**Temperature effects on cavitation bubble dynamics of snapping shrimp (*Alpheus heterochaelis)***

**Meng-Chun Grace Chung**

Under the supervision of Ben Schelling and Dr. Sheila Patek,  
Department of Biology, Duke University

May 2023

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Research Supervisor

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Faculty Reader

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Director of Undergraduate Studies

Honors thesis submitted in partial fulfillment of the requirements for graduation with   
Distinction in Biology in Trinity College of Duke University

**Abstract**

Understanding how environmental conditions influence the marine soundscape is key for monitoring ecosystem health. In coastal soundscapes, snapping shrimp colonies produce constant high intensity acoustic signals that serve important ecological functions for many marine taxa. Field and experimental studies have shown that snap rates increase with warmer temperatures, however, it is unclear if temperature affects the cavitation bubble itself and consequently the sound generated. We tested snapping shrimp (*Alpheus heterochaelis)* in controlled treatments at natural temperatures (12 to 30°C) and at a climate change elevated temperature (33°C). Using a high-speed camera and hydrophone, we filmed the strikes and cavitation bubbles, and measured maximum bubble size, maximum sound pressure level (SPL), and durations of bubble growth, collapse, and rebound. We found that temperature did not have a significant effect on any bubble metrics or SPL, but claw size had a significant impact on bubble size. Bubble size was positively correlated with SPL at all temperatures. Although temperature has little influence at the individual level to alter cavitation bubbles and sound production, changing environmental conditions may affect factors like snapping shrimp physiology and behavior that do directly influence bubble and sound production. Understanding both indirect and direct drivers of acoustic patterns can inform us on using snapping shrimp acoustics as bioindicators in environmental management.

**1. Introduction**

The marine soundscape reveals key characteristics of an ecosystem, including community composition, geophysical features, and ecological processes. It is crucial to a wide range of marine taxa that use acoustic cues for functions like communication, navigation, or reproduction (Hildebrand, 2009). Disruptions in acoustically rich environments may greatly impact large numbers of organisms that depend on acoustic signals (Hildebrand, 2009). Furthermore, shifts in acoustic outputs could lead to cascading effects across species in marine ecosystems (Sueur et al., 2019), and may be caused by changes to sound-producing organisms (e.g., physiology, behavior, or population structure) or to mechanisms of sound production and propagation throughout the marine ecosystem. Currently, little is known about how changes driven by climate change (*e.g.*, rising ocean temperatures) may impact the marine soundscape.

A particularly acoustically rich environment that is susceptible to warming temperatures is shallow coastal waters, where the ambient soundscape is often dominated by colonies of snapping shrimp that produce some of the loudest sounds underwater (Johnson et al., 1947). Congregations of shrimp can generate a continuous crackling noise in the marine soundscape (Johnson et al., 1947), where these acoustic signals serve a wide array of marine activity––including acting as acoustic cues for navigation and larval settlement of other organisms (Simpson et al., 2008). Snapping itself serves a range of functions within snapping shrimp species, including displays of aggression in agonistic intraspecific and interspecific interactions, communication, and mating between females and males (Nolan & Salmon, 1970).

The bigclaw snapping shrimp, *Alpheus heterochaelis* (Fig. 1a)*,* has a large, specialized snapper claw with two parts (Fig. 1b): 1) the propodus, which has a socket, and 2) the dactyl, which has a plunger that fits into the socket. The mechanism of snapping begins with a strike, where the ultrafast closure of the snapper claw displaces the water in the socket and propels a high velocity jet that causes the static pressure to drop below the vapor pressure of water (Versluis et al., 2000; Fig. 2). A cavitation bubble forms along the long axis of the water jet, but static pressure quickly returns to ambient pressure and causes the bubble to rapidly collapse (Versluis et al., 2000; Fig. 2). Often, the collapse of the initial bubble induces a secondary cavitation of many smaller bubbles, known as the rebound, which also collapse rapidly and produce shockwaves (Supponen et al., 2018; Fig. 2). Both bubble collapse events can cause cavitation damage to snapping shrimp prey or predators, though it is the initial bubble collapse that generates a high intensity acoustic signal (Brennen E., 1995; Koukouvinis et al., 2017; Versluis et al., 2000).

Cavitation is a widely studied phenomenon because of its applications in industries like engineering and medicine and its undesirable destructive effects on machinery (Sagar & el Moctar, 2020). However, cavitation in biological systems remains difficult to study due to the complexities of biomechanical systems and the highly variable conditions in which biological cavitation occurs. Mathematical simulations have been extensively employed to study cavitation in snapping shrimp of the *Alpheidae* family (e.g., Hess et al., 2013; Koukouvinis et al., 2017; Versluis et al., 2000), though simplified models are typically used––for instance, employing simplified claw geometries, assumptions of spherical bubble morphology, or barotropic conditions to ignore the dependence of temperature on pressure. Nonetheless, these studies have broadened our knowledge of the core physical mechanisms behind cavitation bubble dynamics and sound generation from cavitation in snapping shrimp.

In non-biological systems, thermodynamic effects on cavitation have been more thoroughly studied. Phan et al. (2022) modeled ambient temperature changes on cavitation dynamics and suggested that bubble radius and collapse time increase with temperature. Phan et al. (2022) also noted that bubbles collapsed less violently at higher temperatures. Kim et al. (2010) found that longer collapse times indicated larger bubble sizes.

The relationship between temperature and bioacoustics responses have also been studied by many researchers. Bohnenstiehl et al. (2016) used hydrophone recordings of an oyster reef habitat and found higher snap rates in summer than winter and a positive correlation between snap rates and the total sound pressure levels (SPL) of the soundscape. Lillis & Mooney (2022) confirmed this experimentally and demonstrated that rising temperatures increase the rate of snapping in snapping shrimp across several behavioral contexts. Lai et al. (2021) reported a significant reduction in peak amplitude of snapping sound waves after exposure to a combination of temperature and pH treatments, but not with higher temperatures alone.

In a precursory study, we showed that temperature did not significantly impact strike kinematics of snapping shrimp due to the thermally robust elastic claw-closing mechanism (Schelling, 2023). Rather, body size had significant impact; larger individuals had slower strikes but produced louder sounds. However, due to the range of body sizes across sampled specimens and the replacement of shrimp across the temperature treatments, it is unclear whether temperature directly impacted cavitation bubble dynamics.

Thus, the purpose of this study was to explore the relationship between temperature and snapping shrimp cavitation bubble dynamics to better understand how warming ocean temperatures may impact the functions of snapping and its role as acoustic signals in the marine soundscape. I predicted that maximum cavitation bubble size would be strongly positively correlated with body size, because larger sockets the claw displace larger volumes of water during a strike. As such, I hypothesized that similarly sized shrimp would produce similarly sized bubble. Additionally, I hypothesized that an individual shrimp (i.e., with a fixed claw size), would produce larger cavitation bubbles at higher temperatures. As ambient temperature increases, the saturated vapor pressure of water increases while water density decreases (Phan et al., 2022), which would allow for less required energy for cavitation. Phan et al. (2022) also found that cavitation bubbles collapsed less violently at higher temperatures. Sound intensity corresponds to the shock wave produced when the cavitation bubble collapses (Brennen E., 1995); therefore, I predicted that SPL of individual snaps would be lower at higher temperatures.

This study utilized the dataset and materials of the aforementioned precursory study on temperature and kinematics, of which I was a collaborator in the data collection. I analyzed the previously filmed high-speed videos and hydrophone recordings of strikes and resulting cavitation bubbles by *A. heterochaelis* in laboratory-controlled temperature treatments to examine the relationship between bubble dynamics, SPL, and ambient water temperature. This study employed experimental data and analyses to circumvent the limits of models that generalize claw biomechanisms or physical properties of the cavitating system and lends itself to validating models and simulations of previous studies on cavitation in snapping shrimp. This study therefore examined change in bubble size and SPL over the natural range of temperatures (10–28°C) experienced by populations of *A. heterochaelis* in Beaufort, NC, as well as a 33°C treatment to mimic rising sea temperatures from climate change.

**2. Materials and methods**

2.1 Animal collection and husbandry

We collected *A. heterochaelis* at an intertidal oyster reef site at the Duke University Marine Lab on Pivers Island in Beaufort, NC. Collections occurred at low tide in March and April of 2022 on four collection dates. Wild snapping shrimp were caught by hand and placed in temporary holding vials. All vials were stored in coolers with water from the site and ice packs, and samples were then transported three hours to Duke University in Durham, NC. In Durham, we moved the shrimp into individual 0.1 x 0.1 x 0.1 m polystyrene cubes with holes for water flow and placed in large holding tanks with fresh artificial saltwater and two constant water filters. The holding room was temperature controlled at approximately 20°C. Snapping shrimp were fed *Artemia nauplii* were fed three times a week.

2.2. Temperature manipulation

We chose the temperatures (12, 15, 20, 25, and 30°C) for the experiment were based on the natural water temperature range at the collection site (NOAA Meteorological Observations; Station ID 8656483; Suppl. A). We also chose a 33°C treatment to simulate a seawater temperature rise of 2°C projected by climate change.

Every week, eight shrimp with at least one intact snapper claw were randomly sampled and transferred in their cubes to a separate tank system that was temperature controlled at 20°C. Approximately one day prior to filming, the system was adjusted to the target temperature to allow the shrimp time to acclimate. The eight individuals were randomly divided into two equal groups and filmed in separate acclimation periods of 24 and 72 hours.

2.3 High-speed camera filming and hydrophone recordings

For each acclimation group, the four shrimp were temporary removed from the tank system to measure and record body metrics (e.g., body length, snapper claw length, and mass (*m*)). A toothpick was attached to the carapace of each animal with a minimal amount of superglue before the shrimp were returned to the holding tank until filming.

One by one, the shrimp were attached to a 3D-printed filming rig by their toothpick and adjusted with their snapper claw closest to the mirror, which was angled at 45° to the camera. A Brüel & Kjær Type 8104 hydrophone was positioned 0.05 m from the snapper claw and recorded samples at 480,000 samples per second. A long toothpick probed the shrimp to prompt a snap response and captured as sequences of images with a high-speed camera (AF-S Micro Nikkor 105 mm 1:2.8 ED, 896x368 pixels, 1/63838 s-1 shutter, 60,000 frames s-1, FastCAM SA-Z, Photron, San Diego, CA, USA).

Only videos of the claw in clear focus during striking were saved with the synchronized audio recording and used for analysis. Videos and recordings were saved as AVI and WVD/CIH files respectively. At least ten strike videos filmed were targeted for each shrimp; fewer were achieved occasionally due to shrimp throwing off their snapper claw. A frame of the calibration was saved for each camera focus adjustment.

2.4 Digitizing

I digitized the videos of strikes and the resulting bubbles in FIJI to measure the maximum bubble size (*B*). I selected the largest bubble size by the frame previous to the start of the bubble collapsing. I measured bubble size through a four-point method, using two points along the long side to measure the maximum length and two points across the short side for the maximum width (Fig. 3). The maximum length and maximum width were then multiplied together as the estimate for maximum bubble size. This method was comparable to a tracing method, where bubble size was measured by tracing the visible outline of the bubble to measure the total 2D area and was chosen thereafter for efficiency (Suppl. B).

Duration metrics were measured as shown in Fig. 2: growth duration (*tg*) from end of the strike to the maximum bubble size, collapse duration (*tc*) from the maximum bubble size to the first bubble collapse, and rebound duration (*tr*) from the first bubble collapse to the second bubble(s) collapse.

Dactyl length (*DL*) was measured via FIJI from the dactyl tip to the dactyl-propodus joint (Fig. 3). Each calibration frames were processed in FIJI/ImageJ (Version 2.9.0/1.53t) to calculate a pixel-per-mm value. The value was then used to convert the pixel measurements of relevant variables in FIJI to metric units.

2.5 Data analysis

I used linear mixed models (LMM) in R (v4.2.2; R Core Team 2021) using the lme4 package (Bates et al., 2015) to evaluate the effect of temperature on a) bubble size, b) SPL, and c) duration metrics––growth time, collapse time, and rebound time. Null models were generated with the individual shrimp as the random parameter and no fixed effect for each tested dependent variable (maximum bubble size and max SPL). I generated separate models with temperature, dactyl length, and mass each as the fixed effect parameter (Table 2). For sound pressure level, I generated additional models with bubble size and collapse time each as fixed parameters. I used AIC model selection to determine significant models by comparing them to the null model. I calculated ∆ AIC for each test model as:

*∆ AIC = (Null model AIC – test model AIC)*

Here, a better fitting model would expect a lower AIC number than the null model. Therefore, only models with positive ∆ AIC values indicated improvement in the model. The boundaries for significance were 2<∆ AIC> 6 for positive support, 6< Δ AIC <10 for strong support, and 10< ΔAIC for very strong support (Burnham & Anderson, 2004; Raftery, 1995).

**3. Results**

A total of 346 videos were filmed from 33 *A. heterochaelis* individuals. Snapping shrimp were able to produce cavitation bubbles and consistent SPLs at all temperature treatments (12-33°C).

3.1 Bubble dynamics

Temperature did not significantly affect any bubble metrics: bubble size (Fig. 4a), distance, or growth/collapse/rebound durations (Table 2). All ∆ AIC values were less than 2, indicating no support (Table 2). However, dactyl length was significantly positively correlated with maximum bubble size (∆AIC = 36.7; Fig. 4b), indicating that strikes by individuals with larger claws produced larger bubbles. Correspondingly, body mass was also a significant predicator of bubble size (∆AIC = 35.5), although it was a slightly weaker model than dactyl length. Dactyl length was also strongly positively correlated with all durations (growth, collapse, and rebound; all ∆ AIC > 10; Fig. 7) which shows that the larger bubbles produced by larger claws also had longer durations overall.

3.2 Maximum Sound Pressure Level (SPL)

Temperature (Fig. 5a), dactyl length (Fig. 5b), and body mass were not significant predictors of maximum SPL (Table 3). However, maximum bubble size was strongly positively correlated with SPL (∆ AIC = 21.4; Fig. 6), indicating larger bubbles produced greater SPLs. Collapse time was also significant predictor of SPL (∆ AIC = 2.8), but was a much weaker predicator compared to bubble size. The positive correlation between bubble size and duration metrics contextualizes collapse time as a predictor of SPL: larger and louder bubbles take longer to collapse and rebound.

**4. Discussion**

Temperature did not significantly impact any metrics that I measured for bubble dynamics or maximum SPL, indicating that the temperature change between 12-33°C is negligible to the physical mechanisms of cavitation bubbles and sound generation. Although ambient temperature does affect cavitation dynamics, which has been shown in non-biological systems (Phan et al., 2022), the temperature difference found in the intertidal oyster reef systems of snapping shrimp does not seem to reach the threshold for temperature to have a measurable effect. That said, this study used short acclimation periods (24 and 72 hours) that may better reflect short-term temperature variation––such as daily fluctuation of shallow waters––rather than extended periods of warmer waters that would be expected under climate change. Further studies could test body size and sound production in long-term exposure to warmer temperatures.

What does have an effect on bubble dynamics is snapping shrimp morphology, particularly claw size. Dactyl length was a very strong predictor of maximum bubble size. The strong positive correlation between dactyl length and bubble size is consistent with the prediction that larger claws with larger sockets displace more water and produce larger bubbles. Similarly, all bubble duration metrics––growth, collapse, and rebound time––were significantly positively correlated with dactyl size, aligning with the results of previous studies as well (e.g., Kim et al. 2010). This is further evidence that larger claws produce larger bubbles that have longer durations, and also suggests that the rate of cavitation does not change significantly across temperature treatments.

Sound production via cavitation in snapping shrimp appear to follow similar physical trends. The strong positive correlation between bubble size and SPL indicates that larger bubbles collapse to produce louder sound intensities. Collapse time was found to be a significant, positive predictor of SPL. Given that the peak SPL occurs after the first collapse and before the rebound, the rate of collapse may indicate how violently the bubble collapses and the intensity of the resulting sound.

Notably, dactyl length is positively correlated with bubble size (Figure 4b), which in turn is positively correlated with maximum SPL (Figure 6), however, dactyl size is not a significant predictor of SPL (Figure 5b). This may be explained by the limitations of the methods to measure bubble size. A one-camera filming method can only give a 2D-view of the cavitation bubble. The orientation of the bubble in the third plane is unknown and introduces error in bubble size measurements due to assumptions such as similar morphology in the bubbles across different strikes of different individuals. The unknown 3D orientation also means that the study’s bubble measurements of max length and max width calculates an inexact overestimation of ‘size’ and cannot be used as a direct proxy for bubble volume. The length and width measurements also overlook differences in bubble morphology (such as squat or elongated bubble shapes), which may influence sound production or bubble volume. Similarly, claw morphology is another unmeasured factor that likely influences individual variation despite similar dactyl or body sizes. Kim et al. (2010) found that bubble collapse time differed between three species of snapping shrimp despite similar body sizes, suggesting that dactyl length is very likely not the only factor (morphological or otherwise) that significantly influences bubble dynamics and sound production. Future studies incorporating new equipment and filming methods––especially those utilizing more than one camera (angle)––would greatly benefit this field of study and explore how claw and bubble morphology affect sound production.

We do know, nonetheless, that temperature has behavioral impacts on snapping shrimp acoustic outputs, particularly that snap rates increase with increasing temperature (Bohnenstiehl et al., 2016; Lillis & Mooney, 2022). Moreover, temperature has physiological impacts on animals, especially poikilotherms like shrimp. The temperature-size-rule in biology suggests that there is a tendency for populations of animals to have larger body sizes in colder temperatures (Daufresne et al., 2009); studies have demonstrated this pattern in marine crustaceans of different environments and feeding habits (Campbell et al., 2021; Jaramillo et al., 2017), which is also consistent with their life history. Marine crustaceans grow at faster rates in warmer temperatures, but also stop growing earlier (Leffler, 1972). Therefore, they reach smaller terminal body sizes compared to individuals living in colder waters who grow slower but over a longer period of time. In the elevated temperatures projected from climate change, I predict that the average body size of snapping shrimp populations may be smaller, indicating smaller snapper claws that produce smaller bubbles and generate lower SPLs (per strike). At the same time, they would be expected to snap at a higher rate (Bohnenstiehl et al., 2016; Lillis & Mooney, 2022). It is possible that the snapping shrimp snap at higher rates to compensate for the quieter snaps they individually produce, however, it is more likely that they snap at a higher rate due to the reduced energy required to open their claw using muscle at higher temperatures (Schelling, 2023).

Previous studies also found a positive correlation between snap rates and the total environmental SPL of the marine soundscape (Bohnenstiehl et al., 2016; Lillis & Mooney, 2022). In the context of my results, the increase in snap rates better explains the higher SPLs of the marine soundscape than changes in sound generation by snapping shrimp (e.g., producing louder snaps). Further research could explore the seasonality of reproduction and growth of snapping shrimp––such as the variation of average body mass and dactyl length in different seasons––and its influence on snapping sound acoustics. Post-spawning seasons could experience a drop in SPL with more juvenile snapping shrimp that have smaller claws and producing smaller and quieter bubbles.

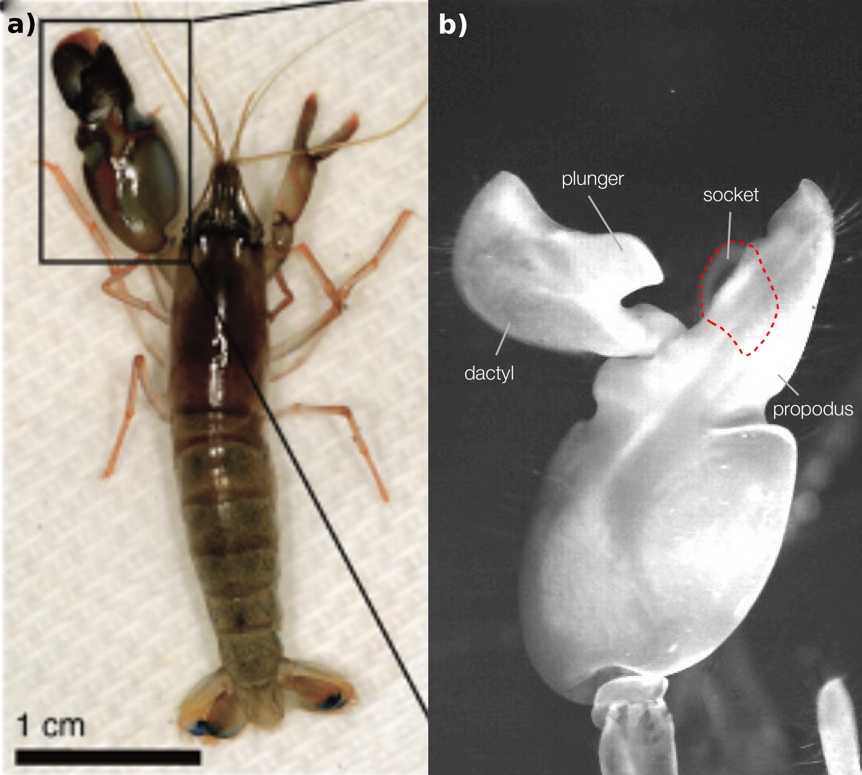
Warming seawater temperatures are not expected to have a direct impact on the mechanisms of sound generation or cavitation bubble dynamics, and as such, likely will not affect the function of cavitation bubbles in behaviors like feeding and defense. However, it is likely that the warming temperatures will induce behavioral or physiological changes in snapping shrimp that have been shown to directly affect snapping shrimp acoustic outputs. Thus, temperature would be expected to have an indirect impact on snapping shrimp bioacoustics overall. If this is the case, changes in their acoustic outputs could impact the role of these snaps as acoustic signals to conspecifics or used by other marine taxa. The impact on marine taxa and in snapping shrimp is unknown due to limited studies on the reception of acoustic signals outside of marine mammals. Further research is needed on how marine taxa in these coastal environments detect acoustic signals in order to estimate the impact on marine taxa and at ecosystem levels. From a precautionary perspective, any bioacoustics changes could have large, cascading effects throughout the ecosystem, because these signals can be used by marine organisms at foundational life stages, such as by larvae for settlement (Simpson et al., 2008).

Snapping shrimp play a large role in the marine soundscape as dominant producers of sound especially in coastal shallow waters. Evidence for the impact of climate change on snapping shrimp acoustics have been shown in this study as well as many previous studies, and highlights the strong potential of climate change to alter marine ecosystems.

**Acknowledgements**

My profound thanks to Dr. Sheila Patek for her guidance and support throughout my time in the Patek Lab. I sincerely thank Ben Schelling for leading the temperature-kinematics study that my thesis was built on and his mentorship throughout both projects. I thank Matthew O'Donnell for his assistance and partnership in animal collection and filming. Thanks also to Hiko Komatsu, Donovan Hardy, and Nhu Bui for assistance in animal collection. Thank you to Dr. Suzanne Cox for designing and 3D-printing the filming rig and advice on modelling cavitation. Thanks also to Dr. Meagan Dunphy-Daly for her support and insightful feedback. I give thanks to lab members for animal husbandry, and the Muser program (Duke University) for leading me to the Patek Lab.

**Figures**

**A picture containing text, indoor

Description automatically generated**

**Figure 1: Snapping shrimp, such as *Alpheus heterochaelis*, use a modified claw to snap. This snapping produces cavitation bubbles.** (a) The snapper claw is much larger, and can be either the left or right claw, or occasionally, both. (b) The snapper claw is comprised of the dactyl, which has a plunger, and the propodus, which has a socket (outlined in red). The plunger fits into the socket during a strike.

**A picture containing shelf

Description automatically generated**

**Figure 2: A high-speed camera and a synchronized hydrophone were used to record prompted snapping shrimp strikes and the resulting cavitation bubbles.** Growth duration (blue) is measured from the end of the strike to the frame at maximum bubble size. Collapse time (orange) is measured from the maximum bubble size to the first collapse. Rebound time (purple) is measured from the first bubble collapse to the second bubble collapse. Bubble duration (green) is considered only for the initial cavitation bubble.

Graphical user interface

Description automatically generated with medium confidence

**Figure 3: Bubble size and dactyl length were measured from a single frame via FIJI.** Maximum length (solid pink) was measured along the long side of the bubble from the claw to the tip of the bubble. Maximum width (dashed pink) was measured perpendicularly to the length from at the widest part of the bubble. Length and width were multiplied together as find the value of bubble size. Dactyl length (solid blue) was measured from the tip of the dactyl (d) to the dactyl-propodus joint.

Chart, scatter chart

Description automatically generated

**Figure 4**: **Temperature did not significantly affect bubble size, but dactyl length was a strong predictor of bubble size.** (A) No significant correlation was observed between temperature and maximum bubble size. Bubble size values mostly overlapped across all temperature treatments. (B) Two trend lines were fitted: black for the natural treatment and red for the climate treatment. The trendlines was fitted using linear mixed models with all observations, accounting for random variation by individual and in number of observations per individual. The two slopes are comparable, and both indicate a strong positive correlation between dactyl length and maximum bubble size. The climate treatment observations appear consistent with the natural treatments.

Chart, scatter chart

Description automatically generated

**Figure 5: Neither temperature nor dactyl length were significant for maximum SPL.** (A) No significant correlation was observed, and observations overlapped across all temperature treatments. (B) No significant correlation was observed. Some outliers can be observed with larger dactyl sizes.

Chart, scatter chart

Description automatically generated

**Figure 6: Neither temperature nor dactyl length were significant for maximum SPL.** Two trend lines were fitted: black for the natural treatment and red for the climate treatment. The trendlines was fitted using a linear mixed model with all observations, accounting for random variation by individual; in number of observations per individual; and in bubble size per observation. Both trend lines indicate a positive correlation between maximum bubble size and maximum sound pressure level. The two trendlines are comparable, although the climate treatment trendline seems to have a steeper slope than the natural treatment.

Chart, scatter chart

Description automatically generated

**Figure 7: Dactyl length was a predictor for all cavitation bubble duration metrics.** Dactyl length was positively correlated with growth duration (orange square), collapse duration (blue circle), and rebound duration (purple diamond).

**Table 1**: Descriptions, symbols, and units of all variables in this study.

|  |  |  |
| --- | --- | --- |
| **Symbol** | **Description** | **Units** |
| *DL* | Dactyl length | mm |
| *m* | Body mass | g |
| *B* | Maximum bubble size | mm2 |
| *SPL* | Maximum sound pressure level | dB re 1 µPa |
| *tg* | Duration of bubble growth from end of strike to max bubble size | ms |
| *tc* | Duration of collapse from max bubble size to the first collapse | ms |
| *tr* | Duration of rebound from first collapse to second collapse | ms |
| *T* | Temperature of treatment | °C |
| *r* | Rate of cavitation bubble collapse | mm2 ms-1 |

**Table 2:** The effect of temperature, dactyl size, and body mass on bubble size, growth duration, collapse duration, and rebound duration were assessed by comparing ∆ AIC scores from the tested LMM to a null model.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | B | | tg | | tc | | tr | |
| **Model** | **∆ AIC** | **Sig.** | **∆ AIC** | **Sig.** | **∆ AIC** | **Sig.** | **∆ AIC** | **Sig.** |
| T | -0.375 |  | 0.765 |  | 1.041 |  | -0.536 |  |
| DL | 36.726 | \*\*\* | 30.713 | \*\*\* | 24.47 | \*\*\* | 45.165 | \*\*\* |
| m | 35.478 | \*\*\* |  |  |  |  |  |  |

Sig. = Significance

\*\*\* ∆ AIC > 10.0, \*\* ∆ AIC > 6.0, \* ∆ AIC > 2.0

**Table 3:** The effects of both independent and response variables on SPL were assessed by comparing ∆ AIC scores from the tested LMM to a null model. The tested variables were temperature, dactyl length, body mass, maximum bubble size, and collapse duration.

|  |  |  |
| --- | --- | --- |
| **Model** | **∆ AIC** | **Sig.** |
| T | 0.317 |  |
| DL | -1.196 |  |
| Mass | -1.508 |  |
| B | 21.414 | \*\*\* |
| tc | 2.798 | \* |

Sig. = Significance

\*\*\* ∆ AIC > 10.0, \*\* ∆ AIC > 6.0, \* ∆ AIC > 2.0

**References**

‌Bohnenstiehl, D. R., Lillis, A., & Eggleston, D. B. (2016). The Curious Acoustic Behavior of Estuarine Snapping Shrimp: Temporal Patterns of Snapping Shrimp Sound in Sub-Tidal Oyster Reef Habitat. *PLOS ONE*, *11*(1), e0143691. https://doi.org/10.1371/journal.pone.0143691

Brennen E., C. E. (1995). *Cavitation and bubble dynamics*. Oxford University Press.

Burnham, K. P., & Anderson, D. R. (2004). Multimodel Inference: Understanding AIC and BIC in Model Selection. *Sociological Methods & Research*, *33*(2), 261–304. https://doi.org/10.1177/0049124104268644

Campbell, M. D., Schoeman, D. S., Venables, W., Abu-Alhaija, R., Batten, S. D., Chiba, S., Coman, F., Davies, C. H., Edwards, M., Eriksen, R. S., Everett, J. D., Fukai, Y., Fukuchi, M., Esquivel Garrote, O., Hosie, G., Huggett, J. A., Johns, D. G., Kitchener, J. A., Koubbi, P., … Richardson, A. J. (2021). Testing Bergmann’s rule in marine copepods. *Ecography*, *44*(9), 1283–1295. https://doi.org/10.1111/ecog.05545

Daufresne, M., Lengfellner, K., & Sommer, U. (2009). Global warming benefits the small in aquatic ecosystems. *Proceedings of the National Academy of Sciences*, *106*(31), 12788–12793. https://doi.org/10.1073/pnas.0902080106

Hildebrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series*, *395*, 5–20. https://doi.org/10.3354/meps08353

Jaramillo, E., Dugan, J. E., Hubbard, D. M., Contreras, H., Duarte, C., Acuña, E., & Schoeman, D. S. (2017). Macroscale patterns in body size of intertidal crustaceans provide insights on climate change effects. *PLOS ONE*, *12*(5), e0177116. https://doi.org/10.1371/journal.pone.0177116

Johnson, M. W., Everest, F. A., & Young, R. W. (1947). The Role of Snapping Shrimp (Crangon and Synalpheus) in the Production of Underwater Noise in the Sea. *Biological Bulletin*, *93*(2), 122–138. https://doi.org/10.2307/1538284

Koukouvinis, P., Bruecker, C., & Gavaises, M. (2017). Unveiling the physical mechanism behind pistol shrimp cavitation. *Scientific Reports*, *7*(1), 13994. https://doi.org/10.1038/s41598-017-14312-0

Leffler, C. W. (1972). Some effects of temperature on the growth and metabolic rate of juvenile blue crabs, Callinectes sapidus, in the laboratory. *Marine Biology*, *14*(2), 104–110. https://doi.org/10.1007/BF00373209

Lillis, A., & Mooney, T. A. (2022). Sounds of a changing sea: Temperature drives acoustic output by dominant biological sound-producers in shallow water habitats. *Frontiers in Marine Science*, *9*. https://www.frontiersin.org/articles/10.3389/fmars.2022.960881

Nolan, B. A., & Salmon, M. (1970). The behavior and ecology of snapping shrimp (Crustacea: Alpheus heterochelis and Alpheus normanni). *Forma Et Functio*, *2*, 289–335.

Phan, T.-H., Kadivar, E., Nguyen, V.-T., el Moctar, O., & Park, W.-G. (박원규). (2022). Thermodynamic effects on single cavitation bubble dynamics under various ambient temperature conditions. *Physics of Fluids*, *34*(2), 023318. https://doi.org/10.1063/5.0076913

Raftery, A. E. (1995). Bayesian Model Selection in Social Research. *Sociological Methodology*, *25*, 111–163. https://doi.org/10.2307/271063

Sagar, H., & el Moctar, O. (2020). Dynamics of a cavitation bubble near a solid surface and the induced damage. *Journal of Fluids and Structures*, *92*, 102799. https://doi.org/10.1016/j.jfluidstructs.2019.102799

Schelling, B. (2023). *Shrimp kinematics paper*.

Simpson, S. D., Meekan, M. G., Jeffs, A., Montgomery, J. C., & McCauley, R. D. (2008). Settlement-stage coral reef fish prefer the higher-frequency invertebrate-generated audible component of reef noise. *Animal Behaviour*, *75*(6), 1861–1868. https://doi.org/10.1016/j.anbehav.2007.11.004

Sueur, J., Krause, B., & Farina, A. (2019). Climate Change Is Breaking Earth’s Beat. *Trends in Ecology & Evolution*, *34*(11), 971–973. https://doi.org/10.1016/j.tree.2019.07.014

Supponen, O., Obreschkow, D., & Farhat, M. (2018). Rebounds of deformed cavitation bubbles. *Physical Review Fluids*, *3*(10), 103604. https://doi.org/10.1103/PhysRevFluids.3.103604

Versluis, M., Schmitz, B., von der Heydt, A., & Lohse, D. (2000). How Snapping Shrimp Snap: Through Cavitating Bubbles. *Science*, *289*(5487), 2114–2117. https://doi.org/10.1126/science.289.5487.2114

**Supplementary Materials**

**Chart

Description automatically generated**

**Supplemental material A: The monthly quartile temperature plot (2005-2012) from Beaufort, NC (sampling location).** The figure shows average sea temperatures of each month of the year using historical data from 2005 to 2012. Data is from NOAA National Data Buoy Center (Station BFTN7 at 34°43′2“ N 76°40’14” W, [).

Chart, scatter chart

Description automatically generated

**Supplemental material B: There was a strong positive correlation between bubble size metrics from the tracing method (y-axis) and four-point method (x-axis) demonstrating comparability of the methods.** A linear regression model was generated (n = 50 observations, N = 8 individuals), showing a strong linear positive correlation between the surface area estimated by the tracing method and the product of max length and max width from the four-point method (giving a rectangular overestimation).