# THE PHYSIOLOGY OF DOLPHINS

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**Cover image:**

Upper image: Bottlenose dolphin "Sylvia" upon release following a brief health assessment over the West Florida Shelf in September 2022. She was given a suction-cup-attached DTAG on her back and an earring-style satellite-linked transmitter on her dorsal fin for investigation of her diving behavior over periods of 24 hours and about two months, respectively, before the tags were released. Photo by the Chicago Zoological Society's Sarasota Dolphin Research Program, taken under NMFS Scientific Research Permit No. 20455.

Lower images: Common dolphin (left) and Atlantic white-sided dolphin (middle), North Atlantic; Commerson's dolphins (right), Falkland Islands. Photos by Sascha K. Hooker.

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CHAPTER

# 14

# Human impacts on dolphins: Physiological effects and conservation

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**Abstract**

In this chapter, we describe aspects of the growing pressure on coastal and inshore common bottlenose dolphins (*Tursiops truncatus*, hereafter referred to as dolphins) as human use of these marine environments increases. While the ultimate outcomes of many threats from humans have been well-documented, less attention has been given to the physiological mechanisms underlying these impacts. We address these physiological mechanisms by using bottlenose dolphins as the basis of discussion, as much is known about this species, and it is an important apex predator that serves as a sentinel species for coastal ecosystem health. For much of this chapter, we will draw upon information available from the dolphin community in Sarasota Bay, Florida, USA, that has been studied for more than 50 years. In some cases, the bottlenose dolphin may also be useful as a model for understanding or predicting impacts to less-studied cetacean species. We make comparisons as appropriate with other cetacean species to look at how anthropogenic disturbances, such as entanglement in fishing gear, boat strikes and disturbance, pollution, and climate disruption may affect the health, survival, and reproductive success.

## Introduction

Around the world, dolphins face increasing threats from human activities, especially in coastal and inshore waters where the overlap of people and dolphins is greatest. Dolphins must contend with threats from fishing activities, vessel traffic, disturbance and harassment, pollution, habitat alteration, and climate disruption. In many cases, dolphins are exposed to multiple concurrent threats. Some of these threats result in acute impacts, leading quickly to death, e.g., asphyxiation, while others may be chronic or sublethal, affecting the ability of the animal to function normally or reproduce successfully. In nearly all cases, physiological considerations play a documented or hypothetical role and may ultimately affect survival. In this chapter, we therefore focus how human activities and alterations to the environment result in disruption of the basic mechanisms of life. In this context, physiology is a broad concept where secondary trauma, for example, an oil spill, results in physiological changes that result in morbidity or direct impacts which are beyond the physiological capacity of the individual and result in death.

Due to the species' accessibility to researchers, extensive work with bottlenose dolphins (*Tursiops truncatus*) has identified many examples of impacts to dolphins from human activities in coastal and inshore waters (Wells and Scott, 2018; Wells et al., 2019). Threats and responses have been studied in considerable detail in the southeastern United States (SEUS), so this chapter will focus primarily on this region, with recognition of the fact that findings and conclusions from the SEUS can be extrapolated to many parts of the world (Vollmer and Rosel, 2013). Patterns of long-term, year-round residency in many of the bays, sounds, and estuaries of the SEUS facilitate understanding of exposures of dolphins to threats and assessment of impacts (Wells and Scott, 2018).

To understand human impacts on dolphins, long-term studies, like those conducted by the Sarasota Dolphin Research Program, working in conjunction with Mote Marine Laboratory's Stranding Investigations Program to document the lives of dolphins, can be very illuminating. The studies performed in Sarasota Bay, Florida, have provided long-term data on physiology, metabolism, behavior, and overall health, along with survival and reproductive success of dolphins. During the period 1985–2020, 26% of identifiable causes of death for Sarasota Bay dolphins have



*The Physiology of Dolphins*
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resulted from human interactions (G.N. Lovewell, pers. comm.). Research on Sarasota Bay dolphins began in 1970 and became the world's longest-running dolphin conservation research program (Wells, 2020). During the first 50 years of this study, the research team has seen tremendous increases in human utilization of, and impacts on, Sarasota Bay and surrounding areas. This long-term resident dolphin community serves as an important reference group against which more at-risk populations can be compared. For example, health indices for the Sarasota Bay dolphins have been compared with those from populations in areas where environmental pollution, such as the *Deepwater Horizon* oil spill, has occurred (e.g., Schwacke et al., 2014; Smith et al., 2017). Differences between sites can build a case for identifying likely impacts from the pollution. For many cetacean species and populations, health and population status information is limited. For this reason, the data provided by health assessments and population and ecosystem monitoring, along the lines of those performed by the Sarasota Dolphin Research Program, are and will be vital to help determine how human use of marine ecosystems affects these species and their survival.

Below we present examples of documented threats to bottlenose dolphins in the SEUS, focusing on what has been learned from Sarasota Bay and vicinity and then discuss physiological considerations associated with each threat.

## Fishing activities

### *Issues*

Accidental bycatch or entanglement of marine species is unfortunately quite frequent, and hundreds of thousands of whales and dolphins die each year as bycatch from fisheries interactions (Read et al., 2006; Hamer et al., 2012). Even more individuals are hurt, wounded, or mutilated by fishing hooks, lines, and nets, which likely result in intense suffering and reduced welfare, survival, and/or reproductive success for the individual animal (e.g., Wells et al., 2008). In the shallow inshore waters along the west coast of Florida, three kinds of fishing activities impact dolphins: recreational hook and line angling, crab pots, and to a much lesser extent, gillnets.

Fishing gear is the leading cause of human-related mortality for Sarasota Bay dolphins, accounting for 20% of stranding cases for which a cause of death could be determined and 79% of all human interaction cases (G.N. Lovewell, pers. comm.). Dolphins die or are seriously injured from ingestion of fishing gear, entanglement in fishing line, terminal tackle, nets or crab trap float lines, or from hooking (Wells et al., 1998, 2008). Following a severe red tide (*Karenia brevis*) harmful algal bloom event in 2005–2006, 2% of the Sarasota Bay resident dolphins died from ingestion of fishing gear as dolphins and anglers were vying for the few remaining fish (Powell and Wells, 2011). In some cases, interactions with anglers and associated gear is a learned behavior from mothers who frequent angling situations and place their naïve calves at risk, often reducing their own reproductive success (Wells, 2019). Dolphins can also come to recognize anglers as a food source, through direct provisioning, from discarded catch or bait, or by depredating fishing gear (Powell and Wells, 2011). Dolphins that engage in unnatural foraging behaviors through interacting with humans are at increased risk of future injuries or mortality from such interactions (Christiansen et al., 2016).

### *Physiological impacts*

Dolphins become entangled in fishing nets or crab trap float lines as they swim into undetected nets, attempt to depredate fish from nets, or try to access crab trap bait or catch fish around the traps. On occasion, they become entangled at such depths that they are unable to reach the surface to breathe, and if they are unable to escape within a few minutes of entanglement, they die from asphyxiation. As a variant of this injury, fishing line attached to catch or bait can become tightly wrapped, multiple times, around the epiglottal beak ("goosebeak") that connects the blowhole to the lungs, through repeated swallowing and regurgitation. As the fish or gear is expelled orally or passes through the gastrointestinal tract, the line can tighten to the point of strangling a dolphin (Wells et al., 2008). Other ingestion-related injuries, including fish hooks embedded in the throat, goosebeak, or esophagus, typically lead to death.

Dolphins with gear involvement that don't die from drowning in gear or strangulation may suffer in other ways from fishing gear-related injury and trauma. Fishing line or fishing nets can easily cut into the soft skin of a dolphin and may lead to severe infections or necrosis or amputation of fins. Multiple, constrictive wraps of line around fin insertions can lead to amputation, blood loss, impaired mobility, or infection (Fig. 1). Dolphins with such severe entanglements may swim away with the gear, but likely die later. Some dolphins survive amputations of the distal ends of their fins (Wells et al., 2008). Amputations, while not necessarily fatal, may limit power production and movement and/or maneuverability, or may reduce a dolphin's ability to use its tail as a weapon against predators, prey, or conspecifics (Tolley et al., 1995; see Chapter 4: Muscles and movement). Entangled fishing line, crab traps, or parts of fishing nets

FIG. 1 Emaciated yearling bottlenose dolphin calf in 2011 in Sarasota Bay, Florida, with gear from five different entanglement events. Although the gear was removed by rescuers, the calf was no longer with its mother several days later and was presumed to have died. *Photo by the Chicago Zoological Society's Sarasota Dolphin Research Program, taken under National Marine Fisheries Service Scientific Research Permit No. 15543.*

also cause increased drag, which increases the energetic cost of swimming and increases the need to obtain more food (van der Hoop et al., 2014; van der Hoop et al., 2018). This gear often collects algae, which causes significant additional drag and can deepen cuts and prevent healing. If the increased drag is substantial, the reduced power output or maneuverability may affect the foraging efficiency, resulting in starvation, or may interfere with predator avoidance or social interactions. Similarly, increased drag from entangling gear is also a major issue for large whales, which result in severe suffering and pain and is a major animal welfare issue for wild populations of cetaceans (Moore, 2021).

### *Mitigation possibilities*

Mitigation through responding in the moment to entanglements is difficult, as they often occur in the absence of trained personnel who can disentangle live dolphins or they are not noted until after the animal has died. Details of entanglements and bycatch situations are rarely obtained as they are often not seen, or only seen by fishermen, and unless there is an independent observer onboard, these mortalities may not be reported. Dedicated fisheries observers are deployed on a limited number of boats for certain commercial fisheries, which helps improve the accuracy of the estimated number of fisheries interactions, and in some cases, autonomous video systems can also provide a level of monitoring, but the extent of loss of cetaceans as bycatch is largely unknown (Kindt-Larsen et al., 2012; Scheidat et al., 2018). This monitoring helps to provide a better understanding of the reasons for the interactions particularly if necropsies have been possible on the cadavers. Dolphins depredate fish from gillnets and mobile trawls and asphyxiate if they become entangled in the nets. The necropsies show full stomachs, net trauma, and evidence of terminal decompression-like symptoms (Moore et al., 2009, 2013).

Some of the tools that can be employed to reduce net fishery bycatch include collaboration with stakeholders, such as local communities and fishermen, international organizations, and governments to help reduce impact. For example, with the help of fishermen, improved knowledge of the driving forces that cause dolphins to be attracted to fish in nets may yield new tools and/or methods to mitigate and reduce bycatch. Approaches may include avoiding certain fishing modalities in some areas during part of the year when migrating animals are present. Another option may be to develop new fishing gear that helps prevent nontarget species from entanglement or capture. This may include nets or lines that larger species are able to break free from and the use of reflective gear, acoustically enhanced gillnets, or acoustic sources (Larsen et al., 2007). For some species, such as harbor porpoises (*Phocoena phocoena*) (Dähne et al., 2017) and common dolphins (*Delphinus delphis*) (Carretta and Barlow, 2011; Larsen and Eigaard, 2014), sound sources referred to as "pingers" are attached to nets to make them aware of the presence of nets and to help them avoid them. However, for some other species, such as bottlenose dolphins, pingers appear to be less effective as a deterrent, and may even serve as "dinner bells" attracting the dolphins to nets, where depredation may occur (Dawson et al., 2013).

Along the west coast of Florida, where recreational angling and crab traps are the primary fisheries of concern for dolphins, education and outreach, including stakeholder meetings, are used extensively to increase public awareness of the issues. In recent years, the Sarasota Dolphin Research Program has adopted an approach of helping the public to appreciate the dolphins as individually identifiable long-term residents—their mammalian neighbors who live in the bay year-round, across multiple decades and generations—rather than anonymous gray creatures of unknown backgrounds. The hope is that if people can better relate to the animals as individuals, they will care more about their potential impacts on them.

Fishery interactions are, at times, exacerbated by dolphins learning to approach humans, especially anglers, because they have obtained food from humans previously (Cunningham-Smith et al., 2006). Each time a dolphin obtains a fish from a human, it reinforces the behavior of approaching humans, making the risky behavior more likely to occur again. Feeding wild dolphins is illegal in the United States under the federal Marine Mammal Protection Act. To help get the word out about why dolphins should not be fed, a 30-s public service announcement has been developed, available here: https://sarasotadolphin.org/help-dolphins/dont-feed-wild-dolphins/.

While prevention is the most desirable approach for minimizing fishery interactions, entanglements continue to occur, leading to a need for mitigation through direct interventions. Where suitable facilities exist nearby, entangled live-stranded dolphins with sufficiently serious injuries can be taken to rehabilitation facilities for treatment, ideally leading to reintroduction to their original range once they have recovered. Such interventions, when successful, can not only provide population-level conservation benefits in terms of increasing dolphin abundance (McHugh et al., 2021), but can also provide opportunities to increase awareness to the general public and local communities. Research has shown that interventions prior to stranding have a greater probability for at least short-term success, as measured by survival beyond 6 weeks postrelease, presumably because the animal is in better condition (Wells et al., 2013). In some cases, it is possible to remove fishing gear by means of long-handled tools, without having to restrain the dolphin (e.g., Wells et al., 1998). In many parts of the SEUS, trained teams of veterinarians, biologists, and handlers work together to catch entangled individuals via long seine nets in shallow water, remove gear, evaluate the injury and condition of the animal, and either release it on-site or bring it into a rehabilitation facility. Current research is exploring the development of sedation via darting to be able to access entangled dolphins in waters where traditional capture techniques are not feasible (e.g., due to water depth). Recent research has documented long-term success of interventions, with 92% of rescued animals surviving longer than 6 weeks, no decline in survivorship over the first 5 years postrelease, and successful reproduction by rescued females (McHugh et al., 2021).

Although individuals may survive fisheries-related injuries, the physiological impact of these injuries are difficult to assess. However, injuries and amputations may, in addition to severe pain and suffering, result in elevated metabolic cost of travel and diving, reduced foraging efficiency and effectiveness, and reduced ability to avoid boats (see Section "Boat strikes and disturbance"). Depending on other environmental changes or disturbances, this may push injured animals closer to the physiological limitations for survival. Thus, understanding the impact of fisheries interaction injuries on physiology may not only be a welfare issue but may also be important for dolphin conservation.

## Boat strikes and disturbance

### *Issues*

Threats to dolphins from vessels are manifested as collisions or disturbances. Direct boat strikes are becoming a major issue of mortality and morbidity for many cetaceans that either live in populated areas or migrate close to shore or through busy shipping lanes. For inshore dolphins, increasing vessel use of shallow waters and seagrass meadows where dolphins cannot dive beneath the vessel makes it more difficult for dolphins to avoid direct strikes (Fig. 2). Along the west coast of Florida, about 4% of mortalities for which cause of death could be determined are ascribed to vessel collisions (G.N. Lovewell, pers. comm.), and about 4% of resident dolphins bear scars from collisions with boats (Wells and Scott, 1997). Dolphins in Sarasota Bay experience a powerboat passing within 100 m once every 6 min during daylight hours (Nowacek et al., 2001). These dolphins often change their behavior as boats approach, including changing whistling patterns, forming a tighter group, diving longer, swimming faster, and changing heading as the vessel gets closer (Nowacek et al., 2001; Buckstaff, 2004).

**FIG. 2** Vessels pass within 100 m of each dolphin in Sarasota Bay once every 6 min during daylight hours (Nowacek et al., 2001). *Photo Credit: Photo by Sarasota Dolphin Research Program, taken under NMFS MMPA Scientific Research Permit.*

**FIG. 3** Adult male bottlenose dolphin in Sarasota Bay, Florida, in 2013 with wounds from a boat propeller. The dolphin did not survive these injuries. *Photo by the Chicago Zoological Society's Sarasota Dolphin Research Program, taken under National Marine Fisheries Service Scientific Research Permit No. 15543.*

## *Physiological impacts*

Boat strikes include direct collision with the hull or injury from the propeller, which may result in immediate death. Less severe boat strikes may result in broken bones and concussion. The former may result in pain which may affect the ability to swim. Broken ribs may cause puncturing of the pulmonary pleura, causing pneumothorax and collapse of the lung. This results in respiratory complications, which prevent gas exchange. Propeller injury results in open wounds, which may result in inflammation and infection. When a propeller damages the fins or flukes, the injury and resulting fin mutilation may affect the ability to move and result in similar problems as entanglement (Fig. 3).

Most boat injuries near Sarasota, Florida, involve propellers slicing into dorsal fins and are not lethal (Wells et al., 2008). Potential concerns about damage to the dolphin's dorsal fin cooling system (Rommel et al., 1998; see Chapter 3: Thermoregulation) adversely affecting a mother's ability to successfully produce offspring appear to not be well supported, as mothers with mutilated or missing dorsal fins have been observed to successfully give birth and rear calves (Wells et al., 2008).

Observations of dolphin responses to disturbance by vessels led to concerns about the potential energetic impacts of the frequently repeated need to alter their behavior (Nowacek et al., 2001; Buckstaff, 2004). However, recent telemetry studies to assess the energetic impact of boat avoidance have found that the energetic costs of individual occasions of avoiding boats in Sarasota Bay appear to be minimal (Allen, 2021). Although the direct energetic costs of each avoidance event may be low (Allen, 2021; up to 3.7% of total daily metabolic cost), the additional costs to the animals of frequent and repeated disruption of important activities and behaviors such as feeding, mating, or nursing in order to avoid being struck by boats, and associated stress, should not be underestimated. Thus, whether this increase in metabolic cost has a significant impact on survival depends on the metabolic and physiological limits for this species and population. This highlights the need to better understand the physiological limits of dolphins, which will help target conservation efforts. Similarly, vessel noise can interfere with acoustic communication with conspecifics (Buckstaff, 2004), which may affect collaborative foraging and also the ability for finding soniferous prey fish, with concomitant impacts on dolphin energetics (Berens McCabe et al., 2010). In an area such as Sarasota Bay, where there are more than 40,000 vessels registered within the two counties that encompass the home range of the resident dolphin community, the cumulative costs of frequent behavioral changes can add up.

## *Mitigation possibilities*

Since it is unlikely that boat traffic will decline as more people move to coastal areas, what approach is best to reduce risks from vessels to dolphins? In Florida, boat speed zones are an effective means of reducing vessel collisions with manatees (*Trichechus manatus latirostris*) in shallow areas they frequent (e.g., Nowacek et al., 2001), and these benefits likely transfer to dolphins using these waters as well. Slow speed zones may also help reduce boat noise and thereby reduce noise pollution. Expanding slow speed zones to encompass all of the waters frequented by dolphins would be impractical and would be met with much resistance by the large proportion of the boating public that is reluctant to accept existing limited regulations.

Technological solutions have been suggested, such as requiring the installation of noise-making devices on vessels, but it is already well documented that dolphins (and manatees) are able to hear approaching vessels without the need for adding more noise to the environment. What is needed is sufficient time for animals to get out of the way of the approaching vessels. The installation of propeller guards can reduce damage from propellers to dolphins, manatees, and sea turtles, but this comes with a cost of decreased engine efficiency and handling and does little to reduce impact injuries.

Along the west coast of Florida, outreach and education efforts are underway to increase awareness among members of the boating public about the risks of boats to dolphins. Of particular importance is increasing vigilance by boat operators, especially in shallow waters where there is insufficient depth to allow a boat to pass over a dolphin without striking it, and educating boaters about the misconception that dolphins are too nimble to be struck by boats. Among the outreach tools in use are downloadable pocket-sized cards that describe federal guidelines about keeping boats at least 50 yards from dolphins to reduce disturbance, as well as other actions that can improve a boater's experience on the water while minimizing risks to dolphins. For examples and videos see: https://sarasotadolphin.org/wp-content/uploads/2020/11/Dolphin-Friendly-Tips-Card-English-16Oct08.pdf; https://sarasotadolphin.org/videos-and-downloads/. With regards to other boat-based human activities that can cause disturbance of dolphins, in the United States, swimming with wild dolphins is prohibited under the federal Marine Mammal Protection Act.

## Pollution

Increasing urbanization and use of the ocean and coastal waters also result in increasing pollution. Pollution covers a broad spectrum of adverse anthropogenic alterations to marine ecosystems. These may come from point sources or nonpoint sources and cause direct or indirect effects for dolphins. For the purposes of this chapter, we will focus on five pollution threats to dolphins: (1) persistent organochlorine pollutants (POPs), (2) oil spills, (3) nutrient loading and harmful algal blooms, (4) freshwater diversions, and (5) noise. Other kinds of pollution, including, for example, heavy metals (Bryan et al., 2007; Woshner et al., 2008), perfluorinated alkyl compounds (Houde et al., 2006), and microplastics and plasticizers (e.g., Hart et al., 2020, 2022) are of additional concern, but concerns and mitigation measures largely mirror those of POPs as presented in this chapter.

### *Issues*

#### POPs

POPs include a large variety of chemicals, such as the well-known PCBs (polychlorinated biphenyls) used in industrial and commercial applications, and pesticides such as DDTs (dichlorodiphenyltrichloroethane) and their metabolites. Some of these ecotoxicants have demonstrated impacts on health and/or reproduction of humans and other animals such as dolphins, leading to the prohibition of their manufacture and use in most industrialized countries around the world (Tornero et al., 2014). In spite of these prohibitions decades ago, some of these chemicals can still be found in many ecosystems and dolphin tissues, earning them their characterization as "persistent" (Kucklick et al., 2011). PCBs can originate from local industrial sites, such as the Environmental Protection Agency Superfund Site off Brunswick, Georgia (Balmer et al., 2011), or may be transported from long distances through airborne deposition, likely from incineration of materials containing PCBs (Wells et al., 2005). DDT and its metabolites typically originate from local urban or agricultural sources (Tornero et al., 2014). These compounds bioaccumulate in fatty tissues and are biomagnified through food webs, resulting in very high concentrations in species at the highest trophic levels, such as dolphins (Tanabe, 2002).

#### Oil spills

Oil spill impacts on dolphins vary with the size of the spill, the nature of the oil and dispersant chemicals, and the duration of exposure (Helm et al., 2015). Dolphins can be exposed to crude and weathered oils from spills and seeps, as well as associated dispersant chemicals through direct contact with the skin, eyes, mouth, and blowhole, and they can also inhale volatile petroleum fractions at the water's surface, ingest oil directly, and consume oil components in food. These exposures can initiate a suite of physiological responses that lead to health and/or reproductive impacts. In addition, oil spills can have indirect effects on short- and long-term prey availability. Resident dolphins maintaining limited ranges in bays, sounds, or estuaries can be at particular risk because of their inability to avoid oil (Tornero et al., 2014; Helm et al., 2015; Wells et al., 2017).

#### Nutrient loading and harmful algal blooms

Even human behavior on land can have direct or indirect impacts on dolphins. One of these is run-off from land that results in high nutrient loads in nearshore waters. Such run-off may result from land clearing, or urbanization where the buried soil gets exposed and nutrients are carried to the ocean by rain. Other kinds of run-off come from golf courses, residential yards, agriculture, or farming, where fertilizer or animal excrement washes into nearby waterways. Similarly, human wastes from sewage system failures or failing septic tanks can increase nutrient loading. This results in increasing nutrient concentrations in the water, such as nitrogen and phosphorous. Changes in nutrient loads are measurable in top-level predators such as bottlenose dolphins. Measurements of nitrogen stable isotope in dolphin teeth tracked changes in nitrogen loads in Sarasota Bay, mirroring improvements in seagrass coverage with implementation of advanced wastewater treatment (Tomasko et al., 2005; Rossman et al., 2013).

Run-off from farm land results in elevated levels of nutrients, called eutrophication. Aquatic organisms, like plankton and algae, can use these nutrients as food to grow and multiply which can lead to algal blooms or dense growth of algae and plankton. As the plankton and algae reproduce, they can block sunlight which causes underlying algae such as seagrass, which are important for filtering the water, to die (Tomasko et al., 2005). The bacteria that help decompose the decaying algae and microorganisms deplete oxygen in the water and thereby cause areas of water with low oxygen levels. These hypoxic or anoxic regions cause fish to move or die, which reduces food resources for predators at higher trophic levels like dolphins.

The excess nutrients can also exacerbate naturally occurring harmful algal blooms, such as *K. brevis* red tides, that occur along the west coast of Florida. When physical and chemical conditions are appropriate, these dinoflagellates are transported from offshore into nearshore waters, and they reproduce rapidly, turning waters reddish-brown. The organisms contain neurotoxins known as brevetoxins (Pierce and Henry, 2008). When the cells lyse, the toxins are released, and in sufficient concentrations, the toxins can kill marine life (fish, sea turtles, seabirds, manatees, dolphins) in large numbers (Fig. 4) (Steidinger et al., 1973; Rycyk et al., 2020).

### Freshwater diversions

The bottlenose dolphin is considered a marine species, primarily found in salinities of >8 ppt, and generally >30 ppt (Hornsby et al., 2017). Potentially adverse anthropogenic alterations to marine ecosystems can include waterway management that changes salinity regimes in areas frequented by dolphins, reducing salinity to below physiologically tolerable limits, leading to potential health and ecological impacts (McClain et al., 2020). Such projects have been undertaken, and are planned on a large scale, in the estuarine systems of Louisiana, to try to mitigate long-term wetland loss (Coastal Protection and Restoration Authority of Louisiana, 2017). For example, the diversion of massive quantities of freshwater and associated sediment from the Mississippi River into Barataria Bay as part of the planned Mid-Barataria Sediment Diversion project, a restoration project resulting from the *Deepwater Horizon* oil spill settlement, could greatly reduce salinity in a region inhabited by thousands of bottlenose dolphins (Coastal Protection and Restoration Authority of Louisiana, 2017; Takeshita et al., 2021).

**FIG. 4** Fish kill caused by red tide harmful algal bloom, off Sarasota, Florida, in 2021. Fish typically begin to die when *Karenia brevis* cell counts exceed about 100,000 cells/L.

Noise pollution

Noise pollution and acoustic disturbance are of increasing concern in the marine environment, and in particular, for cetaceans due to their reliance on sound for communication, navigation, and finding food. Increasing ocean noise, through increased boat traffic, sonar use or even echosounders, may make it more difficult for cetaceans to hear one another and may make it more difficult to use echolocation to navigate and find and catch prey. It has been reported that in stranded dolphins, as many as 57% of all individuals had significant hearing deficits (Mann et al., 2010), which may play a significant role in strandings. Sound may also cause acute stress, and in deep-diving species, exposure to sonar has been linked to mass-strandings (Frantzis, 1998; Jepson et al., 2003). While most of these reports have been associated with naval sonar and deep-diving beaked whales, there are reports that link sonar to strandings in the common dolphin, a species usually found offshore ( Jepson et al., 2005; Bernaldo de Quirós et al., 2019; Fahlman et al., 2021). Closer to shore, noise from boat traffic, industrial activities, and marine construction and demolition may be of greater concern (e.g., Buckstaff, 2004; Buckstaff et al., 2013).

## *Physiological impacts*

### POPs

Lipophilic POPs can have a variety of health and reproductive effects on dolphins, especially through immune system suppression (see Chapter 13: Immunology) or through reduced calf survival from transfer via milk ( Jepson et al., 2016). Blubber, the primary site of metabolic lipid storage, has been shown to also be the primary POP storage site, containing more than 90% of the whole-body burden (Wells and Scott, 2018). Bottlenose dolphins in Sarasota Bay exhibit seasonal variation in blubber dynamics (Wells, 1993), with blubber thickness increasing by more than 30% and lipid content increasing by more than 50% during fall/winter (Wells, 2010). As lipids mobilize from blubber during spring/summer, contaminants may redistribute, leading to elevated tissue concentrations and toxicity (Yordy et al., 2010a). Health effects in bottlenose dolphins include anemia and endocrine system impacts, including reduced thyroid hormone levels and total thyroxine, free thyroxine, and triiodothyronine negatively correlated with blubber PCB concentrations in bottlenose dolphins in the SEUS (Schwacke et al., 2012). Immune system effects suggesting increased susceptibility to infectious disease have also been noted (see Chapter 13) (Lahvis et al., 1995; Schwacke et al., 2012). Individuals with reduced blubber lipid may be at increased risk for exposure-related health effects (Yordy et al., 2010a). It is interesting to note that Yordy et al. (2010a) provided evidence that the melon, a metabolically inert lipid-rich structure, may serve as an alternate storage site for POPs, preventing some blubber contaminants from being directly available to other tissues.

Reproductive success can also be impacted by POPs through calf mortality (Schwacke et al., 2002). Circulating POPs are incorporated into lipid-rich milk and transferred to calves via nursing (Cockcroft et al., 1989; Wells et al., 2005; Yordy et al., 2010b). The process of depuration involves a female transferring nearly 80% of her residue load to her calf during the first few months of nursing, a period that overlaps the period when lipids and their associated contaminants are being mobilized from blubber to accommodate summer water temperatures (Cockcroft et al., 1989; Wells et al., 2005). First-born calves receive higher concentrations than subsequent calves, as they are receiving the contaminants accumulated over the first 10 years of a mother's life, on average, which may be a toxic load. Subsequent calves, born within just 1–2 years of the initial flushing of mother's POPs into the first-born calf, receive lower concentrations and have higher survival rates (Wells et al., 2005).

### Oil spills

Oil pollution may have a number of physiological effects (Helm et al., 2015). In recent years, much has been learned about these effects through studies of dolphins presumed to have been exposed to oil and associated chemicals from the *Deepwater Horizon* spill in 2010 off Louisiana, the worst environmental disaster in history in the United States (NOAA, 2015) (Fig. 5). Schwacke et al. (2017) estimated 30,347 lost cetacean years (95% CI: 11,511–89,746) for dolphins inhabiting Barataria Bay, Louisiana, which was heavily impacted by the spill. Estimated time to recovery for Barataria Bay dolphins was 39 years (95% CI: 24–80). Data from catch-and-release health assessments and population monitoring through photographic identification surveys of oiled sites such as Barataria Bay compared to similar kinds of data from unoiled reference sites have provided a great deal of insight about acute and chronic health and reproductive impacts (Schwacke et al., 2014; Lane et al., 2015; De Guise et al., 2017; Smith et al., 2017).

Oil tends to float at the surface, which may cause direct effects on the skin or respiratory problems (Schwacke et al., 2014; Venn-Watson et al., 2015). Immersion in oil has been shown to cause adrenal lesions and hypoadrenocorticism, which may result in death (Venn-Watson et al., 2015). Dolphins in Barataria Bay, Louisiana, following the *Deepwater*

**FIG. 5** Bottlenose dolphins in Chandeleur Sound, Louisiana, swim beneath oil from the *Deepwater Horizon* in 2010. *AP Photo, Alex Brandon.*

*Horizon* oil spill had a five times higher incidence of moderate-severe lung disease, including alveolar interstitial syndrome, lung masses, and pulmonary consolidation as compared to the reference population in Sarasota Bay, Florida (Schwacke et al., 2009, 2014; Smith et al., 2017). Health assessments done in 2011, 2013, and 2014 on dolphins in Barataria Bay and Mississippi Sound showed that although dolphins in the affected population had improved their overall health in years since, there were still a considerable number of dolphins that suffered from moderate to severe respiratory issues as long as 4 years following the disaster (Smith et al., 2017). Subsequent Barataria Bay health assessments during 2016–2018 found that the prevalence of moderate to severe lung disease did not decrease in the years following the oil spill and in fact may have worsened (Smith et al., 2022).

Impoverished respiratory function affects the ability to dive and forage efficiently. Reduced ability to exchange gases while at the surface may increase the recovery duration at the surface, which in turn reduces the foraging efficiency. Consolidated lungs result in a decreased total lung capacity (see Chapter 6: Respiratory physiology in the dolphin and other whales), which for breath-hold diving vertebrates may reduce the total oxygen store. As the total oxygen store affects the aerobic dive limit, respiratory problems may also affect the dive duration and thereby the foraging efficiency. Reduced respiratory efficiency may also affect the ability for high speed or sustained travel, which in turn may make dolphins less able to escape predators or avoid boat collisions. While the effect of inhalation of aerosolized hydrocarbons is known, the effect of elevated pressure, as happens during a dive, is not known. It is likely that the higher pressure inside the lung that develops during the breath-hold may exacerbate the damage.

Lane et al. (2015) reported on survival and reproductive impacts of the *Deepwater Horizon* oil spill. They found that only 20% of the pregnant dolphins in Barataria Bay produced viable calves, compared to a pregnancy success rate of 83% in the Sarasota Bay, Florida reference population. In Barataria Bay, 57% of unsuccessful pregnant females had been previously diagnosed with moderate-severe lung disease. Overall estimated annual survival rate of the Barataria Bay dolphins was low (86.8%, 95% CI: 80.0%–92.7%) as compared with rates of 95.1% and 96.2% from two unoiled reference populations. In addition, long-term presumed oil-related impacts on immune system function have been found for Barataria Bay dolphins, with trends appearing exaggerated in dolphins born after the spill, suggesting continued exposure to oil or possible multigenerational health impacts (see Chapter 13, De Guise et al., 2021).

## Nutrient loading

Nutrient loading can have direct and indirect effects on dolphins. Wastewater associated with some forms of nutrient loading can contain pathogens that adversely impact dolphin health. Indirect, ecological impacts are of great importance to dolphins. Habitat degradation through loss of seagrasses or eutrophication can reduce prey availability. The exacerbation of natural phenomena such as red tides can have dramatic direct and indirect effects on dolphins. Most directly, the brevetoxins can block sodium channels and cause paralysis and death of fish, invertebrates, seabirds, marine turtles, manatees, and dolphins (Twiner et al., 2012). Dolphins can inhale aerosolized brevetoxins or ingest them in prey fish (Fire et al., 2008). Indirect effects of red tides can reduce dolphin prey fish by more than half (Gannon et al., 2009; Berens McCabe et al., 2010; Rycyk et al., 2020). Loss of prey can lead to behavioral changes, such

FIG. 6 Resident bottlenose dolphin of Sarasota Bay, Florida, with fishing gear ingested during a red tide in 2006.

as shifts in habitat use and social patterns (McHugh et al., 2011). Such shifts, along with the need to shift to different, small prey such as clupeids that remain abundant during red tides could have energetic consequences, when additional foraging, capture, and prey handling effort is required to obtain sufficient numbers of smaller fish to obtain the requisite calories (Bejarano et al., 2017). Thus, nutrient loading can have both direct effects on respiratory function from brevetoxins (see Chapter 6) or cause increased metabolic demand to find sufficient food due to shift in prey availability (see Chapter 2: Energetic costs of rest and locomotion in dolphins). In addition, as mentioned above, when dolphins interact and compete with anglers for the few remaining desirable fish during or after a red tide, dolphins can be seriously injured or die from ingestion of, hooking by, or entanglement in fishing gear (Fig. 6).

Freshwater diversions

Prolonged (days to weeks) immersion in very low salinity waters (~0 ppt) can lead to health impacts through direct contact with the skin and through ingestion. The ability of skin to act as an effective barrier will decline as skin lesions develop, followed by algal, fungal, and/or bacterial overgrowth that may sometimes penetrate the skin, followed in turn by secondary infections (McClain et al., 2020; Takeshita et al., 2021). Consumption of too much freshwater can affect absorption and increase the potential for infections (see Chapter 11: Kidneys and osmoregulation). As suggested by Takeshita et al. (2021), these two routes of exposure may lead to systemic physiological changes, including osmotic imbalance, biochemical aberrations, cellular damage, and the potential for localized or systemic secondary infections or septicemia. In 2019, an Unusual Mortality Event was declared by NOAA in the northern Gulf of Mexico in response to dramatically increased strandings of dolphins with a high prevalence of freshwater-like lesions, following record-breaking precipitation (NOAA, 2019). On occasion, it has been possible to document resolution of health issues when an individual is returned to waters of normal salinity (e.g., Deming et al., 2020). Much remains to be learned about the conditions leading to effects from freshwater exposure. For example, following historic flooding in the Florida panhandle in 2014 that led to lowered salinities over several months, no significant increase in mortality rates was noted, and an anticipated widespread skin lesion outbreak did not occur (Toms et al., 2021). In addition to the potential health consequences of reduced salinity, prey availability is likely to change as well as fish move or die in response to the changing environmental conditions.

Noise pollution

In both water and air, sound is produced by propagation of acoustic waves. Sound waves can travel through any substance, but they travel faster in dense media, e.g., five times faster in water as compared with air. Sound also travels farther in water as compared with air, although the distance traveled is dependent on the frequency of the sound, water depth, salinity, presence of submerged vegetation, physiography, and other features. These physical characteristics of sound affect both dolphins and other cetaceans that use sound to communicate over long distances and echolocation to find and catch prey. Masking from increasing noise is likely to make it more difficult for cetaceans to hear each other or may interfere with the ability to find prey (see Chapter 10: Sensory physiology in delphinids, Buckstaff, 2004). Thus, hearing deficiency may reduce the ability to capture food, interact with conspecifics, avoid predators or boat traffic, or the ability to navigate and may in part explain why a high proportion of stranded dolphins had hearing deficiency (Mann et al., 2010). The only Sarasota Bay resident subject of Mann et al. (2010) was a young female that had separated prematurely from her mother. She had deep cuts in her peduncle from a boat propeller strike, fishing line embedded in the cuts in the peduncle, and high frequency hearing loss; this individual is not believed to have survived postrelease following rehabilitation (Wells et al., 2013). In part to address the question of whether repeated, frequent exposure to noise from intensive small boat traffic has affected the hearing abilities of inshore bottlenose dolphins, auditory evoked potential tests were conducted with Sarasota Bay resident dolphins during health assessments (Wells et al., 2004). No significant hearing loss was found for any of the long-term resident dolphins (Cook, 2006), but it should be noted that these measures were from living, relatively healthy dolphins inhabiting shallow waters, where they are not exposed to noise from large vessels, military activities, or large-scale industrial activities; hearing loss may be an issue in areas with greater exposure to loud noise.

The effect of man-made sonar has received considerable attention and been a matter of intense debate since initial reports that linked naval sonar to mass-strandings of deep-diving beaked whales (Jepson et al., 2003; Fernandez et al., 2005; Bernaldo de Quirós et al., 2019). A considerable international effort followed these initial reports, and as of 2021, it is generally accepted that exposure to powerful sonar results in behavioral changes (e.g., DeRuiter et al., 2013). It has been proposed that both behavioral and physiological changes occur following exposure to powerful sonar that may result in the formation of symptomatic gas emboli (Fahlman et al., 2021). Recent work in the bottlenose dolphin, which has been used as an animal model to understand the physiology of deep-diving cetaceans, suggests that these species have a mechanism that helps regulate gas exchange (see Chapter 6 for the *Selective Gas Exchange* hypothesis) and prevents uptake of $N_2$. When this mechanism fails, as during potential stress following sonar exposure, more $N_2$ is taken up, which leads to development of gas emboli that results in severe symptoms (see Figs. 2 and 4 in Fahlman et al., 2021). This hypothesis, if correct, provides a simple means for mitigation under some circumstances as the stress may be minimized during training or testing exercises by desensitizing cetaceans to the sonar. One method could be to ramp up the sonar source level giving the whales time to leave the area without stress and/or making sure that the exposure duration of each event is short enough for the whales to recover in between exposures. More work is needed on the potential effects of noise on stress in dolphins.

### *Mitigation possibilities*

Pollution mitigation can involve cessation of polluting activities, clean-up, and/or restoration actions; however, in many cases, this may not be possible or practical. For example, production and use of some of the most toxic POPs were halted decades ago in the United States, but concentrations of concern for dolphin health and reproduction are still found at many sites.

POPs remain highly concentrated in some areas where they were produced or released, such as Brunswick, Georgia, leading to concentrations in dolphin tissues that vary inversely with distance of the dolphin ranges from the point source (Balmer et al., 2011). Clean-up of the Environmental Protection Agency Superfund Site near Brunswick has been proposed, with a goal of reducing contaminant concentrations in dolphins. Widespread nonpoint-source deposition of toxic POPs in many other parts of the world precludes the possibility of such clean-up. In these cases, only the passage of time can reduce availability of these contaminants. For example, in Sarasota Bay, Florida, the concentrations of legacy POPs in bottlenose dolphin blubber declined from 2000 through 2009 but leveled off through 2016 at concentrations that may continue to suppress population growth (Kucklick et al., 2022). Elimination of legacy POPs as environmental threats will not happen soon. Hopefully, lessons learned from these legacy pollutants will reduce future threats from development and application of toxic chemicals.

Restoration following oil spills can be very challenging, depending on the size of the area impacted and the severity of the spill. Efforts to restore marine mammals impacted by the *Deepwater Horizon* oil spill are currently in early stages (Deepwater Horizon Natural Resource Damage Assessment Trustees, 2016). While marine mammal populations cannot be restored directly, efforts to provide optimal habitat for population recovery and reduction of other human impacts can contribute to restoration, but much time will be required given the life history of these animals.

Mitigation of nutrient pollution involves preventing nutrients from entering the waterways in the first place. Mechanisms exist that can help control these sources of pollution, including reduced application of fertilizers, advanced wastewater treatment, elimination of septic tanks, and increased use of retention areas that trap nutrients and prevent them from reaching the waterways. As excess nutrients are removed, natural processes such as filtration by seagrass meadows can expedite the process (Tomasko et al., 2005; Rossman et al., 2013). As water clarity improves and sunlight can penetrate deeper, seagrass meadows can expand into deeper waters, providing a positive feedback loop for improving water quality. However, the implementation and effectiveness of these approaches depend on public support and political will, which can sometimes be difficult to mobilize in coastal communities facing a multitude of needs and priorities.

As is the case with nutrient pollution, the best method for mitigating the problems for dolphins associated with exposure to too much freshwater is to not engage in diversions of such magnitude as to make dolphin habitats uninhabitable. However, in Louisiana, where such diversions are occurring and planned, these competing interests appear to have taken precedence over dolphin restoration. Efforts are moving forward to re-establish wetlands lost to previous engineering projects, storms, and sea-level rise, so that they can provide a protective buffer for future storms and sea-level changes, as well as habitat for other forms of wildlife.

In some cases, it may be possible to reduce anthropogenic noise in the coastal marine environment. Underwater construction projects can sometimes use noise barriers, such as steel coffer cells, or bubble curtains to reduce noise (e.g., Buckstaff et al., 2013; Dähne et al., 2017). In some cases, dolphins have demonstrated the ability to adapt their behavior to at least some acoustic changes in their environment. For example, in Sarasota Bay, dolphins did not entirely avoid an area of bridge construction, but dolphin density increased significantly following completion (Buckstaff et al., 2013). Near John's Pass, Florida, female presence declined during a 5-yr bridge construction project, while males showed no response (Weaver, 2015). Although these reports suggest behavioral changes, it is unclear whether there were physiological effects for those individuals that remained in the area.

What may happen if the noise level in the ocean is increased permanently (e.g., the EU Marine Strategy Framework Directive; https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-11/index_en.htm)? One option may be for the animals to increase their level of sound emission. This is similar to what happens in a noisy restaurant where it becomes increasingly difficult to have a conversation as the restaurant becomes increasingly noisy as the evening is progressing. The solution is to increase the source level of your voice so your friends can hear you, but such a compensation only works for a limited noise range and may alter the metabolic cost of communication. However, recent work has shown that sound production is metabolically cheap and communicating louder may not result in a significant metabolic burden (Pedersen et al., 2020). In a confined terrestrial context, disturbed animals can relocate to quieter areas, but because sound transmits well in the ocean, there are fewer options for dolphins to hide from increasing noise levels. Every effort should be made to reduce noise in the marine environment, to not let it get to the point where it results in dolphin hearing loss or behavioral disturbance or forces potentially detrimental changes in habitat use (Fig. 7).

**FIG. 7** Demolition of previous bridge supports during construction of new bridge in Sarasota Bay in 2003 (Buckstaff et al., 2013).

## Climate change

Climate change is likely to have multiple effects on dolphin populations. As greenhouse gases trap more heat, the average temperature of the earth is increasing. Since water has more than four times higher specific heat capacity than air, the ocean acts as a heat sink and moderates the increase in air temperatures. Thus, with time, the water temperature of the surface layers will begin to increase, and this increase will penetrate deeper into the water column. This will affect physiology and could possibly affect thermoregulation (see Chapter 3). Increased water temperatures, in conjunction with increased availability of nutrients from human activities, are likely to increase the occurrence and strength of harmful algal blooms, including red tides, which may have direct health effects and also indirectly reduce food availability, as described above. Increasing water temperatures are also likely to have an impact both directly and indirectly on dolphins and other cetaceans (see Chapter 3). As the temperature of the surface layers increase, currents change, water level rises, and pH decreases, the distribution of prey is likely to change. Temperature-sensitive prey species can either move further down into the water column (not possible in shallow inshore habitats) or move to higher latitudes.

### *Physiological impacts*

Dolphins, like all mammals, maintain a stable core body temperature. Within a given temperature range, called the thermoneutral zone, there is no increase in the metabolic rate. However, temperatures below or above the thermoneutral zone cause an increase in metabolic rate (see Chapters 2 and 3). The increased metabolic rate is caused by physiological processes that help produce additional heat at lower temperatures or increase blood flow to help dump or remove heat at higher temperatures. Both responses help to maintain a stable core temperature. The thermoneutral zone of inactive dolphins accustomed to being housed in human care in ocean pens ranges from 5°C to 30°C (Williams et al., 2001; Yeates and Houser, 2008). As dolphins inhabit warm and temperate regions worldwide, it is likely that the thermoneutral range may vary among populations and also among nearshore, shallow-diving or offshore, deep-diving populations. Still, increased activity during active swimming and prey capture events will increase heat production. In such a case, dolphins may have lower exercise tolerance before overheating. Bottlenose dolphins in Sarasota Bay, Florida, have been found to have significantly higher field metabolic rates in summer than in winter (Costa et al., 2013). During summer, inshore water temperatures can exceed 30°C and approach body temperature, thus limiting the ability of the animals to cool through heat conduction to surrounding waters. Already, dolphin mortality rates are significantly higher during warm seasons than cool seasons, when water-borne pathogens are more prevalent (Buck et al., 2006), but the potential role of water temperature in these mortalities has not been defined (Wells, 2010).

Increasing water temperatures may result in dolphins having thinner blubber layers. As adipose tissue is also a store of energy and water, dolphins in warmer waters may be less capable of handling food shortages and may be unable to fast for long durations. Thinner blubber may also lead to higher circulating concentrations of environmental contaminants that might otherwise be sequestered in blubber (Wells, 2010). Thinner blubber also means a thinner protective layer to be penetrated by predator bites before reaching more vital tissues (Wells, 1993).

Changes in water temperature may not only have direct thermoregulatory effects on dolphins but could affect their prey species. The vertebrate and invertebrate prey of dolphins are ectotherms (they do not regulate their internal body temperature) and so are directly affected by temperature. Most of these are able to survive in a large temperature range but often have a preferred temperature where they live. As water temperatures increase, it is likely that at least some prey species will move, and resident dolphins will need to change their diet. It is possible that some new prey may benefit the dolphins, but changes in diet will likely come with a cost. Bottlenose dolphins eat a wide variety of fish, but they disproportionately select some species because of their sound production characteristics, and they develop specific foraging techniques for different species (Wells, 2019). If new prey have a lower energetic yield, then maintaining an energetic balance may be challenging. The overall effect of changing prey availability is that the combination of energetic cost and the potential need to learn and perfect new foraging and prey capture and/or handling techniques is likely to reduce the foraging efficiency. Thus, to catch the same amount of food, or more as the cost of catching food is increasing, the dolphins may have to spend more time searching and hunting for prey. While the proportion of time spent foraging is likely flexible and can vary seasonally, annually and with prey species, an increasing proportion of time spent in this activity will reduce the time available for other activities that may be important for learning and creating and maintaining social bonds. Eventually, if the metabolic cost of foraging exceeds the energy gain, this might lead to a negative energy balance with the possibility that the dolphin will lose body mass and eventually starve to death if conditions do not change.

Alternatively, if prey species migrate to higher latitudes, the dolphins may follow their familiar prey, which increases the cost of transport and introduces a variety of stressors from changes in habitat, predators, and other ecological parameters. Such movements at the extreme of the species' range have been demonstrated, as identifiable individual bottlenose dolphins in southern California were documented to shift their range more than 600 km to the north during an El Niño warm water event (Wells et al., 1990). However, many inshore bottlenose dolphins away from the extremes of the species range live in year-round, multidecadal, multigenerational community ranges, and they may not leave these ranges easily (Wells and Scott, 2018). Members of some of these communities have not left their long-term ranges in spite of catastrophic environmental changes, from oil spills, major hurricanes, or severe harmful algal blooms that reduced prey by more than 75%—these animals are considered to live in "ecological cul-de-sacs" and whether they will be able to adapt to changing conditions if they refuse to leave their ranges is of concern (Wells, 2010; Tornero et al., 2014). In addition, the impacts from their moving into established ranges of other communities must also be considered.

Whether offshore bottlenose dolphins are strongly bound to a specific home range is not well documented. In Bermuda, for example, re-sightings of individual animals have been reported for several years and it is likely that these populations show site fidelity. For these deep-diving populations, climate change may result in deeper dives to access prey, which result in reduced foraging efficiency as a greater proportion of the dive duration is part of the transport. The greater effort may reduce the aerobic dive limit as increased cost of swimming also elevates the metabolic rate. It is also likely that the elevated metabolic rate increases hypoxia, which may result in molecular changes (see Chapter 8: Genetic and molecular adaptations) and have consequences for immune function (see Chapter 13). Regardless, the metabolic consequences of moving or not moving may result in lower foraging efficiency. Therefore, understanding the metabolic requirements of dolphins is important, especially with regards to how variation in prey alters the metabolic cost for different activities (see Chapter 2). In addition, greater time spent at depth may also increase uptake of $N_2$ and cause greater risk of formation of gas emboli (Fahlman et al., 2021, Fig. 8).

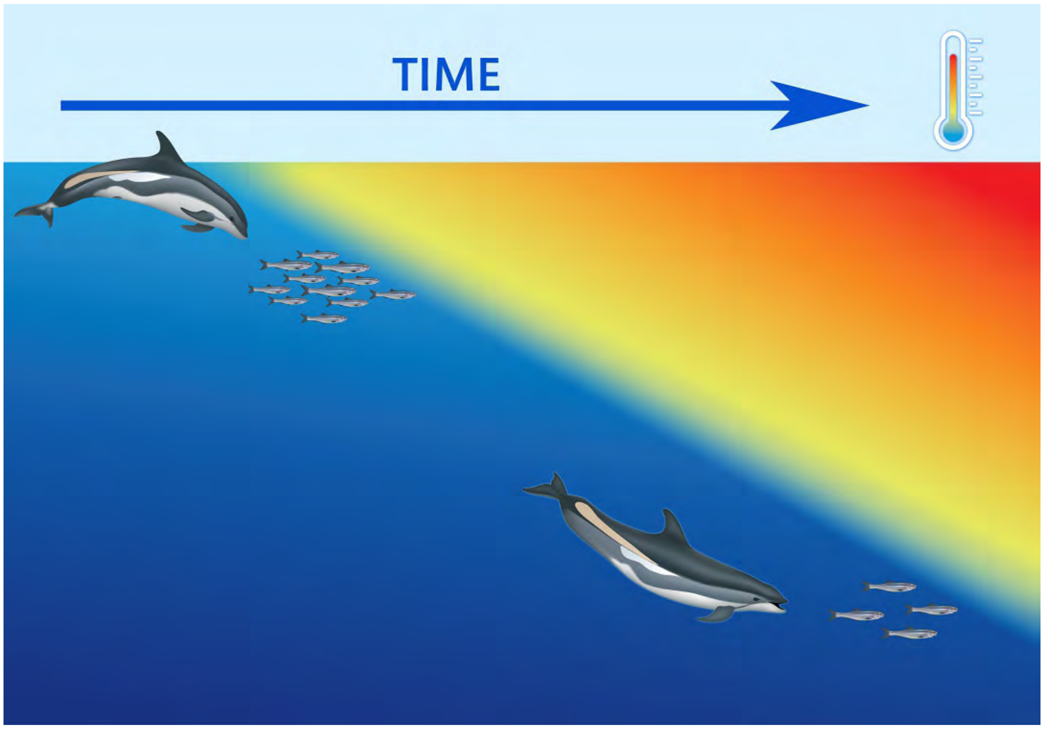


**FIG. 8** Potential effect of climate change where water temperature increases with time (x-axis from left to right), pushing prey deeper in the water column (y-axis increasing depth from top to bottom) with increasing pressure. Dolphins then have to spend more time and energy to get to the prey, which will reduce the total foraging time and efficiency. Colors indicate changes in water temperature, see thermometer. *Illustration by Uko Gorter.*

### Mitigation possibilities

The only effective mitigation option for climate disruption is the cessation of global warming from anthropogenic sources. However, this will require international political (e.g., https://www.ipcc.ch) and economic will that is well beyond what has occurred so far. Increased levels of education and outreach and acceptance of the now-well-established facts surrounding climate change will be necessary to bring about the large-scale changes in attitudes and actions that are required.

## Concurrent and multiple threats

Although the community of resident dolphins in Sarasota Bay has been increasing at a modest average annual rate of 2.1% since 1993 (Lacy et al., 2021), cumulative human impacts may reach a point when compensatory mechanisms may not suffice, which may have detrimental impact on the population. Dolphins in inshore waters are usually not given the option of dealing with one threat at a time. They face multiple concurrent and cumulative threats from natural and anthropogenic sources, and many of these threats have physiological consequences (Tyack et al., 2022). It is up to humans to reduce the threats that are within their power to control, to give the dolphins more degrees of freedom to cope with and adapt to the remaining threats. Inshore bottlenose dolphin populations are bellwethers of coastal ecosystem health. The animals swim through the same waters, breathe the same air, and catch and eat the same fish as their human neighbors in these coastal areas. It is in both the humans' and dolphins' best interest to care for this shared environment.

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