Overview: Coastal Ecosystems, Communities, and Industries

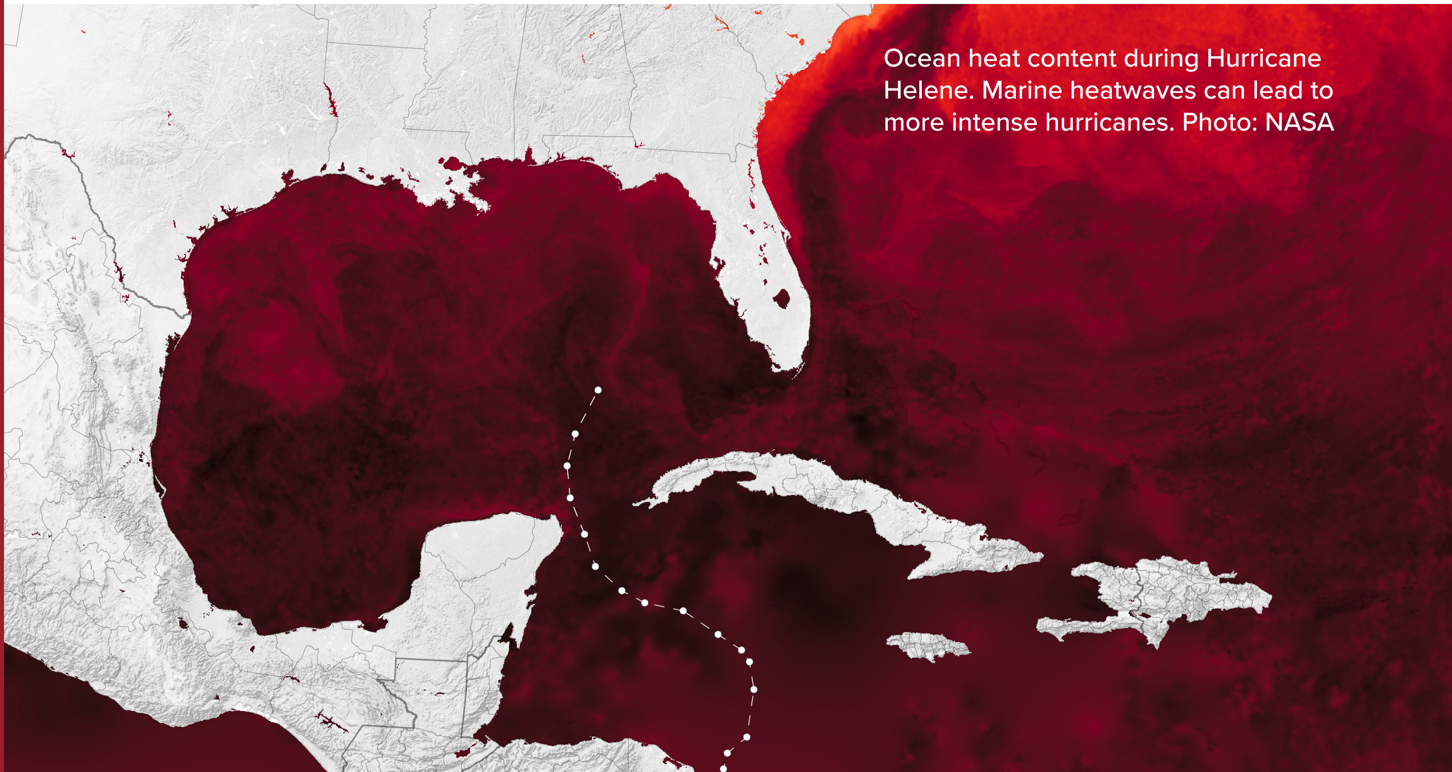
Marine heatwaves (MHWs), extended periods of higher-than-normal ocean temperatures, have myriad impacts on coastal and marine ecosystems, communities, and industries. Through their influence on weather and storms, they can also have impacts that extend further inland. Here we provide an overview of the impacts of MHWs on coastal communities in the Gulf of America (hereafter "Gulf") and Caribbean, separated loosely into economic, social/cultural, health, governance, and species/ ecological impacts.

MHWs can influence regional weather. Specifically, they are associated with hotter and more humid conditions in coastal regions, more severe thunderstorms in the southeast U.S., and higher risk of more and more intense tropical cyclones. Both hurricanes and tornadoes are exacerbated by — but do not require — MHWs to form. Therefore, for the sake of space, we will not discuss the impacts of thunderstorms and tropical cyclones, and instead focus on the impacts of elevated ocean temperatures and corresponding high temperature and humidity in coastal regions.

This document serves as an overall general reference of ideas on the science and impacts of MHWs. More detailed information is contained in a series of short reports focused on:

- Terrestrial Agriculture and Silviculture
- Coastal and Urban Temperature and Humidity
- Corals
- Northern and Southern Quahog (clams)
- Intertidal Crabs
- Energy Infrastructure
- Finfish
- Fisheries
- Harmful Algal Blooms
- Marine Birds, Mammals and Sea Turtles
- Eastern Oyster
- Sargassum
- Seagrass
- Severe Thunderstorms
- Tropical Cyclones/Hurricanes
- Urchins

Additionally, the short reports on agriculture, fisheries, and energy infrastructure include details of industry-specific impacts.



Ocean heat content during Hurricane Helene. Marine heatwaves can lead to more intense hurricanes. Photo: NASA

Economic

MHWs can have economic impacts that are more direct, like the loss of fisheries revenue due to fish species declines, and more indirect like reduced agricultural yields due to diseases facilitated by high temperature and humidity.

High Water Temperatures

Abnormally high water temperatures can both positively and negatively impact target species for fisheries (e.g., fish, shellfish). Tropical species may become more prevalent during MHWs and species living near the sea floor may be less impacted. Therefore, those fisheries may suffer fewer costs or may even see beneficial impacts (Fredston et al. 2023, Smale et al. 2019). However, because the waters in the Caribbean and Gulf are already relatively warm, many of the target species are likely to either move out of normal fishing grounds or be otherwise negatively impacted. This means that fishing fleets may have to adjust their fishing grounds to follow mobile target species (Farchadi et al. 2024), requiring longer trips or trips from different ports that may increase costs. There may also be changes in the timing of fishing and seafood availability; earlier than usual peaks in target species populations due to MHWs can swamp the market and lead to reduced per-catch incomes for fishers (Pershing et al. 2018). If target species experience declines in recruitment and overall population due to stress, then fishers may see reduced catches or production (Plumlee et al. 2024). Management costs may also increase as stock managers have to test the effectiveness of approaches to help populations recover from heatwave impacts (Midway et al. 2024).

The impacts of high water temperatures on marine species can also impact tourism and potential tourism revenue. For example, corals can bleach and eventually die when exposed to long-lasting MHWs. Coral reefs are important attractions for tourists, especially for snorkelers or SCUBA divers. For example, Florida has substantial reef-dependent tourism, with reef-adjacent tourism bringing in around $850 million per year (Spalding et al. 2017). By decreasing the attractiveness and health of coral reefs, MHWs can have negative impacts on regional tourism industries, especially in Florida and the Caribbean.

High Air Temperatures/Humidity

High air temperatures and humidity associated with MHWs could impact worker productivity and tourism revenue along the coast, especially during warm summer months. In the cold months, increases in temperature might allow for increased tourism, depending on visitor preferences (Atzori et al. 2018, Rutty and Scott 2013). However, tourism is likely to decline with increased temperatures during already hot summer months (Atzori et al. 2018, Rutty and Scott 2013, Rutty et al. 2022). In terms of worker safety, in hot, humid conditions, workers will need to work with less intensity and more breaks to remain safe (Brimicombe et al. 2023). This means potentially lost productivity that could lead to reductions in profits during especially hot days.

Changes in air temperatures can impact energy demand. Increased temperatures may decrease heating needs during the cold winter months. However, since the Gulf and Caribbean are relatively warm, even hotter and more humid conditions in the summer would lead to increased cooling demand while also reducing transmission line efficiency (Varianou Mikellidou et al. 2018, Ogden et al. 2019). The combination of increased demand with reduced supply makes high energy prices and power outages more likely (Añel et al. 2017).

Abnormally hot and humid conditions, especially in the summer, can increase the risk of crop damage, failed reproduction, and disease. These impacts lead to reduced agricultural output and thus reduced profits while also increasing prices for consumers (Losinger 2004, Savary et al. 2012). However, in the winter, heatwaves may reduce risk of crop failure from frost, which is especially important for citrus (Shannon and Motha 2015).

Social and Cultural

Alongside economic impacts, MHWs can influence people's livelihoods and communities more broadly. Negative social and cultural impacts can be due to the loss of culturally important species or the inability to do some activities during certain times of day.

High Water Temperatures

High water temperatures can have extensive negative effects on culturally relevant species in the Gulf and Caribbean. For example, in various communities in the state of Veracruz, Mexico, fishers mentioned using sharks and fish species like Spanish mackerel not just for sale/income, but also for food, decoration, handicrafts, medicinal products, and rituals (Escamilla-Pérez et al. 2021). Households in this state rely on marine resources for as much as half of the food they consume (Aldasoro-Said and Ortiz-Lozano 2021); declines in marine food species may therefore require adjustments to local diets and cuisine. Spanish mackerel (*Scomberomorus maculatus*) spawning is temperature sensitive and the species migrates depending on water temperatures (Quinlan 2023, Schrandt et al. 2016) — meaning that heatwaves would impact its abundance and/or reproduction. The species within a culturally important genus of sharks (*Carcharhinus*) vary in their temperature tolerances, but some (like *Carcharhinus plumbeus*) have declines in juvenile swimming performance with high temperatures (Crear et al. 2019) or (like *Carcharhinus limbatus*) show elevated signs of stress after being caught and released at high temperatures (Whitney et al. 2017). If culturally important marine species are impacted by MHWs, they will influence coastal (and especially fishing) communities beyond purely economic impacts.

The fishing industry as a whole can also have substantial social and cultural importance in some communities. For example, the town of San Leon in Galveston Bay has a large recreational fishing center and the town slogan is "A small drinking community with a large fishing problem" (Jacob et al. 2010). While fishing is an important economic activity, its importance can extend beyond income to become part of the town culture, though the social importance will vary by community (Jacob et al. 2010). When this is the case, drastic and consistent declines in fisheries catch can have cascading social impacts in the community (Lozada Perez et al. 2022, Scyphers et al. 2019)

High Air Temperatures/Humidity

Higher than normal air temperature and humidity can impact how people — both residents and tourists — recreate. For example, a survey of tourists in Barbados, Saint Lucia, and Tobago showed that overall, tourists found temperatures below 23C to be unacceptably cool for beach use and temperatures above 34C unacceptably hot for beach use (Rutty and Scott 2013). This means that an increase in cold season temperatures may encourage some people to use the beach when they normally would not, but increased temperatures in the hot summer months would make beach use less likely. Extreme heat (more likely with summer MHWs) can lead to declines in recreational fishing in the Gulf and Southeastern U.S., though fishers might still go out at night and might see increases in fishing in the cooler months (Dundas and von Haefen 2020). More broadly, people might avoid outdoor physical activity and shift to indoor leisure during warm seasons but may be more likely to perform outdoor physical activities during cold seasons (Obradovich and Fowler 2017, Zivin and Neidell 2014). Because the region is already hot, overall declines in outdoor recreation are likely.

Health

MHWs can indirectly influence human health by influencing marine species dynamics and coastal weather conditions.

High Water Temperatures

MHWs can influence the occurrence of harmful algal blooms (HABs). HABs can have negative health effects on nearby human populations by poisoning seafood and causing skin and respiratory irritation (Berdalet et al. 2016). MHWs might reduce the likelihood or intensity of summer HABS in areas with low nutrient concentrations, but are cause for concern in the winter. For coastal areas with relatively high nutrient concentrations, MHWs are more likely to increase HAB occurrence even in warm months, requiring adjustments to beach/coastal land use and seafood sourcing to avoid negative human health impacts.

Declines in fish species catch, and resulting economic hardship, can have mental health impacts on those in the fishing industry (Scyphers et al. 2019). There are limited studies looking directly at the impacts of MHW-induced fishery failures or declines, but studies of fisheries closures document stress/distress and potentially depression for impacted fishers and community members (Scyphers et al. 2019, Smith et al. 2003).

High Air Temperatures/Humidity

As mentioned above, higher than normal temperatures may influence how and when people can safely work. Because the Gulf and Caribbean are relatively warm, excess summer heat is of particular concern for human health. High humidity reduces the effectiveness of sweat-induced cooling, and those out on the water (i.e. commcercial fishers, anglers, lifeguards), especially during MHWs, will be in particularly humid conditions (Alber-Wallerström and Holmér 1985, Di Napoli et al. 2022, Pathmeswaran 2023). Extremely hot temperatures can also exacerbate fisheries worker discomfort and stress as they go between the hot deck and the cold ice holds for fish storage (Johnson et al. 1998). The impacts of elevated temperature and humidity extend inland. Extreme heat can be especially dangerous for those who work outside for long days; U.S. crop workers are 20 times more likely to die of heat-related illnesses than the general civilian workforce (Murbach et al. 2020). There are management adjustments, like increases in rest time, changes in worker effort, and provision of climate control recovery areas, that can mitigate those risks (Brimicombe et al. 2023, Murbach et al. 2020).

High temperatures and humidity can also influence how and when people can safely perform outdoor recreational activities. For example, there are regional-specific guidelines to help reduce exertional heat illnesses for athletes based on temperature, humidity, and other weather variables (like wind and solar radiation) (Grundstein et al. 2015). Afternoon football practices in July and August leave athletes particularly prone to heat illnesses (Grudstein et al. 2023); summer MHWs could exacerbate those hot/humid conditions. Moving practices to evenings could help reduce the likelihood of heat illnesses (Grudstein et al. 2023), though with MHWs those dangerously hot conditions could persist later into the day.

High temperatures/humidity can also stress the energy infrastructure and can lead to either intentional or unintentional blackouts. Energy grid failures during heatwaves can increase risks of heat exhaustion and heatstroke as more residents are exposed to the high temperatures without air conditioning (Stone et al. 2021, Stone et al. 2023).

Hot atmospheric temperatures can also have mental health impacts. For example, in the Greater Houston area, extreme weather events (including heatwaves) were associated with surges in emergency department visits for depression and anxiety (Adepoju et al. 2025). These mental health impacts are likely related to the economic, social/cultural, and other health impacts discussed above; high temperatures/humidity can increase general stress for coastal residents in hot climates like in the Gulf and Caribbean.

Governance

MHWs can influence local and regional governance, most directly for fisheries and marine protected areas, but also for coastal communities impacted by extreme heat and humidity.

High Water Temperatures

MHWs present various governance challenges as species move into unexpected locations and/or fisheries experience potentially large shifts in catch species or amounts. For example, MHWs can drive changes in marine mammal behavior and movement and lead to increases in entanglement risks that require adjustments in fisheries practices to avoid human-wildlife conflict (Samhouri et al. 2021). Management tools that can be effective in other contexts may be less effective during MHWs and could have substantial impacts on fisheries revenue and livelihoods (Samhouri et al. 2021). Similarly, MHWs can prompt higher-than-usual mortality of target species that threaten the long-term sustainability of the fishery and also require management adjustments (Barbeaux et al. 2020).

MHWs can also change the timing of landings such that the market has an unexpected spike in supply that reduces prices and fisher profits (Pershing et al. 2018). Marketing and adjustments to processing capacity can help reduce price swings and profit declines, which are possible with proactive governance and collaboration (Pershing et al. 2018). As an added complication, species can move across multiple jurisdictions, including international exclusive economic zones during MHW events (Welch et al. 2023). This means that proactive management of species populations as a whole would require dynamic management approaches with cooperation across political boundaries (Welch et al. 2023). Governance performed by fishing communities themselves can also mitigate MHW impacts (Pecl et al. 2019). Encouraging fishers to diversify the species caught can help reduce the impacts of declines in any one species (Solís et al. 2020), though they might be less effective in the face of widespread species declines or movements. Adjusting to the impacts of MHWs on coastal fisheries can strain existing governance and management practices and requires flexibility.

High Air Temperatures/Humidity

High temperatures/humidity, akin to heatwaves in the summer months, require adaptive governance strategies to reduce risks to human health and infrastructure (as described above). There are numerous scales and types of responses, ranging from government-led extreme heat plans to more autonomous and small-scale adaptations (McGregor et al. 2024).

Individual and community-based responses are especially important in the Caribbean, and the effectiveness and format of government-led initiatives can vary substantially between cities and across the region (McGregor et al. 2024). Since the region is already warm, there is often some local acclimation and experience dealing with extreme heat, if taken seriously. However, summer MHWs may help push atmospheric temperatures beyond what established responses can mitigate (McGregor et al. 2024). Potential negative impacts extend beyond human health to infrastructure; high temperature and humidity during hot seasons can reduce energy transmission efficiency while increasing energy demand. Management responses to the stress on the energy grid can include rolling blackouts as well as more proactive infrastructure development to be able to reduce energy needs and manage peaks in demand (Garland et al. 2024). Proactive planning could help ensure that the governance structures in place (whether community-led, or government led) are prepared for potential heat spikes related to summer MHWs.

Species and Ecosystems

The impacts of MHWs on marine and coastal species vary, but there are likely negative impacts that can reverberate to impact ecosystems, especially for coral reefs and seagrass ecosystems. Those impacts can also move inland and influence semi-aquatic and terrestrial species.

High Water Temperatures

The Gulf and Caribbean are the primary homes for some species, making them particularly vulnerable to abnormally high water temperatures. For example, Rice's whale (*Balaenoptera ricei*) has only been detected in the Gulf and has a relatively narrow set of prey species (Lettrich et al. 2023, NOAA Fisheries 2024). If those prey species move out of the Gulf or face population declines with MHWs, Rice's whale would likely be heavily affected. A wide array of species could be impacted by MHWs in both positive and negative ways, and these changes further influence species interactions. If corals die due to extended exposures to high temperatures, reef species — globally representing 25% of marine biodiversity — lose their habitats. If seagrass species die, then species like black drum (*Pogonias cromis*), blue crab (*Callinectes sapidus*), and bonnethead sharks (*Sphyrna tiburo*) lose their nursery habitats and may be more vulnerable to predation (Quinlan et al. 2023). If heat stress is strong enough or long-lasting enough, there can shifts away from seagrass ecosystems and toward algae or bare-dominated systems (Serrano et al. 2021, Smith et al. 2023).

High Air Temperatures/Humidity

High air temperatures/humidity can also impact semi-aquatic and terrestrial species that live in the Gulf and Caribbean. For example, adults of the endangered Kemp's ridley sea turtle species primarily live in coastal habitats in the Gulf and have a large nesting site at Rancho Nuevo, Mexico (NOAA fisheries 2025). While there is limited work on this species specifically, high sand temperatures influence the sex ratio of hatchlings and influence hatching success in other sea turtle species (Laloë et al. 2016, Lolavar and Wyneken 2020, NOAA fisheries 2025). High air temperature and humidity can also provide conditions for fungal plant disease development that impact coastal plant species (Jennings et al. 2014, Romero et al. 2021). For example, warm moist conditions common in the southeastern U.S. and Caribbean are optimal for the establishment of pitch canker (*Fusarium circinatum*) (Ganley et al. 2009, Sturrock et al. 2011)) that heavily impacts pine species in the Southeastern U.S. Though much of the direct species and ecological impacts of MHWs are related to high water temperatures, high coastal temperatures and humidity can extend ecological MHW impacts inland to semi-aquatic and terrestrial species.

Conclusions

MHWs can have economic, social/cultural, health, and ecosystem impacts on coastal regions in the Gulf, U.S. Southeast, and Caribbean. The extent and intensity of those impacts will depend both on the characteristics of the MHW (e.g., when it is, how long it lasts, how intense it is) and on the regional characteristics (e.g., is it a fishery-dependent community, does the local government have an extreme heat plan). Though some MHW impacts can be positive (i.e. reduced heating needs in the winter), many of the likely impacts in the Gulf and Caribbean are negative. Proactive management of infrastructure and industries (like energy systems, agriculture) alongside ecosystem-based species management may help mediate some of those impacts, but any management must rely on local expertise and take into account local capacity and conditions.

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GCOOS GULF OF AMERICA COASTAL OCEAN OBSERVING SYSTEM

20 YEARS

Terrestrial Agriculture and Silviculture

Key Message

Marine heatwaves indirectly impact terrestrial agriculture and silviculture by influencing coastal temperatures, humidity, tornadoes, and hurricanes. High temperatures can lead to crop failures in the summer, though reduced frost risk in the winter may benefit frost-susceptible species. Tornadoes and hurricanes cause extensive damage to agricultural and silvicultural industries that can have lasting impacts.

Overview

Conditions in the ocean can influence conditions on the coast and further inland, especially as it relates to weather that influences local agriculture. The Southeastern U.S. and Caribbean play an important role in U.S. agricultural production. For example, Georgia leads the nation in pecan production, Florida is second in citrus fruit production, and Texas leads the nation in cotton and cattle production (USDA 2024, USDA National Agricultural Statistics Service 2023b and 2024a). Puerto Rico, despite its relatively small size, had $703 million in agricultural production in 2022 (USDA National Agricultural Statistics Service 2024b). U.S. Southeastern states also have substantial silvicultural industries with 40% of the country's timber land producing approximately 60% of the nation's timber harvest (Motha 2011, Oswalt and Smith 2014).

Marine heatwaves are associated with higher temperatures and humidity in coastal regions (see coastal temperature short report). Though agriculture in the Caribbean and Gulf is designed to handle heat, there have been severe reductions in crop yields and loss of forage for livestock (and sometimes deaths) associated with extreme summer temperatures (Shannon and Motha 2015). High temperatures impact crop development. For example, above 32C, *Brassica oleracea* (a group of crops that includes cabbage, broccoli, and brussel sprouts) has compromised leaf expansion, reduction in fresh weight, reduced photosynthetic efficiency, and some subtypes see changes in gas exchange rates at high temperatures (Rodríguez et al. 2015). Soil temperatures above 35C can cause seedling death in soybeans, and air temperatures above 30C can impact wheat germination (Motha 2011). Temperature can also influence crop reproduction. For example, air temperatures above 36C lead to declines in corn pollen viability (Motha 2011). On the other hand, some regional crops are particularly susceptible to freezes (e.g., citrus (Shannon and Motha 2015)) and marine heatwaves in the winter months may help reduce freeze-related losses. High summer temperatures can endanger agricultural workers; U.S. crop workers are 20 times more likely to die of heat-related illnesses than the general civilian workforce (Murbach et al. 2020). There are management adjustments, like increases in rest time, changes in worker effort, and provision of climate-control recovery areas, that can mitigate those risks (Murbach et al. 2020).

Silviculture in the South: States in the Southeastern U.S. have 40% of the nation's timberlands and produce about 60% of the nation's timber harvests. Photo: USDA Forest Service.

Both high temperature and high humidity are associated with fungal plant disease outbreaks globally, with humidity playing an especially important role (Romero et al. 2021). High humidity can also have risks for livestock, including high mortality of chicken embryos, pulmonary inflammation in lambs, generally high heat stress, and high prevalence and infectivity of some fungal diseases (Xiong et al. 2017). That said, high humidity can reduce transmission for some airborne pathogens — like the flu virus — and can decrease survival for some bacteria, though it increases survival for others (Xiong et al. 2017).

Marine heatwaves are also associated with more frequent and intense thunderstorms and tropical cyclones (see Severe Thunderstorms and Tropical Cyclones/Hurricanes short reports). Tornadoes, which are particularly prevalent in parts of Mississippi and Alabama, can damage forests by damaging tree branches or uprooting trees (Fortuin et al. 2022)). For some hardwood trees in southern Mississippi, one model indicated a more than 50% probability of uprooting within 30 years, around the time when some timber species are harvested in the region (Fortuin et al. 2022). Hurricanes have also led to extensive damage in the region. For example, in addition to killing more than 1,800 people, Hurricane Katrina led to the deaths of millions of chickens, the loss of around $3 million in milk due to electrical outages, and the extreme damage or deaths of 320 million large trees (Motha 2011, Shannon and Motha 2015). Hurricane Floyd was not a powerful hurricane, but the heavy rainfall led to major flooding that killed millions of farm animals and spread pollution from farm waste lagoons and other facilities across eastern North Carolina (Motha 2011). The 2017 and 2018 hurricane seasons cost billions of dollars in agriculture, livestock, and forest industry losses across the Southeastern U.S. and Caribbean (Wiener et al. 2020). Specifically, hurricanes Irma and Maria had devastating impacts on Puerto Rico, with estimates that Maria destroyed more than 80% of Puerto Rico's 2017 agricultural crop value, especially impacting plantain, banana, and coffee harvests. These losses heavily impacted smaller farms — leading to the loss of more than a 50% of farms with fewer than 10 acres when compared to 2012 numbers (Kenner et al. 2023). Recovery is challenging for all, but especially for those farming crops that become more valuable as they age (e.g., pecans, timber (Wiener et al. 2020)). This is not accounting for the long-term impacts of trauma and personal hardship on farming communities in the region.

There are strategies that can help farmers mitigate the economic risks of extreme weather (including hurricanes), like purchasing crop insurance, diversifying to include alternative sources of income, and farming in multiple locations (Shannon and Motha 2015, Wiener et al. 2020). For forestry, strategies like reducing stand rotation length, diversifying stand management styles, and planting wind-resistant species may reduce hurricane damage (Wiener et al. 2020). However, there is limited information on species- or crop-specific mitigation strategies to inform farm management (Wiener et al. 2020).

Storm Damage: Recovery from storm damage is challenging, especially for crops — like timber — that become more valuable as they age. Photo: National Association of State Foresters.

What this means is that, though marine heatwaves may have limited direct impacts on terrestrial agriculture and silviculture, they can increase the likelihood of conditions that are potentially damaging to workers and crops. Specifically increased summer temperatures and increased intensity of thunderstorms and hurricanes can lead to crop, livestock, and timber losses and can impact worker health and well-being.

Temperature Datasets Commonly Used

Analyses primarily rely on air temperature data if looking directly at the relationship between temperature and crops. However, analyses of ENSO-related impacts use a variety of indices, some of which (like the Oceanic Niño Index or ONI) rely on remotely-sensed sea surface temperature anomalies in the tropical Pacific.

Other Relevant MHW Short Reports

- Coastal and Urban Temperature and Humidity
- Severe Thunderstorms
- Tropical Cyclones/Hurricanes

Resources/Communities of Practice

- World Agrometeorological Information Service (USA) (https://wamis.org/wamis/usa/)
- AgroClimate (http://agroclimate.org/)
- USDA NRCS (https://www.nrcs.usda.gov/)

Hurricane Impacts: Maria destroyed more than 80% of Puerto Rico's 2017 agricultural crop value, especially impacting plantain, banana, and coffee harvests. Photo: USDA.

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GCOOS GULF OF AMERICA COASTAL OCEAN OBSERVING SYSTEM 20 YEARS

Coastal and Urban Temperature and Humidity

Key Message

Marine heatwaves in coastal oceans are associated with more extreme humid heat on land, which can have human health impacts. This is particularly important for coastal cities, where urban heat island effects mean that cities are already relatively hot.

Overview

Conditions at the ocean surface influence conditions in the air above it; therefore elevated ocean temperatures can lead to increased temperature and humidity of the air above the water. If that air moves inland, it brings hotter and more humid temperatures into coastal areas (Hu 2021).

Cities are relatively warm compared to their rural counterparts in most parts of the world (except particularly arid environments, Fan et al. 2017). These relatively high urban temperatures, called the urban heat island effect, are due primarily to relatively low vegetation cover, relatively high amounts of pavement, and high concentrations of human energy use and heat release (i.e. air conditioning units, cars (Oke et al. 2017)).

There is evidence that marine heatwaves co-occur with terrestrial heat waves and extreme humid heat, but the reasons for this relationship are still under study and likely vary by region (Hu 2021, Jia et al. 2024, Pathmeswaran et al. 2022, Pathmeswaran 2023, Sato et al. 2024). Warmer ocean temperatures translate to warmer and more humid air above the ocean. If this air moves inland — even though land in the summer is usually hotter than the ocean during the day — the ocean air will provide less cooling or bring more humidity than usual (Gu et al. 2025, Hu 2021, Jia et al. 2024, Oppong et al. 2024, Pathmeswaran 2023, Chapter 4). This reduced cooling could also occur if the reduced temperature differential between the land and the water leads to weaker afternoon sea breezes that also bring warm ocean air inland (Gu et al. 2025, Oppong et al. 2024, Pathmeswaran et al. 2022, Pathmeswaran 2023, Sato et al. 2024). Alternatively, marine heatwaves can increase terrestrial temperatures by reducing low-level cloud formation and increasing direct heat from the sun (Sato et al. 2024).

Heat stress is the leading cause of weather-related deaths globally (World Health Organization 2024). Areas near the Gulf and the Caribbean are likely to experience increased exposures to potentially lethal temperatures (Dahl et al. 2019, Di Napoli et al. 2022). Increased humidity can have adverse human health impacts as it reduces the effectiveness of sweat-induced cooling (Alber-Wallerström and Holmér 1985, Di Napoli et al. 2022, Pathmeswaran 2023). Because the presence of marine heatwaves can exacerbate the intensity and duration of atmospheric heat waves, proactive planning for exacerbated extreme heat during marine heatwave events could reduce heat-related illness and deaths.

Heat Stress: Increased humidity can have adverse human health impacts as it reduces the effectiveness of sweat-induced cooling. Photo: Mikael Blomkvist.

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

Studies primarily used sea surface temperature data from satellites. The sources and types of coastal/urban meteorological data varied (Hu 2021, Pathmeswaran 2023, Sato et al. 2024)

- No clear thresholds, rely on the Hobday et al. 2016 definition of a marine heatwave (5 or more days above the 90th percentile temperature based on a 30-year baseline) in most cases. Sometimes they use sea surface temperature anomalies.
- For someone doing even light work, a wet bulb globe temperature (a combination of temperature, humidity, solar radiation, and wind) of 33C is considered dangerous. For very heavy work, a wet bulb globe temperature of 25C can be dangerous (Brimicombe et al. 2023)

Resources/Communities of Practice

- American Public Health Association Extreme Heat Resource Hub (https://www.apha.org/topics-and-issues/climate-health-and-equity/extreme-heat)
- CDRI Community of Practice for Extreme Heat Management in Public Transport Systems (https://cdri.world/upload/
- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- Gulf Tree (http://www.gulftree.org/)
- NIHHIS Centers of Excellence (https://www.heat.gov/pages/nihhis-centers-of-excellence)
- NIHHIS Planning and Preparing Tools (https://www.heat.gov/pages/planning-and-preparing)

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GCOOS GULF OF AMERICA COASTAL OCEAN OBSERVING SYSTEM

20 YEARS

Corals

Key Message

Marine heatwaves, especially above four degree heating weeks (and even more so above eight degree heating weeks) are associated with coral bleaching and, if not reversed, can lead to declines in the diversity and abundance of reef-dwelling species.

Overview

Marine heatwaves are defined as periods with higher than normal ocean temperatures. These elevated temperatures can have severe impacts on marine species, especially those like corals that cannot move away from hotter waters.

Corals are invertebrate animals that are related to sea anemones and jellyfish. Hard corals, which produce calcium carbonate skeletons, form coral reefs (NOAA Fisheries 2022). These reefs are the most species-diverse places in the ocean and are important for the survival of many other species; it is estimated that they support 25% of all marine life (NOAA Fisheries 2022, National Ocean Service, 2022). Coral reefs are found in various parts of the world, including in the Gulf and the Caribbean.

Marine heatwaves are associated with coral stress and bleaching. Coral bleaching is the process by which the symbiotic algae, which produce food for the coral, are expelled and the coral turns white (NOAA 2024). Marine heatwaves stress corals and their algal symbionts and, if the elevated temperatures are either intense enough or long enough, the corals will bleach either reversibly or eventually irreversibly (Donner et al. 2017, Gleeson and Strong 1995, Smale et al. 2019). There is a metric, called "degree heating weeks" (DHW), that combines marine heatwave intensity and duration into one number. It is defined as the sum of the amount by which sea surface temperatures (SST) are above a specified bleaching threshold per week over a 12-week period (NOAA Coral Reef Watch 2024). For example, a DHW value of four could be due to four weeks that were each 1C above the bleaching threshold, or one week that was 1.5C above and one week that was 2.5C above the bleaching threshold. Generally, DHW values above eight mean it is highly likely that corals will bleach and sensitive species will die, and with DHW of four it is likely there will be substantial but less extensive bleaching (Donner et al. 2017, Eaken et al. 2010, NOAA Coral Reef Watch 2024). During bleaching events in the Caribbean and Gulf, DHW values as high as 12-16 have been estimated, which are associated with more widespread mortality (Eakin et al. 2010, Feng et al. 2023).

Elkhorn coral: Healthy elkhorn coral at Horseshoe Reef in the upper Florida Keys before the 2023 summer's mass bleaching event. Photo: NOAA.

Staghorn coral: A prolonged marine heatwave in 2023 led to widespread bleaching like that shown on these brain and staghorn corals at Sombrero Key Reef in the Florida Keys. Photo: NOAA.

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

While some analyses use satellite-derived sea surface temperature (Cetina-Herida et al. 2023, Feng et al. 2023), it is important to also use at-reef temperatures when available. Bleaching of mesophotic or deeper reefs can occur without bleaching of surface reefs, partly because it is possible to have subsurface marine heatwaves without a surface marine heatwave (e.g., from a deeper than usual upper mixed layer or hyperpycnal flow (Riegl et al. 2003, Smith et al. 2016)). Thus, a sea surface temperature-based analysis could under-predict bleaching in mesophotic or deeper reefs. Some analyses therefore used at-reef-depth data (Johnston et al. 2019, Smith et al. 2016).

Increased bleaching risk at degree heating weeks of four or more, with more extensive impacts at degree heating weeks above eight (Donner et al. 2017, Eaken et al. 2010)

The Flower Garden Banks reefs off the Texas coast, with variation between the east and west sections, generally see bleaching after 2-3 months of 29C temperatures or 3-4 weeks at 30C (Johnston et al. 2019).

In Packery Channel, Texas, cryptic corals could tolerate temperatures reaching up to at least 31.5C (Epps et al. 2024).

Around the U.S. Virgin Islands, a local version of the degree heating weeks metric was developed and it used a threshold (the baseline above which DHW are calculated) of 29.5C at 30m and it declined by around 0.26C for every added 10m of depth. Put another way, deeper corals saw signs of bleaching at lower temperatures (Smith et al. 2016).

Sometimes bleaching is reversible, and some exposure to moderately high temperatures can even prime corals so they are more resilient to moderate future marine heatwave events (Li 2023, Smith et al. 2023). However, heat stress can increase disease susceptibility, which can further reduce coral cover (e.g., white diseases in *Orbicella spp.*) (Smith et al. 2016). More generally, the impacts of marine heatwaves can be exacerbated by other conditions like extensive light exposure, disease, or pollution (Gonzalez-Espinosa et al. 2021, Riegl et al. 2003, Smith et al. 2016, Smith et al. 2023).

Some species of corals are more susceptible to extreme heat than others, and there is evidence of local adaptation that allow shallow corals to tolerate higher temperatures than deeper corals of the same species (Smith et al. 2016). Corals in deeper water might be exposed to lower temperatures and light conditions, which can lead to lower mortality rates, but slower growth and potentially higher vulnerability to high temperatures (Ruiz-Diaz et al. 2022, Smith et al. 2016). On the other hand, there are some nearshore, shallow corals in the Packery Channel in Texas that can tolerate conditions up to 31.5C (Epps et al. 2024). Also, individuals that are at the warmer edge of their species' range are more likely to be stressed by marine heatwaves because they are closer to a species-specific thermal limit than those in the center or cold edge of their species' range (Smith et al. 2023). There is some evidence that bleaching thresholds are increasing over time, which could be a sign of coral acclimation or longer-term adaptation to increasing ocean temperatures but could also be due to the loss of more susceptible species (Donner et al. 2017, Sully et al. 2019).

It is crucial to monitor marine heatwave intensity and duration for potential bleaching risk as well as reduce other stressors that could exacerbate coral stress (e.g., pollution). There are attempts to increase coral thermal tolerance and reduce coral light exposure during marine heatwaves using geoengineering and genetic techniques but these approaches are still an area of active research and debate (Australian Institute of Marine Science 2024, Miller et al. 2024, Tollefson 2021). Notably, though marine protected areas can be helpful for coral conservation generally, those corals are similarly susceptible to marine heatwave impacts (Bruno et al. 2019).

Resources/Communities of Practice

- Coral Reef Alliance (https://coral.org/en/where-we-work/western-caribbean/)
- Coral Reef Watch (https://www.coralreefwatch.noaa.gov/main/)
- Coral Restoration Consortium (https://www.crc.world/)
- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- IFAS Coral Reef Resources (https://edis.ifas.ufl.edu/topics/coral_reefs)
- National Marine Sanctuaries (https://sanctuaries.noaa.gov/involved/)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- U.S. Marine Biodiversity Observation Network (https://marinebon.org/us-mbon/)

Coral Bleaching: Time series showing elkhorn coral bleaching and dying in 2023. The last image shows the coral skeleton being colonized by filamentous algae. Photo: NOAA.

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Northern and Southern Quahog (*Mercenaria mercenaria* and *M. campechiensis*)

Key Message

Exposure to elevated temperatures (e.g., above 30C) can lead to negative impacts across all life history stages — from eggs and larvae to juvenile and adult clams. Physiological stress and risk of mortality in adult clams is associated with prolonged (2+ months) or severe (above 34C) exposure to heat.

Overview

Marine heatwaves, extended periods of higher-than-normal ocean temperatures, adversely impact a variety of marine intertidal species, including clams.

Northern and Southern Quahog (*Mercenaria mercenaria* and *M. campechiensis*, respectively) are two species of clams found in various parts of North America and the Caribbean (Florida Fish and Wildlife Conservation Commission 2024, Smithsonian Environmental Research Center 2024). *M. mercenaria* lives in sandy to mud-sandy regions in mid-intertidal zones down to about 18m in depth; it is more common in oyster reefs while *M. campechiensis* is primarily in sand and seagrass habitats (Smithsonian Environmental Research Center 2024). Where both species are found together, they can hybridize (Florida Fish and Wildlife Conservation Commission 2024, Smithsonian Environmental Research Center 2024).

Mercenaria campechiensis: Living in sand and seagrass habitats, the Southern Quahog may have better survival in elevated temperatures. Photo: Brenda Bowling, Texas Parks and Wildlife Department

Marine heatwaves impact *Mercenaria* species across life stages. At temperatures above 27-30C for 8-15 weeks, *M. mercenaria* can experience decreased fertilization and hatching success, declines in shell hardness, and increased oxidative stress (Ivanina et al. 2013, Matoo et al. 2013). Eggs in particular do not develop successfully above 32.5C (Davis and Calabrese 1964). *M. mercenaria's* metabolic rate also increases at higher temperatures, which can be harmful if adequate food sources are not available to compensate, including when food sources cannot survive high temperatures (Davis and Calabrese 1964, Ivanina et al. 2013). Related to these stress responses, adult *M. mercenaria* experience higher mortality at temperatures above 27C compared to 22C after five or more weeks of exposure (Ivanina et al 2013). Both adult *M. mercenaria* and *M. campechiensis* show signs of high stress at a molecular level after fewer than four weeks of exposure to high temperature, upregulating genes related to heat stress management (Song et al. 2022). *M. campechiensis* appears to struggle more with high temperatures (34C in this case), potentially because it tends to live in deeper waters than *M. mercenaria* and normally experiences milder temperature fluctuations (Song et al. 2022). However, *M. campechiensis* responses to temperature are not as well studied.

Other factors can stress clams and interact with temperature to impact their reproduction and development. For example, *M. mercenaria* eggs are particularly sensitive to low salinity (below 20 ppt), especially at temperatures above 27C (Davis and Calabrese 1964). However, at higher salinities (22.5-27 ppt), *M. mercenaria* larval growth can be extensive even at 30C.

What this means is that marine heatwaves, especially if they involve prolonged exposures to temperatures above 27-30C or shorter exposures above 32.5C-34C, can lead to declines in clam reproduction and adult survival. Management to minimize species co-stressors (e.g., low salinity) or reduce temperature exposure in aquaculture settings may help minimize negative impacts on clams.

Temperature Impacts: At high temperatures, clams can experience decreased fertilization and hatching success. Photo: Florida Department of Agriculture and Consumer Services.

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

The studies included here were all experimental and so they used temperature sensors within experimental tanks (Davis and Calabrese 1964, Ivanina et al. 2013, Matoo et al. 2013, Song et al. 2022).

- 27C-30C for some negative physiological effects (including mortality) after 8-15 weeks (Ivanina et al. 2013, Matoo et al. 2013)
- Drastic negative effects on egg development above 32.5C (Davis and Calabrese 1964)
- Potential protein damage in adults after four weeks of heat exposure around 34C (Song et al. 2022)
- Neuromuscular decline after 10 days of exposure to 32C (Brothers et al. 2015)

Resources/Communities of Practice

- Aquaculture Information Exchange (https://aquainfoexchange.org/register/)
- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- Gulf Shellfish Institute (https://www.gulfshellfish.org/)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- Shellfish Growers Climate Coalition (https://www.nature.org/en-us/what-we-do/our-priorities/tackle-climate-change/climate-change-stories/shellfish-growers-climate-coalition/)
- U.S. Marine Biodiversity Observation Network (https://marinebon.org/us-mbon/)

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Intertidal Crabs

Key Message

Though there is species-level and likely site-level variation, species of intertidal crabs in the tropical Atlantic are likely to suffer increased adult mortality and reduced reproductive success at shallow water temperatures above 39-41C.

Overview

Marine heatwaves, extended periods of higher-than-normal ocean temperatures, impact a variety of marine species, including crabs found in the intertidal zone. These crustaceans often move between the water and land, though their tolerances for submersion and desiccation vary (Capparelli et al. 2022). As such, they are vulnerable to both high air and high water temperatures.

Crab temperature tolerances vary by species and location. For example, four fiddler crab species found in the Gulf and Caribbean start to experience high mortality at temperatures between 39C and 41C (Capparelli et al. 2022). Though these temperatures are higher than what these species normally experience (Capparelli et al. 2022), shallow water temperatures can exceed this during marine heatwaves (Capparelli et al. 2024). One of the fiddler crab species, *Leptuca speciosa*, which has the lowest temperature tolerance (Capparelli et al. 2022) does have behaviors that help it avoid exposure to high water temperatures. *L. speciosa* individuals in a heatwave can aggregate onto exposed rocks or branches to avoid water approaching their thermal tolerance (around 39C (Capparelli et al. 2024)), though they cannot remain out of the water for too long (Cappareli et al. 2022).

Stone crab survival: Commercially important species like stone crabs have lower larval and juvenile survival a higher temperatures. Photo: Andrea Westmoreland.

Temperature tolerances also vary by life stage. For example, juvenile *L. speciosa* start to experience mortality at lower temperatures than adults (Capparelli et al. 2024). Higher temperatures can also affect molting rates, though some species see increases and some see declines (Gravinese et al. 2022, Quinlan et al. 2023). Hatching and larval

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

Generally see negative outcomes for adults in waters above 40C and declines in survival for earlier life stages above 30C, especially with high salinity or low pH.

- *Callinectes sapidus* (Atlantic blue crab): Molting rate declines between 27C and 34C (Leffler 1972, Quinlan et al. 2023)
- *Leptuca panacea* (Gulf sand fiddler crab): Start to see extensive adult mortality (>50%) around 40.5C (Capparelli et al. 2022)
- *Leptuca speciosa* (Brilliant fiddler crab): High adult mortality between 39C and 40C (Capparelli et al. 2022, Capparelli et al. 2024)
- *Maguimithrax spinosissimus* (Caribbean king crab): Lower larval survival at pH 7.7 and 31C compared to pH 8 at 28C (Gravinese et al. 2022); Faster molting at 31C compared to 28C (which might reduce predation risk) (Gravinese et al. 2022)
- *Menippe adina* (Gulf stone crab): Lower larval and juvenile survival at 35C compared to 30C (Brown et al. 1992, Quinlan et al 2023)
- *Minuca rapax* (Mudflat fiddler crab): Start to see extensive adult mortality (>50%) between 39C and 40C (Capparelli et al. 2022)
- *Minuca vocator* (Atlantic hairback fiddler crab): Start to see extensive adult mortality (>50%) between 39C and 40C (Capparelli et al. 2022)

Heatwave survival: Blue crabs are a valuable fishery that could be impacted by an increased frequency in marine heatwaves, which can especially impact early life stages of crabs. Heatwave impacts can also be exacerbated by other factors, such as changes in salinity or pH. Photo: Jeremy Thorpe.

success can also decline at temperatures above 31C, especially when occurring with low pH (Gravinese et al. 2022, Quinlan et al. 2023).

What this means is that, depending on the timing and intensity of marine heatwaves, crab species, especially during early life stages, can be pushed above their normal temperature tolerances. Some crab species have behavioral adaptations that can insulate them from the impacts of high water temperatures, but high temperatures can be especially detrimental when accompanied by other stressors like high salinity or low pH.

Resources/Communities of Practice

- Aquaculture Information Exchange (https://aquainfoexchange.org/register/)
- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- U.S. Marine Biodiversity Observation Network (https://marinebon.org/us-mbon/)

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Energy Infrastructure

Key Message

Marine heatwaves, by increasing the risk of severe storms and extreme heat, can influence the efficiency, lifespan, and broader health of regional energy infrastructure. However, proactive weatherization and energy system management may help to mitigate some of these risks.

Overview

The impacts of marine heatwaves on energy infrastructure are not well studied. Marine heatwaves probably have minimal direct impacts on energy infrastructure, but can facilitate conditions that strain and potentially damage regional energy systems.

If marine heatwaves exacerbate inland temperature and humidity (see Coastal Temperature/Humidity short report), they can strain existing energy infrastructure during summer months due to increased cooling demand (Oppong et al. 2024, Garland et al. 2024, Varianou Mikellidou et al. 2018). High air temperatures and humidity can also increase the risk of transmission line failures, decreasing available power (Varianou Mikellidou et al. 2018, Garland et al. 2024, Ogden et al. 2019). High air temperatures also impact the performance of steam turbines used in oil refining, increase rates of electricity transformer deterioration, and lower the power cell efficiency and lifespan for solar power (Patt et al. 2013, Varianou Mikellidou et al. 2018). Many of these impacts will be seen with a generally hotter climate, but can be exacerbated by acute temperature and humidity stress facilitated by marine heatwaves. If marine heatwaves occur in colder months, they may reduce energy demand from heating and reduce the likelihood of cold waves that can damage solar infrastructure (Amonkar et al. 2023, Patt et al. 2013). However, since the Southeastern U.S. states (including the U.S. Gulf states) and Caribbean are relatively warm, with a warmer climate there will likely be a net increase in thermal demand (Amonkar et al. 2023).

Marine heatwaves are also associated with increased likelihood of storms that can damage energy infrastructure. High temperatures in the Gulf are associated with severe thunderstorms in the Southeastern U.S. (see Severe Thunderstorms short report). These severe thunderstorms can bring hail, tornadoes, and lightning that can damage energy infrastructure depending on their severity (Patt et al. 2013, Varianou Mikellidou et al. 2018). However, some energy infrastructure can be manufactured to be more resilient to storms; for example solar plates can be built to be more resilient to hail storms, and lightning protection can help moderate risk from lightning for photovoltaic systems (Patt et al. 2013).

Offshore Energy Infrastructure at Risk: While offshore energy infrastructure may not be directly impacted by marine heatwaves, the tropical storms and hurricanes that MHWs can bring put them at risk. Photo: Gulf Research Program.

Similarly, high water temperatures in the Gulf and Caribbean are associated with more and more extreme tropical cyclones and hurricanes (see Tropical Cyclones/Hurricanes short report). Hurricanes can cause extensive damage to energy infrastructure due to a combination of high winds, rainfall, storm surge, and debris (Reed et al. 2010, Varianou Mikellidou et al. 2018). Offshore oil and gas platforms are particularly vulnerable, and for both offshore and onshore oil and gas infrastructure the combination of damage and flooding can also lead to the release of hazardous chemicals (Reed et al. 2010, Rostami and Reza Rahimpour 2023). Offshore wind platforms will similarly have to manage the potential impacts of extreme waves and wind from hurricanes and other severe weather, though there are design approaches that can mitigate risk (Hallowell et al. 2018, Rose et al. 2012). Energy system recovery from hurricanes can be relatively quick but can also be very slow depending on the extent of reductions of electricity production and damage (Gargani 2022, Reed et al. 2010).

Overall, marine heatwaves may not directly influence offshore and onshore energy infrastructure, but can increase the risk of conditions that strain or damage it.

Resources/Communities of Practice

- Climate and Resilience Community of Practice (https://gulfseagrant.org/2024/01/31/climate-and-resilience-cop-meeting-set-for-april/)
- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- Gulf Tree (http://www.gulftree.org/)

Other Relevant MHW Short Reports

- Coastal and Urban Temperature/Humidity
- Severe Thunderstorms
- Tropical Cyclones

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Finfish

Key Message

Marine heatwaves can have impacts on finfish, including range shifts, increased stress, and mortality. However, temperature tolerances and behavioral responses to high temperatures vary widely by species and location.

Managing Finfish: Populations of finfish like gag grouper may benefit from ecosystem-based management approaches. Photo: Florida's Fish and Wildlife Conservation Commission.

Overview

As periods of elevated ocean temperatures, marine heatwaves impact marine organisms, including fish. Fish as an overall group are split into shellfish (e.g., shrimp, crab, clams, oysters) and finfish (e.g., tuna, swordfish, sharks, rays). Here we will focus on finfish, also called true fish. There are more than 1,442 species of finfish in the Gulf, including more than 51 shark species and 49 species of rays and skates (Chen 2017). The *Shorefishes of the Greater Caribbean Information System* run by the Smithsonian Tropical Research Institute includes 1,694 species found in the Caribbean, Gulf, and northern coastal South America (STRI 2023).

Many finfish are ectotherms, especially bony fish (i.e., not sharks/rays), meaning they rely on external conditions for heat and therefore thrive in a relatively narrow range of temperatures (Gale et al. 2013, Haesemeyer 2020). Even species of sharks and rays, which have some internal thermoregulation, get close to their temperature limits in the tropics (Osgood et al. 2021). However, finfish are also mobile and can adjust their location (both depth and horizontally) to adjust their temperature exposure. Because there is so much variation in species temperature tolerances and mobility, we focus here on the different ways that marine heatwaves can impact finfish, starting from behavioral responses and moving to physiological responses and mortality.

As mentioned above, there are behavioral adjustments that finfish can make to avoid high temperatures during marine heatwaves. Examples of protective behaviors include relocation, changes to foraging or movement patterns, and decreased reproductive investment (Smith et al. 2023). For example, at high temperatures, some reef fish will increase their foraging to acquire enough food to counteract increased metabolic demand (Smith et al. 2023). Some sharks are known to temporarily extend their ranges by hundreds to thousands of kilometers during marine heatwave events to adjust for prey movement, increased metabolic demand, and individual temperature exposure (Osgood et al. 2021, Smith et al. 2023). However, some behavioral responses are not advantageous; for example, at high temperatures, some species of bony fish are more likely to run into objects (Gale et al. 2013). Decreased reproductive investment may help adult survival, but also leads to declines in recruitment and, eventually, declines in the overall fish population.

Especially when marine heatwave intensity, extent, or duration goes beyond what behavioral shifts can buffer, high temperatures will also have physiological impacts (Smith et al. 2023). These effects include declines in cardiac function, increased disease susceptibility, decline in food conversion efficiency, increase in stress hormone levels, and increased metabolic demand (Andrews and Stickney 1972, Eaton et al. 2022, Gale et al. 2013, Smith et al. 2023). These impacts can translate into reduced growth and, eventually, mortality. For example, if finfish do not find adequate food to compensate for increased metabolic demand at high temperatures, they will start to lose weight, which is especially dangerous for juveniles (Cox and Coutant 1981, Smith et al. 2023). Some species like southern flounder (*Paralichthys lethostigma*) can end up with biased sex ratios due to high temperatures (Midway et al. 2024), influencing the future reproductive potential of the population.

These physiological stresses, and even some of the behavioral shifts, can lead to increased mortality. For example, increased foraging can make reef species more vulnerable to predation (Smith et al. 2023). Similarly, some bony fish species have higher fishing catch rates at higher temperatures, which can skew stock assessments and impact fisheries management (Bacheler and Shertzer 2020, Smith et al. 2023). Bony fish that are caught and later released in hotter waters also experience higher post-release or discard mortality, which is of particular concern for recreational fisheries (Gale et al. 2013, Whitney et al. 2017). Globally, there have been mass mortality events in both wild and farmed bony fish populations due to high temperatures, often in combination with other stressors (e.g., bacterial infections, harmful algal blooms (Smith et al. 2023)).

That being said, a marine heatwave may not be bad for all finfish species in a given location. Marine heatwaves in temperate regions can allow tropical fish to move into areas that would have otherwise been too cold for them (Smale et al. 2019), and estuaries in the Gulf and Atlantic coasts of the U.S. may see increases in fish abundance with mildly hotter temperatures (Oke et al. 2022). Demersal fish, which live and feed near the sea floor, may also be less negatively impacted than species that are higher in the water column (Fredston et al. 2023). However, since waters in the Gulf and Caribbean are already relatively warm, it is likely that some species will be negatively impacted by heatwaves, though more research is needed.

Certain traits or characteristics can make populations or species of finfish particularly susceptible to negative marine heatwave impacts. For example, species that have low reproductive rates or otherwise slow population growth rates will have a harder time recovering from population declines, including from temperature-induced mortality (e.g., scalloped hammerhead shark, Nassau grouper (Quinlan et al. 2023)). Species that have high habitat specificity or rely on temperature sensitive ecosystems (like coral reefs) may also be particularly vulnerable to marine heatwave impacts (e.g., Gulf sturgeon, gag grouper (Quinlan et al. 2023, Smale et al. 2019, Smith et al. 2023)). Individuals that are at the warm edge of the species range are more likely to experience negative effects of marine heatwaves because they are closer to upper limits of the species thermal tolerance (Smale et al. 2019, Smith et al. 2023).

Managing finfish populations in the context of marine heatwaves benefits from knowledge of species-specific (and even population-specific) responses to temperature across life stages. In lieu of these data (which are lacking for many regional species), there are some general measures that can be effective.

Recovering from heatwaves: Species like Nassau grouper could have a harder time recovering from impacts of MHWs because of low reproduction rates. Photo: Q. Phia.

Reducing other stressors (e.g., pollution, fishing pressure, anoxic conditions) can help minimize conditions that might make temperature-induced stress more dangerous. To do so, however, it is important to adjust for the fact that finfish populations can shift during marine heatwave events and that catchability rates may increase, requiring adjustments to stock assessment protocols and maps of likely population locations. More broadly, finfish are impacted by conditions, including temperatures, that harm their habitats and prey (e.g., coral bleaching, seagrass declines). Therefore, ecosystem-based management may be another useful tool for managing finfish populations in the Gulf and Caribbean (Haugen et al. 2024, NOAA Fisheries 2024).

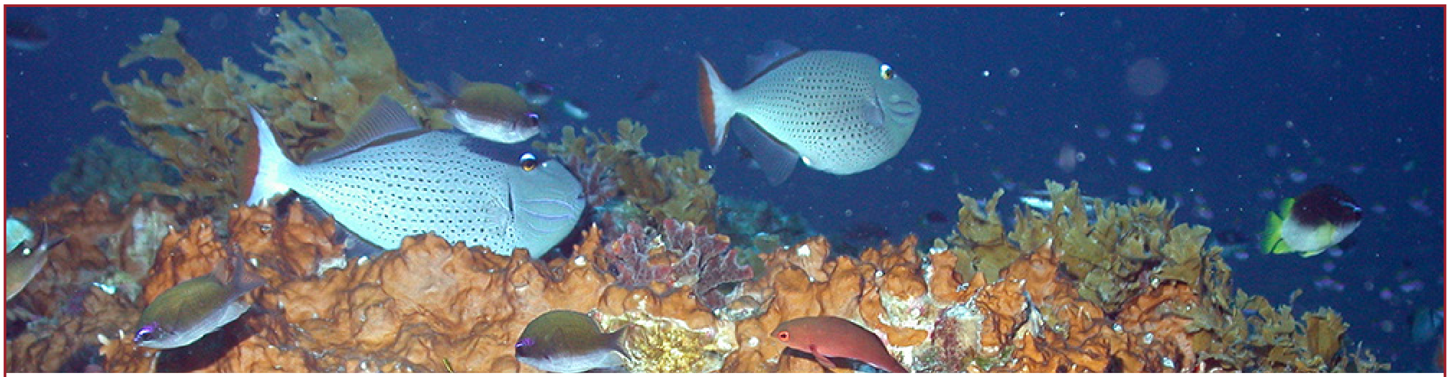
Temperature Datasets Commonly Used and Relevant Temperature Thresholds

Many of the papers cited here are reviews that combine a range of temperature datasets. Large-scale studies often rely on satellite-derived sea-surface temperature data (Smale et al. 2019). However, because finfish are mobile and can change depth, fish-level temperature data or at least subsurface temperature data can provide a much clearer picture of temperature exposure (Bacheler and Shertzer 2020).

Temperature thresholds vary widely by species and population.

Resources/Communities of Practice

- Aquaculture Information Exchange (https://aquainfoexchange.org/register/)
- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- National Marine Sanctuaries (https://sanctuaries.noaa.gov/involved/)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- U.S. Marine Biodiversity Observation Network (https://marinebon.org/us-mbon/)



Temperature Impacts: Marine heatwaves in temperate regions can allow tropical fish to move into areas that would have otherwise been too cold for them. Photo: Flower Garden Banks National Marine Sanctuary/University of North Carolina Wilmington Underseas Vehicle Program.

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GCOOS GULF OF AMERICA COASTAL OCEAN OBSERVING SYSTEM 20 YEARS

Fisheries

Key Message

Marine heatwaves can impact fisheries directly by influencing target species populations and quality, as well as indirectly by contributing to conditions that are harmful to workers and/or infrastructure. There are adaptation options both related to species population management and reducing fisher economic risk, but their feasibility depends on context.

Overview

Marine heatwaves, periods of prolonged higher-than-normal ocean temperatures, impact fisheries by impacting fish species, altering fish habitat, influencing worker safety, and potentially by exacerbating threats from hurricanes. Southeastern U.S. recreational fisheries generate more than $15 billion in annual sales for more than 4.5 million anglers (NOAA Fisheries 2024). Commercial sales from the Gulf and Southeastern U.S. generated more than $37 billion in sales and more than $1 billion in revenue in 2022 (National Marine Fisheries Service 2024). The fisheries in the Gulf, Southeast U.S., and Caribbean vary in their characteristics, but all regions are exposed to high temperatures (Link & Marshak 2018). Due to environmental exposures, U.S. fisheries in the Southeast received nearly $506 million in federal fishery disaster assistance related to environmental causes between 1994 and 2020 (Bellquist et al. 2021).

Fisheries harvest a variety of species, ranging from bivalves (e.g., oysters) to bony fishes (e.g., red snapper). Hereafter we refer to the harvested species as “target species” in the aggregate, with species or group names specified when appropriate.

As discussed in the Northern and Southern Quahog, Eastern Oyster, Intertidal Crabs and Finfish short reports, marine heatwaves can directly impact target species reproduction, growth, development, and eventual survival. The impacts are not uniform across species or regions (e.g., see discussion in Finfish short report); however, negative impacts of marine heatwaves for target species are not uncommon. Recruitment failures, whether due to direct physiological stresses or declines in nursery or breeding habitat (see Corals and Seagrass short reports), lead to reductions in target species populations and thus reduced fisheries income (Smith et al. 2023). If high temperatures lead to increases in catch rates (Bacheler and Shertzer 2020, Smith et al. 2023), heatwaves can require adjustments to stock assessment methods to ensure populations remain above target levels (Bacheler and Shertzer 2020, Smith et al. 2023). If high temperatures lead to declines in food availability, the target species may still be present but smaller than usual or showing signs of stress that reduce quality (Cox and Coutant 1981, Davis and Calabrese 1964, Smith et al. 2023). If the mobile species move out of their normal range, fishing

Managing Fisheries: Marine heatwaves can have direct and indirect impacts on commercial fisheries, leading to lost revenue and production. Photo: Mississippi State University Extension Service

fleets will have to change their locations or adjust for changing species compositions (Farchadi et al. 2024, Smith et al. 2023). For example, the U.S. Atlantic pelagic longline fleet shifts seasonally to follow fish habitat, moving south in the winter/spring and north in the summer/fall. Marine heatwaves in the southern Atlantic lead to larger displacements beyond these normal seasonal fleet movements (Farchadi et al. 2024).

Marine heatwaves can exacerbate terrestrial heat waves or otherwise lead to higher temperature and humidity that impact worker safety and tourism revenue (see coastal temp/humidity section). Fishery workers are often at risk in cold weather (especially due to hypothermia from cold, wet, and windy conditions (Quandt et al. 2013)), and those risks may be somewhat ameliorated by winter season marine heatwaves. However, the impacts in the summer may be less positive. High humidity reduces the effectiveness of sweat-induced cooling, and those out on the water, especially during marine heatwaves, will be in particularly humid conditions (Alber-Wallerström and Holmér 1985, Di Napoli et al. 2022, Pathmeswaran 2023). In hot, humid conditions, workers will need to work with less intensity and more breaks to remain safe, requiring adjustments to profit expectations (Brimicombe et al. 2023). Extremely hot temperatures can also exacerbate worker discomfort and stress as they go between the hot deck and the cold ice holds for fish storage (Johnson et al. 1998). High temperatures can also impact tourism, likely decreasing tourism in the hot coastal Gulf during the summer months (Atzori et al. 2018, Rutty et al. 2022). Tourism can be important for commercial fishers because charter trips, site-seeing tours, and increased seafood demand from restaurants can provide supplementary income.

Marine heatwaves can also increase the likelihood and/or intensity of hurricanes (see Tropical Cyclones/ Hurricanes short report). Hurricanes can damage fisheries directly (e.g., oyster beds) as well as fisheries infrastructure (e.g., boats, storage facilities) (Motha 2011). For example, hurricane Maria led to 20% declines in commercial landings in Puerto Rico. Small-scale fisheries lost around $17.8 million, much of which was due to damage to fishing vessels and shore-side infrastructure. The combination of power outages and fuel shortages further impeded recovery (Agar et al. 2020). Cuban small-scale fisheries also experienced lost income due to damaged infrastructure and lost fishing time spent in repairs after Hurricanes Irma and Alberto. In the short-term, fishers also had to move further offshore to fish due to declines in some target species, though others were more prevalent than before in the nearshore environment (Ramenzoni et al. 2020). The Gulf grouper fishery has also experienced numerous hurricanes. From 2005 to 2009, in just the initial two weeks when hurricane warnings were issued and immediately after they made landfall, the fishery experienced immediate revenue losses close to $1 million (Solís et al. 2013). Hurricanes can impact fisheries by resulting in forgone fishing income, damage to infrastructure, and changes to target species abundances or distributions.

Adaptation options for fisheries exist, though the appropriate approach depends upon the type of fishery, resources available, degree of marine heatwave impacts, and likely future conditions. For example, adjusting processing capacity and marketing can manage market prices to support industry livelihoods despite extreme conditions (Pershing et al. 2018). Reductions in fishing pressure during marine heatwave events may also help avoid overfishing facilitated by higher-than-normal catch rates and reduce excess stress on target species (Bacheler and Shertzer 2020, Gale et al. 2013, Smith et al. 2023). Diversifying target species can help fishers survive the changes in species abundances or fishery closures with lower economic impacts (Solís et al. 2020). Changing planned production volume, modifying the environment, or adjusting timelines may be suitable in an aquaculture context (Hobday et al. 2018). Cooperative governance can help those in the industry manage risk and avoid unintended consequences like massive drops in target species prices with unexpectedly large, early catches (Pershing et al. 2018). Seasonal forecasts can inform the timing and intensity of these adaptive management strategies for regions that are usually suitable for target species, but occasionally experience marine heatwaves (Hobday et al. 2018). If conditions are such that the region is often unsuitable for the target species, or is likely to be unsuitable in the future, then moving farm locations (e.g., for aquaculture) or planning to change fishing zones or target species may be prudent (Hobday et al. 2018). Target species management and monitoring could benefit from data collection by and for fishers themselves who have a direct view of fluctuating species populations. This approach can provide fishers with an opportunity to participate in gathering essential data for management of otherwise often very data poor species (Lozada Perez et al. 2022, Quinlan et al. 2023).

Resources/Communities of Practice

- Aquaculture Information Exchange (https://aquainfoexchange.org/register/)
- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- Gulf Shellfish Institute (https://www.gulfshellfish.org/)
- Gulf Region Oyster Network (https://estuaries.org/oyster-network/)
- Oyster Community of Practice (https://masgc.org/oyster-community-of-practice-summary)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- Shellfish Growers Climate Coalition (https://www.nature.org/en-us/what-we-do/our-priorities/tackle-climate-change/climate-change-stories/shellfish-growers-climate-coalition/)

Other Relevant MHW Short Reports

- Northern and Southern Quahog (clams)
- Intertidal Crabs
- Coastal and Urban Temperature/Humidity
- Corals
- Finfish
- Harmful Algal Blooms
- Eastern Oyster
- Sargassum
- Seagrass
- Tropical Cyclones/Hurricanes

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Harmful Algal Blooms

Key Message

In high nutrient conditions, marine heatwaves can exacerbate harmful algal blooms (HABs). However, in low nutrient conditions (and generally in the Gulf), elevated temperatures are associated with reduced HABs.

Overview

Marine heatwaves are defined as extended periods of anomalously warm (higher than normal) temperatures in the ocean. These higher than usual temperatures impact marine organisms, including algae. This report will focus on microalgae, see the Sargassum short report for a discussion of a common macroalgae.

Algae are small organisms that, like plants, use energy from the sun in the process of photosynthesis to turn inorganic carbon dioxide into food. They are aquatic and can be found in streams, rivers, and oceans. Some algae produce toxins that impact fish and other organisms, including humans. When there are a lot of the toxin-producing plankton, they are described as harmful algal blooms (HABs). Depending on the species causing the HAB and the way the water is discolored, blooms are also called red tides, yellow tides or brown tides. In the Gulf, the predominant HAB species responsible for red tide is *Karenia brevis*, though other species are also present in the Gulf and Caribbean (e.g., *Aureoumbra lagunensis*, *Alexandrium monilatum*, *Karlodinium spp.*, *Ostreopsis spp* (National Ocean Service 2024, NOAA 2016, U.S. National Office for Harmful Algal Blooms. 2019)).

Higher temperatures from marine heatwaves can increase or decrease algae biomass depending on what other conditions are present, especially nutrient levels and ratios (like the ratio of nitrogen to phosphorus). In areas where there are few nutrients, high temperatures often lead to a decrease in algae biomass and thus lower the likelihood of an algal bloom (Errera et al. 2014, Hayashida et al. 2020, Sen Gupta et al. 2020, Tominack et al. 2020, Zhan et al. 2024). At higher temperatures, plankton need to consume more energy in order to manage increased metabolic rates. As a result, they need to make or acquire more food. If there are not enough of or the right combinations of nutrients (especially nitrogen for *K. brevis* in the Gulf (Vargo et al. 2008)), they end up dying and so we see a reduction in biomass, though smaller ones might be able to survive (Zhan et al. 2024). However, in high nutrient conditions, higher temperatures can promote algal growth because they can meet the increased metabolic demand (Hayashida et al. 2020, Sen Gupta et al. 2020). Instead of dying, they can more quickly grow and/or reproduce. That said, other environmental

Heatwaves and HABs: Heatwave impacts on harmful algal blooms depend on multiple factors, including nutrient conditions and environmental variables. Photo: Nadine Slimak

variables (like wind speed, salinity, light availability, ocean currents, and carbon dioxide concentrations) can also influence *K. brevis* biomass (Errera et al. 2014, Tominack et al. 2020). For example, in areas where upwelling normally brings nutrients, if marine heatwaves are associated with reduced upwelling, then there can be declines in algal biomass due to the combination of increased temperature and reduced nutrients from weakened upwelling (Zhan et al. 2024).

What this means is that, depending on nutrient concentrations, marine heatwaves (especially when they push temperatures above 27C-30C for *Karenia brevis*) can be either cause for concern or a likely relief. Papers looking at *Karenia brevis* in the Gulf (specifically in Florida and Texas — Errera et al. 2014, Tominack et al. 2020) have generally seen the latter, where higher temperatures are associated with reduced *K. brevis* biomass. However, there is mixed evidence on whether high temperatures will increase HAB toxicity (Griffith and Gobler 2020) so it is still important to monitor coastal waters for both HAB presence and toxicity.

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

Analyses often use satellite-derived sea surface temperature data (Sen Gupta et al. 2020, Zhan et al. 2024), though some use products that integrate SST with in-situ data to get slightly more depth (e.g., 1-5m for Hayashida et al. 2020).

- Declines in Karenia brevis biomass above 27C-30C in Florida and Texas (Errera et al. 2014, Tominack et al. 2020)
- General marine heatwave definition from Hobday et al. 2016

Resources/Communities of Practice

- GCOOS HABScope (https://habforecast.gcoos.org)
- Gulf of America Alliance (https://gulfofamericaalliance.org)
- HABCAST (https://www.flseagrant.org/harmful-algal-blooms/habcast/)
- National Harmful Algal Bloom Observing Network (https://ioosassociation.org/nhabon/)
- National Marine Sanctuaries (https://sanctuaries.noaa.gov/involved/)
- One Health Harmful Algal Bloom Community of Practice (https://www.cdc.gov/harmful-algal-blooms/programs/index.html)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)

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Marine Birds, Mammals, and Sea Turtles

Key Message

Marine heatwaves have primarily indirect effects on marine birds, mammals, and sea turtles. Elevated water temperatures, especially during breeding seasons, can impact prey availability and habitat quality as well as shifting migration timing and overall species ranges.

Overview

Marine heatwaves, as periods of elevated ocean temperatures, impact marine organisms or those who rely on marine areas for food. Here we use megafauna to refer to relatively large species that rely on marine ecosystems, specifically marine birds, mammals, and sea turtles (sharks are included in the Finfish short report). These are grouped together due to limited data, but due to differences in their biology, marine heatwave impacts also vary widely. Therefore, here we focus on general trends.

At a global scale, marine heatwaves tend to have negative impacts on birds and mammals (Smale et al. 2019). Most research has focused on indirect impacts of marine heatwaves on megafauna (e.g., due to changes in prey distribution or hazards like toxins from harmful algal blooms (Cavole et al. 2016, Smith et al. 2023, Woehler and Hobday 2023)). These indirect effects can be either positive or negative. For example, hurricanes, which tend to be more intense and more frequent with marine heatwaves, restructure coastal ecosystems and often negatively impact marsh birds in the short term, though they often recover and can even thrive due to the disturbance in the long term (Woodrey et al. 2012). If a marine heatwave is accompanied by increased water stratification, prey for seabirds can either be concentrated closer to the surface or become inaccessible and hard to reach, influencing bird body condition and ultimately survival (Woehler and Hobday 2023). Direct effects are less clear. The direct effects of elevated water and nearby air temperature on cetaceans (i.e. whales, dolphins) appear to be minimal at least for offshore populations (Lettrich et al. 2023). However, high air temperatures that can accompany marine heatwaves could reduce hatching success and lead to biased hatchling sex ratios for some sea turtles (Laloë et al. 2016, Lolavar and Wyneken 2020).

Certain characteristics can make populations or species more susceptible to negative marine heatwave impacts. For example, species that have long generation times or otherwise slow population growth rates will have a harder time recovering from population declines, including from temperature-induced mortality (e.g., sperm whales have a reported generation length of 26-32 years with four to seven years between births (Lettrich et al. 2023)). Diet and habitat specificity can increase species vulnerability to climatic shifts in general, including elevated ocean temperatures (Lettrich et al. 2023). For example, seabirds and pinnipeds (e.g., seals) often rely on specific breeding grounds and so can experience mortality or reproductive failures due to changes in prey amounts near those breeding sites (Smith et al. 2023, Woehler and Hobday 2023). That said, some species (like the tropical seabird the Sargasso shearwater) may do well with warmer sea surface temperatures if they occur during the non-breeding season (Precheur et al. 2016, Woehler and Hobday 2023).

Sea Turtle Feeding Grounds: Sea turtles can expand their feeding ranges by hundreds of kilometers in response to marine heatwaves. Photo: Josué Rodríguez

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

Temperature thresholds vary widely by species and population.

Many of the megafauna considered here are highly mobile species and marine heatwaves can therefore prompt large changes in species distributions. For example, sea turtles can expand their ranges by hundreds of kilometers beyond their usual limits in response to marine heatwaves (Smith et al. 2023). Some seabirds might shift their migration timing due to marine heatwaves, which often leads to lower breeding success and population declines (Woehler and Hobday 2023). These shifts can facilitate tourism but also can increase the risk of fishing gear entanglements for marine mammals and sea turtles (Smith et al. 2023).

What this means is that though few direct impacts of marine heatwaves on megafauna have been identified in the Caribbean and Gulf region, there are numerous potential indirect impacts. Species that rely on specific prey or habitats may be especially vulnerable. Species with less habitat specificity may shift their ranges, especially if heatwaves occur during the non-breeding season. Much still remains uncertain about how marine heatwaves will impact regional megafaunal communities, but examples from western Australia and the Pacific coast of North America show that extreme marine heatwaves can hugely impact marine food webs and thus impact marine megafauna (Cavole et al. 2016, Nowicki et al. 2019, Smith et al. 2023, Woehler and Hobday 2023). The management of marine megafauna thus would benefit from an ecosystem-based approach, protecting key prey populations and breeding habitats along with individuals of the species of interest. However, as species move it may be prudent to proactively adjust nearby activities, like fishing and tourism, to avoid conflict and increase benefits from marine megafauna in unusual locations.

Resources/Communities of Practice

- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- National Marine Sanctuaries (https://sanctuaries.noaa.gov/involved/)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- U.S. Marine Biodiversity Observation Network (https://marinebon.org/us-mbon/)

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Eastern Oyster (*Crassostrea virginica*)

Key Message

Marine heatwaves (especially with temperatures above 30C) can decrease eastern oyster (*Crassostrea virginica*) success across life stages, from fertilization to hatching to adult survival.

Overview

Marine heatwaves, extended periods of higher-than-normal ocean temperatures, impact a variety of marine species, including oysters. Oysters are bivalve mollusks that provide habitat for other species, aid with water filtration, and provide food for humans (NOAA Fisheries 2024). *Crassostrea virginica* or the Eastern oyster is the only species of oyster native to the Atlantic coast of North America. It used to be abundant but its numbers have declined. *C. virginica* grows in the nearshore waters of all five U.S. Gulf States and up into the Gulf of St. Lawrence in Canada, often in waters <10m deep (Anson 2011, NOAA Fisheries 2024).

Marine heatwaves impact oysters across life stages. At high temperatures, especially temperatures above 27-30C, *C. virginica* can suffer decreased fertilization success, decreased hatch rates, declines in shell microhardness, increases in oxidative stress, decreased growth, and increased mortality (Ivanina et al. 2013, Lowe et al. 2017, Matoo et al. 2013, McFarland et al. 2022, Rybovich et al. 2016). There is also evidence of increased metabolic rates at higher temperatures (Ivanina et al. 2013), which can be especially problematic if their food sources cannot tolerate high temperatures, leading the oysters to starve (Davis and Calabrese 1964). Because of these impacts, more than 11 days of temperatures above the 90th percentile of normal temperatures have led to poor oyster recruitments in oyster farms in the Gulf (Plumlee et al. 2024). Oysters can also be stressed by high or low salinity, which can be a co-stressor with marine heatwaves (especially with salinity below 10 (Lowe et al. 2017, McFarland et al. 2022, Rybovich et al. 2016)).

What this means is that while a few days of moderate exposure to temperatures above 30C may be survivable for oysters, during extended periods of high temperatures, management to reduce oyster heat exposure, minimize other stressors (especially salinity), or prepare for reduced harvest would be prudent.

Eastern Oyster Survival: Marine heatwaves can decrease oyster success across all life stages, especially when paired with other environmental stressors. Photo: NOAA

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

Many of the papers studying temperature impacts on oysters were experimental, which use tank-level temperature data (Ivanina et al. 2013, Matoo et al. 2013, McFarland et al. 2022). However, air temperatures (evaluated for consistency with sea surface temperatures) have also been used (Plumlee et al. 2024).

- For *Crassostrea virginica*, generally see signs of stress, decreased reproductive success, and increased mortality at temperatures above 27-30C (Ivanina et al. 2013, Lowe et al. 2017, Matoo et al. 2013, McFarland et al. 2022, Rybovich et al. 2016)
- 11+ days in marine heatwave conditions as defined by Hobday et al. 2016 associated with poor recruitment in Mobile Bay and Apalachicola Bay (Plumlee et al. 2024)

Resources/Communities of Practice

- Aquaculture Information Exchange (https://aquainfoexchange.org/register/)
- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- Gulf Shellfish Institute (https://www.gulfshellfish.org/)
- Gulf Region Oyster Network (https://estuaries.org/oyster-network/)
- Oyster Community of Practice (https://masgc.org/oyster-community-of-practice-summary)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- Shellfish Growers Climate Coalition (https://www.nature.org/en-us/what-we-do/our-priorities/tackle-climate-change/climate-change-stories/shellfish-growers-climate-coalition/)
- U.S. Marine Biodiversity Observation Network (https://marinebon.org/us-mbon/)

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Sargassum

Key Message

Marine heatwaves may lead to declines in Sargassum biomass during the hot summer months (both from reduced growth and increased mortality), but Sargassum has regularly occurred in the region since 2011 and is likely to remain, though the timing of when it arrives may shift.

Overview

Marine heatwaves, prolonged periods of elevated temperatures, can impact marine species, including Sargassum. Sargassum is a genus of brown algae or seaweed that floats in the water rather than attaching to the seafloor (NOAA, 2024). Sargassum can serve as food and habitat for a range of marine species; it is essential for loggerhead sea turtles and fisheries species such as amberjack and grey triggerfish. However, when pushed onshore, it can clog water intake pipes, create respiratory irritation, and can lead to costly clean-ups (NOAA 2024, National Ocean Service 2023, Zhang et al. 2024). Sargassum forms a defining part of the Sargasso sea, a patch of ocean off of the Atlantic coast of the U.S. and partly defined by the Gulf Stream. However, the tropical Atlantic now gets a large increase in sargassum biomass near annually and it can travel between the Caribbean, Gulf, and the tropical Atlantic with currents, winds, and eddies (Marsh et al. 2022, Podlejski et al. 2024, Zhang et al. 2024). Various islands in the Caribbean have recently experienced large increases in sargassum biomass that impact beach use and fishing (Hayward and Joseph 2018).

Essential Habitat: Sargassum serves as essential habitat for loggerhead sea turtles and other species, but when pushed onshore can cause a range of problems. Photo: NOAA.

Sargassum growth declines and mortality increases at high temperatures, though the specific thresholds vary by species, subtype, and region. Sargassum growth in the Sargasso Sea and Gulf Stream declines and mortality increases with water temperatures above 28-30C (Marsh et al. 2022, Marsh et al. 2023, Podlejski et al. 2024). However, these thermal limits may not be the same in the Caribbean and Gulf; for example one species sampled near Puerto Morelos, Mexico, had higher growth at 31C than 28C (Magaña-Gallegos et al. 2023, Marsh et al. 2023). More work studying regional sargassum populations is thus needed to confirm local thermal limits. However, overall higher temperatures could lead to shifts in sargassum species composition toward more temperature-tolerant species or subtypes and, depending on the time of year, lead to shifts in the timing of when sargassum arrives into a region (Marsh et al. 2023, Podlejski et al. 2024). It is also possible that marine heatwaves could indirectly stress macroalgae like sargassum due to changes in herbivory or damage from storms but these impacts are poorly defined, especially in the region (Straub et al. 2019).

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

The experimental treatments used temperature loggers (Magaña-Gallegos et al. 2023), while larger-scale analyses often rely on sea surface temperature since sargassum largely floats on the surface when alive (Marsh et al. 2023).

- Increased mortality and declining growth above 28-30C in the Sargasso Sea (Marsh et al. 2022, Marsh et al. 2023)
- Declining growth for *Sargassum natans* collected from Puerto Morelos, Mexico between 28 and 31C (Magaña-Gallegos et al. 2023)
- Increasing growth for *Sargassum fluitans* collected from Puerto Morelos, Mexico between 28 and 31C (Magaña-Gallegos et al. 2023)

Sargassum on Shore: Various islands in the Caribbean have recently experienced large increases in sargassum biomass that impact beach use and fishing. Photo: NOAA/AOML

Resources/Communities of Practice

- EPA Sargassum Inundation Events Impacts (https://www.epa.gov/habs/sargassum-inundation-events-sies-impacts-human-health)
- NOAA office for coastal management (https://coast.noaa.gov/)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- Sargasso Sea Commission (https://www.sargassoseacommission.org/index.php)
- University of South Florida satellite-based Sargassum Watch System (https://optics.marine.usf.edu/projects/SaWS.html)

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Seagrass

Key Message

Seagrass species in the Gulf and Caribbean are likely near their thermal limits and thus especially vulnerable to summertime marine heatwaves.

Overview

Marine heatwaves, prolonged periods of elevated temperatures, have strong impacts on species that are important elements of marine ecosystems, including seagrasses. Seagrasses are the only group of marine flowering plants, providing an array of ecosystem services ranging from carbon sequestration to nursery habitat for fish to sediment stabilization (Nguyen et al. 2021). Two native species of seagrass in the Gulf and Caribbean are *Thalassia testudinum* (turtle grass) and *Syringodium filiforme* (manatee grass) (Marbà et al. 2022). Another species, *Halophila stipulacea*, native to the Red Sea and Indian Ocean, is increasingly found in the Caribbean and coastal Florida (Wesselmann et al. 2021).

S. filiforme has a higher upper thermal limit than *T. testudinum*, but summertime marine heatwaves can exceed both species' thermal tolerances, potentially leading to large-scale die offs, especially in shallow estuarine conditions (Carlson et al. 2018). In general, plants that live in more fluctuating environments are more resilient to hotter conditions than those in more stable thermal conditions, but those in shallow conditions may be exposed to especially high temperatures that prove lethal (Carlson et al. 2018, Nguyen et al. 2021). While the thermal tolerance of *H. stipulacea* is less well studied in the Caribbean, its upper thermal tolerance in the Red Sea and Mediterranean is higher than both *S. filiforme* and *T. testudinum* (Wesselmann et al. 2020, Wesselmann et al. 2021). This higher tolerance means that *H. stipulacea* may be less vulnerable to extreme temperatures than the other two native seagrass species.

Seagrass communities can recover from die off events if favorable conditions return (Carlson et al. 2018, Serrano et al. 2021). However, if the stress is strong enough or long-lasting enough, there can be changes in the dominant seagrass species or even a shift away from seagrass ecosystems and towards algae or bare-dominated systems (Serrano et al. 2021, Smith et al. 2023). Even if seagrasses survive, there are other documented negative impacts of high temperatures ranging from decreased growth rate, to chlorophyll degradation and DNA damage (Nguyen et al. 2021). While seagrasses have a range of responses that can allow them to tolerate some temperature stress (e.g., allocating more biomass below ground (Nguyen et al. 2021)), marine heatwaves in the Gulf and Caribbean may exceed the buffering capacity of these responses for native seagrass species.

Seagrass Survival: Native Gulf and Caribbean seagrasses, like turtle grass, are likely near their upper thermal limits, making them vulnerable to heatwaves. Photo: Jon Brucker, DEP

What this means is that some native seagrasses in the Gulf and Caribbean are vulnerable to especially summer marine heatwaves, though the non-native *H. stipulacea* may be less impacted. Monitoring and restoration of especially shallow reefs or more vulnerable species can help ensure that seagrass ecosystems recover after marine heatwave events (Serrano et al. 2021).

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

Large scale analyses sometimes use remotely-sensed sea surface temperatures (Carlson et al. 2018, Marbà et al. 2022), however it can be difficult for satellite-based sensors to accurately capture shallow and very nearshore water temperatures and so in-situ sensors are also valuable (Carlson et al. 2018).

- *Thalassia testudinum*: High mortality after multiple 2-plus days at 32C-33C (Florida) (Carlson et al. 2018, Marbà et al. 2022); high sod mortality after 4 weeks at 36C and 1 week at 37C (Redfish Bay, TX) (McMillan 1984); see mortality after acute exposure (~24 hours) at 39C (Redfish Bay, TX) (McMillan 1984)

- *Syringodium filiforme*: High mortality after four weeks at 36C (Redfish Bay, TX) (Marbà et al. 2022, McMillan 1984); high mortality after 6+ hours at 39C (Redfish Bay, TX and St. Croix, Virgin Islands) (McMillan 1984)
- *Halophila stipulacea*: High mortality around 36C-39C depending on the population (lower in coastal Greece and Cyprus; highest in coastal Saudi Arabia) (Wesselmann et al. 2020)
- *Halodule wrightii*: High mortality after 4 weeks at 37C (Redfish Bay, TX) (McMillan 1984); start to see mortality after 72-120 hours at 39C (Redfish Bay, TX) (McMillan 1984)

Resources/Communities of Practice

- Seagrass Community of Practice (http://gomseagrass.cnlworld.org/index.html)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- U.S. Marine Biodiversity Observation Network (https://marinebon.org/us-mbon/)

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Severe Thunderstorms

Key Message

Marine heatwaves in the Gulf can provide warm moist air needed for severe thunderstorms inland, although that air needs to travel north for extensive hail or tornadoes to appear.

Overview

Marine heatwaves are defined as extended periods of anomalously warm (higher-than-normal) temperatures in the ocean. These warm waters impact ecosystems, communities, and industries that are in, on or near the water, but those impacts can stretch inland too.

When there are higher-than-normal temperatures in the Gulf, the air above that water also tends to be warmer and, as a result, can hold more moisture. If that air is pushed inland so that it runs into cold air, there can be a rapid rise of warm, moist air that is conducive for severe thunderstorms that can bring hail and/or tornadoes.

There is evidence that high Gulf temperatures are associated with more severe thunderstorms and hail east of the Rocky Mountains from March-May (Molina et al. 2016). The association is particularly clear in the Southeastern U.S. in April and is more likely when there are both colder-than-usual waters in the North Pacific and warmer-than-usual waters in the Gulf (or conditions associated with the La Niña phase of the ENSO cycle) (Allen et al. 2015; Chu et al. 2019; Edwards and Weiss 1996). This is likely because the conditions in the North Pacific can facilitate a northward push of the warm, moist air from the Gulf (Chu et al. 2019). However, warm moist air from the Gulf — particularly with dew points above 65F/18C — is associated with tornadoes in the fall as well (Evans and Guyer 2006). Similarly, anomalously warm sea surface temperatures in the northern Gulf are associated with hail events in the Southern Great Plains region of the U.S. (Texas, Oklahoma, Kansas, Colorado), with the highest hail frequencies in March-May (Jeong et al. 2020).

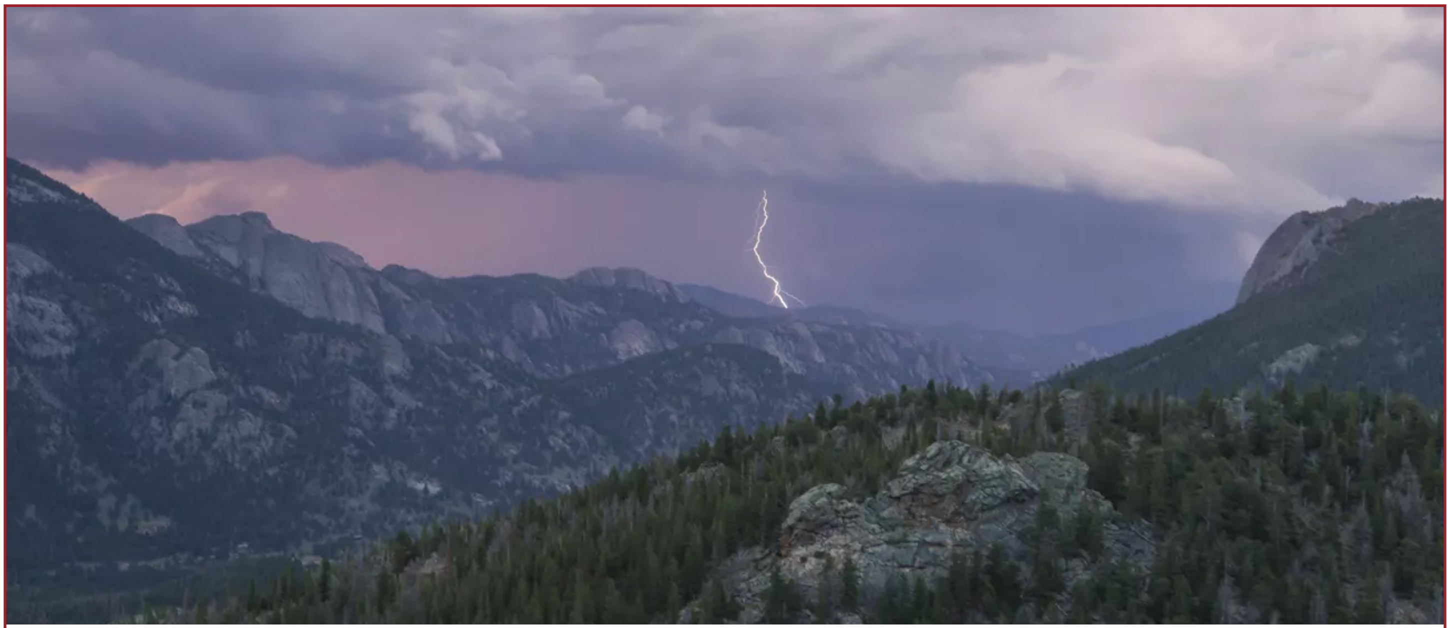
What this means is that, while marine heatwaves alone are not enough to cause severe thunderstorms in the Southeastern U.S., it is worth being vigilant. When there is a marine heatwave, communities should be particularly watchful of conditions that would push warm, moist air north, especially in the spring. The higher-than-normal water temperatures, and the hotter and more moist air that come with them, can provide the energy for severe thunderstorms inland.

Weather Awareness: Higher-than-normal water temperatures can create warm, moist air that provides the energy for severe thunderstorms. Photo: Josh Sorenson

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

Analyses of the relationships between marine heatwaves and severe thunderstorms generally use remotely sensed sea surface temperature data, but can also rely on surface buoy data.

- Moist air with dew points above 65F/18C are associated with tornadoes in the fall (Evans and Guyer 2006)
- Hot April temperatures (no clear threshold) associated with severe thunderstorms (Allen et al. 2015, Chu et al. 2019, Edwards and Weiss 1996, Molina et al. 2016)



Inland Impacts from Marine Heatwaves: There is evidence that high Gulf temperatures are associated with more severe thunderstorms and hail even as far east as the Rocky Mountains between March and May. **Photo: National Park Service.**

Resources/Communities of Practice

- Gulf Tree (http://www.gulftree.org/)
- OSHA Tornado Preparedness and Response (https://www.osha.gov/tornado/preparedness)
- VORTEX-SE (https://masgc.org/vortex-se-engagement)

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GCOOS GULF OF AMERICA COASTAL OCEAN OBSERVING SYSTEM 20 YEARS

Tropical Cyclones/Hurricanes

Key Message

Marine heatwaves in the Gulf and Caribbean can increase the risk of more and more extreme tropical cyclones, including by facilitating the rapid intensification of tropical cyclones/hurricanes that pass through them.

Overview

Marine heatwaves are defined as extended periods of anomalously warm (higher-than-normal) temperatures in the ocean. These warm waters impact ecosystems, communities, and industries that are in or near the water, but can also influence storms that impact a broad range of communities across the region.

High temperatures provide for the warm, humid air that provides energy for tropical cyclones. Hurricanes require the evaporation of warm water; the now humid air is pulled upwards, condensing into clouds (if not destroyed by high-altitude winds), while more warm air from above the water continues to be pulled up. As this process continues, the pressure at the core of the system drops until the system becomes a hurricane (NOAA 2024). The potential energy from the warm water and the warm, moist air that results can be estimated based on sea surface temperature (SST) or ocean heat content (OHC) and higher values of both have been associated with increased tropical cyclone intensity (Liu et al. 2025; Murakami et al. 2018; Kafatos et al. 2006, Radfar et al. 2024; Trenberth et al. 2018). There is also evidence that warmer waters are associated with more hurricanes forming (Murakami et al. 2018), with hurricanes generally requiring water at 28C or higher (NOAA 2024). That said, warm water alone is not sufficient for hurricane and tropical cyclone formation; other factors like wind shear (which in the Gulf may be modulated by temperatures in the central Pacific (Kim et al. 2009)) and ocean stratification influence when and if cyclones will form and whether they will rapidly intensify (Liu et al. 2025, Lopez et al. 2024, Radfar et al. 2024, Shi et al. 2025).

This does not just happen in the north Atlantic. Globally, tropical cyclones that pass through marine heatwaves tend to bring more precipitation and bring that high precipitation over a larger area (Choi et al. 2024, Russel et al. 2019). Because the cyclones are both more intense and can rapidly increase in intensity, they can also bring more damage with less time to evacuate or react.

For example, as Hurricane Ian moved toward Florida, when it reached the West Florida shelf, it hit waters that were warmer than the long-term summer/fall average by 1-2C at the surface and 2-3C below the surface. At that point, it increased from a Category 3 to a Category 5 hurricane within 24 hours. Ultimately, Ian caused the deaths of 156 people and an estimated $112.9 billion in damage. (Liu et al. 2025, Bucci et al. 2023).

Hurricane Survival: 2022's Hurricane Ian made landfall in Lee County, Florida, after intensifying from a Category 3 to a 5 storm in less than 24 hours, leading to 156 deaths. Photo: The National Guard

This means that when there are marine heatwaves in the Caribbean and Gulf, communities should be particularly watchful to see whether tropical cyclones are likely to pass through areas of abnormally warm water. If so, there is an increased chance that the storms will rapidly intensify and have the potential for both stronger winds and more precipitation than might be otherwise expected.

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

Analyses of the relationships between marine heatwaves and tropical cyclones and hurricanes can be done with remotely-sensed sea-surface temperature data (or ocean heat content estimates), but in shallow waters (like the Florida shelf) buoy data with both surface and subsurface estimates can provide more accurate estimates of the heat content of the water (Liu et al. 2025; Trenberth et al. 2018).

- Ocean temperatures of 28C or higher are conducive to hurricane formation (NOAA 2024)
- Rapid intensification with high ocean heat content/temperatures (no clear thresholds); seen with temperatures 1-2C higher than normal at the surface and 2-3C higher than normal below the surface in September in coastal Florida (Liu et al. 2025)
- General marine heat wave definition from Hobday et al. 2016

Resources/Communities of Practice

- FEMA Hurricane Preparedness (https://www.fema.gov/emergency-managers/risk-management/hurricanes)
- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- Gulf Tree (http://www.gulftree.org/)
- Regional Sea Grant offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)

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GCOOS GULF OF AMERICA COASTAL OCEAN OBSERVING SYSTEM

20 YEARS

Green Sea Urchin (*Lytechinus variegatus*)

Key Message

Even though *L. variegatus* is an urchin species with a relatively broad geographic range and protective behavioral responses to stress exposure, it faces potentially fatal declines in physiological capacity after 5-10 days of exposure to high water temperatures.

Overview

Marine heatwaves, extended periods of higher-than-normal ocean temperatures, impact a variety of marine species, including urchins. The green sea urchin, *Lytechinus variegatus*, is found in the western Atlantic from Brazil to North Carolina and into the Caribbean (Brothers et al. 2015, Watts et al. 2013). It is predominantly found in seagrass habitats and its herbivory directly affects seagrass bed density (Watts et al. 2013).

L. variegatus has some behaviors that it can use to manage stressful conditions. It can reduce its light exposure (a co-stressor with temperature) by covering itself with some kind of marine material (Brothers et al. 2015). While useful during acute exposures (e.g., one day) to high temperatures, after 10 days of exposure to 32C, it suffers neuromuscular decline that limits its ability to cover itself as well as its ability to right itself after flipping over (Brothers et al. 2015). Five days of exposure to high temperatures increases *L. variegatus* metabolism while reducing its ingestion efficiency and consumption rate (Lemoine and Burkepile 2012). Because of this mismatch, after extended exposure to high temperatures, *L. variegatus* would be unable to get the nutrients it needs to survive and would die (likely between 32C and 33C (Lemoine and Burkepile 2012)).

What this means is that, even though *L. variegatus* has a wide geographic range and some behaviors that can adjust for stress exposure, it is still likely to struggle with multiple consecutive days of exposure to high temperatures (above 31C-32C). Because it is an important herbivore in seagrass ecosystems, during marine heatwave events management of seagrass should take into account not only seagrass heat tolerance but also the change in herbivory from species like *L. variegatus*.

***Lytechinus variegatus*:** Sea urchins will struggle to survive during multiple consecutive days of exposure to high temperatures. Photo: NOAA.

Covering Up: Sea urchins cover themselves with marine debris for protection. During high temperatures, they lose this ability. Photo: Friends of the Tampa Bay Aquatic Preserves.

Interconnections Matter: During marine heatwaves, management of seagrass should take also take into account changes in herbivory from species like *L. variegatus*. Photo: James St. John.

Temperature Datasets Commonly Used and Relevant Temperature Thresholds

The studies included were experimental and so relied on tank-level temperature data.

- Fatal stress with 5+ days above 31C
- Increase in metabolism with decline in consumption and ingestion efficiency after five days at 31C (Lemoine and Burkepile 2012)
- Neuromuscular decline after 10 days of exposure to 32C (Brothers et al. 2015)

Resources/Communities of Practice

- Gulf of America Alliance (https://gulfofamericaalliance.org/)
- Regional Sea Grant Offices (https://seagrant.noaa.gov/our-story/about-sea-grant/)
- U.S. Marine Biodiversity Observation Network (https://marinebon.org/us-mbon/)

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