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2018 Continues Record Global Ocean Warming

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The increasing heat-trapping gases emitted by human activities into the atmosphere produce an energy imbalance between incoming solar radiation and outgoing longwave radiation that leads to global heating (Rhein et al., 2013; Trenberth et al., 2014; von Schuckmann et al., 2016). The vast majority of global warming heat ends up deposited in the world's oceans, and ocean heat content (OHC) change is one of the best—if not the best—metric for climate change (Cheng et al., 2019). In 2018, continued record heat was measured in the Earth's climate system. In fact, 2018 has set a new record of ocean heating, surpassing 2017, which was the previous warmest year ever recorded (Cheng et al., 2018) (Fig. 1).

Based on the new update of the Institute of Atmospheric Physics (IAP) ocean analysis (see "Data and methods" section), the total ocean heat anomaly in 2018, relative to a 1981–2010 baseline, and for the upper 2000 m of the world's oceans, is $(19.67 \pm 0.83) \times 10^{22}$ J. This level of thermal energy places 2018 as the hottest year ever recorded. Figure 1 shows the progression of upper 2000 m OHC since the late 1950s. The ranking of the five warmest years (Table 1) makes the past five years the warmest years on record. This supports the provisional announcement by the World Meteorological Organization in November 2018 that "the ocean heat content was the highest or 2nd highest on record". And the new record in 2018 confirms the perspective (Cheng et al., 2019) that ocean warming continues and has been accelerating since the 1990s (compared with 1960 to the 1980s).

The heating was distributed throughout the world's oceans, with the vast majority of regions showing an increase in thermal energy (Fig. 1). The Southern Ocean (south of 30°S) and Pacific Ocean showed more warming than the Atlantic Ocean and Indian Ocean (Shi et al., 2018; Swart et al., 2018). The Southern Ocean and Pacific Ocean (north of 30°S) were $(6.91 \pm 1.70) \times 10^{22}$ and $(5.97 \pm 1.07) \times 10^{22}$ J above the 1981–2010 period, respectively. In comparison, the values for the Atlantic Ocean (north of 30°S) and Indian Ocean (north of 30°S) were $(4.95 \pm 1.97) \times 10^{22}$ and $(1.84 \pm 1.97) \times 10^{22}$ J. The spatial pattern also indicates some imprints of internal variability in the climate system (Cheng et al., 2018). For example, in 2018, the tropical Pacific transformed from a La Niña state in the early part of the year into a weak El Niño condition later (see "Data and methods" section). The heat was recharged in the equatorial regions within 10°S–5°N (Fig. 1), leaving negative OHC anomalies in the north subtropical Pacific Ocean (5°–15°N). The Indian Ocean continued its rapid warming trend since the 1990s, partly linked to both anthropogenic forcing and the Pacific Decadal Oscillation (Li et al., 2018).

Increases in ocean heat are incontrovertible proof that the Earth is warming (Fig. 1). The long-term trend of ocean heat is a major concern both in the scientific community and for the public at large. The increased temperatures cause a thermal expansion of water and a rise in sea level (Nerem et al., 2018; WCRP Global Sea Level Budget Group, 2018). The increase in ocean heat of $(19.67 \pm 0.83) \times 10^{22}$ J in 2018 resulted in a 29.5 mm global mean sea level rise above the 1981–2010 average, and 1.4 mm above 2017. The resulting sea level rise exposes coastal freshwater supplies to saltwater intrusion, makes communities

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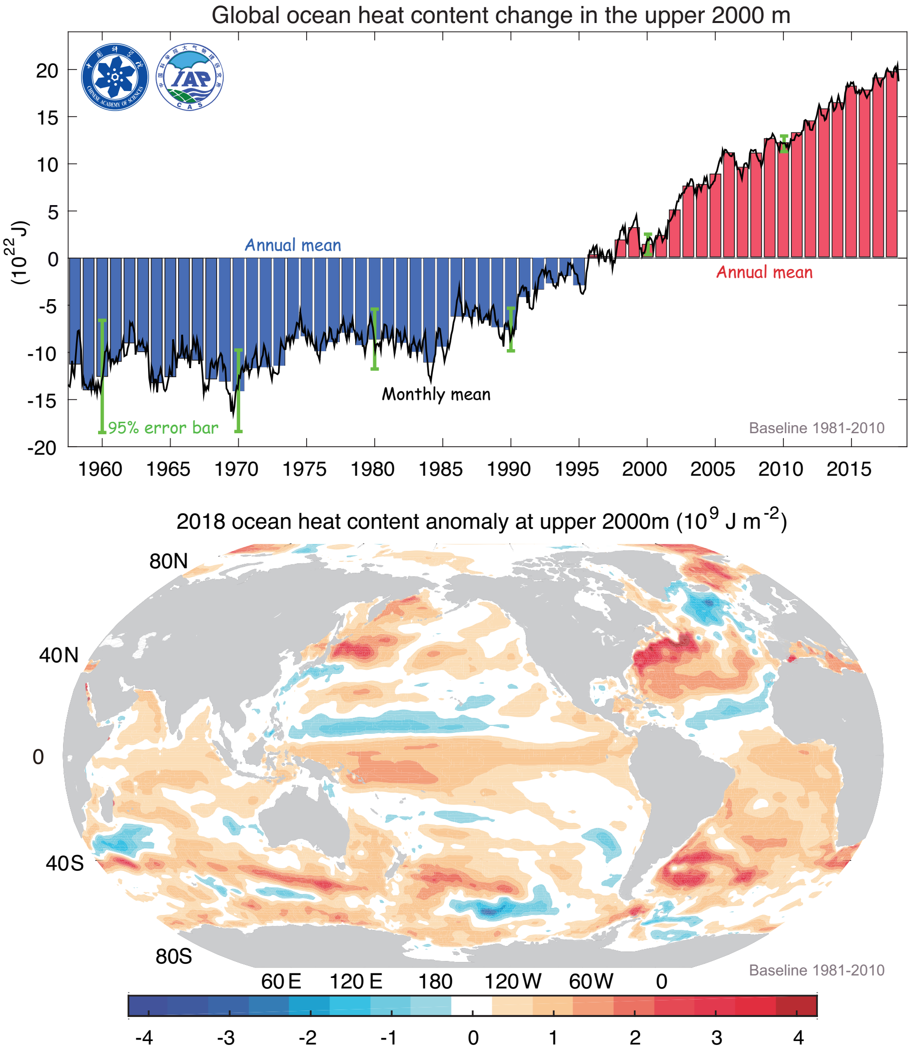

Fig. 1. Upper panel: Change in 0–2000 m OHC from 1958 to 2018. Each bar shows the annual mean relative to a 1981–2010 baseline (positive in red and negative in blue). The green error bar indicates the 95% confidence interval, and the black line is the monthly time series. Lower panel: Annual mean OHC anomaly for the upper 2000 m in 2018 relative to a 1981–2010 baseline. Units: 10^9 J m^{-2}. Source: IAP ocean analysis.

Table 1. Top five warmest years in the ocean since 1958. The OHC values in the upper 2000 m are the anomalies (units: J) relative to the 1981–2010 average.

Rank	Year	OHC (J)
1	2018	$19.67 \pm 0.83 \times 10^{22}$
2	2017	$18.76 \pm 0.80 \times 10^{22}$
3	2015	$17.99 \pm 0.70 \times 10^{22}$
4	2016	$17.47 \pm 0.76 \times 10^{22}$
5	2014	$16.22 \pm 0.70 \times 10^{22}$

more susceptible to storm surges, and threatens coastal infrastructure. The current sea level and its associated pattern is expected to continue and accelerate in the near future (Fasullo et al., 2018).

The increase in ocean heat (Fig. 1) also affects the planet's weather systems, by raising air temperatures and supplying more moisture; warmer air can hold more moisture at a rate of about 7% $°C^{-1}$ (Trenberth, 2011). In turn, this leads to increases in the intensity of storms and heavy rains (Patricola and Wehner, 2018; Trenberth et al., 2018). In 2018, the world experienced a number of major tropical storms, some of which developed very rapidly and many caused death and destruction. These included hurricanes Florence and Michael in the Atlantic, and major typhoons Jebi, Maria, Manghut and Trami in the

Pacific. Typhoon Mangkhut was the planet's most intense storm of 2018, with winds of 287 km h^{-1}; it caused huge damage in Hong Kong. Several of these storms caused major flooding, especially Florence in the Carolinas. Other storms also led to major flooding events in Japan in July, and Kerala in India this past summer. Several hurricanes passed or hit Hawaii (e.g., Olivia, Lane), with Lane dropping more than 50 inches (1270 mm) of rain on Hawaii. It was the second-largest rainfall total from a tropical cyclone in the United States since 1950 (after Harvey in 2017). Hurricanes and other storms are natural phenomena and they are affected by many other factors besides ocean changes, but conditions allowing for the formation of severe hurricanes are occurring more often because of the record high OHC, with increases in intensity, lifetime, size, and especially increases in heavy rainfall (Patricola and Wehner, 2018; Trenberth et al., 2018; Wu et al., 2018).

Other consequences of ocean warming include declining ocean oxygen (Schmidtko et al., 2017), bleaching and death of corals (Hughes et al., 2018), melting sea ice and ice shelves directly through bottom heating (WCRP Global Sea Level Budget Group, 2018), increasing marine heat waves (MHWs) (Oliver et al., 2018), and altered impacts of natural variability such as ENSO (Fasullo et al., 2018). These consequences are not fully but at least partly attributable to ocean warming (IPCC, 2018). For example, 99% of the coral reefs will bleach if the surface warming reaches 2°C in 21st century because of ocean warming and acidification (IPCC, 2018). In 2018, MHWs were recorded in the Northwest and Southwest Pacific and the Northwest and Southwest Atlantic Ocean from sea surface temperature records. MHWs are defined as periods of extreme warm sea surface temperature that persist for days to months (Frölicher et al., 2018), supported by higher than normal OHC. MHWs in Northeast China during July–August 2018 took a heavy toll on sea cucumber farms. In addition to ocean-related effects, there are other indirect effects of ocean heating, such as increased drought intensity, heatwaves, and risk of wildfire.

Ocean warming clearly indicates a global warming since the 1950s, and the consequences of warming oceans are also clear. This global warming is a consequence of greenhouse gas (GHG) trapping of heat radiation within the Earth's system. Owing to the longevity of carbon dioxide and other GHGs, plus the thermal inertia of the climate system (Le Quéré, 2018), mitigating changes and the risk of major socioeconomic consequences due to ocean and global warming hinges on taking steps to immediately reduce GHGs emissions (Gattuso et al., 2018; IPCC, 2018).

Data and methods

The method used here, which was developed at the IAP, involves calculating ocean temperatures down to 2000 m using observations from various measurement devices (Abraham et al., 2013; Cheng et al., 2017). The data are available at http://159.226.119.60/cheng/. The in-situ temperature measurements that were input into the IAP calculation are available from the National Oceanic and Atmospheric Administration/National Center for Environmental Information (NOAA/NCEI) (Boyer et al., 2013). The Argo observing network was implemented in around 2005, which has significantly improved the ocean-measurement capability (Argo, 2000). The Argo data are collected and made freely available by the International Argo Program and the contributing national programs (http://www.argo.ucsd.edu; http://argo.jcommops.org). The Argo Program is part of the Global Ocean Observing System. Note that relatively little is known about the deep ocean below 2000 m because observations at these depths are sparse (Argo data are mainly available for the upper 2000 m). The information on Hurricane Mangkhut came from https://www.aljazeera.com/news/2018/09/china-hongkong-brace-typhoon-mangkhut-toll-rises-28-180916054503320.html. ENSO information can be found at https://origin.cpc.ncep.noaa.gov/products/analysis_ monitoring/ensostuff/ONI_v5.php.

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