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Aircraft-Produced Sonic Booms and Marine Life, a Literature Review

Siddharth Ghosh[1] and Noah Bressman[#]

[1]James M. Bennett High School, USA
[#]Advisor

ABSTRACT

With the advent of new-age supersonic aircraft such as NASA's X-59, Boom Supersonic's Overture, and Spike Aerospace's S-512, there is an emergent need to investigate their environmental consequences. This review evaluates existing research and information to determine what is currently known about supersonic aircraft and their potential impacts on marine life through a three-step process. 1) Determining possible characteristics of sonic booms produced by the aircraft: the aircraft being evaluated in this article produce low-frequency (0.1-100 Hz) sounds with surface PLdBs (perceived surface loudness decibel levels) around 70-75 dB. 2) Assessing the behavior of similar sounds as they interact with the ocean: sonic booms have been observed to penetrate the ocean for 98-164 ft, but this depth can vary due to differences between the experimental and real-life flight conditions. A separate effect, produced by sonic booms' contact with the ocean surface, may penetrate deeper as infrasound. 3) Evaluating the potential consequences of these sounds on marine life: the continuous production of sonic booms along flight paths worldwide raises concerns about possible noise pollution, adding to the existing issue of oceanic anthropogenic noise pollution. Existing literature on underwater noise pollution—with similar frequencies and comparable intensities—shows negative impacts on marine reproduction, communication, stress levels, and physical health. This review contributes to broader ongoing discussions surrounding the resurgence of supersonic aviation and its environmental impact. Further research is necessary to assess the impact that transoceanic supersonic flight could have on marine ecosystems to truly determine supersonic flight's environmental footprint.

Introduction

Supersonic flight was first accomplished in 1947 when the United States Air Force (USAF) sent an experimental aircraft to exceed Mach 1 and return to a safe landing. Following this initial experiment, supersonic flight continued to be researched, and the first scheduled commercial supersonic passenger service, onboard the Concorde, took flight in 1976 (1). Its ability to cut travel times in half made it highly sought after, yet it created powerful sonic booms while flying at supersonic speeds. In order to meet the existing restrictions on sonic booms, airlines spent heavily on modifying flight paths. Those costs, the fatal Air France flight 4590 accident, and the other costs of development, caused the Concorde to no longer be financially viable, and the project was shut down in 2003 (2,3). High operating costs and loud sonic booms would also lead to the cancellation of the Boeing 2707 and Lockheed L-2000 projects. The only other supersonic aircraft to see commercial service was the USSR's Tupolev Tu-144, but it would only last in commercial service for three years due to reliability and safety issues (4). Recent aviation programs, such as Boom Supersonic and Spike Aerospace, have begun to re-explore supersonic flight, promoting new streamlined designs that promise to minimize the aircraft's sonic booms. Both companies advertise over-water supersonic flights, as current regulations prohibit commercial and civilian supersonic flights over land (5, 6, 7, 8). At the same time, NASA has recently unveiled their X-59, their experimental quiet supersonic aircraft which promises to reduce powerful sonic booms to barely-audible sonic thumps (9). While flights over water would minimize impacts on land-based life, they open the possibility of affecting marine life, since these flights will add to global traffic, they can potentially contribute to existing sources of anthropogenic noise pollution. Sounds produced by existing maritime routes (Figure 1), which display the most commonly used path between their host and destination city, are visibly comparable to that of aircraft (Figure 2).

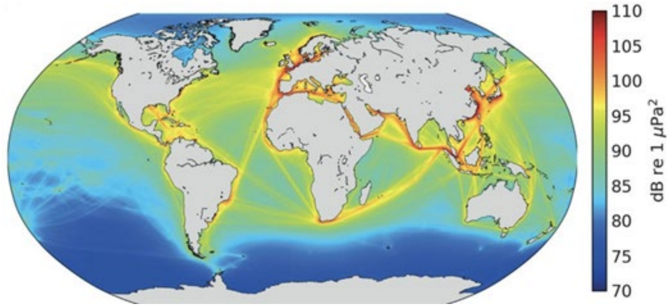

Figure 1. (left): Average sound level at 100 Hz produced by marine traffic estimated globally; based on automatic identification system (AIS) data for 2014. (11)

Figure 2. (right): Visualization of over 58,000 individual flight paths, with lighter blue strands indicating shorter and overlapping flights and darker blue strands representing longer flights with little to no overlap; created using Geographical Information Systems (GIS) technology (12).

A Supersonic Commercial Market Estimation, conducted by the Georgia Institute of Technology, identified a “supersonic commercial flight demand of 47 to 786 daily global [supersonic] flights in 2036 and 71 to 1,180 daily global [supersonic] flights in 2050, corresponding to low and high demand scenarios respectively” (10). Because the manufacturers of new-age supersonic aircraft pledge to be environmentally conscious, it is important to analyze how sustainable their flights can be.

Principles of a Sonic Boom

While the speed of sound varies based on the conditions, the accepted speed of sound is around 750 miles an hour, or Mach 1. When an object moves through space, it creates ripples of air, known as air-pressure waves. If the object moves faster than Mach 1, the pressure waves that it generates collide together to form shock waves. These shock waves are conical and are generated continuously from the nose and tail of the object for as long as it moves at supersonic speeds.

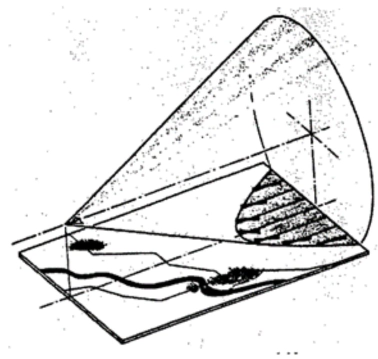

Figure 3. (left): A supersonic aircraft's conical sonic boom and it's contact patch with the surface (shaded) (13)

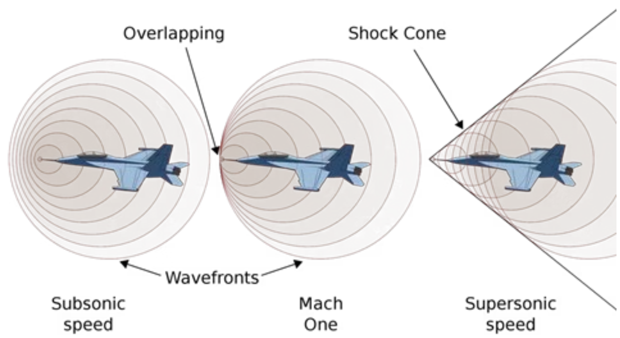

Figure 4. (right): Comparison of wavefronts at Subsonic, Sonic, and Supersonic Speeds (14)

The sound created by the shock waves is known as a *sonic boom,* which is formed by the sudden drop in air pressure that follows an increase in pressure caused by the shockwaves (Figures 3&4). The audible boom created by the shock waves is not formed by the difference in pressure, but rather by the speed at which the pressure changes.

There are two different types of sonic booms: N waves, which are N-shaped and generated from a steady, constant flight; and U waves (or focused booms), which are U-shaped, and caused by flights that are maneuvering at supersonic speeds. The primary difference between N waves and U waves aside from their shape is the difference in the behavior of their pressure. N waves generally carry a lower pressure difference to the surface but cover a wider area, while U waves carry a higher pressure, up to 2-5 times that of N waves but cover a smaller area. Passenger aircraft typically produce N waves as they do not maneuver at supersonic speeds (15). Altitude also determines the nature of the sonic boom experienced at the surface. As the shock waves are produced by the aircraft, if the aircraft moves at a higher altitude, the shock waves have to travel a greater distance before reaching the surface and therefore would be less audible at sea level. Because of the conical shape of the shock waves, however, the spread of the sonic boom heard on the surface also increases with altitude. Typically, the range of the sonic boom heard on the surface is approximately 1 mile for 1,000 feet of altitude that the object is flying at. Therefore, if an object is flying at 30,000 feet, the sonic boom is heard for 30 miles. Boom Supersonic's Overture, estimated to fly around 60,000 ft. would therefore have a predicted spread of around 60 miles. Essentially, the greater the altitude that an object is at, the greater the distance that its sonic booms will be audible for, but the weaker and less audible its sonic booms will be; and the lower the altitude that an object is at, the smaller the distance that its sonic booms will be audible for, but the stronger and more audible its sonic booms will be. Sonic booms generally occur at a frequency between 0.1 and 100 hertz,

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relatively low when compared to subsonic aircraft and most industrial noise. Aerodynamics also plays a role in the intensity of a sonic boom. Larger and heavier aircraft displace more air to generate the necessary lift to keep them airborne, which results in stronger and louder sonic booms being produced (16-17).

Notably, the frequency range of a sonic boom also includes infrasound, which occurs below 20 hertz and is known to be significantly more powerful at traveling long distances with little dissipation, due to its increased wavelength (18).

Section 1: Supersonic Aircraft and their Sonic Booms

This review considers three aircraft—NASA's X-59, Boom Supersonic's Overture, and Spike Aerospace's S-512—all being developed with one common goal: to minimize the force of their sonic booms such that they become discreet "sonic thumps". While Boom and Spike intend to utilize their aircraft for commercial use, NASA's X-59 is an experimental aircraft intended to be a platform for future developments and research (9). NASA's X-59 model was subjected to scale testing in a supersonic wind tunnel to determine how effective its noise-reducing design features were. NASA's goal is to get the PLdB of their aircraft down to 70, a significant decrease from the Concorde's 105 (19+20). A 1.62% scale model of the X-59 was placed in the Glenn Research Center 8-by-6-foot Supersonic Wind Tunnel for testing and was run at approximate Mach numbers of 1.36, 1.4, and 1.7 with various flap and aileron deflections, a horizontal stabilator, and a T-tail that can be set at various deflection angles (20), as shown in figures 5&6.

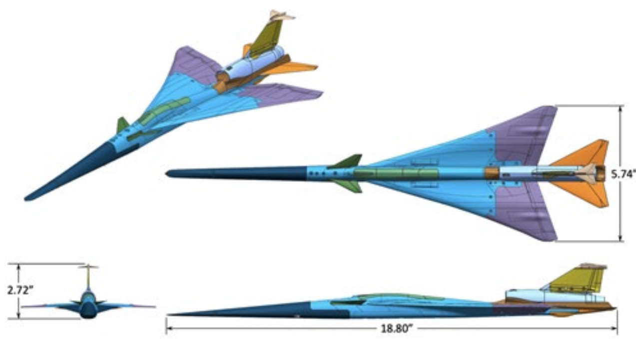

Figure 5. (left): 4 view of 1.62% scale model of X-59 aircraft (20)

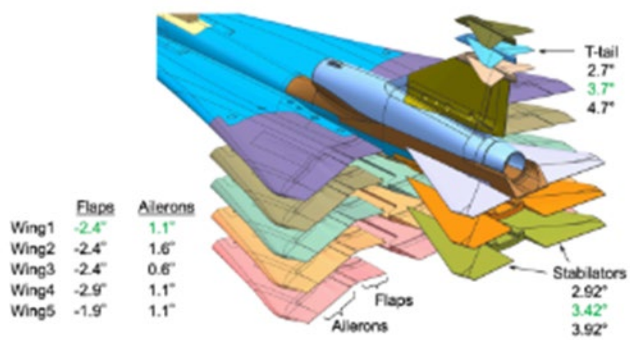

Figure 6. (right): Control surface variations for model, baseline angles for cruise flight in green (20)

One of the design elements, a smooth underbelly to reduce downward energy from its sonic boom, was reflected in the Schlieren Images during testing as shown in Figure 7.

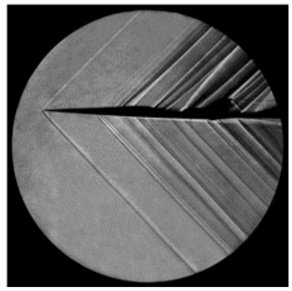

Figure 7. Cleaned up schlieren image of X-59 during wind tunnel testing at Mach 1.4 with 0 degrees roll angle (20)

Note that the Schlieren image was taken during wind tunnel testing, and the mounting arm is visible on the dorsal side of the aircraft, slightly in front of the rudder. The X-59 also features an elongated nose, comprising nearly half the aircraft's length. This is intended to displace the air as smoothly as possible, which reduces the intensity of the sonic boom, similar to the design principle of Japan's high-speed train system, where a long tapered nose subdued a sonic boom that would be produced from its exiting tunnels at high speeds (21). The sonic boom is expected to be about 75 PLdB at ground level (20). Similarly to the X-59, Boom Supersonic's Overture and Spike Aerospace's S-512 are promised to be designed with minimizing noise pollution in mind (22, 23).

Spike Aerospace claims their S-512 will be much smaller than the Concorde, carrying just 18 passengers, and will produce a negligible sonic thump with a PLdB of under 70, which will be weak enough to not interfere with humans on land. Spike states that the S-512's sonic boom signature on the ground is further minimized through the use of their advanced proprietary Computational Fluid Dynamics (CFD) software, to optimize shape parameters of the wing and fuselage to minimize shock wave strength and through refinement of flow expansion regions to mitigate the strength of the waves. This software was used to conduct repeated analysis until "low-sonic-boom flight was achieved in multiple scenarios" (24).

The noise-reducing capabilities of the Spike S-512 and Boom Overture aircraft's designs have not been independently validated, therefore the data provided by their manufacturers must be considered when evaluating their possible impact, organized in Table 1.

Table 1. Comparison of speed and sonic boom specifications between different manufacturers (16, 25, 26, 24, 28, 29)**:**

Manufacturer	Model	Sonic Boom Frequency	Sonic Boom PLdB (at surface)	Speed
NASA	X-59	0.1-100 Hz	75 dB	Mach 1.36-1.7
Boom Supersonic	Overture	0.1-100 Hz	Unknown	Mach 1.7
Spike Aerospace	S-512	0.1-100 Hz	Less than 70 dB	Mach 1.6

Aside from their wind tunnel testing, NASA also conducted a propagation simulation study to predict the global variations of the X-59's sonic boom's intensity. This study, shown in Figure 8, anticipates a global variation ranging between -3 and +1 dB from the mean due to climatic differences (25).

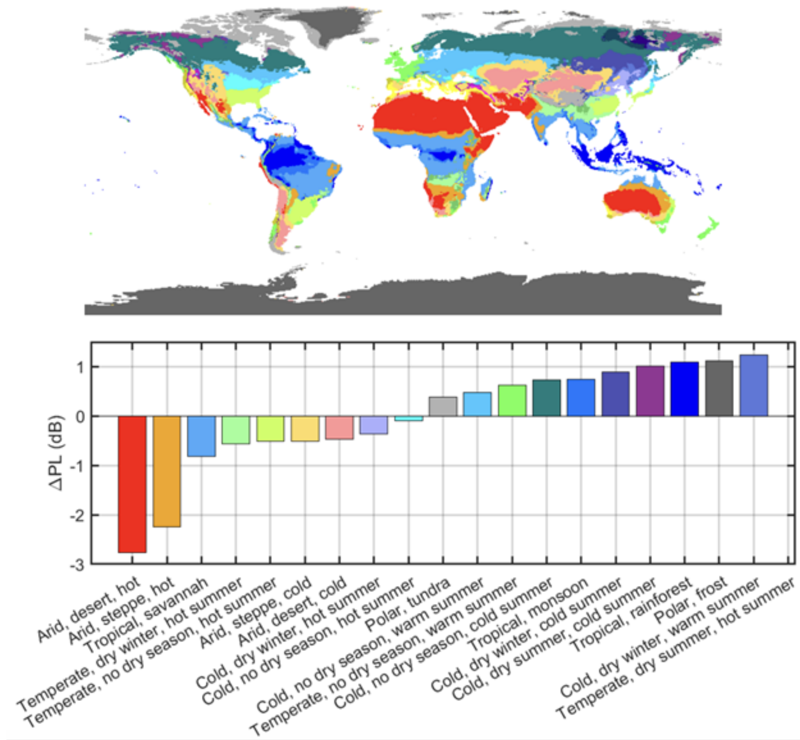

Figure 8. Predicted global variations of X-59 sonic boom intensity from the mean (25)

Section 2: Underwater Behavior of Sonic Booms

To understand the behavior of a given sound underwater, both its frequency and its intensity must be considered. In this review, the sonic booms' PLdB is based on manufacturer data, and the frequency is assumed to range from 0.1 - 100 Hz, based on the United States Air Force's accepted frequency range for a sonic boom. Sounds within the 1 - 100 Hz frequency range fall under the Very Low Frequency (VLF) category (16). A human's land-based hearing depends on a complex process that translates sound waves traveling through the air into electrical signals that are then carried to and perceived by the brain (30). Most marine life, however, has evolved to perceive sounds traveling underwater so their sensitivity to underwater noise is considerably higher (31). Sound waves travel over 4 times faster in water (~4921 ft/sec) than in air (~1115 ft/sec) (32). Given this information, an experimental simulation was run on the penetration of sonic boom energy into the ocean. This simulation, prepared for the Federal Aviation Administration (FAA) and Department of Transportation (DoT), provided comparisons between theoretically predicted sonic boom spectra at 0, 15, 100, and 1000 ft depths and measured deep-ocean ambient spectra over frequencies ranging from 0.01 to 10,000 Hz, shown in Figures 9&10. These predictions show sonic booms affect underwater noise levels to depths of 15 ft or more when in the frequency range of 0.15 - 200 Hz. They tend to exceed the underwater ambient noise upper limit most, even at depths of 100 ft, when at around 10 Hz. Simulation 1, shown in Figure 9, is run given a velocity of 1,500 ft/sec ≅ 1022.727 mph ≅ Mach 1.33 and a duration of 0.1 seconds. Simulation 2, shown in Figure 10, is run given a velocity of 2,500 ft/sec ≅ 1704.545 mph ≅ mach 2.22 and duration 0.3 seconds. Between the two, simulation 1 is more realistic to new-age supersonic aircraft flights based on speed. It must be noted, however, that both simulations were carried out with a peak pressure (P_O) of 2.5 lb/ft^2 ≅ 119.7 Pa ≅ 135.54 dB SPL (sound pressure level in decibels) (33).

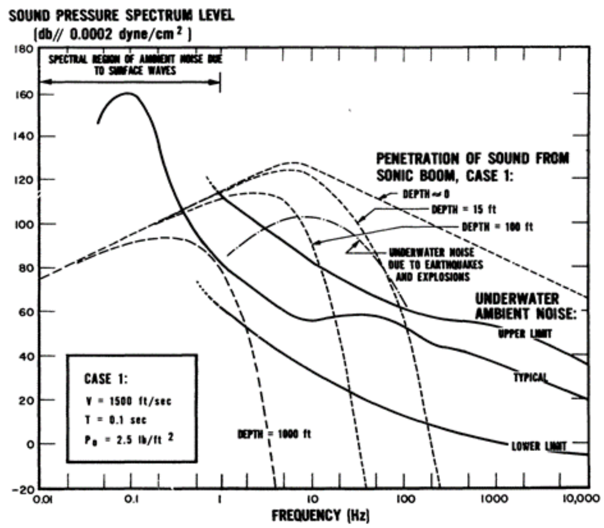

Figure 9. (left): Comparison of Underwater Sound Pressure Spectrum Levels between sonic booms and ambient noise with velocity = ~Mach 1.33 and duration 0.1 sec (33)

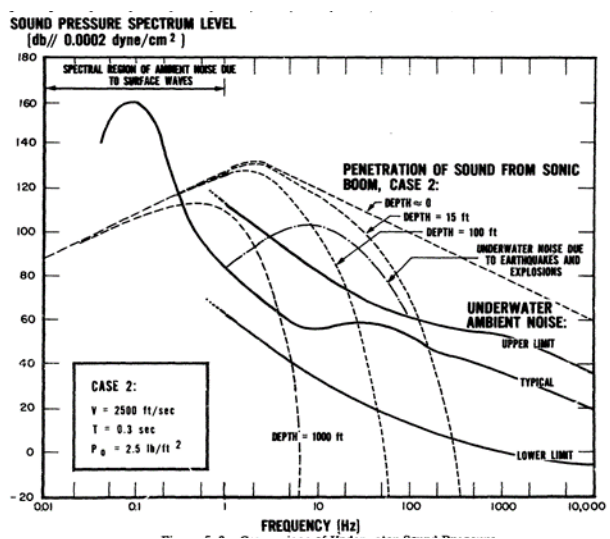

Figure 10. (right): Comparison of Underwater Sound Pressure Spectrum Levels between sonic booms and ambient noise with velocity = ~Mach 2.22 and duration 0.3 sec (33)

A later practical experiment making field measurements of sonic boom penetration into the ocean observed sonic booms traveling no further than ~164 ft into the water. However, the conditions of the test that determined this data were quite different than the real-world conditions of new-age supersonic flights, as the F-4 aircraft being used for testing flew up to 1km away horizontally from the hydrophones recording audio, likely diminishing the true depth recorded (15). It must also be noted that the size, speed, and altitude of the F-4 aircraft differed from the expected values of the X-59, Overture, and S-512, reflected in Table 2.

Table 2. Comparison of size, speed, and cruising altitude between different aircraft (27, 29, 34, 35, 36, 37, 38)

Aircraft Model:	McDonell F-4 (in test)	NASA X-59	Boom Overture	Spike S-512
Size in ft. (wingspan/length)	~38.42/58.25	29.6/99.7	106/201 expected	60/131 expected
Speed in Mach	1.07-1.26	1.36-1.7 scale tested (1.4 expected)	1.7 expected	1.6 expected*
Altitude in ft.	~2,000 - 20,000	55,000 expected	60,000 expected	60,000 expected*

*Not officially announced figures

To determine the specifics of whether this difference should significantly impact the depth that sonic booms produced by new-age supersonic aircraft travel into the water, further practical research, more specific to the conditions of Overture, S-512, and X-59 flights, is vital. Notably, the contact of sonic booms with the ocean surface also generates a second effect (likely 3-4 Hz) that penetrates significantly deeper into the ocean and can be perceived by marine life as infrasound (39).

Moreover, it is possible that, in a shallow sea, the transmitted evanescent energy from the sonic boom can reflect at the seabed, enhancing underwater sound levels. This effect can be more pronounced if the aircraft speed coincides with the speed of seismic interface waves supported by the seabed, as depicted in Figure 11 (40).

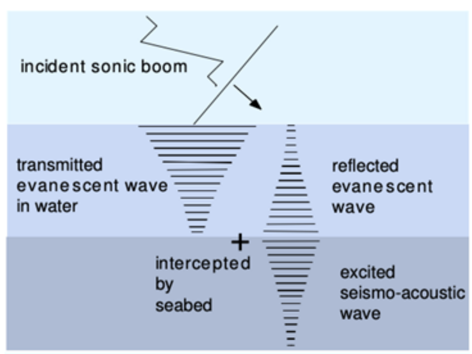

Figure 11. The behavior of incident sonic boom energy in water. Sonic boom energy transmitted as an evanescent wave in water, intercepted by the seabed which produces an excited seismo-acoustic wave that reflects an evanescent wave (40).

Spike Aerospace states that, although sonic booms produced by the S-512 will likely penetrate the surface of the water, they will not propagate more than a few hundred feet and as a result, will have a low impact on the marine ecosystem (41), however this has not been practically tested yet.

Theoretically, when underwater, VLF sound waves can travel for long distances. With increasing depth, the speed of sound decreases with cooler temperatures following a gradient called the thermocline. At the bottom of the thermocline, where temperature decrease is minimal, pressure continues increasing which causes the speed of sound to increase again. This creates a barrier effect and causes sound waves to refract upward, thus traveling the path of lower resistance. The space within this barrier is referred to as the SOFAR

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(Sound Fixing And Ranging) channel, shown in Figure 12. The continued up-and-down refraction within the SOFAR channel allows sound to travel thousands of meters, to the point where they can be picked up across vast oceanic distances. The depth of the SOFAR channel depends on the temperature and salinity of the water and can be as deep as 600-1200 meters at low latitudes, or as shallow as 0 meters, the surface itself, at high latitudes (32, 42).

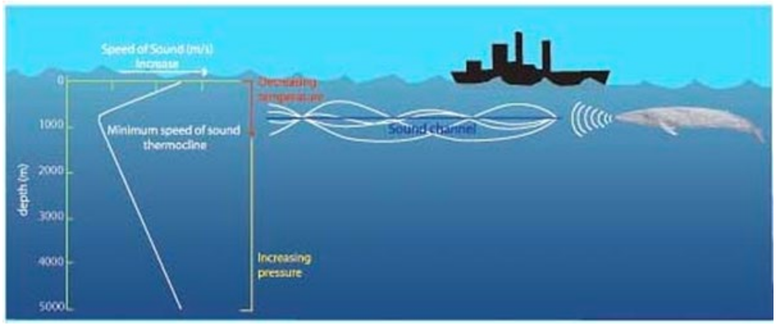

Figure 12. SOFAR Channel as a result of the Thermocline (32)

Section 3: Effects of Sonic Noise Pollution on Marine Life

Around 150 ft, the depth that aircraft-produced sonic booms have been observed to reach underwater, lies the epipelagic zone of the ocean. Also called the "sunlight zone", this area is frequented by numerous marine animals. These include whales, dolphins, billfishes, tunas, jellyfish, and sharks (43). With continuous sonic booms (16) produced along the 600+ "profitable routes" that could be flown by one company alone (44), as well as predictions for potentially several hundred daily supersonic flights in the near future (10), the concern for underwater noise pollution becomes significant.

Much of marine life uses auditory perception as a primary sense—an adaptation that, over millions of years, has allowed them to use it for communication, navigation, and other necessary life processes (11). Marine animals have evolved to develop separate hearing structures, allowing for auditory perception underwater, as shown in Figure 13. The sound production and hearing ranges of various types of marine animals and sources of anthropogenic noise pollution, depicted by Figure 14, overlap with the 0.001-0.1 kHz range for sonic booms (note: the frequency range for sonic booms is different from that of typical aircraft noise, which is what is shown in Fig. 14) (11, 16).

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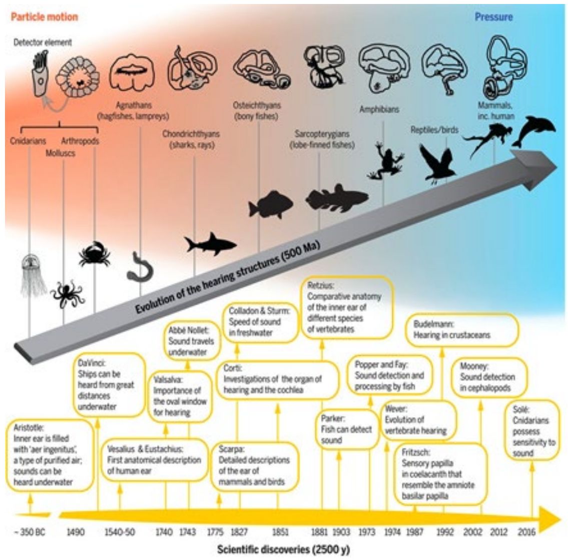

Figure 13. (left): Display of the evolution of hearing structures in various types of animals and scientific discoveries of hearing (11)

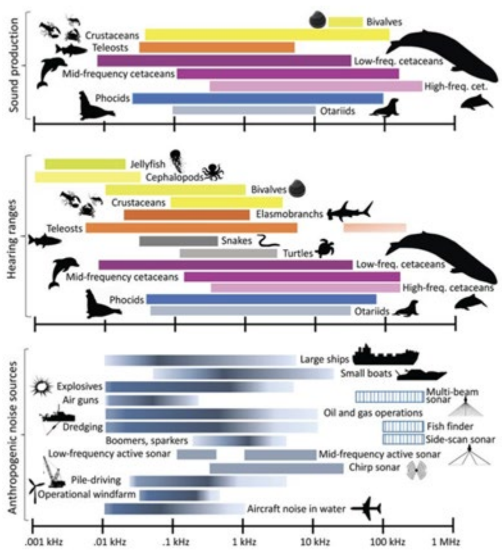

Figure 14. (right): Approximate sound production and hearing ranges of various anthropogenic noise sources (sonic booms are not included due to the fact that supersonic flights are not currently widely used) as well as the ranges of various marine animals (11).

Studies on existing noise pollution, which often has similar characteristics (comparable frequencies and intensities), can offer insight into some possible effects of sonic booms on marine life.

Beluga whales have been observed to flee locations when exposed to icebreaker noise levels between 94 and 105 dB (45); icebreakers have been observed to emit frequencies centering near 10, 50, and 100 Hz- while reaching peak source levels- during ice-breaking operations (46).

Anthropogenic marine noise can cause increased stress in marine animals (47), usually measured by the levels of stress hormones like cortisol. High levels of cortisol can lead to negative effects on the growth, reproduction, maturation, immunity, and as a result, the survival of the animal. Experiments have shown that artificial noise, such as underwater ship noise at levels of 150-156 dB, can increase cortisol levels significantly, by up to 120% in the case of common carp and gudgeon (48). Even at relatively lower levels, from around 135 - 142 dB, boat noise caused giant kelpfish to exhibit acute stress responses. While levels of cortisol and stress increase with noise pollution, their response is more severe when noise is arrhythmic and unpredictable (49, 50), as in the case of sonic booms.

Noise pollution also affects the antipredatory behavior of fish. Boat noise in levels averaging around 134 - 146 dB has been shown to cause delayed flight reactions in fish. Damselfish, for example, responded slower and less often to predatory attacks in the presence of boat noise. Their natural predator, the dusty dottyback, consumed twice as much prey in the presence of boat noise, which can result in changes in population and the food chain (51).

Marine animals such as larval coral reef fish use sound to orient themselves. Using it as a way to locate and settle within coral reefs, larval coral reef fish often become attracted to sounds they are exposed to at a young age. When 4 species of 3-week-old larval damselfish were exposed to 12 hours of artificial noise, they became attracted to it over the natural reef noise (52). This can negatively influence their sound-based activities. Over 800 diverse fish species are known to produce sounds and even more are known to receive them, often for communication with each other, especially during reproduction (53). These signals are often low frequencies below 200 Hz and are susceptible to acoustic masking from increased background noise. Sound is also frequently used by fish for social interactions. For example, in the presence of underwater tonal noise, African cichlid fish (*Astatotilapia burtoni)* are less likely to interact with each other, females have reduced hearing capabilities, and females are likely to produce fewer offspring (54).

Direct anatomical damage caused by sonic noise pollution is unlikely but can be a concern for high-energy sound waves traveling through the ocean. Being a force, sound can damage single cells or organs. Sperm whales, for example, use their spermaceti (an organ that allows them to focus sound waves) to overwhelm prey with high-intensity sound to hunt (55). It should be noted that the sound produced by sperm whales is significantly higher intensity than that produced by supersonic aircraft such as the Concorde, so it's less likely that sonic booms produced by their noise pollution can physically harm marine animals as significantly as Sperm whales' spermaceti. Invertebrates use sensitive organs called statocysts for balance, orientation, and information on their body position. In the presence of high noise levels, statocysts in invertebrates, as well as ears and swim bladders in fish, can be harmed, resulting in loss of buoyancy control, disorientation, and stranding. When exposed to low-frequency sound around 157-175 dB, 2 species of squid, 1 species of octopus, and 1 species of cuttlefish were shown to experience "massive acoustic trauma" after just 2 hours. When continued up to 96 hours, the injuries became more pronounced and worsened as time went on (56).

Negative effects on reproduction and survival may also be severe consequences of noise pollution on marine animals, as boat-induced noise pollution has been shown to impair parental behavior and offspring survival of spiny chromis fish. Under noise conditions similar to those when a boat is present, males exhibited heightened aggression and defensive behavior, resulting in them spending 25% less time on feeding (57).

A secondary effect, generated by the interaction of sonic booms with surface waves, has been "shown to dominate the deepwater wave field", suggesting its "relative importance to infrasound perception by marine mammals" (39). While little is known about the depth, intensity, or exact frequency that this low-frequency infrasound can possess, it should be considered when evaluating possible impacts of sonic booms on marine life and areas for further research.

Cod and salmon, among others, have been known to perceive sounds down to below 1 Hz. When their environment was exposed to infrasound in scientific experiments, they were observed to actively avoid the source of the low-frequency noise (58). Although this experiment was run on fish traveling in rivers, salmon and cod are known to swim for hundreds of miles in the open ocean (59, 60).

Overall, Figure 15 displays an estimate of studies that have been conducted on effects of noise on different aspects of various types of animals, as of early 2021 (the publication date of the source article).

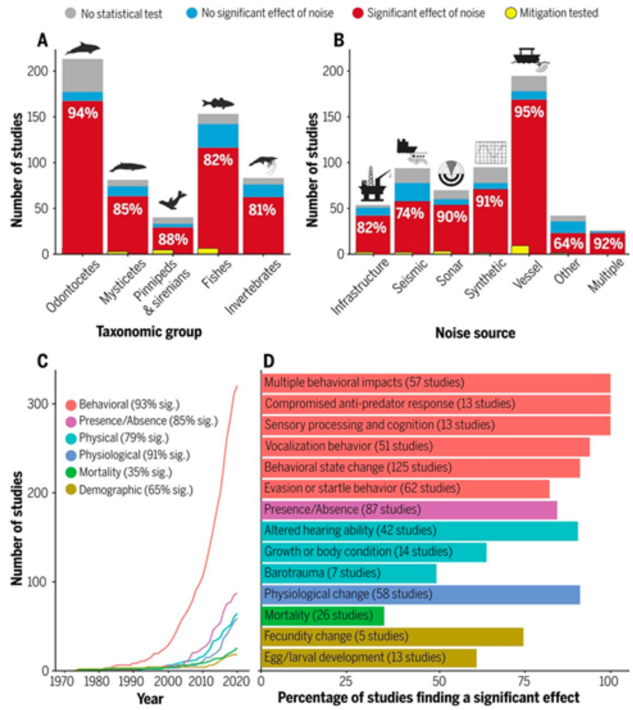

Figure 15. A broad estimation of existing studies on the effects of sonic noise pollution on marine life and their concentrations on different aspects of the issue; A and B display the total number of studies found categorized by taxa in graph A and source of noise pollution in graph B. Graph C depicts the studies over time, split by effect focus and percentage of significant noise effects found, while Graph D shows the percentage of studies in each subcategory that found a significant effect of noise, represented as a percentage of the total number of studies (11).

It must be noted that it is highly difficult to determine the exact impact that anthropogenic sound has on marine animals as our understanding of their hearing responses in the real world is highly limited. Often based on the range of signals they and their predators produce, and limited by visibility, many responses of marine animals' ecology and behavior cannot be documented (61).

Methods

An exhaustive literature review revealed no practical research on the impact of aircraft-produced sonic booms on marine life in the last two decades, predating the inception of the aircraft being reviewed by this paper. The exception was the scale wind tunnel testing performed by NASA on their X-59, but even this was not conducted in the field. Consequently, there was a lack of literature that could directly correlate sonic booms generated by modern supersonic aircraft with their potential impacts on marine ecosystems. As a result, the review was divided into 3 distinct segments: 1) Determining possible characteristics of sonic booms produced by the aircraft; 2) Assessing the behavior of similar sounds as they interact with the ocean; 3) Evaluating the potential consequences of these sounds on marine life. References were sourced directly from government websites, university publications, the official websites of the aircraft manufacturers, and peer-reviewed scientific journals. The references for the properties of sonic booms (associated with their frequency and decibel ranges) generated by the Overture, X-59, and S-512 were directly sourced from the respective manufacturers' official websites, as well as accepted publications on sonic booms authored by NASA and the US Air Force. With the frequency and decibel ranges of the sonic booms, the next step was to predict their behavior underwater, drawing upon publications by the National Oceanic and Atmospheric Administration (NOAA) and Washington University. Once underwater, they could be treated as any sound of that decibel and frequency range. Finally, utilizing the information on the sonic booms' underwater behavior, the potential effects of aircraft-produced sonic booms on marine life could be determined. To this end, references such as NOAA, the National Institutes of Health (NIH), and other select peer-reviewed scientific journals were utilized.

Conclusions

New-age supersonic aircraft produce sonic booms of similar frequencies within the 0.1-100 Hz range. Spike Aerospace and NASA each promote thorough, targeted testing and development of their aircraft to minimize the intensities of their sonic booms. The S-512 and X-59's anticipated sonic booms are of similar intensities, around 70-75 dB while Boom's official estimation has not yet been released. NASA is the only manufacturer of the three that has not only released results of practical scale testing of its aircraft (through a supersonic wind tunnel), but it has also unveiled the assembled X-59, expected to fly in 2024. Underwater noise pollution of similar frequency and comparable, although higher, intensity to sonic booms being produced by the aircraft has been observed to negatively impact reproduction, communication, stress levels, antipredatory behavior, orientation, physical health, and/or species fitness of numerous marine animals, from fish to cephalopods to mammals. Sonic booms have been observed to penetrate the ocean for 98-164 ft, but the conditions this test was performed under, involving aircraft of different size, traveling at slower speeds, and at lower altitudes, as well as having horizontal inaccuracy from the microphones used to measure the sonic boom strength, are significantly different from the expected conditions of new-age supersonic flight. Supersonic aviation is likely inevitable, given the increasing demand for lower travel times and development in the aviation industry. The sheer quantity of supersonic flights anticipated in the near future opens a concern for underwater noise pollution and its associated concerns on marine ecosystems. To be able to precisely determine the true effects of aircraft-produced sonic booms on underwater ecosystems, further research is crucial.

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Notations

Frequently Used Abbreviations:
PLdB: Perceived Loudness Decibel [level]
SOFAR: Sound Fixing and Ranging (channel)
VLF(s): Very Low Frequency/Frequencies
dB: Short form for decibel (unit of sound intensity)
Hz: Short form for hertz (unit of frequency)

Notable Terms

New-Age Supersonic Aircraft: Referring to Boom Supersonic's Overture, Spike Aerospace's S-512, and NASA's X-59

Sonic Thumps: Referring to sonic booms below 75 dB, which have minimal impact on land life.

References

1. Anderson, J. D. (n.d.). *Research in supersonic flight and the breaking of the sound barrier*. NASA. https://history.nasa.gov/SP-4219/Chapter3.html
2. Terefe, N., Eidsmore, X., & Farah, A. (2019, June 25). *Why the Concorde was discontinued and why it won't be coming back*. blog.museumofflight.org. https://blog.museumofflight.org/why-the-concorde-was-discontinued-and-why-it-wont-be-coming-back
3. Barry, B. (2019, September 5). *How Concorde pushed the limits – then pushed them too far*. National Geographic. https://www.nationalgeographic.co.uk/science-and-technology/2019/08/how-concorde-pushed-limits-then-pushed-them-too-far
4. Frede, K. C., & Takahashi, T. T. (n.d.). Microsoft word - frede_aiaa_scitech2020_final - faculty - ASU engineering. https://labs.engineering.asu.edu/aircraft-design/wp-content/uploads/sites/115/2023/03/AIAA-2020-1956.pdf
5. Boom Supersonic (2023, June 20). *Flyby - as demand for international summer air travel surges, passengers look to a supersonic future*. https://boomsupersonic.com/flyby/as-demand-for-international-summer-air-travel-surges-passengers-look-to-supersonic-future
6. *Reintroducing supersonic flight: Quiet, efficient & responsible*. Spike Aerospace. (2023, December 20). https://www.spikeaerospace.com/
7. *Federal Aviation Administration, DOT §91 - govinfo*. GovInfo. (n.d.). https://www.govinfo.gov/content/pkg/CFR-2013-title14-vol2/pdf/CFR-2013-title14-vol2-sec91-119.pdf
8. Skalecky, J. (2018, September 12). *Federal Aviation Administration*. Supersonics. https://www.faa.gov/sites/faa.gov/files/2022-07/Skalecky-REDAC_Supersonics_v8.pdf
9. Margetta, R., & Ellis, S. (2024, January 12). *NASA, Lockheed Martin reveal X-59 quiet supersonic aircraft*. NASA. https://www.nasa.gov/news-release/nasa-lockheed-martin-reveal-x-59-quiet-supersonic-aircraft/
10. Weit, C. J., Wen, J., Anand, A., Mayakonda, M. P., Zaidi, T. A., & Mavris, D. N. (n.d.). A methodology for supersonic commercial market estimation and Environmental Impact Evaluation (part I). https://www.a-anand.com/Conferences/Papers/AEC_SST_Part_I_Paper.pdf
11. Duarte, C. M., Chapuis, L., Collin, S. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., Gordon, T. A., Halpern, B. S., Harding, H. R., Havlik, M. N., Meekan, M., Merchant, N. D., Mikis-Olds, J. L., Parsons, M., Predragovic, M., Radford, A. N., Radford, C. A., Simpson, S. D., & Juanes, F. (n.d.). *The soundscape of the Anthropocene Ocean | science*. Science. https://www.science.org/doi/10.1126/science.aba4658
12. Markieta, M. (2013, May 28). *In pictures: Global flight paths*. BBC News. https://www.bbc.com/news/in-pictures-22657086
13. Laney, H., & Cavanagh, R. C. (2000, June). *Supersonic Aircraft Noise At and Beneath the Ocean Surface: Estimation of Risk for Effects on Marine Mammals*. United States Air Force Labaratory. https://apps.dtic.mil/sti/pdfs/ADA395062.pdf
14. Boyd, I. (2019, July 11). *Commercial supersonic aircraft could return to the skies*. The Conversation. https://theconversation.com/commercial-supersonic-aircraft-could-return-to-the-skies-113022
15. Sohn, R., Vernon, F., Hildebrand, J., & Webb, S. (2000, June). *Field measurements of Sonic Boom penetration into the Ocean*. The Journal of the Acoustical Society of America. https://pubmed.ncbi.nlm.nih.gov/10875353/#:~:text=The%20sonic%20boom%20pressure%20amplitude,significantly%20deeper%20than%20high%20frequencies.

16. *Sonic boom*. Air Force. (n.d.). https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104540/sonic-boom/
17. Dryden Flight Research Center. (n.d.). *Sonic Booms*. NASA Facts. https://www.nasa.gov/wp-content/uploads/2021/09/120274main_FS-016-DFRC.pdf?emrc=f4b1ff
18. *Infrasound monitoring*. CTBTO. (n.d.). https://www.ctbto.org/our-work/monitoring-technologies/infrasound-monitoring
19. Banke, J. (2023, August 2). *Sonic boom heads for a Thump*. NASA. https://www.nasa.gov/aeronautics/sonic-boom-heads-for-a-thump/
20. Durston, D. A., Wolter, J. D., Shea, P. R., Winski, C. S., Elmiligui, A. A., Langston, S. L., Bozeman, M. D., Carter, M. B., & Bellido, C. A. (2023). *X-59 Sonic Boom Test Results from the NASA Glenn 8-by-6-Foot Supersonic Wind Tunnel*. NASA Technical Reports Server. https://ntrs.nasa.gov/api/citations/20220015668/downloads/AIAA%20Paper%2C%20X-59%208x6%20SB%20Test%20221018%20DD.pdf
21. U.S. Department of Health and Human Services. (2016, July 22). *Designs found in nature can inspire new products and solutions*. National Institute of Deafness and Other Communication Disorders. https://www.noisyplanet.nidcd.nih.gov/have-you-heard/nature-designs-inspire-new-products-solutions
22. Supersonic, B. (2023a, April 27). *Flyby - the new sound of supersonic: Q&A with Boom's principal acoustic engineer*. https://boomsupersonic.com/flyby/the-new-sound-of-supersonic-q-a-with-booms-principal-acoustic-engineer
23. *Reintroducing supersonic flight: Quiet, efficient & responsible*. Spike Aerospace. (n.d.). https://www.spikeaerospace.com/#:~:text=The%20Spike%20S%2D512%20Supersonic,time%20with%20barely%20a%20peep
24. Staff, S. (n.d.). *Spike S-512 supersonic jet will produce almost no sonic boom*. Spike Aerospace. https://www.spikeaerospace.com/spike-s-512-supersonic-jet-will-produce-almost-no-sonic-boom/
25. Doebler, W. J., & Sparrow, V. W. (2023, December 5). *Simulations of X-59 sonic thumps and traditional sonic booms propagated around the world for three atmospheric models*. NASA. https://ntrs.nasa.gov/api/citations/20230016991/downloads/2aNSb3_Doebler_global_boom_sim_20231117.pdf?attachment=true
26. *Flyby - it's about time for a bold new era of Supersonic Flight*. Boom. (2022, July 19). https://boomsupersonic.com/flyby/its-about-time-for-a-bold-new-era-of-supersonic-flight
27. Staff, S. (2015, October 29). *Spike S-512 supersonic jet will produce almost no sonic boom*. Spike Aerospace. https://www.spikeaerospace.com/spike-s-512-supersonic-jet-will-produce-almost-no-sonic-boom/
28. *Overture*. Boom. (n.d.). https://boomsupersonic.com/overture
29. *QUESST*. NASA. (n.d.). https://www3.nasa.gov/specials/Quesst/
30. U.S. Department of Health and Human Services. (2022, March 16). *How do we hear?*. National Institute of Deafness and Other Communication Disorders. https://www.nidcd.nih.gov/health/how-do-we-hear
31. *Understanding sound in the Ocean*. NOAA Fisheries. (n.d.). https://www.fisheries.noaa.gov/insight/understanding-sound-ocean#:~:text=Light%20can%20only%20penetrate%20a,a%20variety%20of%20complex%20sounds.
32. *Understanding ocean acoustics*. NOAA Ocean Explorer. (2022, August 26). https://oceanexplorer.noaa.gov/explorations/sound01/background/acoustics/acoustics.html

33. Waters, J. F., & Glass, R. E. (1970, June). *Penetration of Sonic Boom Energy into the Ocean: an Experimental Simulation*. Defense Technical Information Center. https://apps.dtic.mil/sti/pdfs/AD0711963.pdf
34. *X-59 Paper Desktop Model*. NASA. (2023, July 6). https://www.nasa.gov/stem-content/x-59-paper-desktop-model/#:~:text=The%20single%2Dseat%20X%2D59,Mach%201.4%2C%20or%20925%20mph.
35. *F-4 phantom II*. Holloman Air Force Base. (n.d.). https://www.holloman.af.mil/About/Fact-Sheets/Display/Article/317295/f-4-phantom-ii/
36. *Quiet & Sustainable Supersonic Flight*. Spike Aerospace. (2023a, December 20). https://www.spikeaerospace.com/s-512-supersonic-jet/quiet-supersonic-flight/
37. *Verdict media limited*. Aerospace Technology. (n.d.). https://www.aerospace-technology.com/projects/spike-s-512-supersonic-business-jet/#:~:text=Spike%20S%2D512%20will%20have%20an%20exterior%20length%20of%20131ft,will%20be%2084%2C000lbs%20each.
38. Cheng, H. K., & Edwards, J. R. (n.d.). *Underwater Noise and Sound Produced by Aerial Sonic Boom*. Defense Technical Information Center. https://apps.dtic.mil/sti/tr/pdf/ADP022900.pdf
39. Chapman, D. M., & Godin, O. A. (n.d.). Sonic booms in shallow water: The influence of the seabed. https://cradpdf.drdc-rddc.gc.ca/PDFS/unc94/p521961_a1b.pdf
40. Staff, S. (2015a, March 2). *Spike aerospace researching impact of supersonic flight on Marine Wildlife*. Spike Aerospace. https://www.spikeaerospace.com/spike-aerospace-researching-impact-of-supersonic-flight-on-marine-wildlife/
41. *NOAA Ocean Explorer: Sounds in the sea 2001: Diagram of How Sound Travels Underwater*. NOAA Ocean Explorer Podcast RSS 20. (2022, August 26). https://oceanexplorer.noaa.gov/explorations/sound01/background/acoustics/media/sofar.html
42. *Open ocean*. Oceana. (n.d.). https://oceana.org/marine-life/open-ocean/#:~:text=The%20epipelagic%20is%20home%20to,sharks%2C%20and%20many%20other%20groups.
43. Supersonic, B. (2023c, September 15). *Flyby - supersonic progress*. https://boomsupersonic.com/flyby/supersonic-progress-update-from-boom-supersonic
44. Au, W., Cato, D., Hofman, R., McCarthy, E., Potter, J., Schmidt, H., Thiede, J., & Tyack, P. (Eds.). (2003). *effects of noise on marine mammals*. National Library of Medicine. https://www.ncbi.nlm.nih.gov/books/NBK221255/
45. Roth, E. H., Schmidt, V., Hildebrand, J. A., & Wiggins, S. M. (2013). *Underwater radiated noise levels of a research icebreaker in the Central Arctic Ocean*. The Journal of the Acoustical Society of America. https://pubmed.ncbi.nlm.nih.gov/23556567/
46. Weilgart, L. (2018, May 1). The impact of ocean noise pollution on fish and invertebrates. https://thegreentimes.co.za/wp-content/uploads/2022/01/impact-of-ocean-noise-pollution-on-fish-and-invertebrates.pdf
47. de Soto, N. A. (2016). *Peer-reviewed studies on the effects of anthropogenic noise on marine invertebrates: From scallop larvae to giant squid*. PubMed. https://pubmed.ncbi.nlm.nih.gov/26610940/
48. Wysocki, L. E., Dittami, J., & Ladich, F. (2006, April). *Ship noise and cortisol secretion in European freshwater fishes*. ResearchGate. https://www.researchgate.net/publication/222561472_Ship_noise_and_cortisol_secretion_in_European_freshwater_fishes
49. Nichols, T. A., Anderson, T. W., & Širović, A. (2015, September 24). *Intermittent noise induces physiological stress in a coastal marine fish*. PubMed. https://pubmed.ncbi.nlm.nih.gov/26402068/

50. Simpson, S. D., Radford, A. N., Nedelec, S. L., Ferrari, M. C., Chivers, D. P., McCormick, M. I., & Meekan, M. G. (2016, February 5). *Anthropogenic noise increases fish mortality by predation*. Nature News. https://www.nature.com/articles/ncomms10544
51. Simpson, S. D., Meekan, M. G., Larsen, N. J., McCauley, R. D., & Jeffs, A. (2010, August 4). *Behavioral plasticity in larval reef fish: Orientation is influenced by recent acoustic experiences*. OUP Academic. https://academic.oup.com/beheco/article/21/5/1098/198790
52. Radford, A. N., Kerridge, E., & Simpson, S. D. (2014, March 11). *Acoustic communication in a noisy world: Can fish compete with anthropogenic noise?*. OUP Academic. https://academic.oup.com/beheco/article/25/5/1022/215541
53. Butler, J. (2019, November 4). *The Impact of Anthropogenic Noise on Fish Behavior, Communication, and Development*. LSU Digital Commons. https://web.archive.org/web/20220119122535id_/https://digitalcommons.lsu.edu/cgi/viewcontent.cgi?article=6142&context=gradschool_dissertations
54. NOAA. (2023, January 30). *Sperm whale*. NOAA Fisheries . https://www.fisheries.noaa.gov/species/sperm-whale
55. André, M., & Durfort, M. M. (2011, November). *Low-frequency sounds induce acoustic trauma in cephalopods*. ResearchGate. https://www.researchgate.net/profile/Carmen-Quero-2/publication/230821027_Low-frequency_sounds_induce_acoustic_trauma_in_cephalopods/links/02e7e539ee5ef85be7000000/Low-frequency-sounds-induce-acoustic-trauma-in-cephalopods.pdf
56. Nedelec, S. L., Radford, A. N., Pearl, L., Nedelec, B., McCormick, M. I., Meekan, M. G., & Simpson, S. D. (2017, June 14). *Motorboat noise impacts parental behaviour and offspring survival in a reef fish*. Proceedings. Biological sciences. https://pubmed.ncbi.nlm.nih.gov/28592667/
57. Buxton, I. (2006). *Low Frequency Noise and Infrasound*. Wise Energy. http://wiseenergy.org/Energy/Health/Infrasound_and_land_based_animals.pdf
58. NOAA. (2024, January 2). *Atlantic Cod*. NOAA Fisheries. https://www.fisheries.noaa.gov/species/atlantic-cod
59. *How far do salmon travel?*. U.S. Geological Survey. (n.d.). https://www.usgs.gov/faqs/how-far-do-salmon-travel#:~:text=Salmon%20first%20travel%20from%20their,to%20reach%20their%20feeding%20grounds.
60. *What are common underwater sounds?*. Discovery of Sound in the Sea. (2022, July 25). https://dosits.org/science/sounds-in-the-sea/what-are-common-underwater-sounds/