescales, this ocean warming is largely attributed to human-induced greenhouse gas emissions and aerosols[4]. However, OHC variability is also evident at other timescales, including year-to-year variability linked to the El Niño–Southern Oscillation (ENSO)[5]. Although these interannual fluctuations are small (particularly compared to other climate indicators, such as global mean surface temperature), the combined effect with long-term trends determines total annual OHC[6]. Given that 2023 was the warmest year on record for global surface temperature, it is to be expected that OHC also exhibited a record value[3].

Here, we document the status of OHC for 2023, focusing on gridded observations (the IAP/CAS-OHC dataset[3], which compiles all available measurements from the surface down to the abyss) supplemented by deep ocean observations below 2000 m (ref. 7), satellite observations[8,9] and state-of-the-art climate model results[6] (Supplementary Information).

Changes in 2023 ocean heat content

According to IAP gridded in situ observational data, total global OHC accumulation since 1960 reached 464 ± 55 ZJ (1 ZJ = 10^{21} Joules; throughout, uncertainty represents 90% confidence intervals) in 2023 — the highest levels since reliable records started (Fig. 1a). In fact, OHC records have been broken every year since 2017, highlighting continued ocean warming. For instance, year-on-year increases of 10 ± 6 ZJ were observed from 2019 to 2020, 19 ± 6 ZJ from 2020 to 2021, and 18 ± 8 ZJ from 2021 to 2022, culminating to an increase of 16 ± 10 ZJ from 2022 to 2023. The slightly smaller increment in 2022–2023 compared to the previous two years is likely associated with increased ocean heat release associated with anomalously high sea surface temperature in the tropical Pacific Ocean during the El Niño event in 2023. This slightly reduced heat gain does not affect the long-term continuous increases.

Ocean heat accumulates at different magnitudes depending on the depth level (Fig. 1a) owing to various oceanographic mechanisms[4]. Of the 464 ± 55 ZJ heat accumulated since 1960, 40%, 24%, 28% and 8% are stored within the 0–300 m, 300–700 m, 700–2000 m and >2000 m layers, respectively (consistent with estimates from ten available datasets[2]). In 2023, these values reflect OHC of 185.0 ± 2.9 ZJ (increasing by 17.3 from 2022) for 0–300 m; 110.6 ± 39.7 ZJ (a reduction of 1.3 ZJ from 2022) for 300–700 m; 131.2 ± 32.8 ZJ (a reduction of 0.8 ZJ from 2022) for 700–2000 m; and 37.4 ± 0.5 ZJ (an increase of 1.2 ZJ from 2022) for >2000 m. In general, 2023 reflects greater heat accumulation in the upper layers compared to the deeper layers, consistent with the slower response of the deep ocean to anthropogenic forcings. Some specific differences from 2022 to 2023 also reflect heat redistribution associated with El Niño, namely the redistribution of heat from the 100–700 m layer (−12.8 ZJ from 2022) to the 0–100 m layer (+ 29.0 ZJ from 2022) associated with more tropical thermocline flatting in the Indo-Pacific basin compared to La Niña years and neutral conditions[5].

Changes in OHC also exhibit spatial differences linked to greenhouse gases, aerosol effects and natural variability[3]. All major basins exhibit warming, albeit at different rates. The upper 2000 m Atlantic and Southern Oceans (south of 35 °S) have warmed at a rate of 2.25 ± 0.11 ZJ yr^{-1} and 2.04 ± 0.12 ZJ yr^{-1}, respectively, from 1960 to 2023; that is to say, faster than the Pacific (1.77 ± 0.13 ZJ yr^{-1}) and Indian (0.65 ± 0.08 ZJ yr^{-1}) Oceans (Fig. 1a). In particular, the deep (700–2000 m) warming of the Atlantic Ocean (0.85 ± 0.06 ZJ yr^{-1}) and Southern Oceans (0.67 ± 0.08 ZJ yr^{-1}) is much stronger than that observed in the Pacific (0.36 ± 0.05 ZJ yr^{-1}) and Indian Oceans (0.20 ± 0.04 ZJ yr^{-1}). This basin-wide difference is mainly due to changes in the deep-reaching ocean circulations and stronger mixing in the Atlantic and Southern Oceans that takes heat more efficiently into the deep layers. From 2022 to 2023, the Atlantic, Southern, and Indian Oceans continued the long-term increase of 0–2000 m OHC of 4.3 ZJ, 7.8 ZJ, and 3.2 ZJ, respectively. By contrast, the upper 2000 m of the Pacific Ocean lost −0.1 ZJ heat.

As alluded to, OHC changes in 2023 provide evidence of ongoing and accelerated heat gain. The acceleration is mainly associated with the elevated ocean warming rate since the 1990s, with a two- to four-fold increase in the rate of OHC since this time[2,10] (Fig. 1b; Supplementary Tables 1,2). For instance, the full-depth OHC rate increased from 0.16 ± 0.02 W m^{-2} dec^{-1} over 1960–2023, 0.19 ± 0.03 W m^{-2} dec^{-1} over 1975–2023, 0.06 ± 0.04 W m^{-2} dec^{-1} over 1990–2023,

Key points

- Full-depth OHC peaked in 2023, with 40%, 24%, 28%, and 8% of heat accumulated within the 0–300 m, 300–700 m, 700–2000 m and below-2000 m layers, respectively, since 1960.
- In situ and satellite approaches indicate an increasing — and accelerating — global heating rate, with a trend of 0.16 ± 0.02 W m^{-2} dec^{-1} estimated from 1960–2023.
- Observed global ocean warming in 2023 is consistent with the projection of the CMIP6 multi-model-median.

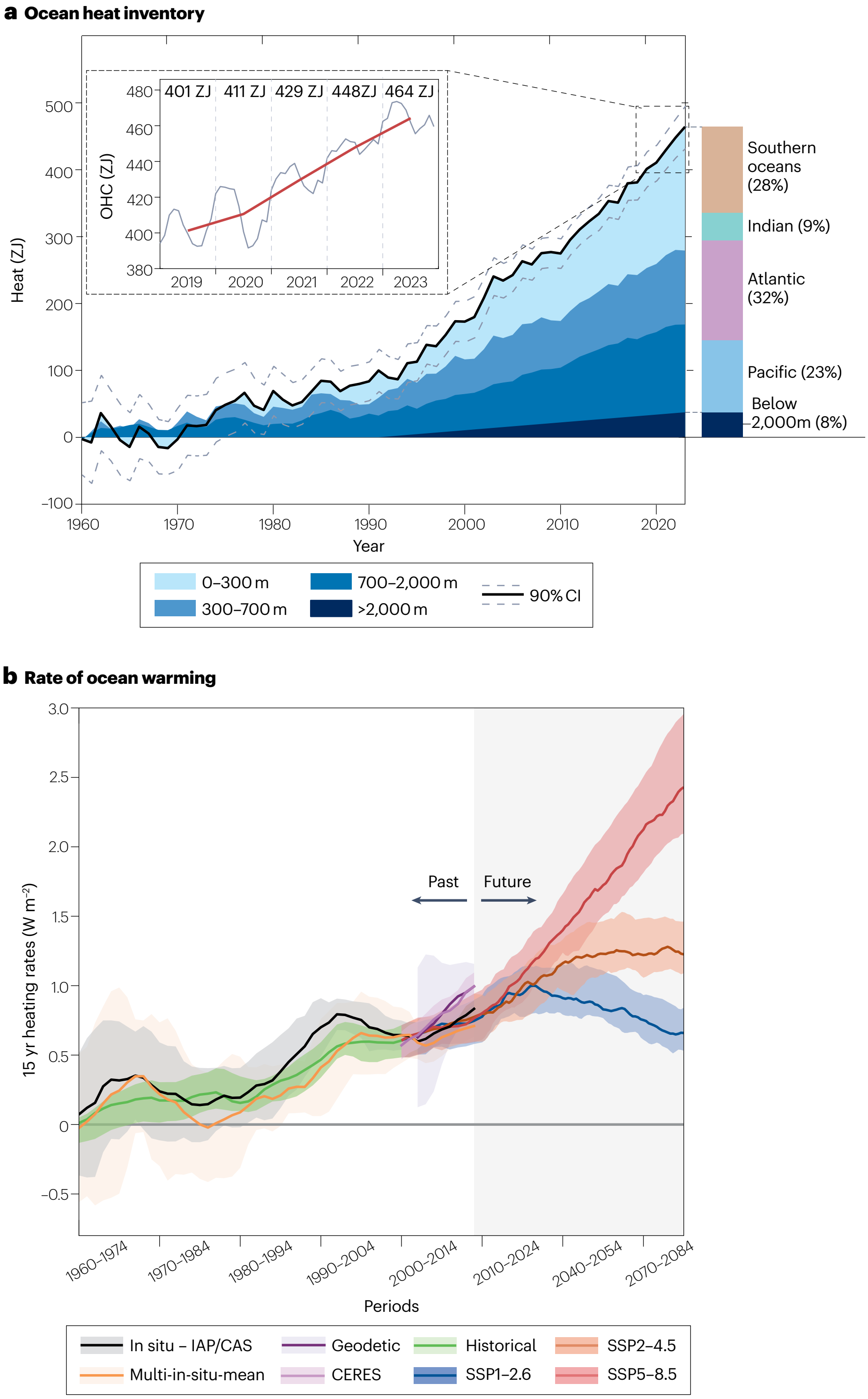

Fig. 1 | Ocean heat content and its rate from 1960 to 2023. a, Full-depth ocean heat content time series from observations[3] relative to a 1958–1962 baseline. Blue shadings indicate OHC changes by depth layer; OHC for the upper 2000 m is from ref. 3 and OHC below 2000 m is adapted from ref. 7 (using a linear increase of 1.17 ± 0.51 ZJ yr^{-1} after 1992 and assuming a zero heating rate before 1991). Grey dashed lines represent the 90% confidence interval (CI) of the OHC estimate, calculated by summing the uncertainty estimates of upper[3] and lower[7] depth layers. The bar on the right depicts the 1960–2023 total heat accumulation by the ocean basin and the below-2000 m layer. The inset displays monthly OHC since January 2019, with the red line depicting the annual means. **b**, Running 15-year OHC heating rates (solid lines) and uncertainties (shading) for the full-depth in situ data[3,7], the full-depth multi-in situ-data[7,10], the geodetic estimate[9], satellite observations at the top of the atmosphere (Clouds and the Earth's Radiant Energy System, CERES)[8], and various CMIP6 multi-model-medians[6]. For observational datasets, uncertainty is represented by 1.65 standard deviations of the linear weighted least squares regression in each 15-year sliding window[10]. For CMIP6, a 17–83% model spread is shown to quantify model uncertainty based on 24 models listed in ref. 1. The *x*-axis is scaled after 2023. Various lines of evidence outline that ocean warming reached the highest observed levels in 2023, continuing the ongoing and accelerating trend that models suggest will continue into the future in the absence of drastic emissions reductions.

to 0.35 ± 0.06 W m^{-2} dec^{-1} over 2005–2023 (Supplementary Tables 3–6; Supplementary Fig. 1, the acceleration is calculated by taking two times the quadratic term of a quadratic regression).

Supporting evidence for ocean warming

In addition to direct evidence from in situ observations, estimates of 2023 OHC changes can also come from other sources, including sea level budgets, model simulations and the Earth's energy imbalance (EEI) (Fig. 1b). As ocean warming, together with ice melt on land, is a major driver of sea level rise[4], the sea level budget can be used to quantify OHC. Geodetic data[9] updated through November 2023 independently confirm that 2023 experienced the highest OHC on record, yielding a total heat increase of 37 ± 21 ZJ from 2022. Although larger than direct in situ measurements, these values are within their range of uncertainty (Fig. 1a). The CMIP6 multi-model-median forced with SSP2-4.5 (an intermediate emission scenario that approximately reflects current emissions) is even more consistent with observations: total heat gains of 14 [10, 20] ZJ (17–83% CI for model results) are apparent from 2022 and 368 [283, 445] since 1960. The choice of the emission scenario has only a small effect on the current OHC increase.

Beyond 2023, these different data products and approaches also provide supporting evidence for OHC acceleration. However, specific numbers differ owing to dataset differences, time periods and methodological choices (Supplementary Tables 3–6). As above, in situ observations suggest an acceleration of OHC gain of 0.16 ± 0.02 W m^{-2} dec^{-1} for IAP/CAS and 0.15 ± 0.03 W m^{-2} dec^{-1} for multi-in situ-data ensemble mean over 1960–2023 (Fig. 1b). For 2005–2023, geodetic data suggest an acceleration of 0.54 ± 0.39 W m^{-2} dec^{-1}. The CMIP6-MMM (with SSP2-4.5 after 2014) reveals an almost identical long-term acceleration as compared to the observations: from 0.15 [0.13, 0.21] W m^{-2} dec^{-1} over 1960–2023 to 0.19 [-0.00, 0.36] W m^{-2} dec^{-1} over 2005–2023 (Fig. 1b). CMIP6 models project that this warming acceleration will only cease between about 2030 and 2040 under a low-emission scenario (SSP1-2.6)[1], by which time full-depth ocean warming rate peaks at ~1 W m^{-2}. For the simulated higher emission paths, ocean warming acceleration will continue throughout the twenty-first century.

Given that ocean warming provides direct evidence that the climate system is out of thermal equilibrium and, hence, accumulating heat, the Earth's Energy Imbalance (EEI)[8] can also be used as a supporting metric. Radiometric data estimates based on satellite observations at the top of the atmosphere (Clouds and the Earth's Radiant Energy System, CERES) indicate an annual mean EEI of 1.8 ± 0.7 W m^{-2} from 2022 to 2023. EEI using geodetic OHC amounts to 2.5 ± 1.4 W m^{-2} from 2022 to 2023. These EEI estimates are broadly similar and within uncertainties with the OHC-based estimates (assuming 90% of the heat goes into the ocean), which is 1.1 ± 0.8 W m^{-2}. As for other OHC metrics, the EEI is increasing. For instance, radiometric data suggest an increasing EEI of 0.57 ± 0.18 W m^{-2} dec^{-1} over 2005–2023, consistent with the geodetic OHC acceleration of 0.54 ± 0.39 W m^{-2} dec^{-1} over the same period (Fig. 1b; Supplementary Table S6). The increase of EEI calculated using in situ OHC data over the same periods are 0.35 ± 0.06 W m^{-2} dec^{-1} for IAP/CAS data and 0.21 ± 0.17 W m^{-2} dec^{-1} for the ensemble mean of other in situ observational data (Supplementary Table S6).

Collectively, these various lines of evidence confirm a robust long-term ocean warming acceleration, with the warming trend progressively increasing since the 1960s. These long-term warming trends set the stage for the record-high OHC in 2023.

Summary

OHC reached a record high in 2023, continuing its long-term increasing trend. Ocean warming has already led to pervasive impacts and consequences, for example, altering ocean circulation, rising sea level and vertical stratification, intensifying tropical cyclones, reducing ocean oxygen levels, melting sea ice and ice sheets from below, busting marine heat waves, and other extremes[1]. With the ocean's large thermal inertia, deep ocean warming is expected to continue for at least hundreds of years. Thus, the consequences of ocean warming are expected to become even more severe. Indeed, the level and the rate of warming depend critically on socioeconomic scenarios, which makes OHC a policy-relevant metric[1]. Detecting changes in ocean warming is crucial for informed decision-making in international climate negotiations to limit anthropogenic warming to specific levels. As a result, it requires sustained and extended monitoring of OHC (and EEI), improved understanding and reduction of uncertainty, and reconciliation of the various heating rate estimates and approaches.

Data availability

Argo data were collected and made freely available by the International Argo Program and the national programmes contributing to it (https://argo.ucsd.edu, https://www.ocean-ops.org). The IAP/CAS (Institute of Atmospheric Physics, Chinese Academy of Sciences) observation and model data used are available at www.ocean.iap.ac.cn.

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Published online: 4 April 2024

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Acknowledgements

L. C. acknowledges financial support from the National Natural Science Foundation of China (grant number 42076202), the new Cornerstone Science Foundation through the XPLORER PRIZE; Youth Innovation Promotion Association, Chinese Academy of Sciences; National Key Scientific and Technological Infrastructure project "Earth System Science Numerical Simulator Facility" (EarthLab). Research by M. H. was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). Research by K. v. S. was carried out at Mercator Ocean International, France. We thank B. Beckley for providing updated GMSL data utilized in the geodetic analysis. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output through the Earth System Grid Federation. The Argo Program is part of the Global Ocean Observing System.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43017-024-00539-9.