GLOBAL WARMING

Coral reefs in peril in a record-breaking year

Climate change and its impacts on coral reefs have reached unchartered territory

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The upper ocean is undergoing unprecedented changes in conditions, ecosystems, and communities. These changes can be traced back to the early 1980s, when mass coral bleaching first appeared. Marine heatwave (MHW)–driven events are strongly correlated with rising sea surface temperature (SST) and climate cycles such as El Niño–Southern Oscillation (ENSO). SSTs in 2023 have been starkly different because extreme MHWs have engulfed much of the eastern tropical Pacific (ETP) and wider Caribbean. Many Caribbean reef areas experienced historically high heat stress that started much earlier (1 to 2 months) and was sustained for longer than the usual recorded seasonal changes. Patterns of SST from the past 40 years indicate that unprecedented mass coral bleaching and mortality will likely occur across the Indo-Pacific throughout 2024. These trends will worsen unless greenhouse gas (GHG) emissions decrease, with coral-dominated ecosystems likely to face substantial losses, leading to long-term damage to ecosystems and people across Earth's tropical regions (*1*).

Earth experienced its warmest days since 1910 in early July 2023, as well as the warmest month for SSTs (see the figure and fig. S1). Anomalously high SSTs in the ETP and wider Caribbean are more extensive now than in any other year on record (which started in the early 1980s). Individual coral reefs reached record levels of heat stress up to 12 weeks ahead of previously recorded peaks. Heat stress puts immense pressure on vital but fragile tropical ecosystems such as coral reefs, mangrove forests, and seagrass meadows. For example, Newfound Harbor Key, a coral reef in the Florida Keys, accumulated heat stress that was almost three times the previous record, with this occurring 6 weeks ahead of previous peaks (see the figure and fig. S2). This trend has occurred at all reefs in the Florida Keys and at many reefs throughout the wider Caribbean.

Historical data suggest that the present MHWs that are occurring throughout the ETP and wider Caribbean will likely be the precursor to a global mass coral bleaching and mortality event over the next 12 to 24 months as the El Niño phase of ENSO continues. ENSO is a recurring climate pattern that involves periodic changes in the temperature of waters in the central and eastern tropical Pacific Ocean, where El Niño is a warm phase that causes higher SSTs and La Niña is the cool phase. The difference between each ENSO phase (a natural cycle) is being amplified by climate change (*2*). The present El Niño conditions are predicted to persist for at least the first quarter of 2024. Since 1950, an El Niño state that is present for the last 6 months of a given year and for at least 3 months in the following year has occurred seven times. In every instance except one, the second year was the warmer of the two; the cooling effect of the Mount Pinatubo eruption in the Philippines during June 1991 thwarted this pattern in 1991–1992. Since 1997, every instance of these El Niño pairs led to a global mass coral bleaching and mortality event. The global extent of heat stress is indicated by degree heating week (DHW). DHW is a satellite-based metric of heat stress that measures the accumulation of daily SST anomalies over a 12-week period, with values at or above 4 indicating coral bleaching (see the figure). Crucially, 2023 is the first year of a potential pair of El Niño years with the warmest average global SST for February to July on record.

Warming seas and associated MHWs disrupt the intricate balance of marine ecosystems, such as coral reefs, that affects the distribution, health, and abundance of many species and ecological processes. Mass coral bleaching occurs when corals become stressed from factors such as SST, which causes them to lose their brown microbial symbiont, turning them white. At low-stress levels, the symbionts may return to coral tissues over a few months. Increasingly, stress levels are killing corals irrespective of their bleaching status. Seabirds and marine mammals that require specific temperatures for breeding, feeding, and migration are also at risk, as are large-scale biogeochemical cycles, such as the nitrogen cycle that drives nutrient generation (*1*, *3*, *4*). Furthermore, the increased prevalence of harmful algal blooms and the spread of invasive species and diseases are additional consequences of warming seas, which can have cascading effects throughout the food web and associated marine ecosystems. Outbreaks of coral disease have occurred for months to years after all prior mass bleaching events in the wider Caribbean, which has often led to higher rates of mortality than the initial heat stress (*5*). These effects, coupled with the present record-breaking MHWs in the ETP and wider Caribbean, are a poignant reminder of the risks of unchecked GHG emissions and attendant global warming (*3*, *6*).

Until now, efforts to curtail GHG emissions to the Paris Agreement objectives (i.e., maintaining global warming well below 2°C and aligning with 1.5°C over the long term) are failing. Instead, the global temperature trajectory is trending toward a 3°C increase over preindustrial levels by 2100 (*2*). This spells dire consequences for coral reefs and many other ecosystems, given the ongoing repercussions at 1.1°C of warming and the anticipated impacts that are likely at 3°C (*2*, *6*).

The persistence of coral reefs beyond the next few decades remains in serious jeopardy (*3*). Rising sea temperatures, coupled with other stressors such as ocean acidification and pollution, have severely weakened the resilience of coral reefs. Changes are insidious yet fundamental. Limited reproductive success of corals has been documented in the wider Caribbean for more than 20 years (*7*), making these reefs more vulnerable to disease outbreaks and extreme weather events. For example, a single thermal event in the Galápagos Islands in 1982–1983 drove levels of coral mortality to 95 to 99% and the complete loss of coral reef structures over 10 years with no recovery (*8*). Since May 2023, mass coral bleaching has occurred in multiple countries in the ETP (Mexico, Costa Rica, El Salvador, Colombia, and Panama) and in much of the Caribbean and Florida, which illustrates that a large-scale heat-stress event is underway.

Higher bleaching tolerance within coral species or across reef zones is associated with generally modest increases in thermal tolerance [i.e., +1°C in the Florida Keys (*9*)] or has

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occurred in locations that have not yet experienced the severe heat stress that is expected over the next few decades [e.g., Panama (*10*)]. Furthermore, increased bleaching tolerance in corals because of an association with heat-tolerant algal symbionts (*Durusdinium* spp.) often comes with substantial physiological costs, such as reduced calcification and carbon transfer (*11*).

Some initiatives that focus on increasing bleaching tolerance through the introduction of heat-tolerance genes into natural populations ("assisted evolution") have shown some promise (*12*). However, scaling up such restoration efforts remains challenging, especially when bleaching resistance is not necessarily connected to coral survival (*4*, *13*). The rapidly increasing rate of SST rise exacerbates challenges because corals struggle to keep up with increasingly hostile conditions. As the intensity of MHWs has escalated, some historically dominant reef-building coral groups (e.g., staghorn *Acropora* species) have been observed to die abruptly (i.e., they slough tissue) rather than die from the loss of symbiotic dinoflagellates (through bleaching).

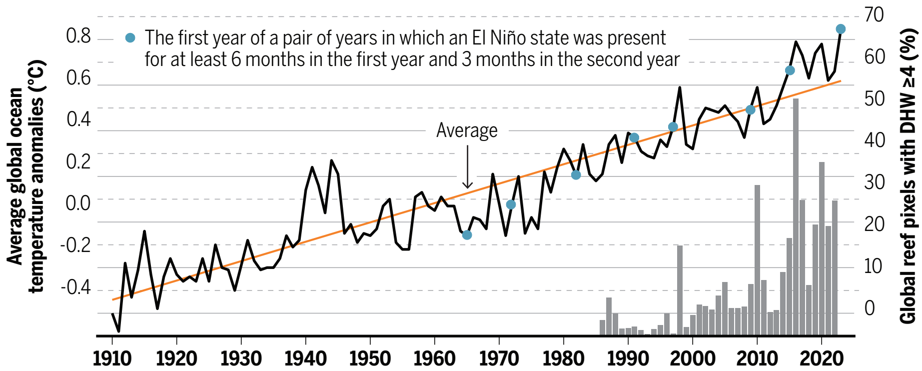
Consequently, identifying reef stress through observations of mass coral bleaching (especially with aerial surveys) will become increasingly challenging as corals decrease and specific coral groups die without bleaching. Management metrics must also move from bleaching-dominated measurements to those that focus on the death of corals and downstream consequences. Better mortality assessments require improvements in spectral analysis to separate skeletal epilithic algal growth from living coral tissue. Additionally, extension of the geographical scale and frequency of in-water reef surveys, by using advancements in robotics and image analysis through artificial intelligence, are needed. These improved in-water observations will also provide an important resource for improving satellite monitoring products. Stress monitoring metrics, such as DHW, would benefit from improved spatial and temporal resolution (e.g., to 100-m resolution at subdaily timescales). Large-scale coral mortality is much more destructive to reefs than large-scale bleaching. Dead coral skeletons are broken down by the combined effects of physical, biological, and chemical erosion, with recovery impeded by the instability of the resulting reef framework. As the architecturally complex, three-dimensional reef structures are eroded, the vital habitat that many coral reef–associated species depend on disappears, leading to ecosystem collapse (*4*). Importantly, this could undermine the persistence of as much as 25% of ocean biodiversity (*2*).

New approaches and strategies are urgently needed to mitigate the impacts of climate change, which have been recognized as a major threat to coral reefs for more than 40 years (*1*). Given the magnitude and speed of the changes to oceanic conditions, a comprehensive system should integrate measures to reduce GHG emissions and limit further warming and acidification of the oceans. Additionally, efforts to enhance the resilience of marine ecosystems, including protecting critical habitats and refugia, are equally important. Actions must integrate marine- and land-based approaches, including establishing and enforcing regulations within protected areas, promoting sustainable fishing practices, and reducing coastal pollution (*2*, *14*). Adaptive management practices are also crucial, given rapid environmental changes. Monitoring programs that track oceanic conditions, ecological indicators, and species distributions can provide valuable insights for decision-making and conservation planning. Furthermore, fostering international collaboration and knowledge exchange is essential for sharing best practices, lessons learned, and technological innovations that can aid in preserving marine ecosystems.

Identifying and safeguarding coral reef sites that are least exposed to climate change offers a scalable and targeted response that can assist in prioritizing investments and guiding adaptive management. Climate exposure varies between locations owing to local oceanography and other factors (*15*). Reefs that are the least exposed to ocean warming can be prioritized and protected from stressors unrelated to climate change, such as pol-

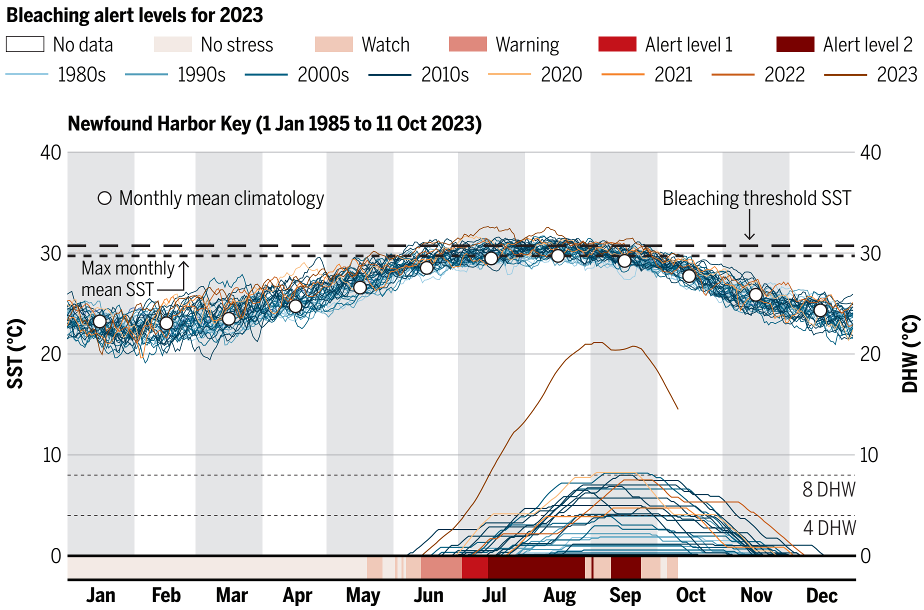
Coral heat stress

Average global ocean temperature anomalies from February to July each year (1910 to 2023) are increasing. This is coupled with increased periods of degree heating weeks (DHW) ≥4 (when coral bleaching is likely to occur). Data are from the National Oceanic and Atmospheric Administration (NOAA; www.ncei.noaa.gov), using climatology between 1901 and 2000 as the reference.



Newfound Harbor Key

At Newfound Harbor Key, annual sea surface temperature (SST) and DHW show substantial increases between 1985 and 2023. Data are from the NOAA's Coral Reef Watch version 3.1 (https://coralreefwatch.noaa.gov).



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lution, overfishing, and unsustainable coastal development. Once climate conditions stabilize, less-exposed reefs could serve as a source of reproductive materials (larvae), aiding corals in reclaiming these invaluable tropical seascapes (*15*). Such strategizing assists in addressing the scaling challenge, particularly with the limited resources available to manage the vast expanses of coral reefs that are being affected globally.

Given the complex and interconnected nature of marine ecosystems such as coral reefs, a comprehensive approach is necessary for mitigating the impacts of changing oceanic conditions. This approach should include rapid and scalable efforts to reduce GHG emissions as a global emergency, thereby limiting further warming and acidification of the oceans. Simultaneously, exploring technologies for preserving coral stocks and other important reef organisms for future dissemination is critical. It is essential to remain open-minded to new ideas while acknowledging the challenges inherent in addressing the global issues facing coral reefs at the appropriate scales and costs. Nonetheless, swift action needs to be taken to safeguard 25% of ocean biodiversity and the future of more than half a billion people worldwide who depend on coral reefs. ■

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SUPPLEMENTARY MATERIALS

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ASTRONOMY

The drivers of massive star evolution

An elusive population of stripped binary stars is finally revealed

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Although the Sun appears lonely in space, most stars born with higher masses are locked into cosmic dances with at least one companion (*1*). This pairing, however, comes neither without risk nor without consequence. Theoretical models predict that for many stars with birth masses 8 to 25 times that of the Sun, their outer layers are stolen by nearby partners (*2*). Yet despite the high predicted numbers, detection of such stripped stars has been elusive. On page 1287 of this issue, Drout *et al.* (*3*) report electromagnetic observations that finally reveal the missing population, confirming a key prediction of binary star evolution. Additional analysis of the stars' physical properties by Götberg *et al.* (*4*) further supports the idea that these systems are progenitors to neutron star binaries, including those recently detected by their bursts of gravitational waves.

Stars come to life within contracting gas clouds in interstellar space. Most are born with masses around or lower than that of the Sun. Occasionally though, the stellar nursery produces much more massive and luminous objects. Unlike the Sun, which will shine for another 5 billion years, these cosmic beasts live fast and die young, exhausting their nuclear energy source in just a few million years (*5*). Across the Universe, these rare massive stars serve as beacons of light, powering galaxies such as the Milky Way and allowing astronomers to observe stars at cosmological distances (*6*). A quantitative understanding of how massive stars live and die is thus important well beyond stellar physics, influencing research fields as diverse as the evolution of galaxies and the early cosmos, the origin and frequency of gravitational wave bursts, and the production of chemical elements essential for life.

In the classical picture of massive star evolution, a star is born in isolation and lives most of its life fusing hydrogen within its deep core. From the outside, it looks bright and blue because of its hot surface temperature of several 10,000 K. When core-hydrogen becomes depleted, the star expands, and its outer layers cool off. Depending on the exact mass and detailed physics (much of it still insufficiently understood) of the stellar interior, surface, and gas outflow, the evolved object may then directly explode as a supernova or shrink and heat up again before meeting its demise (*3*, *5*). Either way, the massive star ultimately ends up as a tiny and dense neutron star or a black hole, alone in a dark cosmos.

Over the past years, however, evidence has accumulated that this basic scenario may need considerable revision (*7*). Interactions between the individual components of massive binary systems are now believed to both be very common and have profound implications for stellar life. In tight binary systems, large amounts of mass can spill over from one object to the other, substantially altering the mass of both stars. Because mass is the overarching parameter controlling evolution, the life cycles and final fates of these interacting stars can deviate considerably from the classical scenario. The net results of such binary interactions are diverse (*8*) and depend on quantities such as the initial separation and masses of the interacting stars as well as their internal, surface, and outflow structures.

One of the most robust predictions of the influence of a close binary companion on massive star evolution is the existence of a population of stars that have been stripped of their hydrogen-rich envelopes by the nearby companion (*8*). Although stripped stars have been observed at the uppermost end of the mass spectrum (*9*), the expected large population of objects produced from stars with 8 to 25 solar masses at birth has never been observed. This is not a trivial issue because it is in this mass range that one expects to find most progenitors of hydrogen-deficient supernovae, binaries emitting fiercely in high-energy x-rays, and gravitational wave mergers involving

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