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Record High 2024 Sea Surface Temperatures: Impacts on coral reefs and ocean circulation

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Abstract

2024 surpassed 2023 as the hottest year in recorded history (Cheng *et al.,* 2025; Copernicus, 2025, https://climate.copernicus.eu/global-climate-highlights-2024). During 2024 Extremely High Sea Surface Temperature Events (EHSSTEs, here referred to as "HotSpots") proliferated over larger oceanic areas, extended deeper, and persisted longer, than since global SST satellite mapping began in the 1980s. Record High SSTs caused coral bleaching mortality in every coral reef region of the world during 2024 except the Hawaiian Islands, including West Papua, which had never suffered high temperature bleaching. SST patterns in 2024 continued to show accelerated global heat transport from the tropics to polar regions and reduction in ocean vertical mixing. Both act as strong positive climate feedbacks by increasing global warming, Arctic amplification, ice melting, and global sea level rise, while reducing ocean overturning circulation. Coral reefs are undergoing accelerating extinctive evolution, as each new hotter HotSpot causes death of more temperature-sensitive coral populations, and the species that depend on them for food and shelter. They are being replaced by weedy and invasive coral species that provide inferior ecosystem services and exotic species that smother, but don't build, reefs, causing increasing shore erosion. As the result of the last two record hot years, coral ecosystem collapse is now at the point that only direct cooling methods, such as increases in earth's sunlight reflectivity, can possibly reduce ocean surface temperature fast enough to save the rain forests of the ocean from impending ecocide.

Introduction: Coral bleaching HotSpots

Extremely High Sea Surface Temperature Events are measured by the Coral Bleaching HotSpot Index (Goreau and Hayes, 1994: https://coralreefwatch.noaa.gov/product/5km/index.php), a more physiological measure of extreme temperature stress than Marine Heat Wave (MHW) indices (Laufkotter*, et al*., 2020; He, *et al.,* 2024), because they are based on extreme high temperature exposures exceeding coral bleaching limits.

Regional coral bleaching, caused by local stresses has been known for more than a century, but large-scale mass coral reef bleaching across entire ocean basins only began when the Earth's oceans passed the temperature tipping point for coral bleaching in the 1980s (Goreau and Hayes, 2021). Bleaching is a general coral stress response that can be induced by almost any stress (Goreau and Hayes, 1994; Hayes and King, 1995; Glynn, 1996), except acidification. When a coral's skeleton is entirely dissolved in acid, the living coral tissue does not bleach and regrows a new skeleton if transferred to alkaline sea water (Fine and Tchernov, 2007). Nevertheless, almost every article about ocean acidification shows photos of corals bleached by high temperature, a condition NOT caused by acidification!

The original coral bleaching threshold of +1C anomaly above the average temperature of the warmest month for one month was determined by comparing field observations and NOAA satellite SST data (Goreau, *et al.,* 1993), and was chosen to represent field conditions in which almost all reef corals bleached white, but not so severe as to cause significant mortality except to the most vulnerable species (Hayes and Bush, 1990). Similarly, in round numbers, +2C anomaly for a month causes even greater mortality to most corals except the most resistant species. Temperature thresholds vary between and within species (Williams and Bunkley-Williams, 1990, Glynn, 1996). Corals can take months to bleach if temperatures rise slowly, but we have seen corals die in less than a week, too fast to bleach, following sudden extreme temperature rises. Since bleaching is a general stress response (Hayes and King, 1995), additional stresses from high sedimentation, nutrients, pollution, predation, and disease can cause bleaching at lower temperatures, especially in areas subject to multiple anthropogenic stresses such as Florida or the South China Sea (Liu*, et al.*, 2024; Whittaker and De Karlo, 2024).

Existence of multiple bleaching stresses has served as an excuse by politicians, elected officials, and climate change deniers to deny the primary role of high temperature causing large-scale mass coral reef bleaching and blame everything other than global warming as the cause of coral bleaching mortality. Governments have refused to preserve and protect coral reefs, the Earth's most climate-sensitive ecosystem, from dangerous impacts of global warming and sea level rise, as required to meet the goals of the UN Climate Change Conference, in order to avoid commitment to greenhouse gas reductions. Delay and deny tactics have prevented effective action to reduce thermal stress on coral reefs for more than 35 years. If adequately financed and rapidly implemented, the last tropical coral reefs might be saved and imminent global coral reef ecocide avoided (Goreau and Hayes, 2021)

2024 Record temperature distributions: Methods and results

Maps from Copernicus (https://climate.copernicus.eu/global-climate-highlights-2024) show the extent of record highs for both air and sea surface temperatures during 2024 (Figures 1-3).

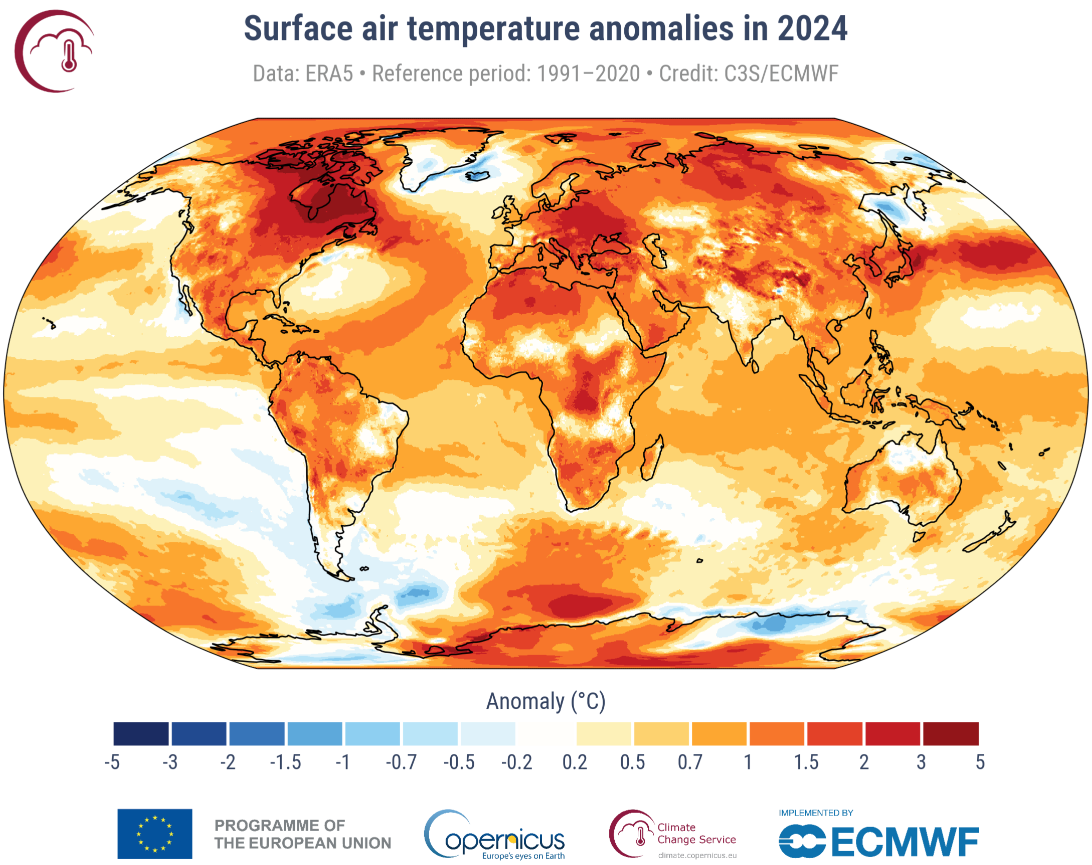

FIGURE 1. Air temperature anomalies during 2024 (in dark red) were generally highest over land (Copernicus, 2025). Severe drought and forest fires took place in Canada, Siberia, Amazonia, and the Congo Basin.

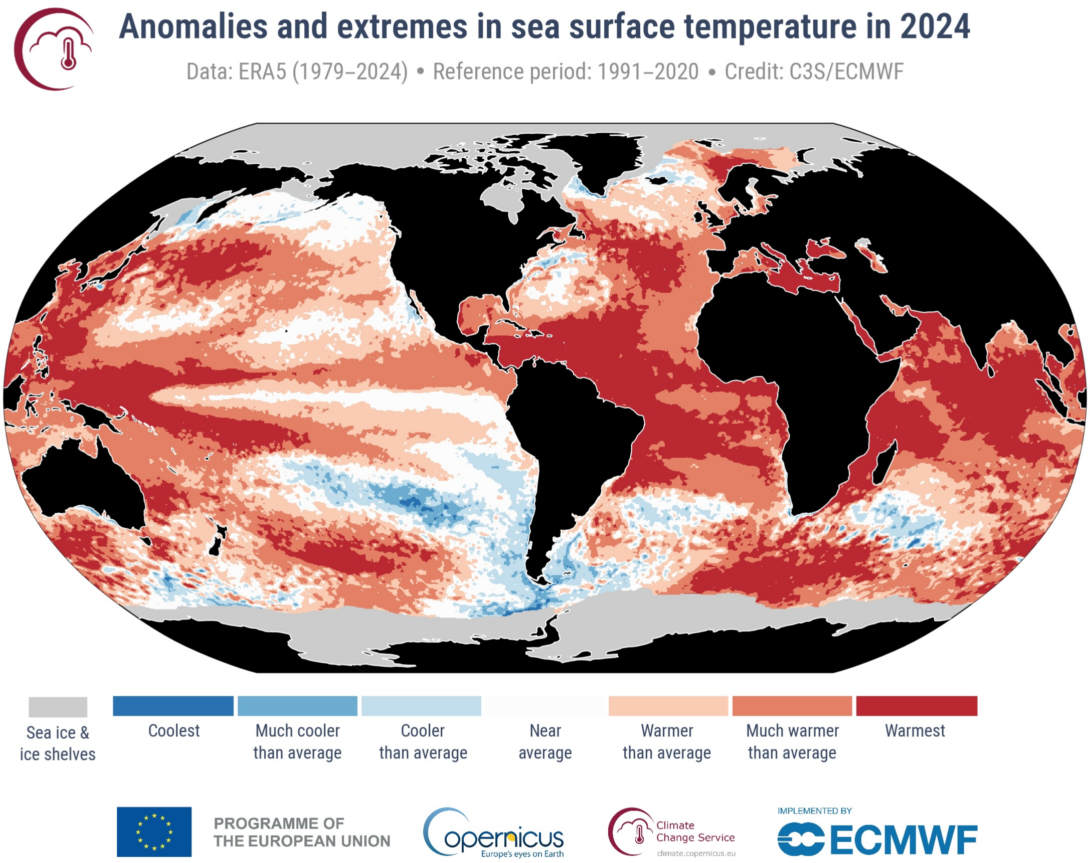

FIGURE 2. SST record high areas during 2024 in dark red occurred in all oceans (Copernicus, 2025). The Southeast Pacific was least affected, cooled by high winds and waves.

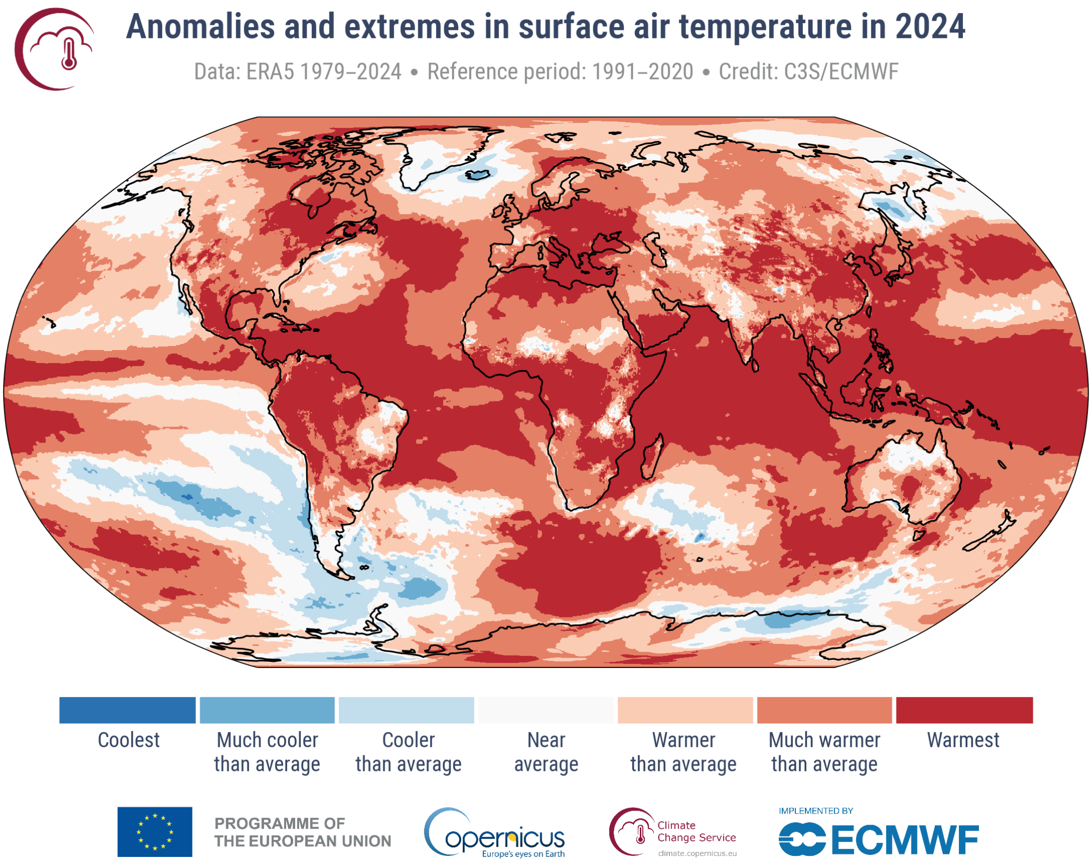

FIGURE 3. Record high surface air temperatures during 2024 in dark red were mainly over the ocean (Copernicus, 2025).

These maps clearly show that while the highest temperatures occurred on land, the oceans served as the major reservoir of excess heat, and suggest that small decreases in heat exchange due to vertical mixing between the surface and deep ocean waters may play a role in causing more heat to remain at the surface, causing increased intensity of HotSpots. Future continuation of the 2023-2024 trend is an existential threat to all remaining shallow coral reefs.

Results: 2024 Maximum HotSpot and Maximum Degree Heating Week Maps

Maximum HotSpot temperatures from the 2024 NOAA satellite sea surface temperature data base are shown in Figure 4: (https://coralreefwatch.noaa.gov/product/5km/index.php).
Maximum Degree Heating Weeks (the product of HotSpot temperatures and their durations in weeks) in 2024 are shown in Figure 5: (https://coralreefwatch.noaa.gov/product/5km/index.php).

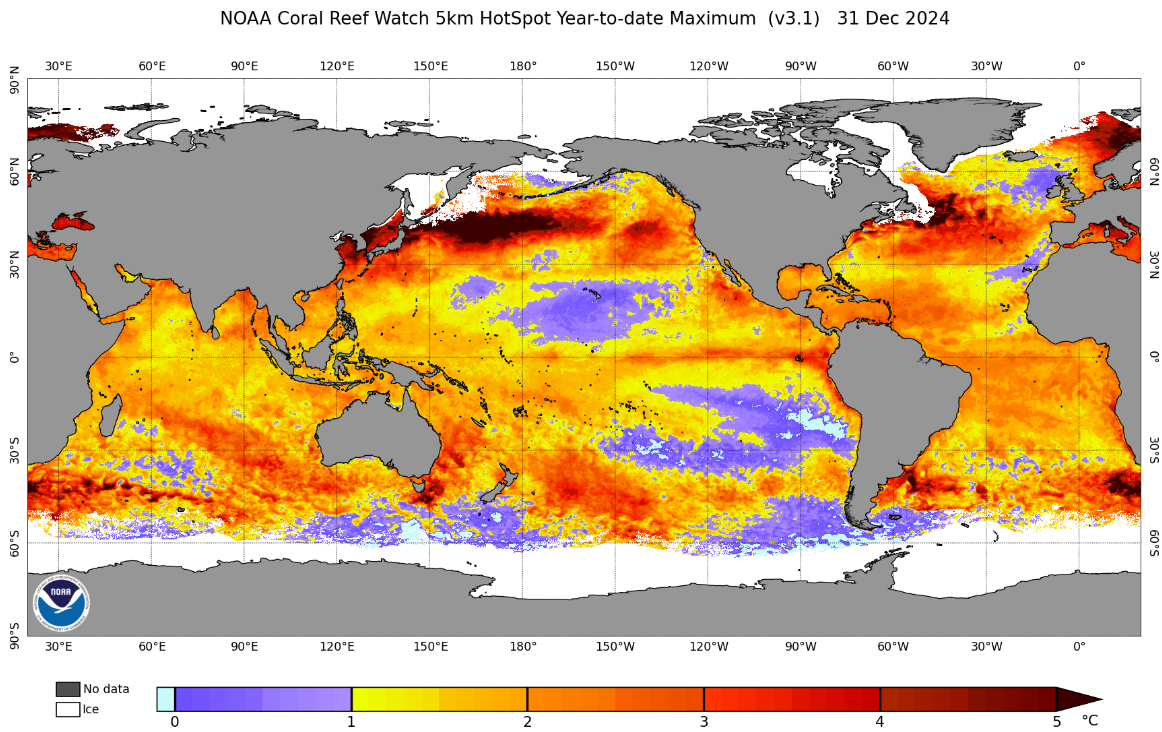

FIGURE 4. 2024 maximum HotSpot (https://coralreefwatch.noaa.gov/product/5km/index.php)

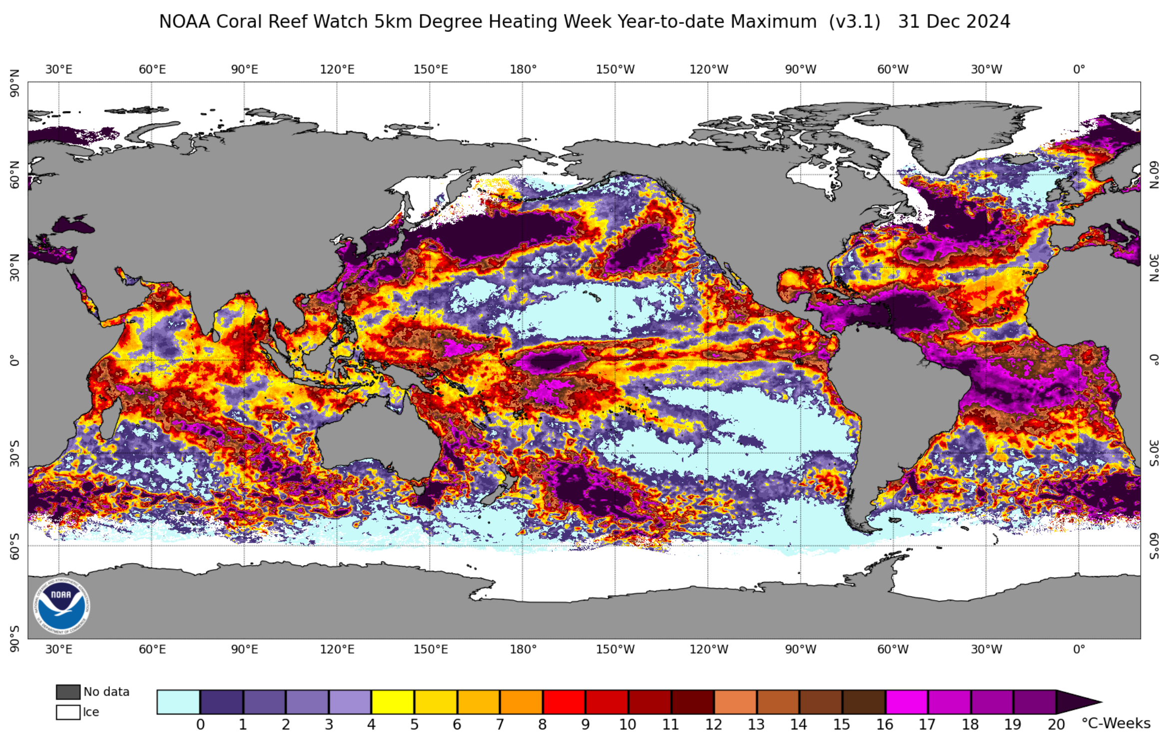

FIGURE 5. 2024 Maximum degree heating weeks (https://coralreefwatch.noaa.gov/product/5km/index.php)

Results: 2024 comparison of extreme HotSpot distributions with 2023.

Comparing the spatial pattern of HotSpots events during 2024 (Figures 4 and 5) to 2023, the previous record hottest year (Goreau and Hayes, 2024), shows that overall HotSpots were hotter, and lasted longer in 2024 than in 2023. This was especially pronounced in the Indian Ocean, Western Pacific, Eastern Caribbean, and in zonal belts at 40-50 degrees North and South latitudes, extending into the Arctic Ocean.

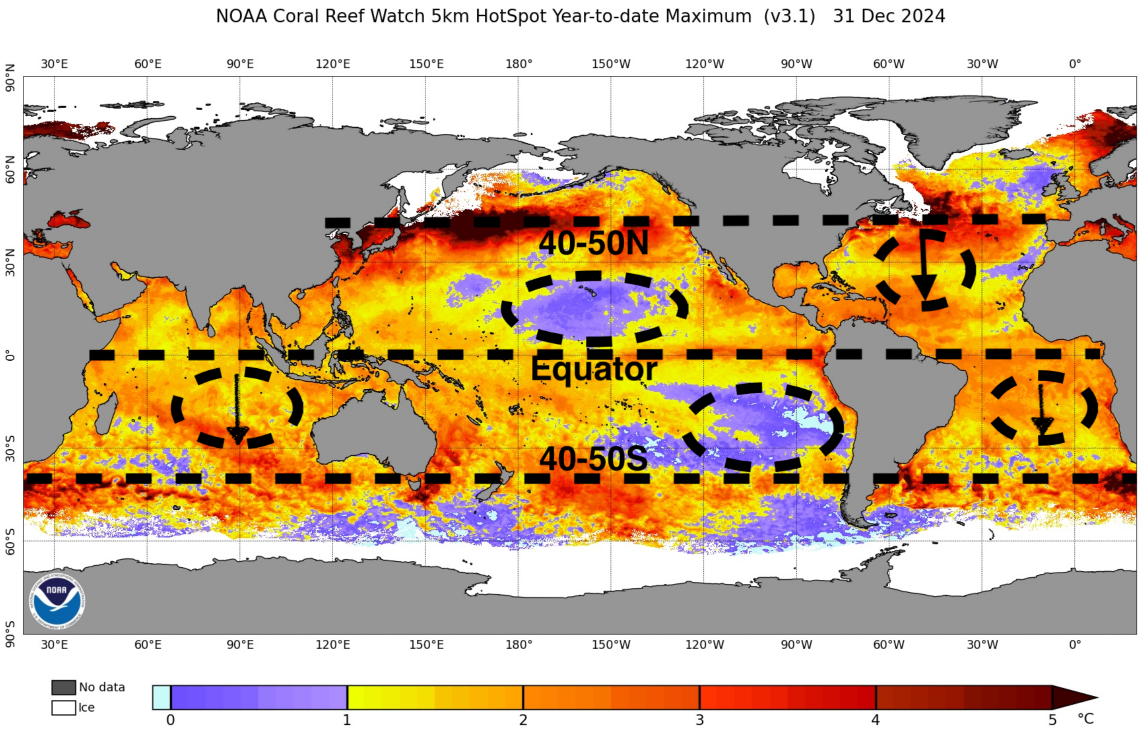

FIGURE 6. 2024 Extreme High Sea Surface Temperature Events with major patterns of heat accumulation shown. Notice the zonal belts of higher temperature (dashed lines) at mid latitudes and failure of three of 5 major ocean downwelling gyres (dashed ovals with downward arrows).

Figure 6 shows that heat absorbed in the tropical ocean is being very rapidly transported poleward, accumulating primarily at latitudes 40-50 degrees North and South (horizontal dashed lines) where, rather than in the Equatorial Zone where most heat is absorbed (Trenberth, 2022). During 2024 three of the five major ocean downwelling gyres (dashed ovals with downward pointing arrows) nearly ceased downwelling heat (downward arrows shown in the SE Indian Ocean, the SE Atlantic, and the NE Atlantic). Only the SE and the NE Pacific downwelling gyres (ovals without arrows) remained stable, pumping surface heat into deeper waters.

Rapid transport of heat poleward, rather than accumulating in the tropics, provides major multiple positive feedbacks on global warming and global sea level rise because it accelerates polar warming, ice melting, sea level rise, and albedo increase (Wadhams, 2017), while at the same time reducing the Atlantic Meridional Overturning circulation (Trenberth, 2022; Pontes and Menviel, 2024; Turner *et al*., 2024).

Slowdown of deep ocean mixing circulation reduces ocean overturning and amplifies surface ocean warming (Trenberth, 2022). The 2023 and 2024 HotSpot maps suggest a declining trend in global vertical ocean mixing, increasing residence time of deep ocean waters, delaying their re-equilibration with the surface thermal balance further into the future ("warming in the pipeline"). The current ocean mixing time is around 1,500 years (Gebbie and Huybers, 2012), but changes in ocean circulation are not included in most climate projections.

A small decrease in vertical mixing can cause large increases in SST, as appears to have happened in 2024. Three of the five major ocean down-welling gyres practically ceased pumping ocean surface heat downwards in 2024, compared to 2023 (Figure 6). Reduced downwelling of surface waters results in greater accumulation of surface heat and likely a significant and overlooked contributor to 2024 record high global temperatures. Changes in SST are also inducing reduction of cloudiness in mid latitudes, accelerating warming in the mid-latitude zone (Loeb *et al*., 2020; Tselioudis et al., 2024; Goessling *et al*., 2024).

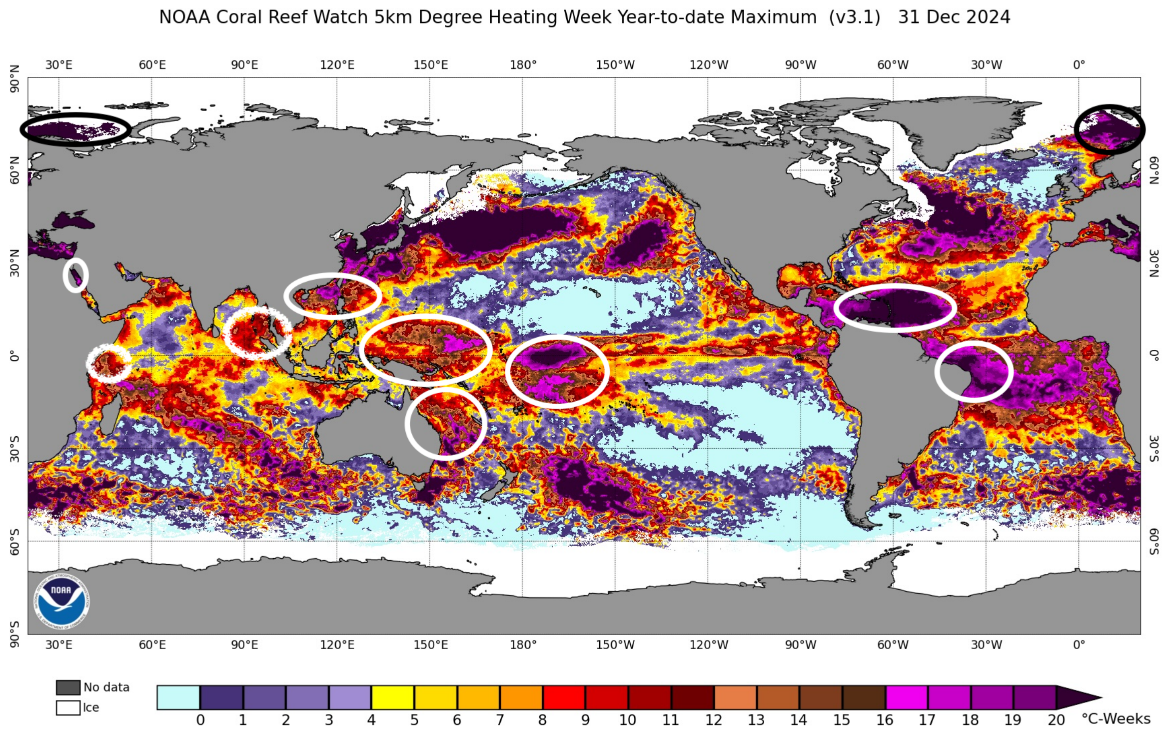

FIGURE 7. Exceptional heat events of biological significance in 2024 on Maximum DHW map. EHSST events are clustered along the latitude 40-50 North and South latitudes and in the areas in highlighted white ovals in the tropics and black ovals in Arctic waters.

The white ovals shown in Figure 7 are coral reef areas that had local reports of serious coral bleaching mortality in 2024. They include all coral reef regions of the world, excepting only the Hawaiian Islands. Areas especially badly affected by coral mortality according to reports from local divers (personal communications from colleagues and postings on the coral list server) included the Caribbean (especially Eastern and Southern), Brazil, the northern Red Sea, East Africa, Thailand, the South China Sea, Papua-New Guinea, Micronesia, the Central Pacific, and both Western and Eastern Australia (Figure 7), with the Great Barrier Reef suffering the worst excess temperatures and massive coral mortality yet (Byrne et al., 2024) It is impossible to get good living coral coverage data after these events because there are few long-term monitoring programs, almost all collapsed during COVID, and dive shops won't report bleaching anymore because it is "bad for business". Coral "restoration" projects based on fragmentation methods failed completely whenever it got too hot (Foo and Asner, 2020), and very few survived 2023 and 2024.

Poleward transport of heat is resulting in the most extreme HotSpots lying outside the tropics. We draw special attention to the latitudinal bands at 40-50 N & S marked by lines, where the most intense heating is accumulating. The extraordinary mid-latitude ocean surface warmth seems to be linked to greater weather variability in mid latitudes, for example fueling extreme heat waves, floods, and even local cold snaps, as an ironic consequence of global warming.

These HotSpot areas are outside the range of coral reefs, the focus of this paper, but all marine organisms in these areas, attached, free living, bottom dwelling, and free swimming, are being affected by unprecedented HotSpots. The biological effects on extratropical biomes include large scale die offs (Szuwalski, *et al.,* 2023; Calbet, 2024; Brachetti, *et al.,* 2024), efforts of pelagic species to migrate towards cooler climates (Griffiths, *et al.,* 2024), local mass extinctions (Song, *et al.,* 2021; Zarzyczny *et al.,* 2024), diseases (Menge, *et al.,* 2016; Smith, *et al.*, 2023), and spread of invasive species (Malve, *et al.,* 2024). These will not be summarized here, as this paper focuses on coral reefs, it is too soon for more definitive information on 2024 yet to be available, and it is expected that a great deal of data will soon be published.

We draw special attention to the unprecedented HotSpots in the Russian Arctic Ocean, which reached up to 7-9 degrees C above average for around 5 months (marked with black ovals). This raises concerns about accelerating ice melt, permafrost melting, and possible release of frozen CO_2 and CH_4, which will be discussed in a separate paper (Goreau and Sarkisian, submitted).

Results: 2024 Coral bleaching

All coral reef regions were affected by HotSpots in 2024 except the Hawaiian Islands. The Eastern Caribbean, the Central Pacific, and the Great Barrier Reef were especially badly affected. At time of submission of this paper, most of Papua-New Guinea, the Solomon Islands, Vanuatu, both coasts of Australia are likely to bleach in early 2025 as well.

Perhaps the only place that had previously escaped severe high temperature bleaching events, Raja Ampat in Western Papua (Indonesia), regarded the most biodiverse reefs on Earth, bleached severely for the first time during 2024 (https://youtu.be/qIGOaow6iuw, https://youtu.be/Tqyct_vxCkc). Local divers blamed untreated sewage from an out-of-control tourist dive industry, but bleaching followed several months of local SSTs above the bleaching limit and were likely caused by high temperature, although local pollution is an exacerbating local bleaching driver. Raja Ampat reefs are remarkable because hard coral growth is confined to shallow water by a sharp thermocline. Below this boundary the slopes are covered with soft corals, sponges, and cyanobacteria. The water is cold and turbid, due to intense upwelling of deep cold water entrained by the Indonesian Through-Flow from the Western Pacific into the Eastern Indian Ocean. Such local refuges from bleaching are vanishing world-wide as their corals are likely to die whenever rising temperatures exceed their upper tolerance limits.

A unique case of coral reefs being saved on a local scale by exceptional local weather conditions is shown by the Playa Coral and Laguna de Maya Marine Protected Area at Bahia de Matanzas, Cuba. Coral conditions at this site are now regarded as the finest in Cuba by the University of Havana Institute of Marine Science coral monitoring team led by Dr. Patricia Gonzalez. This site had the least high temperature stress of any reef in the Caribbean in both 2023 (Figure 8) and 2024 (Figure 9). The Playa Coral and Laguna de Maya Marine Reserve, located in this small cool spot, was probably the only Caribbean reef area that avoided significant bleaching damage in 2023 and 2024, due to unique circumstances related to local cloudiness, rains, turbidity, ocean currents, and localized upwelling (NYAS, 2024). The exceptional conditions of the corals there make it a prime location for propagating surviving corals with methods that speed up coral growth and stress resistance, like Biorock electrical stimulation methods (New York Academy of Sciences, 2024).

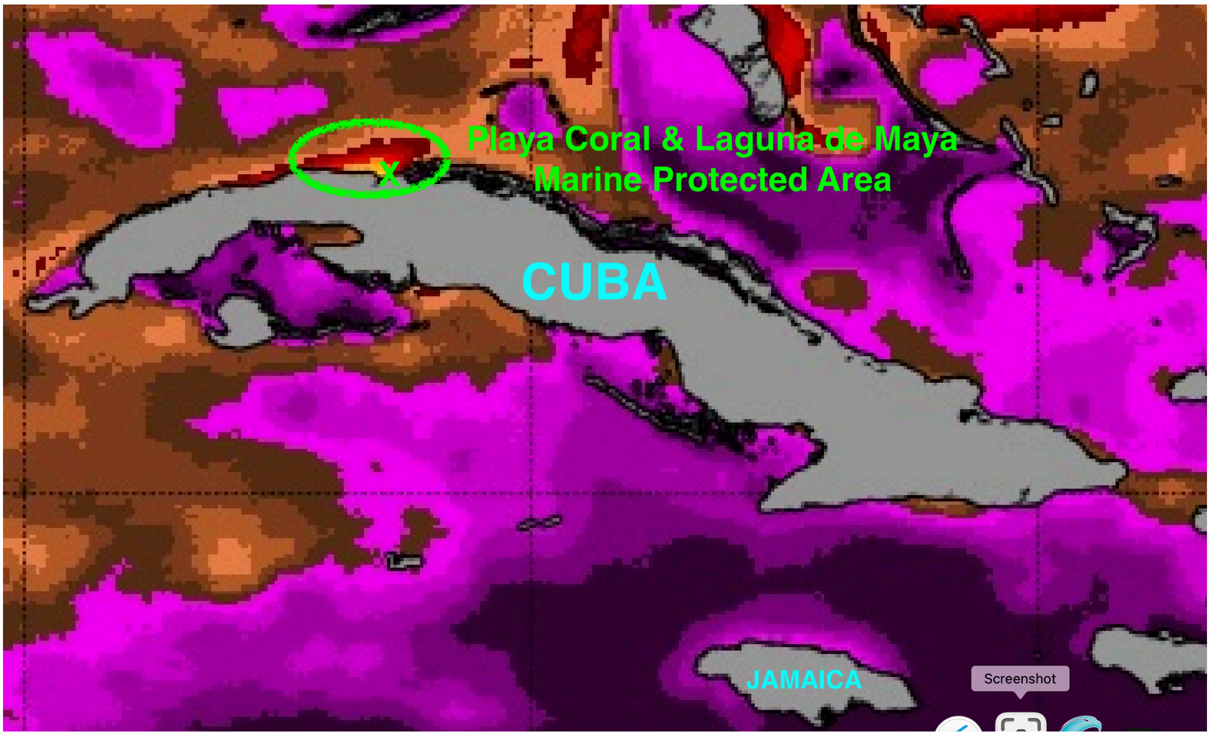

FIGURE 8. 2023 Maximum DHW maps showed a small exceptional area of cool water in the Bahia de Matanzas, Cuba. DHW temperature scale same as previous figures. This figure is a magnification of the Caribbean image in Goreau & Hayes, 2024.

A key factor in this area having the coolest reefs in the Caribbean in 2023 (Figure 5) and 2024 (Figure 6) is that NW Cuba is impacted directly by the Gulf of Mexico Loop Current. The current hits the NW Cuban coast from the north, and is reflected to form the core of the Gulf Stream flow northwards. The reflection appears to induce a narrow band of shelf edge upwelling, cooling the water by about one tenth of a degree. This local cooling seems to have saved the reefs so far (Figure 10), but will be overwhelmed if global warming continues uncontrolled.

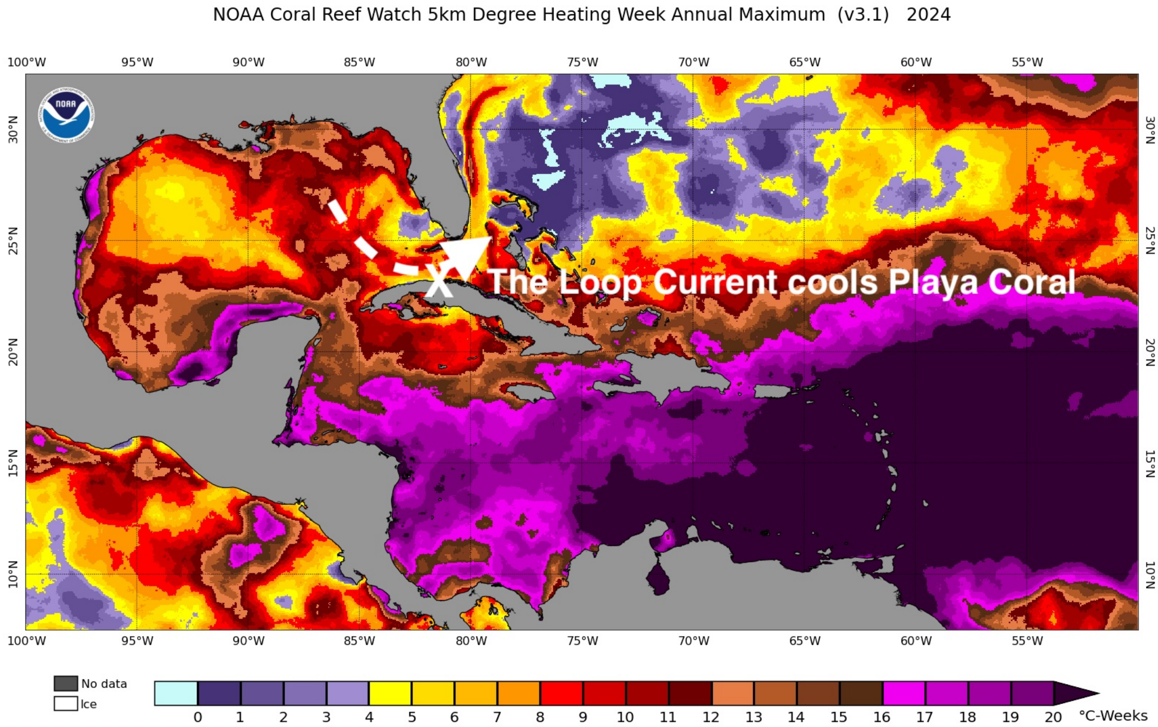

FIGURE 9. 2024 Maximum DHW map for Caribbean showing that Playa Coral (X mark) was again cooled by the loop current (white dashed arrow), avoiding the severe bleaching in the Eastern and Southern Caribbean. In both 2023 and 2024 a very thin light blue band hugs the coast along Playa Coral.

FIGURE 10. Healthy corals in the Playa Coral & Laguna de Maya Marine Protected Area, Cuba, January 24, 2025, photograph by Luis Muiño. https://dive.site/es/explore/dive-centers/atlantis-varadero-coral-beach-base-0gxL?location=varadero-73Rj

Discussion: Comparison with 1986-2022 Satellite SST records show increasing apparent bleaching thresholds and frequency as temperature sensitive corals die

Comparison of the 2024 and 2023 maximum HotSpot and Maximum DHW with the previous global maps since 1986 (Data appendix. See animations to track changes in extreme high temperature events worldwide on year by year maps at:

https://youtu.be/6OyKgtrGXHc
https://youtu.be/8XlRwGAFVds

These clearly show how exceptional 2023 and 2024 were in terms of HotSpot duration compared to previous years and their extreme recent persistence in mid latitudes in recent years, standing out from even the most extreme previous ENSO years.

In general, HotSpots are becoming hotter, lasting longer, and appearing more frequently. But there is considerable regional variability, and some areas are warming much faster than others, such as the Great Barrier Reef. Coral bleaching has changed from irregular regionally distinct patterns, often influenced by teleconnections to El Niño Southern Oscillation (ENSO) index variations of roughly 6-8 years (Trenberth, 2022), into nearly annual events. The Maldives did not have a major bleaching event between 1998 and 2016, years when the ENSO and Indian Ocean Oscillations added up, but has since had several smaller bleaching events. The Great Barrier Reef has had more than a dozen major bleaching events since 1986 visible on the HotSpot maps, at first often 5-8 years apart, but becoming more frequent, and now becoming quasi-annual (see data appendix for the maps from 1986 through 2024 which can be seen as a time lapse animation). Since some coral bleaching survivors require more than a year to recover from bleaching, don't reproduce while bleached, and free-swimming coral larvae and algae are even more sensitive to high temperatures than adult attached coral colonies (Sammarco and Strychar, 2013), annual bleaching seasons are now overlapping, and many surviving adult corals are unable to reproduce.

Coral bleaching can only continue as long as there are living corals left to bleach, and these are steadily vanishing almost everywhere as the result of repetitive bleaching events and increasingly extreme HotSpots. Each event kills coral colonies most sensitive to high temperature, so Darwinian evolutionary selection is underway for the survivors. Mass bleaching now takes place at higher temperatures than those that caused earlier events (clearly visible from the time series images in the data appendix), simply because the most vulnerable corals are gone. This apparent increase in bleaching thresholds is not necessarily because corals are acclimating or adapting to higher temperatures, as has been claimed (Buddemeier and Smith, 1999).

In most coral reefs the species that used to be most abundant, especially *Acroporas* and *Montiporas*, have practically vanished, and are being replaced by weedy corals (*Porites* and *Pocillopora* in the Indo-Pacific, *Porites* and *Millepora* in the Caribbean). These spread rapidly by breeding on a lunar cycles rather than annually, and brooding their larvae, allowing them to very rapidly cover dead reef rock. Most never build large reefs because they are "determinate" species, genetically programmed to reproduce fast, grow to a small maximum size, and die young. Unfortunately, these weedy species rarely provide significant ecosystem services such as fish habitat or wave protection. They are somewhat more resistant to high temperatures, but also will die whenever temperatures get slightly warmer. The major exception are the *Porites* corals, the most stress resistant of all, which are now taking over coral reefs because they are the last survivors. Nevertheless, they too are very close to their upper temperature limits, and will die if temperatures continue to increase faster than evolutionary adaptation can take place. The collapsing biodiversity of hard coral reefs is being overwhelmed by spread of invasive soft corals, sponges, tunicates, and algae, many of exotic origin and recent spread. These species smother dead reef, promote its disintegration by bio-erosion, and don't grow wave-resistant limestone reefs that keep up with sea level rise and superior fish habitat, which only healthy hard coral reefs provide.

If global warming is not stopped, reefs will be dominated by a handful of weedy hard coral species and invasive non-coral species that smother corals and don't grow limestone reefs, and tropical shorelines will wash away because dead coral reefs that provided and protected their white sand beaches will erode and crumble (Zhang et al., 2024; Storlazzi *et al.,* 2024). There is a slight possibility of new weedy species of hard corals becoming prominent, as has observed with a *Montipora* species in Micronesia

(Bernardi et al., 2024). Clones of a different species of *Montipora* have overgrown up to 100 meters of dead and living coral reef in the Maldives since the 2016 mass bleaching die off (T. Goreau, personal observations, December 2024). While these extraordinarily fast-growing corals may provide some hope for propagation, it is not yet known how vulnerable they will be to the next major bleaching event.

Conclusions: Direct cooling and albedo feedback for reversing coral reef ecocide

In 2025, following two years of record coral bleaching and mortality, global coral reef ecocide is already largely over, caused primarily by global warming and other insults to coral health from humans using the oceans, atmosphere, and soils as sewers. If these negative climate and ecological trends are not reversed immediately by deliberate and conscientious international action, it is only a matter of time before the extreme ecological events cause the last surviving coral reefs to die. Based on past severe hyperthermal extinctions, coral reefs could take millions of years to re-evolve after the runaway overshoot warming our current path will take us on.

Accelerated collapse of coral reef ecosystems in 2023 and 2024 leaves little, if any, time left for effective coral reef salvation. GHG pollution must stop, and the polluters must pay to remove their pollution (Goreau, 1987), but it is already probably too late to turn off our fossil fuel addiction and regenerate our ecosystems fast enough to stabilize CO2 at safe levels for coral reefs (Goreau, 2014). Even if we had wise and informed leaders, universal political good will, adequate and properly allocated funding, and a global commitment to future generations, these methods won't work fast enough UNLESS physical methods are also used to directly cool the planet (Baird, 2024) or make the Earth more reflective and less dark (Baiman, *et al.,* 2024). The refusal of the largest fossil fuel producers to reduce production marks the final death sentence for coral reefs.

This is not the place to discuss global cooling options (Baiman, *et al.,* 2024), but survival of coral reefs for the next several million years now depends on immediate large-scale implementation of such direct cooling technologies. Our advice to those in decision-making positions is to come to the rescue of both global coral reef ecosystems and human populations that bear the brunt of this threat. There is no time to waste if services of the reef community and contributions of people from coral reef coasts are to be salvaged. Lack of support to these populations would be unforgivable, irretrievable and inhumane. We can only hope action comes in time to save the Rainforests of the Ocean and their people from fossil fuel ecocide.

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Data appendices

1986-2024 maximum HotSpots and Degree Heating Weeks:

https://youtu.be/6OyKgtrGXHc

https://youtu.be/8XlRwGAFVds

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