**No evidence for heat-triggered wasting in giant California sea cucumbers (*Parastichopus californicus*)**

Introduction, Methods and Results (Nov 2021)

Jonathan Farr and Declan Taylor

BMSC Directed Studies

**Introduction:**

Anthropogenic climate change is increasing the intensity, duration, size, and frequency of marine heat waves and warm water anomalies with consequences across the globe (Allan et al., 2021; Frölicher et al., 2018; Oliver et al., 2021).  Marine heatwaves have damaging and potentially catastrophic effects on marine ecosystems and human economies (Di Lorenzo & Mantua, 2016). They have bottom-up trophic impacts on ecosystems, driving sudden and large-scale die-offs at all trophic levels from thermal stress, starvation, toxicity, and hypoxia (Cavole et al., 2016; Di Lorenzo & Mantua, 2016; Suryan et al., 2021; von Biela et al., 2019).

For example, the 2014-2015 warm water anomaly in the Northeast Pacific Ocean (nicknamed “the Blob”) drastically reduced the abundance of subarctic copepods, krill, and sand lace, which caused starvation-induced die-offs of species from salmon to sea birds (Cavole et al., 2016; von Biela et al., 2019). This marine heat wave significantly harmed commercial, recreational, and subsistence fisheries, and triggered the closures of open water fisheries including salmon and tuna (Cavole et al., 2016; Di Lorenzo & Mantua, 2016). It also triggered a large harmful algal bloom which resulted in closures of economically important shellfish fisheries (Cavole et al., 2016; Di Lorenzo & Mantua, 2016; Frölicher et al., 2018). The multi-year impacts of the 2014-2015 warm water anomaly and others of comparable severity have driven sudden and significant change as they can push ecosystem resilience past ecological tipping points (Harley & Paine, 2009; von Biela et al., 2019; Wernberg et al., 2015).

{ADD LEADING SCENTENCE}

At an individual level, marine heatwaves directly impact marine organisms in a number of ways. Certain species already close to their thermal tolerances are killed directly (Dong et al., 2011; Oliver et al., 2017). Thermal stress can negatively impact an organism’s fitness by modifying their behaviour and food/nutrient requirements (Kühnhold et al., 2017). Marine heat waves also exert indirect effects on marine organisms, modifying natural processes such as disease dynamics. For example, temperature has been shown to regulate the virulence of marine diseases in corals and algae (Case et al., 2011). In the NE Pacific, sea star wasting disease epidemics have decimated populations of several sea star species over the last decade. Wasting is assumed to be infectious (Work et al., 2021), with epidemics being exacerbated or triggered by environmental factors including warm temperatures (Aquino et al., 2021; Bates et al., 2009; Eisenlord et al., 2016; Harvell et al., 2019; Hewson et al., 2018, 2020). Sea star wasting disease is an ambiguous set of usually-lethal symptoms including twisted arms, lesions, deflation/loss of turgor, lost arms, lack of grip strength in tube feet, and disintegration (Bates et al., 2009; Hewson et al., 2018; Menge et al., 2016). Recent reports have indicated that wasting may affect more than just sea stars: giant California sea cucumbers (*Parastichopus californicus)* displaying wasting symptoms have been reported in small numbers throughout the Salish Sea and the Northwest Coast of British Columbia and Alaska since 2014 (Hewson et al., 2020; Schroeder, 2017).

A recent sea cucumber wasting event occurred in Nanoose Bay, B.C., Canada, from August – October 2021 (Em Lim, *personal communication*). This event followed several severe regional heat waves (Kotyk, 2021). There is insufficient evidence to confirm that wasting-like symptoms were *not* caused by direct heat stress, as reported in farmed *Holothuria scabra* (Delroisse et al., 2020), or a heat-unrelated viral or bacterial disease as observed in farmed *Apostichopus japonicus* (Deng et al., 2008; Liu et al., 2010). However, based on our knowledge of SSWD, warm water anomalies could plausibly play an etiological role though heat stress interactions with disease dynamics, as reported in corals, algae, oysters, and sea stars (Case et al., 2011; Hewson et al., 2018; Oliver et al., 2017). Understanding whether giant California sea cucumber wasting is linked to MHWs is important for informing management efforts seeking to protect this important species.

Sea cucumbers, often underappreciated, provide several important ecological and economic services. As benthic detritivores, sea cucumbers break down organic matter and are thus important for nutrient recycling (Wheeling et al., 2007). Sea cucumbers maintain sediment health for bacteria and other detritivores through bioturbation and sediment cleaning (Purcell et al., 2016). Giant California sea cucumbers seasonally lose their internal organs in a poorly understood process that may be caused by absorption of the internal organs or expulsion by evisceration (Fankboner & Cameron, 1985; Swan, 1961). This loss of internal organs is hypothesized to be part of a seasonal senescence that could affect their behaviour and therefore confound our experiment (Brothers et al., 2015). North America is also seeing a growing sea cucumber harvest industry (Hannah et al., 2013; van Dam-Bates et al., 2016); in British Columbia alone the total industry is worth 10.2 million dollars (Fisheries and Oceans Canada, 2021). Given their importance, evaluating how marine heat waves may impact sea cucumbers is a pressing concern, especially considering recent heat stress events the NE Pacific Ocean (Harvell et al., 2019).

This study seeks to assess the direct lethal and sublethal effects of marine heat waves ongiant California sea cucumbers (*Parastichopus californicus*), and to enhance our understanding of the cause of sea cucumber wasting. Evaluating how marine heat waves affect giant California sea cucumbers is important to understand the risks facing the sea cucumber harvesting industry and to inform future research into the impacts of marine heat waves on sea cucumbers. We simulated a MHW in a controlled laboratory setting to test three hypotheses. We hypothesized that prolonged elevated temperature exposure will cause direct mortality, changes in behaviour, and increased wasting symptoms due to physiological stress. Based on our hypothesis, we make three predictions: 1) we will observe greater mortality with higher temperatures; 2) we will observe changes in movement rates and stress responses as temperature increases; and 3) we will observe wasting symptoms only in warmer temperature treatments.

**Methods:**

*Study organisms*

63*Parastichopus californicus* were collected by divers Em Lim and Siobhan Gray in Scott’s Bay and the entrance to Bamfield Inlet in Barkley Sound, British Columbia (48°50'02"N, 125°08'45"W) in July 2021. All were gathered from the shallow subtidal, between {NUMBER} and {NUMBER} depth. We placed the cucumbers in 19 cm deep flow-through sea tables at the Bamfield Marine Sciences Centre, which had a constant flow of seawater from Barkley Sound. The sea cucumbers were fed with kelp, plankton cultures and bloodworms. The cucumbers remained in the lab for {NUMBER} days prior to the start of the experiment. As part of a separate study, individuals were tagged with several types of tags and monitored; the results of this study indicated that the tags did not affect the sea cucumbers’ behaviour or survival (Lim et al., unpublished data).

We measured sea cucumber size as some studies have shown that body size can affect the thermal tolerance of marine organisms (Di Santo & Lobel, 2017; Kelley et al., 2011). We weighed sea cucumbers twice, 24 hours apart, to get an average wet weight. We conducted a pilot study before the start of our experiment to determine how many cucumbers had their internal organs. Prior to the start of the experiment, we isolated cucumbers into individual containers for 24 hours to determine if they were defecating.

*Experimental Design*

Our experiment exposed sea cucumbers to 12ºC, 17ºC, and 22ºC temperature treatments. The 12ºC control treatment represents the average seawater temperature 50 meters below surface in Barkley Sound, while 17ºC mimics a high subtidal temperature and 22ºC represents an extreme heat event that is unlikely to occur under natural circumstances (Chen et al., 2021b; Pawlowicz, 2017; Xuereb et al., 2018).

We separated the sea cucumbers into three temperature treatments (N22ºC treatment = 18, Ncontrol & 17ºC treatments = 19, N = 56). Sea cucumbers were separated into 30 bins with 2 cucumbers in each (except 4 bins in which only housed one cucumber). Each treatment consisted of two sea tables with a total of 10 bins. Cucumbers were randomly assigned to bins, and bins were randomly assigned to sea tables. The bins sat in 5cm deep water baths that were either at the temperature of the sea tables’ flow through system (12ºC), standing at ambient (room) temperature (17ºC), or heated with two 800W aquarium heaters to 24ºC, to keep the bins at 22ºC. The temperature treatments lasted from 09:00 on November 09 (Day 1) to 01:00 on November 13 (Day 5) for a total of X hours of heat exposure, and bucket temperature was ramped up over 24h on Day 1 and decreased over 8h on Day 5 to limit temperature shock. In the 22ºC treatment, the water bath was circulated around the sea table with powerhead aquarium pumps to ensure even temperature distribution. We monitored temperature in every bin at least twice daily. We used a water-permeable divider to separate cucumbers within bins to allow for individual identification throughout the experiment. We did not provide sea cucumbers with food during the experiment.  Water changes were done as need to keep nitrate and ammonium levels below 0.5. Fresh sea water was heated to the appropriate treatment temperature prior to water changes. We exposed sea cucumbers to treatments for 82 hours and monitored them for 7 days afterwards for mortality and wasting symptoms.

*Measuring Sea Cucumber Stress & Wasting*

Sea cucumbers stiffen as a defense mechanism and for structural maintenance (Motokawa & Tsuchi, 2003). We determined these two metrics of stiffness using two different ordinal scales. First, we gently palpated the cucumber for 10 seconds to mimic an attempted predation event. We assigned the cucumber a score of 0 if it failed to stiffen and felt like the texture of fat, a score of 1 if it stiffened to the level of un-flexed muscle and a score of 2 if the cucumber got comparably stiff to a flexed bicep muscle. Secondly, we removed each cucumber from their tank and placed them on a 5 cm x 5 cm elevated platform to measure their ability to maintain their structure over 5 seconds. We assigned the cucumber a score of 0 if it failed to stiffen at all, a score of 1 if it failed to remain stiff when placed on the platform, a and a score of 2 if it maintained its structure for the entire 5 seconds (Figure 1). Each stiffness test was performed daily.

A picture containing text

Description automatically generated**Figure 1**. Structural maintenance stiffness tests on *Parastichopus californicus* indicating a score of 0 (left), 1 (center) or 2 (right).

To measure cucumber activity, we recorded movements each minute over a 15-minute period for every morning of the experiment. We used a 5 by 5 cm grid on the bottom of the containers as a reference to standardize movement classifications (Figure 2). We considered cucumbers to have moved if their head travelled from one junction of the grid to another.

We checked sea cucumber tanks every 12 hours for evisceration, an act where they partially or fully expulse their inner organs. We also determined if spawning had occurred, since heat-stress induced spawning has been reported in other sea cucumber species (Battaglene et al., 2002). Spawning was only able to be measured per-bucket instead of per-cucumber because the gametes, especially sperm, would flow from one side of the bucket to the other and we were unable to determine which of the cucumbers had spawned.

We assessed cucumbers for ulcers on the 4th, 5th, 6th, and 12th days of the experiment. We classified ulcers as either minor or major ulcers based on their size and visual appearance (Figure 3). We considered minor ulcers to be small lesions on the ends of spines, which did not have severe discoloration, where the dermis was not fully removed. Scars and closed ulcers were not counted. We considered major ulcers to be open wounds that were fully through the dermis, where white tissue could be seen beneath. We then determined the maximum number of minor and major ulcers per cucumber across the experiment’s duration.

A picture containing indoor, appliance, kitchen appliance

Description automatically generated

**Figure 2**. Plastic containers with 5 x 5cm grids used to house *P. californicus* throughout the experiment. Bins were divided by a permeable divider. Sea cucumbers were provided with oxygen using a bubbler and water changes were done as needed to keep ammonia and nitrate levels low.

A picture containing indoor

Description automatically generated**Figure 3**. Minor (left) and major (right) ulcers on *Parastichopus californicus*. Scale bars represent ~1 cm on each image.

*Statistical Methods*

To examine how sea cucumber mortality varied across treatments, we tested the data for parametric assumptions and then used a Kruskal-Wallis (K-W) test followed by a Dunn’s Kruskal- Wallis (Dunn’s K-W) test for multiple comparisons. We then built a logistic regression model with cucumber mortality as the response variable and evisceration, defecation status, initial droop and squeeze scores, and initial weight as explanatory variables. The objective of this analysis was to understand what factors, other than temperature treatment, affected mortality. We used forward GAIC model selection to investigate which combination of these variables best explained the variation in sea cucumber mortality.

We determined if the two sea cucumber stiffness metrics (antipredator response and structure maintenance) were correlated using spearman’s rank correlation coefficient. We assumed that these metrics represent two different types of stiffening behaviour, regardless of correlation strength, and modelled them separately. For both response variables, we constructed full ordinal regression models with the following predictor variables: temperature treatment, date as a categorical variable for each individual date, and the interaction term between treatment and date. We restricted our measurement period to the days preceding (Day 1), during (Day 2-4) and immediately after the heat treatment (Day 5). We included individual cucumber identity as a random effect to account for repeated measures on the same individuals over time. We also included bucket ID and sea table ID as random effects to account for our paired (two cucumbers per bucket) and blocked (five buckets per sea table) experimental design. We used AIC model selection to determine the most parsimonious models (ΔAIC > 2). From top selected models we calculated 95% confidence intervals and considered effects to be significant if confidence intervals did not overlap zero.

We compared activity scores between treatments on specific days of interest with K-W and Dunn’s K-W tests. We looked at Day 1 (pre-experiment), Day 2 initial heat shock and Day 12 (long-term recovery). We then fit a generalized additive model to activity score, which we identified as having a zero-adjusted negative binomial distribution. We included temperature treatment, date (measured as categorical) and the interaction between treatment and date as fixed effects in the full model. We included individual, sea table and bucket ID as random effects. We used backward AIC step-selection to find the variables that best explained the variation in activity scores.

We used a Kruskal-Wallis rank sum test to compare the number of buckets with spawning cucumbers across temperature treatments. To examine the effect of temperature on the likelihood of a cucumber eviscerating, we created a logistic regression model with treatment, weight, and defecation status as explanatory variables in the full model, and sea table as a random effect. We conducted forward AIC model selection to determine appropriate explanatory variables.

To assess which variables affected the maximum number of minor ulcers, we used a generalized additive model. We determined that the number of minor ulcers best fit a geometric distribution. We modelled the maximum number of minor ulcers as a function of treatment, weight, evisceration, and defecation status. We included sea table and bucket as random effects.

All statistical analyses were conducted in R version 4.0.3. Dunn’s K-W tests were done using the *dunnTest* function in package FSA (Derek et al., 2021). Models for mortality effects, activity score, evisceration, and minor ulcers were conducted using the *gamlss* function, and model selection was done using the *stepGAIC* function, both from package GAMLSS (Rigby et al., 2021). We determined the most appropriate distribution for activity scores and the number of minor ulcers using the *fitDist* function in package GAMLSS (Rigby et al., 2021). Ordinal regression models were conducted using the *clmm* function in package ordinal (Christensen, 2019); model selection for these models was conducted using the *dredge* function in package MuMIN (Barton & Barton, 2020). We considered results to be significant at P < 0.05 or if 95 % confidence intervals did not overlap zero.

**Results**

The temperature treatments for the experimental heatwaves varied slightly from the target temperatures (Figure 4). The mean temperature of the 12°C treatment was 12.5°C, but varied from 11.2-14.0°C; the mean of the 17°C treatment was 16.8°C but ranged from 14.9°C to 17.9°C; the mean of the 22°C treatment was 21.9°C but varied from 20.0°C to 23.3°C.

Five mortalities occurred in the 22°C treatment on day 3 (*N*=2), day 4 (*N*=1), day 6 (*N*=1) and day 7 (*N*=1) of the experiment (Figure 4). Mortality was significantly different across temperature treatments (K-W χ2 = 11.383, df = 2, p = 0.00337). There was no significant difference between the 12°C and 17°C treatments (Dunn’s K-W Z = 0, p = 1), but the 22°C treatment had significantly higher mortality than the 12°C (Dunn’s K-W Z = 2.935, adj. p = 0.00334) and 17°C (Dunn’s K-W Z = -2.935, adj. p = 0.00334) treatments. Based on forward AIC selection, our null model was the best fit, indicating that evisceration, defecation status, initial droop and squeeze score, and weight did not significantly predict mortality in the 22°C treatment.

**Diagram

Description automatically generated**

**Figure 4**. Water temperatures over the duration of our experiment. Day 1, the start of the warming, was November 09. Each black line indicates a single bin housing 1 or 2 cucumbers. The 3 coloured lines indicate target temperatures for the heat treatments.

Over the course of the experiment, skin ulcers occurred in all three treatments. Minor ulcers were observed on 17 cucumbers in the 12ºC treatment, 15 cucumbers in the 17ºC treatment, and 10 individuals in the 22ºC treatment (Figure S1). Major ulcers were observed in only the heat treatment: on the final day of the treatment, two cucumbers had 1 and 4 ulcers respectively. Neither of these individuals died, and after the heat treatment stopped their major ulcers appeared to heal and were re-classified as minor ulcers on day 12 of the experiment. The maximum number of minor ulcers per individual was not significantly explained by treatment, weight, evisceration, or defecation status, because all explanatory variables were excluded from the final backward-selected model (Table S1).

Sea cucumber stiffness, as measured by antipredator response and structure maintenance, was lower in the 22ºC and 17ºC treatments compared to the 12ºC treatment (Figures 5, 6). Antipredator response and structure maintenance were significantly positively correlated with each other (rs = 0.53, p < 0.001; Figure S2). Backward-selected models indicated that temperature treatment and day affected both stiffness metrics (Table S2, S3). There was a significantly lower likelihood of high antipredator stiffness values for the 17°C (p = 4.80 x 10-5) and 22°C (p = 5.88 x 10­-9) treatments relative to the control. Sea cucumber antipredator stiffness scores were significantly likely to be lower on day 2 (p = 1.16 x 10­-6), day 3 (p = 1.33 x 10­-7), day 4 (p = 2.06 x 10­-6) and day 5 (p = 5.05 x 10­-8) than on day 1 (Table S2). For structural stiffness, cucumbers were significantly less likely to have high stiffness scores relative to the control treatment in the 17°C (p = 1.99 x 10-7) and 22°C (p = 2.44 x 10­-11) treatments. Structural stiffness values were significantly likely to be lower than day 1 on day 3 (p = 1.37 x 10­-5), day 4 (p = 2.50 x 10­-5) and day 5 (p = 8.66 x 10­-5), but not on day 2 (p = 0.0627; Table S3). In both antipredator and structural stiffness metrics, there were no significant differences in the likelihood of low stiffness values between 17°C and 22°C treatments, as indicated by the high degree of overlap in 95% confidence intervals (Figure S3).

Chart

Description automatically generated

**Figure 5**. *Parastichopus californicus* stiffness as measured by antipredator defense over the duration of the heat treatment (days 1-5) and on recovery days after the treatment ended (day 7 and 12). Dashed lines indicate the days during which heat was applied. Antipredator response was categorized by manually palpating the cucumber to mimic the occurrence of an attempted predation event.

Chart

Description automatically generated

**Figure 6.** *Parastichopus californicus* stiffness as measured by structural maintenance over the duration of the heat treatment (days 1-5) and on recovery days after the treatment ended (day 7 and 12). Structural maintenance stiffness was categorized by placing a stiff cucumber on an elevated platform for 5 seconds and determining if they could maintain their posture. Dashed lines indicate the days during which heat was applied.

Minor differences in activity scores were observed between treatments over the duration of the experiment, and overall, they decreased compared to day 1 (Figure 7). Seven days after the heat treatment ended (day 12), activity scores appeared comparable to those observed on day 1. Notably, on day 2 (the first day of the heat treatment), activity scores in the 22ºC treatment were much lower (median = 0) than the 12°C (median = 2.5) or 17°C (median = 3) treatments. Differences between treatments were not statistically significant on day 1 (K-W χ2 = 2.28, df = 2, p = 0.319) or day 12 (K-W χ2 = 1.81, df = 2, p = 16). On day 2 the difference was significant (K-W χ2 = 6.21, df = 2, p = 0.0448), but not between treatment pairwise comparisons of 12°C and 17°C (Dunn’s K-W, Z = 0.540, p = 0.589), 12°C and 22°C (Dunn’s K-W Z = 2.39, p = 0.0506) or 17°C and 22°C (Dunn’s K-W Z = -1.87, p = 0.124). Model results indicated that treatment did not have a significant overall effect on activity scores, but elapsed treatment days did (Table S4). Activity scores on day 3 (p = 0.0105), 4 (p = 0.00274) and 5 (p = 0.00991) were all significantly lower than on day 1. Day 2 was not significantly lower (p = 0.797).

Chart, box and whisker chart

Description automatically generated

**Figure 7.** Boxplot visualizing *Parastichopus californicus* activity scores across heat treatments throughout the duration of the experiment (days 1-5) and the days after the heat treatment ended (day 7 and 12). Activity scores were determined by counting the number of movements made by each individual sea cucumber over a 15-minute period between 09:00 and 11:00. Dashed lines indicate the days during which heat was applied.

Over the course of the experiment, evidence of stress spawning (eggs or sperm) occurred in 11 buckets. Nine of these buckets were in the 17ºC and 22ºC treatments. There was no significant difference in per-bucket spawning between temperature treatments (K-W χ2 = 1.94, df = 2, p = 0.379). We also observed 12 cucumbers across all treatments eviscerate their digestive organs. Logistic regression results indicated that treatment temperature does not explain a significant amount of the variance in evisceration data because it was excluded from our forward selected model (Table S5). However, weight (p = 0.0383) and defecation status (p = 0.0163) were included in the top model as significant predictors of evisceration (Table S5). Two cucumbers in the heat treatment eviscerated their respiratory trees in addition to their internal organs (Figure 8). One cucumber died 12 hours after respiratory evisceration, the other was observed to have died 68 hours after. The latter cucumber was severely impacted by eviscerating its respiratory tree; stiffness values and activity scores all dropped to zero for the days it remained alive. Despite the traumatic evisceration, it continued to move extremely slowly and wave its mouth parts until it died.

A picture containing text

Description automatically generated**Figure 8.** The eviscerated digestive tract (left) and respiratory tree (right) of *Parastichopus californicus* in the 22ºC treatment. Respiratory tree (A) and digestive tract (B) were both eviscerated in right panel. Sea cucumbers frequently expel their digestive tract as a stress response, but respiratory tree evisceration only occurred twice in the 22ºC treatment and was followed by mortality.

**Supplementary Information**

**Table S1**. Results from geometric regression model examining the effect of treatment and weight on sea cucumber maximum lesion counts.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Variable | Coefficient | Standard error | T | P |
| (intercept) | 0.965 | 0.157 | 6.15 | 9.35e-08 \* |

**Table S2**. Results of ordinal regression model examining the effect of treatment and date on sea cucumber antipredator defense stiffness. Asterisks indicate significant effects.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Variable | Coefficient | Standard error | T | P |
| Treatment: 17C | -3.03 | 0.748 | -4.07 | 4.80e-05 \* |
| Treatment: 22C | -4.76 | 0.818 | -5.82 | 5.88e-09 \* |
| Date: 2 | -3.09 | 0.634 | -4.86 | 1.16e-06 \* |
| Date: 3 | -3.39 | 0.643 | -5.28 | 1.33e-07 \* |
| Date: 4 | -3.00 | 0.632 | -4.75 | 2.06e-06 \* |
| Date: 5 | -3.62 | 0.664 | -5.45 | 5.05e-08 \* |

**Table S3**. Results of ordinal regression model examining the effect of treatment and date on sea cucumber structural maintenance stiffness. Asterisks indicate significance.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Variable | Coefficient | Standard error | T | P |
| Treatment: 17C | -2.99 | 0.575 | -5.20 | 1.99e-07 \* |
| Treatment: 22C | -4.05 | 0.606 | -6.68 | 2.44e-11 \* |
| Date: 2 | -0.976 | 0.524 | -1.86 | 0.0627 |
| Date: 3 | -2.30 | 0.528 | -4.35 | 1.37e-05 \* |
| Date: 4 | -2.22 | 0.527 | -4.21 | 2.50e-05 \* |
| Date: 5 | -2.12 | 0.541 | -3.93 | 8.66e-05 \* |

**Table S4**. Results from the backward-selected regression model with a zero-adjusted negative binomial distribution examining the effect of treatment and date on sea cucumber activity scores. Asterisks indicate significance.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Variable | Coefficient | Standard error | T | P |
| (intercept) | 1.78 | 0.0740 | 24.05 | < 2e-16 \* |
| Date: 2 | 0.0279 | 0.109 | 0.257 | 0.797 |
| Date: 3 | -0.289 | 0.112 | -2.58 | 0.0105 \* |
| Date: 4 | -0.331 | 0.109 | -3.03 | 0.00274 \* |
| Date: 5 | -0.328 | 0.126 | -2.60 | 0.00991 \* |

**Table S4**. Results from forward-selected logistic regression model examining the effect of evisceration as a function of defecation status and weight. Asterisks indicate significant effects.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Estimate | Std. Error | t-value | P |
| (Intercept) | 1.7126 | 1.1281 | 1.518 | 0.135 |
| Poop (yes) | -2.780 | 1.1202 | -2.482 | 0.0163 \* |
| Weight | -0.004309 | 0.002029 | -2.124 | 0.0383 \* |

Chart, box and whisker chart

Description automatically generated

**Figure S1**. Maximum number of minor ulcers found on each individual *Parastichopus californicus* during the heat treatment, compared between the three temperature treatments.  We examined sea cucumbers for ulcers and classified them as minor or major (Figure 3) based on their apparent severity.

Chart, scatter chart

Description automatically generated

**Figure S2:** Scatter plot displaying the relationship between *Parastichopus californicus* stiffness metrics. Spearman’s rank correlation coefficient indicated a high degree of correlation between metrics (rs = 0.53, p < 0.001). Stiffness metrics were measured daily for each sea cucumber throughout the experiment.

Chart, box and whisker chart

Description automatically generated

**Figure S3**. Ordinal regression coefficient and 95% confidence intervals from two AIC selected models with stiffness as antipredator defense or structural maintenance as the response variables. Variable reference categories were Temp: 12°C and Day 1. If confidence intervals overlap 0 (dashed line) the effect is non-significant.

**Literature Cited**

Allan, R. P., Arias, P. A., Berger, S., Canadell, J. G., Cassou, C., Chen, D., Cherchi, A., Connors, S. L., Coppola, E., Cruz, F. A., Diongue-Niang, A., Doblas-Reyes, F. J., Douville, H., Driouech, F., Edwards, T. L., Engelbrecht, F., Eyring, V., Fischer, E., Flato, G. M., … Zickfeld, K. (2021). IPCC: Climate Change 2021: The Physical Science Basis. *Cambridge University Press. In Press.*, 42. https://www.ipcc.ch/report/ar6/wg

Aquino, C. A., Besemer, R. M., DeRito, C. M., Kocian, J., Porter, I. R., Raimondi, P. T., Rede, J. E., Schiebelhut, L. M., Sparks, J. P., Wares, J. P., & Hewson, I. (2021). Evidence That Microorganisms at the Animal-Water Interface Drive Sea Star Wasting Disease. *Frontiers in Microbiology*, *11*. https://doi.org/10.3389/fmicb.2020.610009

Bates, A. E., Hilton, B. J., & Harley, C. D. G. (2009). Effects of temperature, season and locality on wasting disease in the keystone predatory sea star Pisaster ochraceus. *Diseases of Aquatic Organisms*, *86*(3), 245–251. https://doi.org/10.3354/dao02125

Battaglene, S. C., Seymour, J. E., Ramofafia, C., & Lane, I. (2002). Spawning induction of three tropical sea cucumbers, Holothuria scabra, H. fuscogilva and Actinopyga mauritiana. *Aquaculture*, *207*(1–2), 29–47. https://doi.org/10.1016/S0044-8486(01)00725-6

Brothers, C. J., Lee, R. W., & Nestler, J. R. (2015). The uptake of dissolved organic material by the sea cucumber Parastichopus californicus (Stimpson) and its potential role in visceral regeneration. *Journal of Experimental Marine Biology and Ecology*, *469*, 69–75. https://doi.org/10.1016/J.JEMBE.2015.04.016

Case, R. J., Longford, S. R., Campbell, A. H., Low, A., Tujula, N., Steinberg, P. D., & Kjelleberg, S. (2011). Temperature induced bacterial virulence and bleaching disease in a chemically defended marine macroalga. *Environmental Microbiology*, *13*(2), 529–537. https://doi.org/10.1111/j.1462-2920.2010.02356.x

Cavole, L. M., Demko, A. M., Diner, R. E., Giddings, A., Koester, I., Pagniello, C. M. L. S., Paulsen, M. L., Ramirez-Valdez, A., Schwenck, S. M., Yen, N. K., Zill, M. E., & Franks, P. J. S. (2016). Biological impacts of the 2013–2015 warm-water anomaly in the northeast Pacific: Winners, Losers, and the Future. *Oceanography*, *29*(2), 273–285. https://doi.org/10.5670/oceanog.2016.32

Chen, Z., Shi, J., Liu, Q., Chen, H., & Li, C. (2021a). A Persistent and Intense Marine Heatwave in the Northeast Pacific During 2019–2020. *Geophysical Research Letters*, *48*(13). https://doi.org/10.1029/2021GL093239

Chen, Z., Shi, J., Liu, Q., Chen, H., & Li, C. (2021b). A Persistent and Intense Marine Heatwave in the Northeast Pacific During 2019–2020. *Geophysical Research Letters*, *48*(13). https://doi.org/10.1029/2021GL093239

Cox, D. R. (1972). Regression Models and Life-Tables. *Journal of the Royal Statistical Society: Series B (Methodological)*, *34*(2), 187–202. https://doi.org/10.1111/J.2517-6161.1972.TB00899.X

Delroisse, J., Van Wayneberghe, K., Flammang, P., Gillan, D., Gerbaux, P., Opina, N., Todinanahary, G. G. B., & Eeckhaut, I. (2020). Epidemiology of a SKin Ulceration Disease (SKUD) in the sea cucumber Holothuria scabra with a review on the SKUDs in Holothuroidea (Echinodermata). *Scientific Reports*, *10*(1). https://doi.org/10.1038/S41598-020-78876-0

Deng, H., Zhou, Z. C., Wang, N. Bin, & Liu, C. (2008). The syndrome of sea cucumber (Apostichopus japonicus) infected by virus and bacteria. *Virologica Sinica*, *23*(1), 63–67. https://doi.org/10.1007/S12250-008-2863-9

Di Lorenzo, E., & Mantua, N. (2016). Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, *6*(11), 1042–1047. https://doi.org/10.1038/nclimate3082

Di Santo, V., & Lobel, P. S. (2017). Body size and thermal tolerance in tropical gobies. *Journal of Experimental Marine Biology and Ecology*, *487*, 11–17. https://doi.org/10.1016/J.JEMBE.2016.11.007

Dong, Y. wei, Yu, S. shan, Wang, Q. lin, & Dong, S. lin. (2011). Physiological responses in a variable environment: Relationships between metabolism, hsp and thermotolerance in an intertidal-subtidal species. *PLoS ONE*, *6*(10). https://doi.org/10.1371/journal.pone.0026446

Eisenlord, M. E., Groner, M. L., Yoshioka, R. M., Elliott, J., Maynard, J., Fradkin, S., Turner, M., Pyne, K., Rivlin, N., Van Hooidonk, R., & Harvell, C. D. (2016). Ochre star mortality during the 2014 wasting disease epizootic: Role of population size structure and temperature. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1689). https://doi.org/10.1098/rstb.2015.0212

Fankboner, P. V., & Cameron, J. L. (1985). Seasonal atrophy of the visceral organs in a sea cucumber. *Canadian Journal of Zoology*, *63*(12), 2888–2892. https://doi.org/10.1139/Z85-432

Fisheries and Oceans Canada. (2021). *Integrated Fisheries Management Plan Summary, Sea Cucumber (Apostichopus californicus) By Dive, Pacific Region*. https://www.pac.dfo-mpo.gc.ca/fm-gp/mplans/sea-cucumber-holothurie-ifmp-pgip-sm-eng.pdf

Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. *Nature*, *560*(7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9

Hannah, L., Pearce, C. M., & Cross, S. F. (2013). Growth and survival of California sea cucumbers (Parastichopus californicus) cultivated with sablefish (Anoplopoma fimbria) at an integrated multi-trophic aquaculture site. *Aquaculture*, *406*–*407*, 34–42. https://doi.org/10.1016/J.AQUACULTURE.2013.04.022

Harley, C. D. G., & Paine, R. T. (2009). Contingencies and compounded rare perturbations dictate sudden distributional shifts during periods of gradual climate change. *PNAS*, *106*(27), 11172–11176. www.pnas.org/cgi/content/full/

Harvell, C. D., Montecino-Latorre, D., Caldwell, J. M., Burt, J. M., Bosley, K., Keller, A., Heron, S. F., Salomon, A. K., Lee, L., Pontier, O., Pattengill-Semmens, C., & Gaydos, J. K. (2019). Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (Pycnopodia helianthoides). *Science Advances*, *5*(1), 1–9. https://doi.org/10.1126/sciadv.aau7042

Hewson, I., Bistolas, K. S. I., Quijano Cardé, E. M., Button, J. B., Foster, P. J., Flanzenbaum, J. M., Kocian, J., & Lewis, C. K. (2018). Investigating the complex association between viral ecology, environment, and northeast Pacific Sea Star Wasting. *Frontiers in Marine Science*, *5*(MAR). https://doi.org/10.3389/fmars.2018.00077

Hewson, I., Johnson, M. R., & Tibbetts, I. R. (2020). An Unconventional Flavivirus and Other RNA Viruses in the Sea Cucumber (Holothuroidea; Echinodermata) Virome. *Viruses*, *12*(1057). https://doi.org/10.3390/v12091057

Kelley, A. L., de Rivera, C. E., & Buckley, B. A. (2011). Intraspecific variation in thermotolerance and morphology of the invasive European green crab, Carcinus maenas, on the west coast of North America. *Journal of Experimental Marine Biology and Ecology*, *409*(1–2), 70–78. https://doi.org/10.1016/J.JEMBE.2011.08.005

Kotyk, A. (2021, August 13). More than a dozen weather records broken in B.C. in latest heat wave. *CTV News Vancouver*. https://bc.ctvnews.ca/more-than-a-dozen-weather-records-broken-in-b-c-in-latest-heat-wave-1.5546239

Kühnhold, H., Kamyab, E., Novais, S., Indriana, L., Kunzmann, A., Slater, M., & Lemos, M. (2017). Thermal stress effects on energy resource allocation and oxygen consumption rate in the juvenile sea cucumber, Holothuria scabra (Jaeger, 1833). *Aquaculture*, *467*, 109–117. https://doi.org/10.1016/j.aquaculture.2016.03.018

Liu, H., Zheng, F., Sun, X., Hong, X., Dong, S., Wang, B., Tang, X., & Wang, Y. (2010). Identification of the pathogens associated with skin ulceration and peristome tumescence in cultured sea cucumbers Apostichopus japonicus (Selenka). *Journal of Invertebrate Pathology*, *105*(3), 236–242. https://doi.org/10.1016/J.JIP.2010.05.016

McCullagh, P. (1980). Regression Models for Ordinal Data. *Journal of the Royal Statistical Society: Series B (Methodological)*, *42*(2), 109–127. https://doi.org/10.1111/J.2517-6161.1980.TB01109.X

Menge, B. A., Cerny-Chipman, E. B., Johnson, A., Sullivan, J., Gravem, S., & Chan, F. (2016). Sea Star Wasting Disease in the Keystone Predator Pisaster ochraceus in Oregon: Insights into differential population impacts, recovery, predation rate, and temperature effects from long-term research. *PLoS ONE*, *11*(5). https://doi.org/10.1371/journal.pone.0153994

Motokawa, T., & Tsuchi, A. (2003). Dynamic Mechanical Properties of Body-Wall Dermis in Various Mechanical States and Their Implications for the Behavior of Sea Cucumbers. *Biological Bulletin*, *205*(3), 261–275. https://doi.org/10.2307/1543290

Oliver, E. C. J., Benthuysen, J. A., Bindoff, N. L., Hobday, A. J., Holbrook, N. J., Mundy, C. N., & Perkins-Kirkpatrick, S. E. (2017). The unprecedented 2015/16 Tasman Sea marine heatwave. *Nature Communications*, *8*(May), 1–12. https://doi.org/10.1038/ncomms16101

Oliver, E. C. J., Benthuysen, J. A., Darmaraki, S., Donat, M. G., Hobday, A. J., Holbrook, N. J., Schlegel, R. W., & Sen Gupta, A. (2021). Marine Heatwaves. *Annual Review of Marine Science*, *13*, 313–342. https://doi.org/10.1146/annurev-marine-032720-095144

Pawlowicz, R. (2017). Seasonal Cycles, Hypoxia, and Renewal in a Coastal Fjord (Barkley Sound, British Columbia). *Atmosphere - Ocean*, *55*(4–5), 264–283. https://doi.org/10.1080/07055900.2017.1374240

Purcell, S., Conand, C., Uthicke, S., & Byrne, M. (2016). Ecological Roles of Exploited Sea Cucumbers. *Oceanography and Marine Biology: An Annual Review*, *54*, 367–386. https://doi.org/10.1201/9781315368597-8

Schneider, K., Silverman, J., Woolsey, E., Eriksson, H., Byrne, M., & Caldeira, K. (2011). Potential influence of sea cucumbers on coral reef CaCO3 budget: A case study at One Tree Reef. *Journal of Geophysical Research: Biogeosciences*, *116*(G4). https://doi.org/10.1029/2011JG001755

Schroeder, L. (2017). Wasting-like lesions occurring on California Sea Cucumbers. *The Dredgings*, *57*(3), 3. www.PNWSC.org

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., & Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(33), 8252–8259. https://doi.org/10.1073/PNAS.1810141115

Suryan, R. M., Arimitsu, M. L., Coletti, H. A., Hopcroft, R. R., Lindeberg, M. R., Barbeaux, S. J., Batten, S. D., Burt, W. J., Bishop, M. A., Bodkin, J. L., Brenner, R., Campbell, R. W., Cushing, D. A., Danielson, S. L., Dorn, M. W., Drummond, B., Esler, D., Gelatt, T., Hanselman, D. H., … Zador, S. G. (2021). Ecosystem response persists after a prolonged marine heatwave. *Scientific Reports*, *11*(1), 1–17. https://doi.org/10.1038/s41598-021-83818-5

Swan, E. F. (1961). Seasonal evisceration in the sea cucumber, Parastichopus californicus (Stimpson). *Science*, *133*(3458), 1078–1079. https://doi.org/10.1126/science.133.3458.1078

van Dam-Bates, P., Curtis, D., Cowen, L., Cross, S., & Pearce, C. (2016). Assessing movement of the California sea cucumber Parastichopus californicus in response to organically enriched areas typical of aquaculture sites. *Aquaculture Environment Interactions*, *8*, 67–76. https://doi.org/10.3354/AEI00156

von Biela, V., Arimitsu, M. L., Piatt, J. F., Heflin, B. M., & Schoen, S. (2019). Extreme reduction in condition of a key forage fish during the Pacific marine heatwave of 2014–2016. *Marine Ecology Progress Series*, *613*, 171–182.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesank, C., Beebee, T. J. C., Fromentin, J.-M., Hoegh-Guldberg, O., & Bairlein, F. (2002). Ecological responses to recent climate change. *Nature*, *419*. www.nature.com

Wernberg, T., Bennett, S., Babcock, R. C., Bettignies, T. De, Cure, K., Depczynski, M., Dufois, F., Fromont, J., Fulton, C. J., Hovey, R. K., Harvey, E. S., Holmes, T. H., Kendrick, G. A., Radford, B., Santana-garcon, J., Saunders, B. J., Smale, D. A., Thomsen, M. S., Tuckett, C. A., & Tuya, F. (2015). Climate-driven regime shift of a temperate marine ecosystem. *Science*, *353*(6295), 169–172. https://doi.org/10.1126/science.aad8745

Wheeling, R. J., Verde, E. A., & Nestler, J. R. (2007). Diel cycles of activity, metabolism, and ammonium concentration in tropical holothurians. *Marine Biology*, *152*(2), 297–305. https://doi.org/10.1007/S00227-007-0683-3

Work, T. M., Weatherby, T. M., DeRito, C. M., Besemer, R. M., & Hewson, I. (2021). Sea star wasting disease pathology in Pisaster ochraceus shows a basal-to-surface process affecting color phenotypes differently. *Diseases of Aquatic Organisms*, *145*, 21–33. https://doi.org/10.3354/DAO03598

Xuereb, A., Kimber, C. M., Curtis, J. M. R., Bernatchez, L., & Fortin, M.-J. (2018). Putatively adaptive genetic variation in the giant California sea cucumber (Parastichopus californicus) as revealed by environmental association analysis of restriction-site associated DNA sequencing data. *Molecular Ecology*, *27*(24), 5035–5048. https://doi.org/10.1111/MEC.14942