

Supplementary Materials & Methods.

Heatwave Analysis

Methods: Heatwave dynamics (i.e., duration, rate of onset, and maximum intensity) were determined by analyzing an 18-year temperature dataset (2002-2020) from the NERRS Ploeg Channel monitoring station in Padilla Bay, WA (48°33'22.8"N 122°31'51.2"W). The station code is PDBBPWQ and the dataset was downloaded from the NERRS Centralized Data Management Office (<https://cdmo.baruch.sc.edu/dges/>). The R package *heatwaveR* (Schlegel and Smit, 2018) was used to identify heatwaves in the timeseries based on a selection criteria of daily mean temperatures exceeding the 90th percentile of the long-term seasonal climatology for a minimum of 5 consecutive days (Hobday et al., 2016).

Results: A total of 45 events were detected in the 18-year dataset. Heatwaves occurred during all months at a roughly equal frequency between seasons (11 or 12 per season). Maximum intensity ranged from 1.67° - 5.33°C above seasonal climatology, with a mean (\pm SD) of 2.97 \pm 0.79°C. However, there was a clear seasonal fluctuation in maximum heatwave intensity as the strongest events occurred in late-spring and summer. The most extreme event occurred in June 2014. It reached a maximum intensity of 5.32°C with a rate of onset of 0.56 °C \times d-1 and lasted for eight consecutive days (Table S1). Event duration ranged from 5 to 20 d (mean 7.3 \pm 3.1 d) while rate of onset ranged between 0.08° C \times d-1 to 1.01°C \times d-1 (mean 0.46 \pm 0.22°C \times d-1). There was a weak relationship between maximum intensity and rate of onset. More intense heatwaves tended to manifest more quickly, but there were several outlying events (linear regression, $p = 0.00289$, $r^2 = 0.1696$). There was no relationship between maximum intensity and event duration. However, there was a weak negative relationship between rate of onset and duration, such that heatwaves that manifested quickly had shorter durations (linear regression, $p = 0.0087$, $r^2 = 0.1297$). Again, there were clear outlying events to this trend. The period around the 2014-2016 North Pacific Heatwave produced more heatwaves and the most intense events compared to any other period in the timeseries (2014: 7 events, 2015: 12 events, 2016: 7 events, Fig. S1). Most other years experienced just 1-2 events, but a smaller heatwave outbreak occurred during 2003-2005 with 3 – 4 events per year (Fig. S1). Detailed characteristics of the top 10 heatwave events are listed in Table S1.

Converting pH_{NIST} to pH_T

Methods: To reduce the error associated with seawater pH measurements calibrated on the NIST scale (Dickson et al., 2015), an extensive cross-calibration was made between the handheld Orion electrode and the diode array spectrophotometer to produce a robust probe-specific linear relationship to convert pH_{NIST} values measured with the handheld to pH_T. A total of 36 seawater sample will prepared by stripping or adding small amounts of dissolved CO₂ to seawater to achieve pH levels across the range of pH values recorded during the experiment. All measurements were made room temperature (20-23°C) and a salinity of 32. After vigorously mixing the seawater samples, pH_{NIST} was recorded with the handheld electrode and then the sample was immediately injected into the jacketed cuvette and pH_T was measured with the diode array spectrophotometer (Love et al., 2017). A conversion formula was derived by fitting the relationship with a linear model ($\text{pH}_T = 0.91344 \times \text{pH}_{\text{NIST}} + 0.59905$, $R^2 > 0.99$)

Table S1. Summary of the top 10 heatwave events detected at the Ploeg Channel Monitoring Station in Padilla Bay, WA from 2002-2020. Cumulative intensity is sum of daily positive temperature anomaly for the duration of the heatwave.

| Rank | Duration (days) | Start | Peak | Max intensity (°C) | Cum. Intensity (°C) | Rate of onset (°C d ⁻¹) |
|------|--------------------|-----------|-----------|--------------------------|---------------------------|---|
| 1 | 8 | 6/3/2014 | 6/8/2014 | 5.32 | 30.82 | 0.56 |
| 2 | 5 | 4/19/2016 | 4/22/2016 | 4.71 | 17.21 | 0.67 |
| 3 | 6 | 6/8/2015 | 6/11/2015 | 4.64 | 21.24 | 0.65 |
| 4 | 10 | 6/23/2015 | 6/26/2015 | 4.03 | 34.24 | 0.33 |
| 5 | 7 | 7/20/2003 | 7/23/2003 | 4.01 | 18.86 | 0.61 |
| 6 | 6 | 7/23/2004 | 7/25/2004 | 3.96 | 16.74 | 0.79 |
| 7 | 6 | 5/26/2015 | 5/30/2015 | 3.93 | 18.58 | 0.53 |
| 8 | 5 | 4/30/2016 | 5/3/2016 | 3.87 | 13.33 | 0.57 |
| 9 | 6 | 7/31/2014 | 8/4/2014 | 3.78 | 16.18 | 0.54 |
| 10 | 13 | 3/30/2016 | 4/1/2016 | 3.56 | 32.16 | 0.84 |

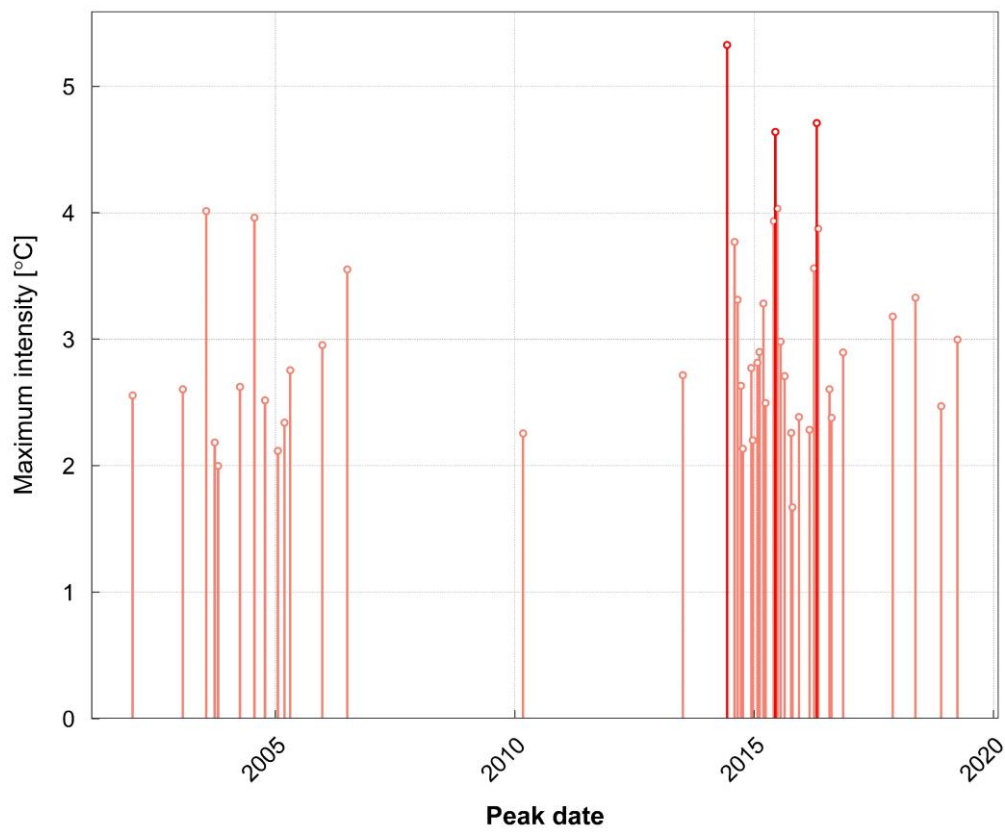


Fig. S1. A lolli-plot of all detected heatwave events. The vertical red lines denote the maximum intensity (°C) of each event.

References

Dickson, A. G., Camões, M. F., Spitzer, P., Fiscaro, P., Stoica, D., Pawlowicz, R. and Feistel, R. (2015). Metrological challenges for measurements of key climatological observables. Part 3: seawater pH. *Metrologia* **53**, R26-R39.

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Love, B. A., Olson, M. B. and Wuori, T. (2017). Technical Note: A minimally invasive experimental system for pCO₂ manipulation in plankton cultures using passive gas exchange (atmospheric carbon control simulator). *Biogeosciences* **14**, 2675-2684.

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Table S2. Pearson correlation coefficients matrix of treatment conditions, morphometric traits, and PC 1-4 scores. Traits are abbreviated as standard length (SL), somatic body area (SBA), head width (HW), eye width (EW), post-yolk body depth (PYBD), post-vent body depth (PVBD), yolk-sac area (YSA), and dry weight (DW).

| | Temp | pCO ₂ | SL | SBA | HW | EW | PYBD | PVBD | YSA | DW | PC1 | PC2 | PC3 | PC4 |
|------------------|--------|------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Temp | - | - | -0.628 | -0.461 | -0.135 | -0.431 | -0.16 | -0.454 | -0.472 | -0.177 | -0.482 | 0.004 | -0.478 | 0.065 |
| pCO ₂ | - | - | -0.086 | -0.146 | -0.148 | -0.166 | -0.121 | -0.174 | 0.194 | 0.144 | -0.101 | 0.327 | 0.076 | -0.014 |
| SL | -0.628 | -0.086 | - | 0.906 | 0.536 | 0.608 | 0.487 | 0.725 | 0.463 | 0.403 | 0.858 | -0.134 | 0.309 | -0.224 |
| SBA | -0.461 | -0.146 | 0.906 | - | 0.733 | 0.626 | 0.72 | 0.81 | 0.435 | 0.431 | 0.948 | -0.181 | 0.001 | -0.161 |
| HW | -0.135 | -0.148 | 0.536 | 0.733 | - | 0.481 | 0.687 | 0.55 | 0.359 | 0.322 | 0.776 | -0.139 | -0.435 | 0.201 |
| EW | -0.431 | -0.166 | 0.608 | 0.626 | 0.481 | - | 0.403 | 0.567 | 0.332 | 0.207 | 0.697 | -0.293 | 0.374 | 0.497 |
| PYBD | -0.16 | -0.121 | 0.487 | 0.72 | 0.687 | 0.403 | - | 0.574 | 0.436 | 0.412 | 0.778 | 0.022 | -0.501 | 0.042 |
| PVBD | -0.454 | -0.174 | 0.725 | 0.81 | 0.55 | 0.567 | 0.574 | - | 0.315 | 0.305 | 0.816 | -0.287 | 0.099 | -0.285 |
| YSA | -0.472 | 0.194 | 0.463 | 0.435 | 0.359 | 0.332 | 0.436 | 0.315 | - | 0.679 | 0.621 | 0.652 | 0.147 | 0.181 |
| DW | -0.177 | 0.144 | 0.403 | 0.431 | 0.322 | 0.207 | 0.412 | 0.305 | 0.679 | - | 0.576 | 0.714 | 0.048 | -0.122 |
| PC1 | -0.482 | -0.101 | 0.858 | 0.948 | 0.776 | 0.697 | 0.778 | 0.816 | 0.621 | 0.576 | - | - | - | - |
| PC2 | 0.004 | 0.327 | -0.134 | -0.181 | -0.139 | -0.293 | 0.022 | -0.287 | 0.652 | 0.714 | - | - | - | - |
| PC3 | -0.478 | 0.076 | 0.309 | 0.001 | -0.435 | 0.374 | -0.501 | 0.099 | 0.147 | 0.048 | - | - | - | - |
| PC4 | 0.065 | -0.014 | -0.224 | -0.161 | 0.201 | 0.497 | 0.042 | -0.285 | 0.181 | -0.122 | - | - | - | - |

Table S3. Summary statistics for LMMs and ANOVAs testing growth traits. Results for LMMs testing individual PC scores and morphometric traits. Numerator degrees of freedom (NumDF) and denomination degrees of freedom (DenDF) are presented. ANOVA results are given for yolk consumption rate (YCR), embryo growth rate (GR), and production efficiency (PE). Significant test results are denoted in bold.

| LMMs | | | | | |
|--------|-------------------------|-------|---------|---------|--------|
| Trait | Factor | NumDF | DenDF | F | p |
| PC1 | pCO ₂ | 1 | 12 | 1.347 | 0.268 |
| | Temp | 1 | 12 | 22.709 | <0.001 |
| | pCO ₂ × temp | 1 | 12 | 0.212 | 0.654 |
| PC2 | pCO ₂ | 1 | 12 | 10.270 | 0.008 |
| | Temp | 1 | 12 | 0.424 | 0.527 |
| | pCO ₂ × temp | 1 | 12 | 1.919 | 0.191 |
| PC3 | pCO ₂ | 1 | 12 | 0.452 | 0.514 |
| | Temp | 1 | 12 | 17.423 | 0.001 |
| | pCO ₂ × temp | 1 | 12 | 0.907 | 0.360 |
| PC4 | pCO ₂ | 1 | 12 | 0.017 | 0.898 |
| | Temp | 1 | 12 | 0.362 | 0.559 |
| | pCO ₂ × temp | 1 | 12 | 0.125 | 0.730 |
| SL | pCO ₂ | 1 | 12 | 3.442 | 0.088 |
| | Temp | 1 | 12 | 54.230 | <0.001 |
| | pCO ₂ × temp | 1 | 12 | 0.037 | 0.851 |
| SBA | pCO ₂ | 1 | 12 | 3.313 | 0.094 |
| | Temp | 1 | 12 | 21.062 | <0.001 |
| | pCO ₂ × temp | 1 | 12 | 0.001 | 0.987 |
| HW | pCO ₂ | 1 | 12 | 1.269 | 0.282 |
| | Temp | 1 | 12 | 1.401 | 0.259 |
| | pCO ₂ × temp | 1 | 12 | 0.751 | 0.403 |
| EW | pCO ₂ | 1 | 12 | 3.422 | 0.089 |
| | Temp | 1 | 12 | 22.948 | <0.001 |
| | pCO ₂ × temp | 1 | 12 | 1.238 | 0.288 |
| PYBD | pCO ₂ | 1 | 12 | 0.945 | 0.350 |
| | Temp | 1 | 12 | 1.646 | 0.224 |
| | pCO ₂ × temp | 1 | 12 | 0.180 | 0.679 |
| PVBD | pCO ₂ | 1 | 12 | 5.599 | 0.036 |
| | Temp | 1 | 12 | 38.016 | <0.001 |
| | pCO ₂ × temp | 1 | 12 | 0.004 | 0.952 |
| YSA | pCO ₂ | 1 | 12 | 3.552 | 0.084 |
| | Temp | 1 | 12 | 20.8990 | <0.001 |
| | pCO ₂ × temp | 1 | 12 | 2.071 | 0.176 |
| DW | pCO ₂ | 1 | 12 | 1.191 | 0.297 |
| | Temp | 1 | 12 | 1.803 | 0.204 |
| | pCO ₂ × temp | 1 | 12 | 1.091 | 0.317 |
| ANOVAs | | | | | |
| Trait | Factor | DF | F | p | |
| YCR | pCO ₂ | 1 | 0.556 | 0.133 | |
| | Temp | 1 | 70.500 | <0.0001 | |
| | pCO ₂ × temp | 1 | 0.102 | 0.653 | |
| GR | pCO ₂ | 1 | 0.984 | 0.341 | |
| | Temp | 1 | 131.732 | <0.0001 | |
| | pCO ₂ × temp | 1 | 0.016 | 0.902 | |
| PE | pCO ₂ | 1 | 0.018 | 0.896 | |
| | Temp | 1 | 8.761 | 0.012 | |
| | pCO ₂ × temp | 1 | 0.028 | 0.869 | |

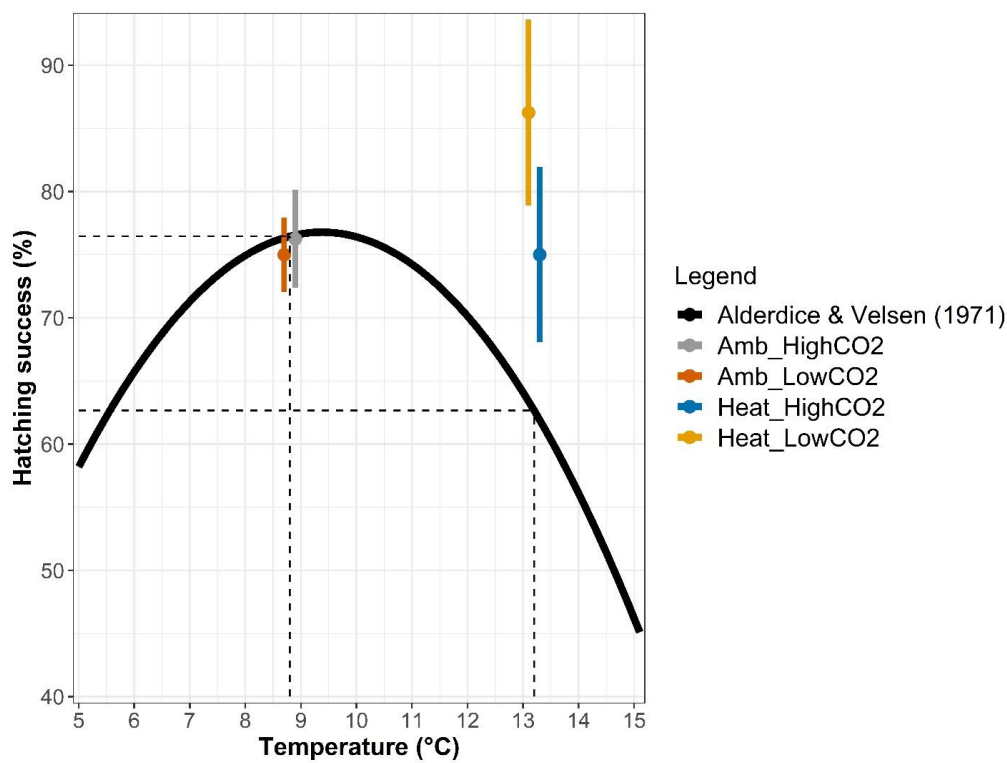


Fig. S2. The thermal reaction norm for embryo survival in Pacific herring. Colored circles denote the average hatching success \pm s.d. under the four treatment conditions tested in this study. The solid black curve shows the temperature reaction norm for embryo survival (%) under static temperatures predicted by Alderdice & Velsen (1971) at salinity of 32. Dashed lines connect the predicted survival rates for the ambient temperature regime ($\sim 8.8^{\circ}\text{C}$) and maximum heatwave intensity ($\sim 13.2^{\circ}\text{C}$).

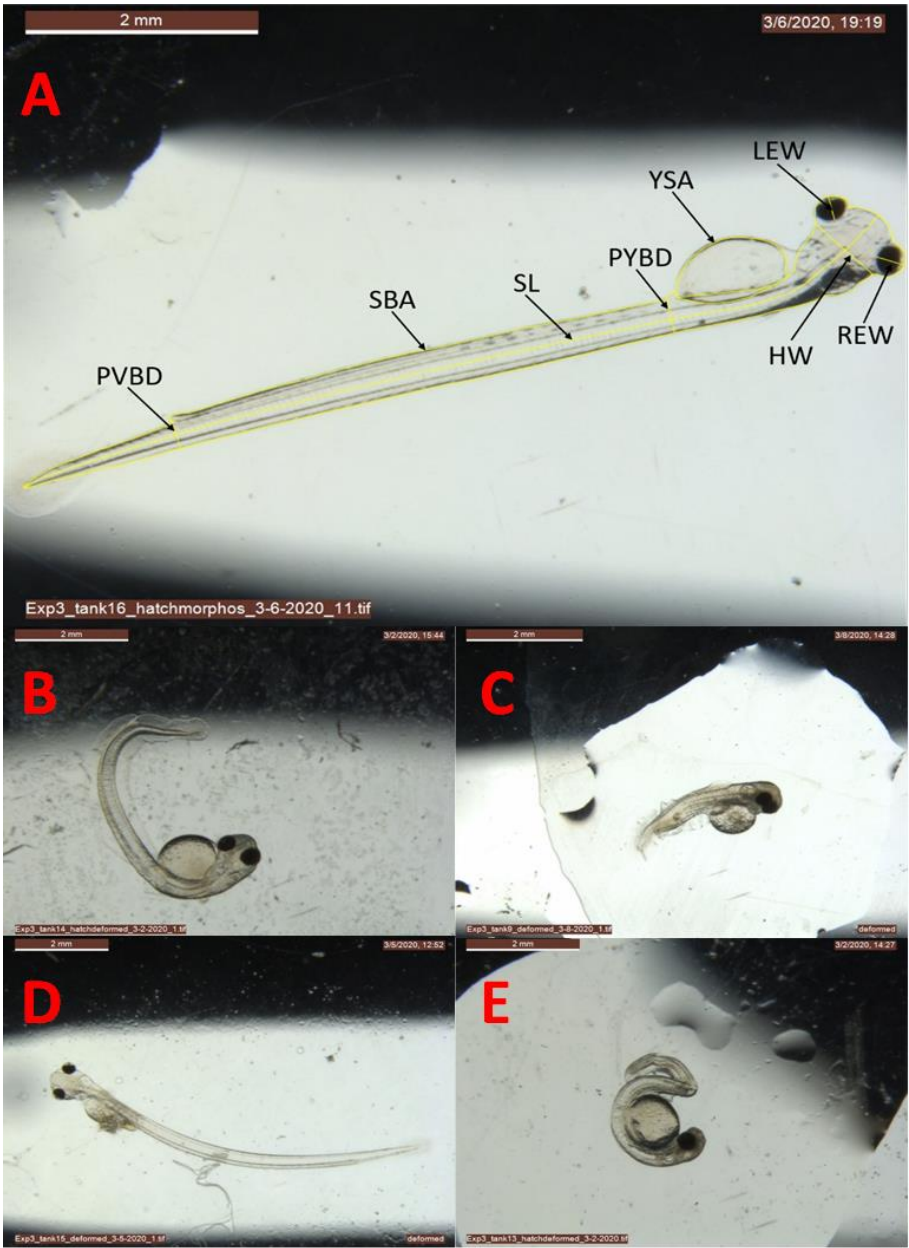


Fig. S3. A. Schematic of the eight morphometric measurements made on healthy hatchlings; PVBD (post-vent body depth), SBA (somatic body area), SL (standard length), PYBD (post-yolk body depth), YSA (yolk sac area), HW (head width), LEW (left eye width), REW (right eye width). **B.** Developmental anomaly: notochord curvature **C.** Developmental anomaly: notochord shortening and underdeveloped jaw. **D.** Developmental anomaly: yolk sac edema. **E.** Developmental anomaly: notochord twist and underdeveloped jaw.