STATE OF THE CLIMATE IN 2024

THE TROPICS

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American Meteorological Society

Cover Credit:

Historic flooding in the River Arts District of Asheville, North Carolina, caused by Hurricane Helene. Photograph courtesy of Stephan Pruitt/Fiasco Media. http://www.fiasco-media.com/

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h. Tropical cyclone heat potential

—J. Trinanes and I-I. Lin

Tropical cyclone heat potential (TCHP) is an indicator of the amount of heat stored in the upper ocean that can potentially promote tropical cyclone (TC) intensification because, in addition to sea surface temperatures (SST), subsurface thermal structure is important for TC genesis and development (Shay et al. 2000; Goni and Trinanes 2003; Lin et al. 2008; Kang et al. 2024; Gao et al. 2025). TCHP is the ocean heat content calculated by integrating the ocean temperature between SST and the 26°C isotherm (D26), which has been reported as a useful predictor for TC intensification (Leipper and Volgenau 1972; Mainelli et al. 2008; Dare and McBride 2011; Knaff et al. 2018). TCs traveling over regions of high TCHP conditions experience higher enthalpy fluxes from the ocean into the atmosphere, favoring intensification and leading to reduced SST cooling (e.g., Lin et al. 2013). Areas in the ocean with TCHP values above 50 kJ cm^{-2} have been statistically linked to TC intensification, including rapid intensification. Rapid intensification is typically defined to be when maximum sustained wind speed increases by at least 30 kt in a 24-hour period and generally occurs in situations in which atmospheric and oceanic conditions are favorable (e.g., Shay et al. 2000; Mainelli et al. 2008; Lin et al. 2020; Knaff et al. 2018, 2020). In addition to upper ocean heat content, upper ocean salinity conditions may also modulate TC intensification as storms traveling over areas of fresh water-induced barrier layers may receive increased air–sea heat fluxes caused by reduced upper ocean mixing and cooling (e.g., Balaguru et al. 2012; Domingues et al. 2015).

In this section we present an assessment and analysis of the upper-ocean heat content conditions during 2024 based on estimates of two parameters: 1) TCHP (e.g., Goni et al. 2009, 2017) global anomalies with respect to their long-term mean (1993–2022) and 2) TCHP anomaly value differences in 2024 compared to conditions observed in 2023. TCHP anomalies during 2024 (Fig. 4.40a) were computed for June–November in the Northern Hemisphere and November 2023–April 2024 in the Southern Hemisphere. The seven regions where TCs are known to form, travel, and weaken/intensify are highlighted in Fig. 4.40. In all these regions, TCHP values exhibit large temporal and spatial variability due to mesoscale features (e.g., surface currents and associated eddies and rings), and short- to long-term modes of climate variability (e.g., the North Atlantic Oscillation, the El Niño–Southern Oscillation [ENSO], the Pacific Decadal Oscillation). The differences in TCHP anomalies between 2024 and 2023 presented in Fig. 4.41 are computed for the primary months of TC activity in each hemisphere as described above.

TCHP anomalies during 2024 exhibited above-average values in all TC regions, and basins with positive anomaly reaching 30 kJ cm^{-2}, showing favorable ocean conditions for TCs, though the increase in the southwest Pacific and northeast Pacific was less pronounced (Fig. 4.40a). Because 2023 was dominated by El Niño, while 2024 saw a transition from El Niño early on to La Niña-like conditions by the end of the year (section 4.1), the TCHP difference between 2023 and 2024 is positive over the western North Pacific (~20 kJ cm^{-2}) while the eastern North Pacific TCHP

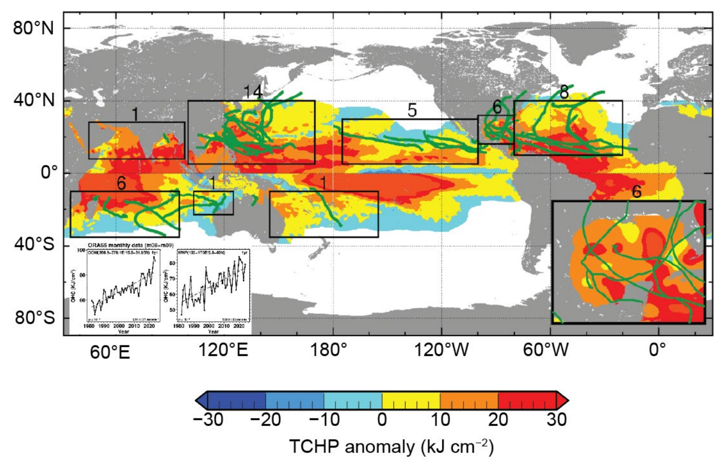

Fig. 4.40. Global anomalies of tropical cyclone heat potential (TCHP; kJ cm^{-2}) during 2024 computed as described in the text. The numbered boxes indicate the seven regions where tropical cyclones (TC) occur: from left to right: southwest Indian, North Indian, northwest Pacific, southeast Indian, South Pacific, northeast Pacific, and North Atlantic (shown as Gulf of America/Gulf of Mexico and tropical Atlantic separately). The green lines indicate the trajectories of all TCs reaching at least Category 1 (1-minute average wind ≥64 kts) and above during Nov 2023–Apr 2024 in the Southern Hemisphere and Jun–Nov 2024 in the Northern Hemisphere, while purple lines indicate Category 1 TCs that occurred outside these periods. The numbers above each box correspond to the number of Category 1 and above cyclones that traveled within each box. The Gulf of America/Gulf of Mexico conditions are shown in the inset in the lower right corner. The two boxes at the bottom left show 40-year ocean heat content (OHC) trends in the northwest Pacific and the Gulf of America/Gulf of Mexico, calculated from the European Centre for Medium-Range Weather Forecasts' Ocean Reanalysis System 4 (ORAS4) data.

difference between 2023 and 2024 is negative (Fig. 4.41). This is understandable given that during the 2023 El Niño event, eastern North Pacific SSTs were much higher when compared to a year that shifted toward La Niña conditions (i.e., 2024). Pronounced TCHP positive differences in 2024 (as compared to 2023) were also observed in the southwestern Indian Ocean. In addition to the 2024 comparison with respect to the climatology in Fig. 4.40a and interannual differences with 2023 in Fig. 4.41, long-term ocean heat content (OHC) trends over major TC basins were calculated using 43 years of ocean reanalysis data from the European Centre for Medium-Range Weather Forecasts' Ocean Reanalysis System 4 (ORAS4) data. As given in the examples below (Figs. 4.40b,c), both the northwest Pacific Ocean and the Gulf of America/Gulf of Mexico exhibit robust increases in OHC of ~5 KJ cm^{-2} decade^{-1} to 6 KJ cm^{-2} decade^{-1}. This long-term increase indicates an overall tendency for OHC to be more favorable for TC development and intensification.

In terms of individual storms, Hurricane Milton (October 2024) was the most intense TC globally. The storm rapidly intensified to Category 5 intensity over the southern part of the Gulf of America/Gulf of Mexico, where the water was relatively shallow. Over this shallower water region, the OHC computation from satellite altimetry can have more uncertainty, as the entire water column temperature can be above 26°C. As indicated by Price (2009) and Pun et al. (2019), since the entire (shallow) water column over this shallow region is warm, the TC-induced ocean cooling effect can be greatly inhibited, allowing for a high sea–air heat flux favoring intensification. Hurricane Helene traveled in a south-to-north trajectory across the Gulf of America/Gulf of Mexico and rapidly intensified to a Category 4 hurricane (on the SSHWS) before making landfall in Florida. As in Fig. 4.40, the OHC in the Gulf of America/Gulf of Mexico was anomalously positive. Helene's translation speed was fast during its rapid intensification period (~11 m s^{-1}). This fast translation speed can also effectively reduce the TC-induced ocean cooling effect to favor sea–air heat fluxes, since the faster the translation speed, the smaller the cooling effect (Price 1981; Chang et al. 2020). Furthermore, both Hurricanes Milton and Helene occurred during a marine heatwave (Choi et al. 2024).

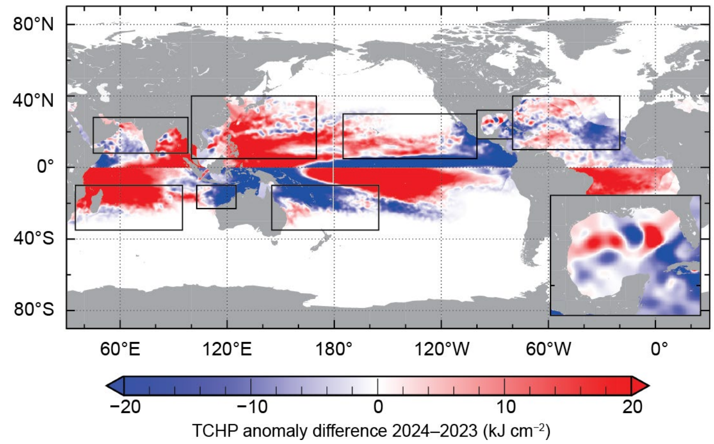

Fig. 4.41. Tropical cyclone heat potential (TCHP) anomaly difference between the 2024 and 2023 tropical cyclone seasons (kJ cm^{-2}; Jun–Nov in the Northern Hemisphere and Nov–Apr in the Southern Hemisphere). The Gulf of America/Gulf of Mexico conditions are shown in the inset in the lower right corner.

Another TC that notably intensified over extremely high OHC was Cyclone Chido over the southwestern Indian Ocean. In December 2024, Chido rapidly intensified to Category 4 and made landfall in southeast Africa with a confirmed death toll of ~170. Finally, over the western North Pacific, Super Typhoon Yagi intensified to Category 4 over OHC of 80 kJ cm^{-2}–90 kJ cm^{-2} over the South China Sea. It was one of the most damaging TCs to both China and Vietnam in recent years, with a death toll exceeding 800.

In summary, increased ocean heat content, along with warm SSTs, favor TC development given similar atmospheric dynamic conditions such as vertical wind shear. From a TC-ocean perspective, the TC-induced cooling effect is inhibited when OHC is high (e.g., Shay et al. 2000; Rogers 2017; Lin et al. 2021). From an interannual perspective, 2024 was primarily an ENSO-neutral year for the Northern Hemisphere TC season, as compared to 2023 when El Niño conditions predominated during the Northern Hemisphere TC season. On longer time scales, OHC in the western north Pacific and Gulf of America/Gulf of Mexico has increased from 5 kJ cm^{-2} decade^{-1} to 6 kJ cm^{-2} decade^{-1} over the past four decades.