nature ecology & evolution

SUPPLEMENTARY INFORMATION

https://doi.org/10.1038/s41559-020-1114-9

In the format provided by the authors and unedited.

# Developmental cost theory predicts thermal environment and vulnerability to global warming

**Dustin J. Marshall[1*], Amanda K. Pettersen[2], Michael Bode[1,3] and Craig R. White[1]**

[1]Centre for Geometric Biology, Monash University, Melbourne, Victoria, Australia. [2]Lund University, Lund, Sweden. [3]Queensland University of Technology, Brisbane, Queensland, Australia. *e-mail: dustin.marshall@monash.edu

**Supplementary Information**

*1. Functions characterising the relationship between temperature and metabolic rate, and temperature and development*

In a previously published study [1], we characterised the relationship between temperature and our traits of interest (Supplementary Table 1) using simple exponential functions. We used these functions for mathematical simplicity, and because they are the formal notation for longstanding '$Q_{10}$' measures of temperature dependence in classic physiology studies (e.g.[2]). In the present study however, we were particularly interested in understanding how developmental costs change across a broader thermal range. Furthermore, we repeatedly observed that simple exponential equations linking development to temperature tended to systematically underestimate development times at relatively higher temperatures. Consequently, we modified the simple exponential equation for development to include a constant. An exponential equation with a constant also has a long history in studies of developmental physiology [3] and so is equally in keeping with physiological tradition. The biological interpretation of an exponential with a constant is that while development time may be highly temperature dependent, above a certain temperature, development time can never equal 0 (where c >1). In other words, an exponential with a constant has the intuitive appeal in that, at very high temperatures, development is not instantaneous.

Perhaps more importantly, including a constant is supported by the data. **Supplementary Figure 1** shows the fit of a simple exponential versus one including a constant – the function lacking the constant consistently underestimated development times at the highest temperatures**.** Formal statistical analyses for species for which we had high levels of replication confirmed this difference in fit (Supplementary Table 2). In hindsight we should have fit this more complex function in our earlier study, but when we re-analysed the results presented there with our more complex function - our results were qualitatively unchanged.

We considered fitting a more complex function for metabolic rate as well (i.e. including a constant), but we found no evidence for better fits with a more complex function across the temperature ranges for which metabolism was explored (Supplementary Table 2). As such, we retained a simple exponential function for this parameter, which carries the reasonable assumption that metabolic rate will fall to essentially zero at sufficiently cold temperatures, outside of the range of temperatures considered here.

Our goal here was not to explore the mechanistic drivers of why development and temperature covary with temperature the way they do, instead we were interested in the consequences of their covariance for shaping the costs of development and the thermal niche. However, we should note that our functions bear very close resemblance to more mechanistic descriptions of the temperature-dependence of metabolic rate and development [4-6]. An interesting next step would be to integrate the mechanistic drivers of these temperature dependencies into Developmental Cost Theory but this is beyond the scope of our endeavour here.

*2. The relationship between temperature, metabolism and development beyond the usual temperature range.*

Throughout our analyses, we use exponential functions to describe the relationship between temperature and metabolism, and temperature and development. In reality however, the relationship between temperature and our traits of interest are more complex. At extreme temperatures (for a particular organism), metabolic processes will fail and development will slow. Thus across a large temperature range, metabolism and development almost certainly show more complex relationships with temperature and probably resemble classic Thermal Performance Curves (TPCs; [7]). We used exponential functions instead of more complex polynomials that resemble TPCs for several reasons.

Despite our expectation that metabolism and development show a TPC-like form, there are only a few data to support that expectation (see **Supplementary Figures 2 & 3**). Instead, for the most part, it seems that physiologists tend to measure traits like metabolism and development within temperature ranges that do not suppress metabolism and cause mortality. Thus, while we might suspect more complex relationships between temperature and our traits of interest across all possible temperatures, the available data across all of the taxa here only support the exponential functions used here. In other words, more complex functions cannot be parameterised based on the available data for most species. The lack of data on metabolism and development outside of unstressful temperature ranges may explain why other frameworks that focus on the temperature-dependence of traits use similar functions to ours (e.g. [4-6]).

Importantly, while we must therefore restrict our inferences about developmental costs and their minimisation to a temperature range that excludes more stressful temperatures, the exclusion of these temperatures does not influence our conclusions. To explain, our theory finds that a single (usually intermediate) temperature minimises the costs of development. Within that temperature range we also find that mortality is extremely low and weakly affected by temperature (see Results). Consequently, any consideration of temperatures beyond that range would cause additional mortality and reduce fitness even further. Thus, restricting our theory to within the natural or nonstressful temperature range captures the space that both minimises mortality and energy costs, so $T_{opt}$ is likely to be a good predictor of the temperature that maximises fitness.

*3. Description of environmental temperature*

For those species that overlapped with [1], we used the estimates of environmental temperature compiled there. As reported in [1], we collated mean values of natural temperature ranges ('T range') experienced by each species during the early life history when offspring are non-feeding and entirely dependent on maternally derived energy (i.e. throughout the 'dependent phase'). Where T range was not specified for the studies that measured *MR(T)* and *D(T)*, we searched the literature for studies reporting temperature ranges for each species in similar locations (see [1] for details). The level of detail, and the resolution of data regarding temperature ranges provided by different studies varied enormously. In some instances, daily temperature estimates were provided throughout the relevant developmental period while other studies reported only maximum and minimum temperatures for the area in which the species live.

Importantly however, there are likely to be systematic differences between the temperatures experienced by terrestrial species and aquatic species. Relative to aquatic environments, terrestrial habitats are far more thermally heterogeneous, with ubiquitous microhabitat variation in the temperatures that developing organisms experience. For example, shaded and unshaded microhabitats can differ by 11°C within the same $m^2$ [8] and clearly some species select oviposition sites based on local thermal conditions. Perfectly characterising the thermal environment of species that select specific thermal microhabitats is unfeasible for a meta-analysis such as this [9] but we took several steps in order to assess the reliability of our analyses.

First, we compared regressions of $T_{opt}$ with $T_{min}$ and $T_{max}$ in addition to $T_{mid}$. We found the same qualitative patterns regardless of the temperature descriptor we used but $T_{opt}$ was a better fit in terms of $R^2$ (Supplementary Table 3). Thus, there is a relationship between $T_{opt}$ and environmental temperature, regardless of how environmental temperature is characterised.

Second, because creating a nest for developing eggs can alter the thermal environment of the developing embryos profoundly, we compared terrestrial species that did or did not nest. We defined nesting as any non-egg material or structure that parents create or shape to house developing offspring. We found that metabolism and development have evolved to minimise development costs in temperatures in both groups but that in nesting species, $T_{opt}$ is systematically warmer than $T_{mid}$. These results suggest that terrestrial nesting species have the capacity to significantly alter the thermal environment that their offspring experience. Nevertheless, across both nesting and non-nesting species, there was a strong positive relationship between $T_{opt}$ and $T_{mid}$.

Supplementary Table 1. Studies included in meta-analysis for the temperature sensitivity of development time (*D*), metabolic rate (*MR*), Survival in different temperatures (S), and Temperature range (TR) for 71 species. Where only one study was used for all available parameters, no specific parameter is specified.

| Taxon | Temperature range (°C) | Reference |
|---|---|---|
| ***Chordata*** | | |
| Actinopterygii (class): | | |
| *Chanos chanos* | 23-33 | 1 (D,MR,TR) |
| *Chondrostoma nasus* | 10-19 | 2 |

| | | |
|---|---|---|
| *Clarias gariepinus* | 20-30 | 3 (D, MR), 4 (TR) |
| *Clupea harengus* | 8-12 | 5(D), 6 (MR,TR)7(S) |
| *Coregonus clupeaformis* | 0.5-8 | 8(D,MR,TR) 9 (S) |
| *Danio rerio* | 20-32 | 10 |
| *Dicentrarchus labrax* | 10-20 | 11 (D,TR), 12 (MR) 13(S) |
| *Gadus morhua* | 4-10 | 14(D,S), 15 (MR), 16 (TR) |
| *Hypomesus pretiosus* | 10-16 | 17 (D,MR,TR) 18 (S) |
| *Leuciscus cephalus* | 12-28 | 19 (D,TR), 20 (MR) |
| *Leuresthes tenuis* | 12-25 | 21 (D, S), 22 (MR,TR) |
| *Melanogrammus aeglefinus* | 4-10 | 23 (D), 15 (MR), 16 (TR, S) |
| *Merluccius productus* | 11-14 | 24 (D,MR,TR) |
| *Mugil cephalus* | 20-27 | 25 (D,S,TR), 26 (MR) |
| *Oncorhynchus mykiss* (*Salmo gairdneri*) | 6-13 | 27 (D S,MR), 28 (TR) 29 (S) |
| *Oncorhynchus tshawytscha* | 3-16 | 30 (D, MR), 31(TR) 32 (S) |
| *Oryzias latipes* | 20-29 | 33 |

| | | |
|---|---|---|
| *Pseudopleuronectes americanus* | 2-8 | 34 (D,MR,TR) |
| *Pleuronectes platessa* | 3-10 | 35 (D, S), 6 (MR), 36 (TR) |
| *Rutilus rutilus* | 8-24 | 37 (D,TR), 20 (MR) |
| *Salmo salar* | 0-16 | 38 (D,S), 39 (MR), 40 (TR) |
| *Salmo trutta fario* | 3-11 | 41,42 (D,MR), 43 (TR) |
| *Salvelinus alpinus* | 4-8 | 44 |
| *Salvelinus fontinalis* | 5-9 | 45 (D,S), 46 (MR,TR) |
| *Scardinius erythrophthalmus* | 10-22 | 47 (D), 20 (MR), 48 (TR) |
| *Scomber japonicus* | 11-23 | 49 (D, MR, TR) |
| *Scomber scombrus* | 8-18 | 50 (D,TR, S), 51 (MR) |
| *Tautoga onitis* | 16-22 | 52 (D,MR,TR) 53 (S) |
| *Xyrauchen texaus* | 10-22 | 54 |
| Amphibia (class): | | |
| *Bufo terrestris* | 13-40 | 55 (DT), 56 (MR,TR) |
| *Crinia nimbus* | 0-15 | 57 (D, MR, TR) |

| | | |
|---|---|---|
| *Neoceratodus forsteri* | 15-25 | 58 (D, MR, TR) |
| *Pseudophryne bibronii* | 7-22 | 59 (D, MR), 60 (TR) |
| *Rana pipiens* | 6-28 | 61 (D), 56 (MR,TR) 62 (S) |
| Chondrichthyes (class): | | |
| *Heterodontus portusjacksoni* | 15-22 | 63 (D), 64 (MR,TR, S) |
| Reptilia (class): | | |
| *Apalone spinifera* | 18-29 | 65 (D,MR,TR) 66 (S) |
| *Bassiana duperreyi* | 17-24 | 67 (D,MR),68 (TR) 69 (S) |
| *Caretta caretta* | 24-31 | 70 (D,MR), 71 (TR,S) |
| *Chelonia mydas* | 22-29 | 72 (D,MR),73 (TR)70(S) |
| *Crocodylus johnsoni* | 28-34 | 74 (D,MR,TR) |
| *Lampropholis guichenoti* | 24-28 | 67 (D,MR, S), 75 (TR) |
| *Macrochelys temminckii* | 18-29 | 65 (D,MR,TR) 76 (S) |
| *Sphenodon punctatus* | 15-25 | 77 (DR,MR), 78 (S, TR) |
| *Trachemys scripta* | 18-29 | 65 (D,MR,TR) 79 (S) |

| | | |
|---|---|---|
| *Trionyx triunguis* | 24-33 | 80 |
| ***Arthropoda*** | | |
| Insecta (class): | | |
| *Brevicoryne brassicae* | 10-30 | 81 (D,MR,TR) |
| *Chironomus sp.* | 13-33 | 82 (D,TR), 83 (TR) 84 (S) |
| *Culex pipiens* | 15-33 | 85 (D,MR), 86 (TR) |
| *Drosophila melanogaster* | 16-29 | 87 (D), 88 (MR), 89 (S,TR) |
| *Erynnis propertius* | -12-26 | 90 (MR, TR), 91 (D) |
| *Gynaephora groenlandica* | 0-32 | 92 (MR, T) 93 (D) |
| *Hippodamia convergens* | 10-35 | 94 (D), 95 (MR, TR) |
| *Melanoplus differentialis* | 16-32 | 85 (D,MR), 96 (TR) |
| *Melanoplus sanguinipes* | 14-39 | 97 (D,TR), 98 (MR) 99 (S) |
| *Oncopeltus fasciatus* | 13-35 | 100 (D,MR), 101(TR) |
| *Ostrinia nubialis* | 15-30 | 85 (D,MR), 102 (TR) |
| *Polypedilum sp.* | 5-15 | 103(D), 83 (MR,TR) |
| *Solenopsis invicta* | 17-24 | 104 (D,TR), 105 (MR) |

| | | |
|---|---|---|
| *Tribolium confusum* | 18-38 | 106 (D,S,TR), 85 (MR) |
| *Neohelice granulate* (*Chasmagnathus granulata*) | 15-24 | 107 |
| *Euphausia superba* | -1-2 | 108 (D,TR), 109 (MR) 110 (S) |
| *Hyas araneus* | 3-15 | 111 (D,S,TR), 112 (MR) |
| ***Bryozoa*** | | |
| *Bugula neritina* | 12-24 | 10 |
| ***Echinodermata*** | | |
| *Dendraster excentricus* | 8-16 | 113 (D,MR), 114 (TR, S)) |
| *Strongylocentrotus purpuratus* | 4-20 | 115 (D), 116 (MR), 117 (TR, S) |
| *Odontaster validus* | -0.5-0 | 118 |
| ***Mollusca*** | | |
| *Chorus giganteus* | 10-16 | 119 |
| *Loligo opalescens* | 7-14 | 120 (D), 121 (MR), 122 (TR) |
| *Loligo reynaudii* | 12-17 | 123 (D,TR, S), 124 (MR) |
| *Mytilus edulis* | 6-18 | 125 (D,TR), 126 (MR) |
| *Octopus maya* | 15-27 | 127 (D,MR,TR) |

| | | |
|---|---|---|
| *Stramonita canaliculata* (*Thais haemastoma canaliculata*) | 22-28 | 128 |

Supplementary Table 2. Comparison of fits for exponential functions with and without a constant included for those species for which there was sufficient data.

| Species | Trait | Model | Akaike's Information Criterion |
|---|---|---|---|
| *Bugula neritina* | Metabolism | $MR(T) = \delta e^{a.T}$ | 191 |
| | | $MR(T) = \delta e^{a.T} + g$ | 193 |
| | Development | $D(T) = de^{-bT}$ | 2052 |
| | | $D(T) = de^{-bT} + c$ | 1563 |
| *Danio rerio* | Metabolism | $MR(T) = \delta e^{a.T}$ | 586 |
| | | $MR(T) = \delta e^{a.T} + g$ | 588 |
| | Development | $D(T) = de^{-bT}$ | 4001 |
| | | $D(T) = de^{-bT} + c$ | 3536 |

Supplementary Table 3. Comparison of regressions between $T_{mid}$, $T_{min}$ or $T_{max}$ and $T_{opt}$, their fit and whether the slope and intercept significantly differ from 1 and 0 respectively. Note that these are simple (nonphylogenetic) regressions.

| Temperature parameter | Regression equation | Slope different to 1? | Intercept different to 0? | $R^2$ |
|---|---|---|---|---|
| $T_{opt}$ | $T_{opt} = 1.05 \times T_{opt} + 0.39$ | No | No | 0.84 |
| $T_{min}$ | $T_{opt} = 0.99 \times T_{min} + 7.07$ | No | Yes | 0.75 |
| $T_{max}$ | $T_{opt} = 0.789 \times T_{max} - 0.27$ | Yes | No | 0.66 |

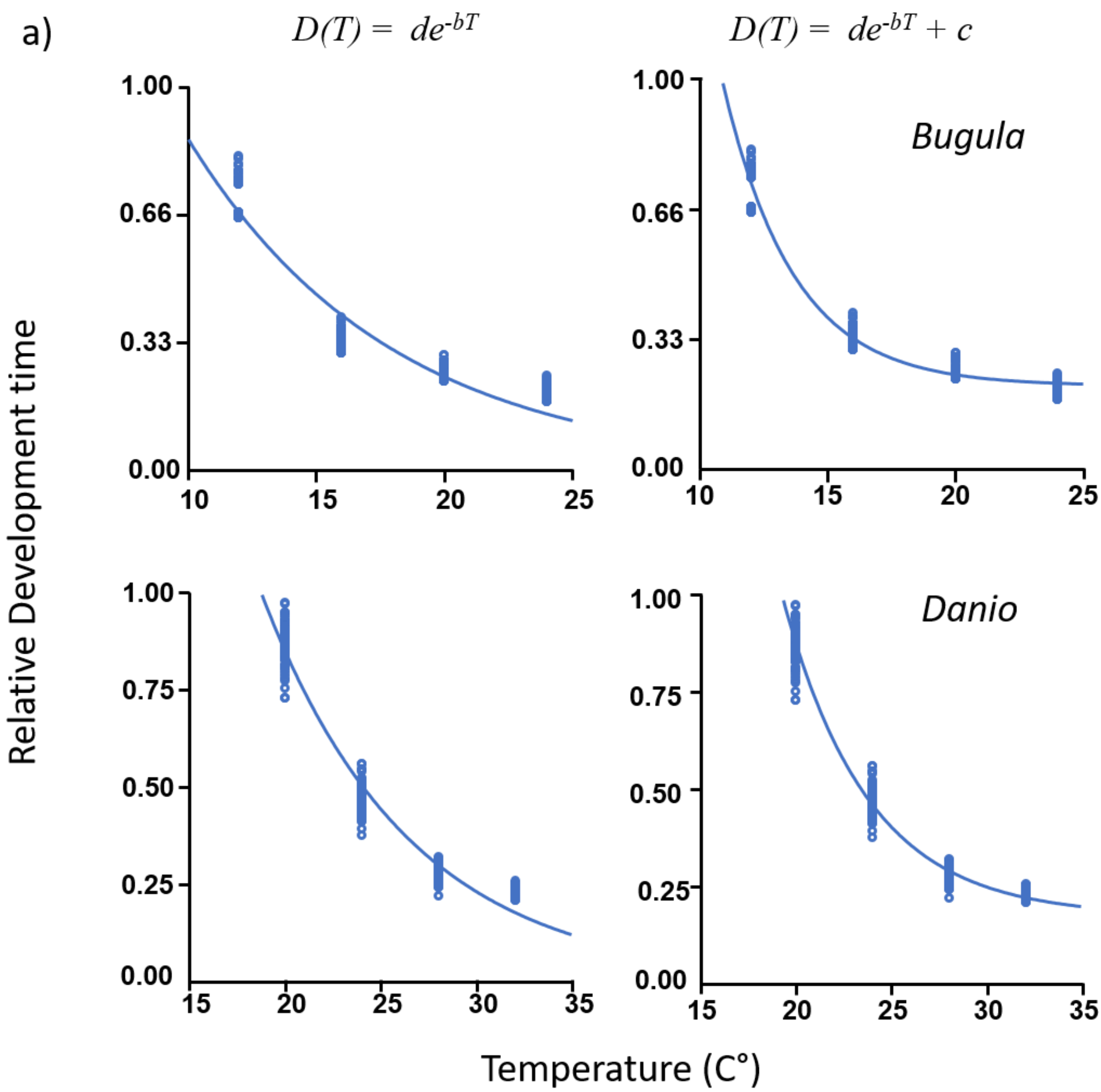
Supplementary Table 4. Summary table of $T_{mid}$, $T_{opt}$, Predicted percentage increase in developmental costs at 20% above $T_{opt}$ and equivalent decrease in survival for same temperature change.

| Species | $T_{mid}$ | $T_{opt}$ | Costs @ $T_{opt}$+20% | Survival @ $T_{opt}$+20% |
|---|---|---|---|---|
| *Apalone spinifera* | 23.5 | 29.3 | 7.2 | 0 |
| *Bassiana duperreyi* | 20.9 | 27.1 | 6.7 | 0 |
| *Brevicoryne brassicae* | 18 | 16.7 | 3 | |
| *Bryobatrachus nimbus* | 10 | 13 | 1 | |
| *Bufo terrestris* | 26.5 | 25.2 | 3.2 | |
| *Bugula* | 18 | 18.3 | 3.1 | |
| *Caretta caretta* | 27.3 | 30.6 | 6.9 | 0 |
| *Chanos chanos* | 28 | 32 | 2.5 | 2.3 |
| *Chasmagnathus granulata* | 19.5 | 20.7 | 1.7 | 0 |
| *Chelonia mydas* | 25.5 | 28.9 | 16.1 | 0 |
| *Chironomus sp* | 23.8 | 21.6 | 3.4 | 0 |
| *Chondrostoma nasus* | 14.5 | 15.5 | 10.5 | 12 |
| *Chorus giganteus* | 13 | 14.4 | 3 | 8.2 |
| *Clarias gariepinus* | 25 | 30.3 | 21.6 | |
| *Clupea harengus* | 10 | 11.3 | 4.4 | 0 |
| *Coregonus clupeaformis* | 4.3 | 5.6 | 1.3 | 0 |
| *Coregonus lavaretus* | 6 | 8.7 | 3.3 | |
| *Crinia nimbus* | 7.5 | 13.9 | 4.5 | |

| | | | | |
|---|---|---|---|---|
| *Crocodylus johnstoni* | **31** | 42.2 | 15.2 | |
| *Culex pipiens* | 24 | 21.2 | 16.2 | |
| *Danio* | 26 | 28.7 | 17.5 | |
| *Dendraster excentricus* | **12** | 20.4 | 5.6 | 0 |
| *Dicentrarchus labrax* | 15 | 21.3 | 4.9 | 0.6 |
| *Drosophila melanogaster* | 22.5 | 25 | 10.5 | 6.4 |
| *Erynnis propertius* | 7 | 4.6 | 1.3 | |
| *Euphuasia superba* | 0.5 | -0.8 | 4.5 | 0 |
| *Gadus morhua* | 7 | 10.2 | 4.6 | 0 |
| *Gynaephora groenlandica* | 16 | 13.7 | 1.2 | |
| *Heterodontus portusjacksoni* | 18.5 | 19.6 | 11.6 | 0 |
| *Hyas araneus* | 8.8 | 12.8 | 4.4 | 0 |
| *Hypomesus pretiosus pretiosus* | 13 | 6.7 | 3.2 | 0 |
| *Lampropholis guichenoti* | 26 | 26.5 | 45.4 | 14.3 |
| *Leuciscus cephalus* | 19.9 | 16.3 | 12.6 | |
| *Leuresthes tenuis* | 18.5 | 22.2 | 7.0 | 0 |
| *Loligo opalescens* | 10.8 | 6.7 | 0.2 | |
| *Loligo reynaudii* | 14.5 | 11.9 | 7.7 | 0 |
| *Macrochelys temminckii* | 23.5 | 31.8 | 2 | |
| *Melanogrammus aeglefinus* | 7 | 8.5 | 0.8 | 3 |
| *Melanoplus differentialis* | 23.9 | 23.3 | 21 | |

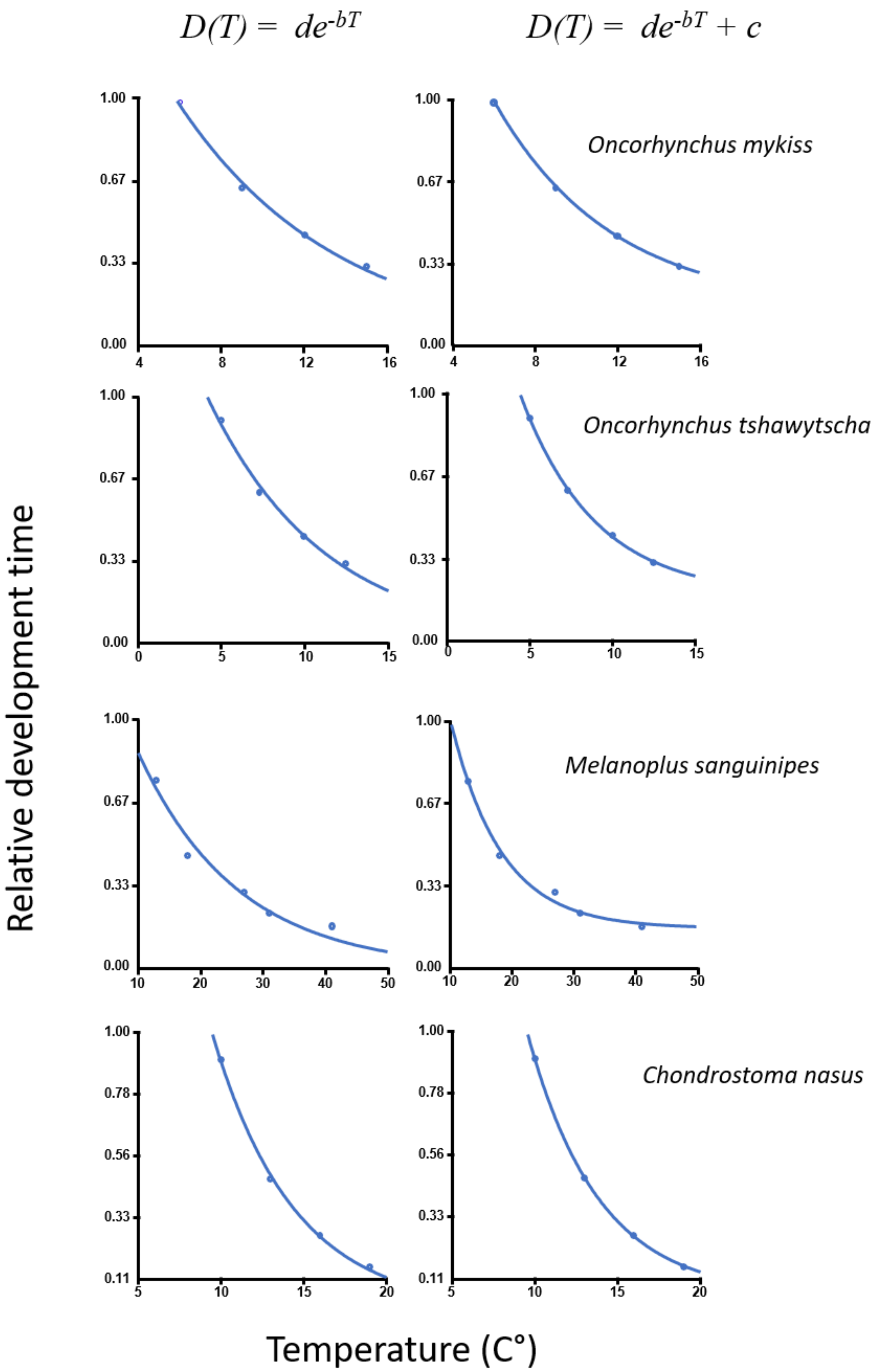
| | | | | |
|---|---|---|---|---|
| *Melanoplus sanguinipes* | 26.5 | 23.3 | 4.1 | 0 |
| *Merluccius productus* | 12.5 | 11.4 | 0.6 | |
| *Mugil cephalus* | 23.5 | 21 | 6.4 | 0 |
| *Mytilus edulis* | 12 | 14.9 | 6.2 | |
| *Neoceratodus forsteri* | 20 | 24.4 | 11.4 | |
| *Octopus maya* | 21 | 17.4 | 1.4 | |
| *Odontaster validus* | -0.3 | -0.8 | 0.7 | 0 |
| *Oncopeltus fasciatus* | 24 | 21 | 21.7 | |
| *Oncorhynchus mykiss* | 9.5 | 10.5 | 1.5 | 0.3 |
| *Oncorhynchus tshawytscha* | 9.5 | 9.4 | 3.3 | 0 |
| *Oryzias latipes* | 24.5 | 22.2 | 6.5 | 0 |
| *Ostrinia nubilalis* | 22.5 | 24.6 | 10.6 | |
| *Pleuronectes platessa* | 6.5 | 7.9 | 6.4 | 2 |
| *Polypedilum sp* | 10 | 5.5 | 0.3 | |
| *Pseudophryne bibronii* | 14.5 | 16.7 | 9 | |
| *Rana pipiens* | 17 | 22.6 | 14.3 | 8 |
| *Rutilus rutilus* | 15.8 | 17.9 | 8.6 | |
| *Salmo salar* | 8 | 11.9 | 10.6 | 8 |
| *Salmo trutta fario* | 7 | 9 | 3.4 | 0 |
| *Salvelinus alpinus* | 6 | 6.2 | 1.6 | 0 |
| *Salvelinus fontinalis* | 6 | 9.1 | 2.3 | 0 |
| *Scardinius erythrophthalmus* | 16 | 11 | 1.1 | |
| *Scomber japonicus* | 17 | 17 | 6.7 | 0 |
| *Scomber scombrus* | 13 | 13.9 | 7.5 | 3.5 |

| | | | | |
|---|---|---|---|---|
| *Sphenodon punctatus* | 20 | 22.2 | 12 | 0 |
| *Strongylocentrotus purpuratus* | 12 | 11.9 | 2.4 | 0 |
| *Tautoga onitis* | 19 | 17.8 | 14.8 | 8 |
| *Thais canaliculata* | 25 | 25.3 | 10.1 | 0 |
| *Trachemys scripta* | 23.5 | 29.9 | 17.1 | |
| *Tribolium confusum* | 27.5 | 27.1 | 20.6 | 5 |
| *Trionyx triunguis* | 28.5 | 33.8 | 10.8 | 35 |
| *Xyrauchen texanus* | 16 | 17.3 | 2.4 | 0 |

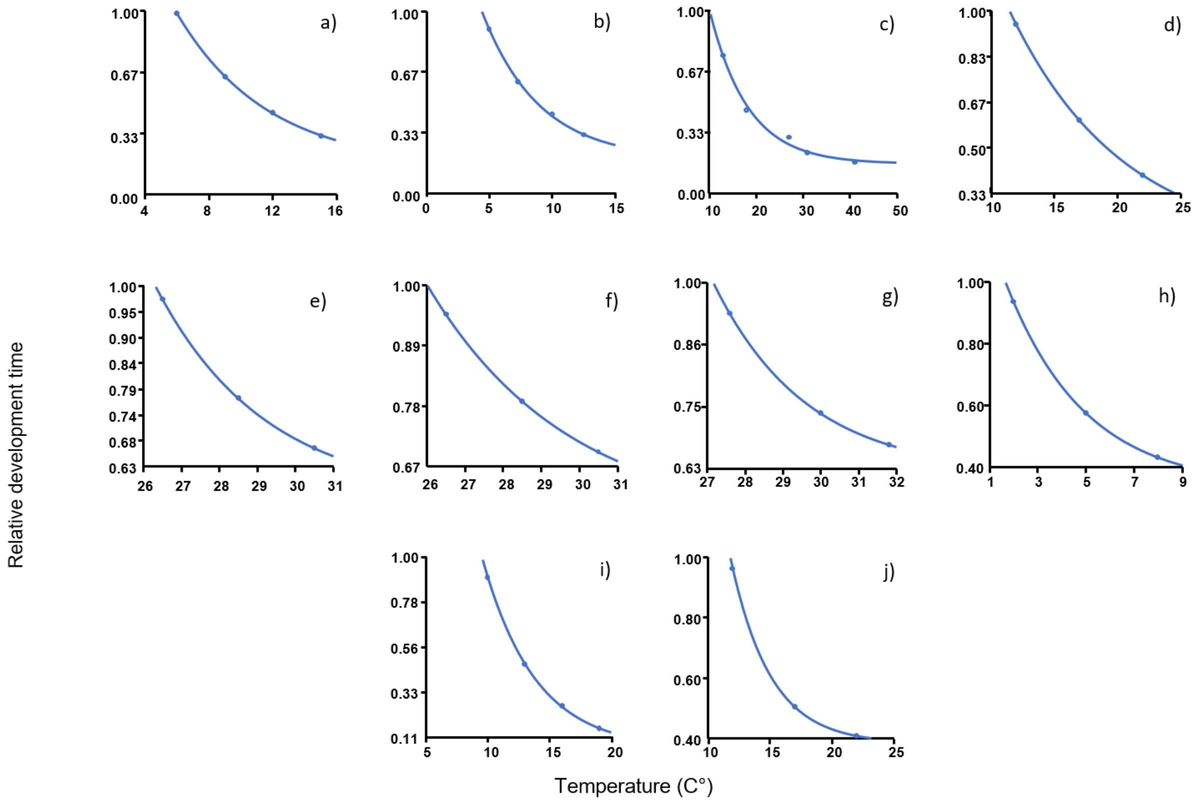

a)
D(T) = de-bT
D(T) = de-bT + c
Bugula
Danio
1.00
0.66
0.33
0.00
0.75
0.50
0.25
10
15
20
25
30
35
Relative Development time
Temperature (C°)

123

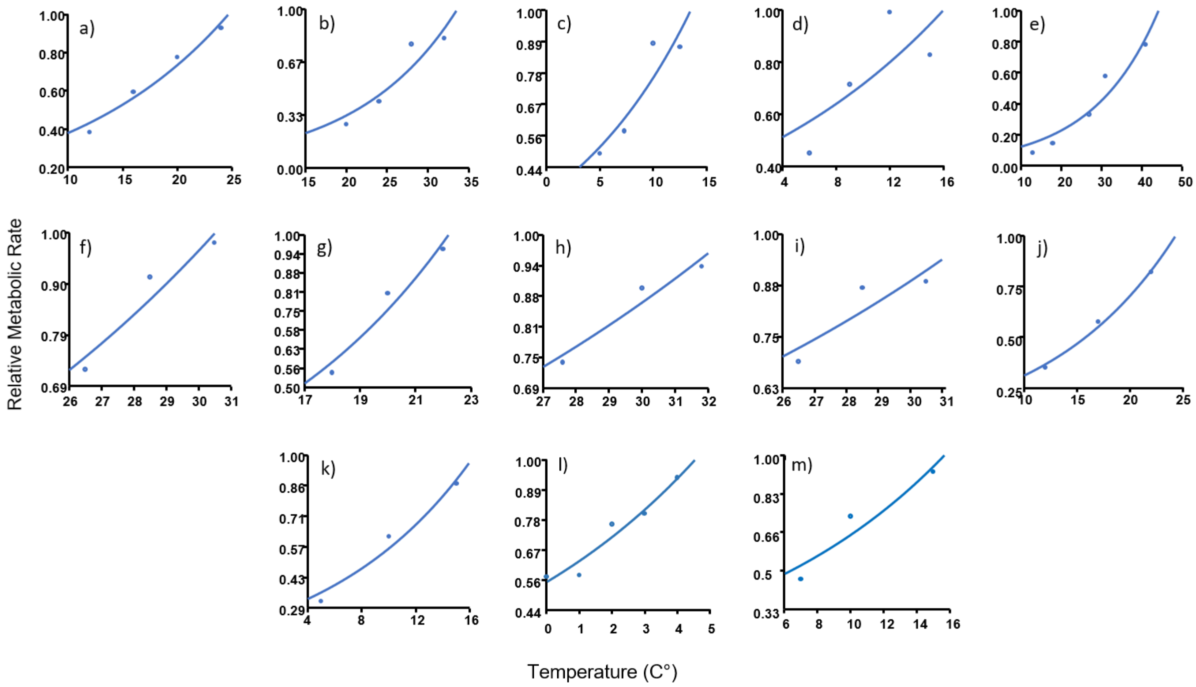
b)


$D(T) = de^{-bT}$
$D(T) = de^{-bT} + c$
Oncorhynchus mykiss
Oncorhynchus tshawytscha
Melanoplus sanguinipes
Chondrostoma nasus
Relative development time
Temperature (C°)

Supplementary Figure 1 a) & b) Examples of comparison of models describing the temperature dependence of development time with and without a constant for those species for which we have data obtained at four or more temperatures. For most species, dots represent means for those temperatures; lines are the predicted lines of best fit given the model. For *Danio rerio* and *Bugula neritina*, because we had access to the raw data, we included all of the replicates rather than just the means.




Supplementary Figure 2. Examples of relationships between temperature and (relative) development time. Species shown are a) *Oncorhynchus mykiss*; b) *Oncorhynchus tshawytscha*; c) *Melanoplus sanguinipes*; d) *Dendraster excentricus*; e) *Apalone spinifera*; f) *Trachemys scripta*; g) *Caretta caretta*; h) *Coregonus clupeaformis*; i) *Chondrostoma nasus*; j) *Pseudophryne bibronii*.




Supplementary Figure 3. Examples of relationships between temperature and (relative) metabolic rate. Species shown are a) *Bugula sp.*; b) *Danio sp.*; c) *Oncorhynchus tshawytscha*; d) *Oncorhynchus mykiss*; e) *Melanoplus sanguinipes*; f) *Apalone spinifera*; g) *Sphenodon punctatus*; h) *Caretta caretta*; i) *Trachemys scripta*; j) *Pseudophryne bibronii*; k) *Bryobatrachus nimbus*; l) *Euphausia superba*; m) *Clupea harengus*.

## Literature Cited


1 Pettersen, A. K., White, C. R., Bryson-Richardson, R. J. & Marshall, D. J. Linking life-history theory and metabolic theory explains the offspring size-temperature relationship. *Ecol. Lett.* **22**, 518-526, (2019).

2 Pantin, C. F. A. Temperature and the Viscosity of Protoplasm. *J. Mar. Biol. Assoc. U.K.* **13**, 331-339, (1924).

3 McLaren, I. A. Some relationships between temperature and egg size, body size, development rate, and fecundiy, of the copepod *Pseudocalanus*. *Limnol. Oceanograph.* **10**, 528-538, (1965).

4 O'Connor, M. I. *et al.* Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. *Proc. Natl. Acad. Sci. USA* **104**, 1266-1271, (2007).

5 Gillooly, J. F., Charnov, E. L., West, G. B., Savage, V. M. & Brown, J. H. Effects of size and temperature on developmental time. *Nature* **417**, 70-73, (2002).

6 Zuo, W. Y., Moses, M. E., West, G. B., Hou, C. & Brown, J. H. A general model for effects of temperature on ectotherm ontogenetic growth and development. *Proc. R. Soc. B-Biol. Sci.* **279**, 1840-1846, (2012).

7 Huey, R. B. & Kingsolver, J. G. Evolution of thermal sensitivity of ectotherm performance. *Trends Ecol. Evol.* **4**, 131-135, (1989).

8 Goller, M., Goller, F. & French, S. S. A heterogeneous thermal environment enables remarkable behavioral thermoregulation in *Uta stansburiana*. *Ecol. Evol.* **4**, 3319-3329, (2014).

9 Chown, S. L., Addo-Bediako, A. & Gaston, K. J. Physiological diversity: listening to the large-scale signal. *Funct. Ecol.* **17**, 568-572, (2003).

10 Walsh, W. A., Swanson, C. & Lee, C. S. Effects of development, temperature and salinity on metabolism in eggs and yolk-sac larvae of milkfish, *Chanos chanos* (Forsskål). *J. Fish Biol.* **39**, 115-125, (1991).

11 Kamler, E., Keckei, H. & Bauer-Nemeschkal, E. Temperature-induced changes of survival, development and yolk partitioning in *Chondrostoma nasus*. *J. Fish Biol.* **53**, 658-682, (1998).

12 Kamler, E. *et al.* Temperature-induced changes of early development and yolk utilization in the African catfish *Clarias gariepinus*. *J. Fish Biol.* **44**, 311-326, (1994).

13 Haylor, G. S. & Mollah, M. F. A. Controlled hatchery production of African catfish, *Clarias gariepinus*: The influence of temperature on early development. *Aquat. Living Resour.* **8**, 431-438, (1995).

14 Johnston, I. A., Vieira, V. L. A. & Abercromby, M. Temperature and myogenesis in embryos of the Atlantic herring *Clupea harengus*. *J. Exp. Biol.* **198**, 1389-1403, (1995).

15 Almatar, S. M. Effects of acute changes in temperature and salinity on the oxygen uptake of larvae of herring (*Clupea harengus*) and plaice (*Pleuronectes platessa*). *Mar. Biol.* **80**, 117-124, (1984).

16 Peck, M. A., Kanstinger, P., Holste, L. & Martin, M. Thermal windows supporting survival of the earliest life stages of Baltic herring (*Clupea harengus*). *ICES J. Mar. Sci.* **69**, 529-536, (2012).

17 Mueller, C. A. *et al.* Embryonic critical windows: changes in incubation temperature alter survival, hatchling phenotype, and cost of development in lake whitefish (*Coregonus clupeaformis*). *J. Comp. Physiol. B Biochem. Syst. Environ. Physiol.* **185**, 315-331, (2015).

18 Brooke, L. T. Effect of different constant incubation temperatures on egg survival and embryonic development in lake whitefish (*Coregonus clupeaformis*). *Trans. Am. Fish. Soc.* **104**, 555-559, (1975).

19 Jennings, S. & Pawson, M. The development of bass, *Dicentrarchus labrax*, eggs in relation to temperature. *J. Mar. Biol. Assoc. U.K.* **71**, 107-116, (1991).

20 Dalla Via, J., Villani, P., Gasteiger, E. & Niederstätter, H. Oxygen consumption in sea bass fingerling *Dicentrarchus labrax* exposed to acute salinity and temperature changes: metabolic basis for maximum stocking density estimations. *Aquaculture* **169**, 303-313, (1998).

21 Devauchelle, N. & Coves, D. Sea bass (*Dicentrarchus labrax*) reproduction in captivity: gametogenesis and spawning. *Aquat. Living Resour.* **1**, 215-222, (1988).

22 Geffen, A. J., Fox, C. J. & Nash, R. D. M. Temperature-dependent development rates of cod *Gadus morhua* eggs. *J. Fish Biol.* **69**, 1060-1080, (2006).

23 Laurence, G. C. Comparative growth, respiration and delayed feeding abilities of larval cod (*Gadus morhua*) and Haddock (*Melanogrammus aeglefinus*) as influenced by temperature during laboratory studies. *Mar. Biol.* **50**, 1-7, (1978).

24 Laurence, G. C. & Rogers, C. A. Effects of temperature and salinity on comparative embryo development and mortality of Atlantic cod (*Gadus morhua* L.) and haddock (*Melanogrammus aeglefinus* (L.)). *ICES J. Mar. Sci.* **36**, 220-228, (1976).

25 Garreton, M. S. *Bioenergetics of yolk utilization in embryos and yolk-sac larvae of the surf-smelt Hypomesus pretiosus pretiosus (Girard, 1855) under different incubation temperatures*, (1983).

26 Lee, C. G. & Levings, C. D. The Effects of Temperature and Desiccation on Surf Smelt (*Hypomesus pretiosus*) Embryo Development and Hatching Success:

Preliminary Field and Laboratory Observations. *Northwest Sci.* **81**, 166-171, 166, (2007).

27 Kupren, K., Mamcarz, A., Kucharczyk, D. & Krejszeff, S. Influence of water temperature on eggs incubation time and embryonic development of fish from genus *Leuciscus*. *Pol. J. Nat. Sci.* **23**, 461-481, (2008).

28 Wieser, W. & Forstner, H. Effects of temperature and size on the routine rate of oxygen consumption and on the relative scope for activity in larval cyprinids. *J. Comp. Physiol. B Biochem. Syst. Environ. Physiol.* **156**, 791-796, (1986).

29 Smyder, E. A. & Martin, K. L. M. Temperature effects on eggs survival and hatching during the extended incubation period of California grunion, *Leuresthes tenuis*. *Copeia* **2002**, 313-320, (2002).

30 Ehrlich, K. F. & Muszynski, G. Effects of temperature on interactions of physiological and behavioural capacities of larval California grunion: Adaptations to the planktonic environment. *J. Exp. Mar. Biol. Ecol.* **60**, 223-244, (1982).

31 Martell, D. J., Kieffer, J. D. & Trippel, E. A. Effects of temperature during early life history on embryonic and larval development and growth in haddock. *J. Fish Biol.* **66**, 1558-1575, (2005).

32 Bailey, K. M. The early life history of the pacific hake, *Merluccius productis*. *Fish. Bull.* **80**, 589-598, (1982).

33 Sylvester, J. R. & Nash, C. E. Thermal tolerance of eggs and larvae of Hawaiian striped mullet, *Mugil cephalus* L. *Trans. Am. Fish. Soc.* **104**, 144-147, (1975).

34 Walsh, W. A., Swanson, C., Lee, C. S., Banno, J. E. & Eda, H. Oxygen consumption by eggs and larvae of striped mullet, *Mugil cephalus*, in relation to development, salinity and temperature. *J. Fish Biol.* **35**, 347-358, (1989).

35 Rombough, P. J. Growth, aerobic metabolism, and dissolved oxygen requirements of embryos and alevins of steelhead, *Salmo gairdneri*. *Can. J. Zool./Rev. Can. Zool.* **66**, 651-660, (1988).

36 Pankhurst, N. W., Purser, G. J., Van Der Kraak, G., Thomas, P. M. & Forteath, G. N. R. Effect of holding temperature on ovulation, egg fertility, plasma levels of reproductive hormones and in vitro ovarian steroidogenesis in the rainbow trout *Oncorhynchus mykiss*. *Aquaculture* **146**, 277-290, (1996).

37 Kwain, W.-h. Embryonic Development, Early Growth, and Meristic Variation in Rainbow Trout (*Salmo gairdneri*) Exposed to Combinations of Light Intensity and Temperature. *J. Fish. Res. Board. Can* **32**, 397-402, (1975).

38 Rombough, P. J. Energy patitioning during fish development: additive or compensatory allocation of energy to support growth? *Funct. Ecol.* **8**, 178-186, (1994).

39 Alderdice, D. F. & Velsen, F. P. J. Relation between temperature and incubation time for eggs of Chinook salmon (*Oncorhynchus tshawytscha*). *J. Fish. Res. Board. Can* **35**, 69-75, (1978).

40 Murray, C. B. & McPhail, J. D. Effect of incubation temperature on the development of five species of Pacific salmon (*Oncorhynchus*) embryos and alevins. *Can. J. Zool.* **66**, 266-273, (1988).

41 Marty, G. D., Hinton, D. E. & Cech Jr., J. J. Effect of incubation temperature on oxygen consumption and ammonia production by Japanese medaka, *Oryzias latipes*, eggs and newly hatched larvae. *Environ. Toxicol. Chem.* **9**, 1397-1403, (1990).

42 Laurence, G. C. Laboratory growth and metabolism of the winter flounder *Pseudopleuronectes americanus* from hatching through metamorphosis at three temperatures. *Mar. Biol.* **32**, 223-229, (1975).

43 Fox, C. J., Geffen, A. J., Blyth, R. & Nash, R. D. M. Temperature-dependent development rates of plaice (*Pleuronectes platessa* L.) eggs from the Irish Sea. *J. Plankton Res.* **25**, 1319-1329, (2003).

44 Ryland, J. S. & Nichols, J. H. Effect of temperature on the embryonic development of the plaice, *Pleuronectes Platessa* L. (teleostei). *J. Exp. Mar. Biol. Ecol.* **18**, 121-137, (1975).

45 Herzig, A. & Winkler, H. The influence of temperature on the embryonic development of three cyprinid fishes, *Abramis brama*, *Chalcalburnus chalcoides mento* and *Vimba vimba*. *J. Fish Biol.* **28**, 171-181, (1986).

46 Brannas, E. Emergence of Baltic salmon, *Salmo salar* L., in relation to temperature: a laboratory study. *J. Fish Biol.* **33**, 589-600, (1988).

47 Hamor, T. & Garside, E. T. Developmental rates of embryos of Atlantic salmon, *Salmo salar* L., in response to various levels of temperature, dissolved oxygen, and water exchange. *Can. J. Zool.* **54**, 1912-1917, (1976).

48 Elliott, J. M. & Elliott, J. A. Temperature requirements of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change. *J. Fish Biol.* **77**, 1793-1817, (2010).

49 Wood, A. H. The effect of temperature on the growth and respiration of fish embryos (*Salmo Fario*). *J. Exp. Biol.* **9**, 271-276, (1932).

50 Jungwirth, M. & Winkler, H. The temperature dependence of embryonic development of grayling (*Thymallus thymallus*), Danube salmon (*Hucho hucho*), Arctic char (*Salvelinus alpinus*) and brown trout (*Salmo trutta fario*). *Aquaculture* **38**, 315-327, (1984).

51 Réalis-Doyelle, E., Pasquet, A., De Charleroy, D., Fontaine, P. & Teletchea, F. Strong effects of temperature on the early life stages of a cold stenothermal fish species, brown trout (*Salmo trutta* L.). *PLoS ONE* **11**, e0155487, (2016).

52 Gruber, K. & Wieser, W. Energetics of development of the alpine charr, *Salvelinus alpinus*, in relation to temperature and oxygen. *J. Comp. Physiol.* **149**, 485-493, (1983).

53 Marten, P. S. Effect of temperature variation on the incubation and development of brook trout eggs. *Progress. Fish. Cult.* **54**, 1-6, (1992).

54 Cook, C. J., Burness, G. & Wilson, C. C. Metabolic rates of embryos and alevin from a cold-adapted salmonid differ with temperature, population and family of origin: implications for coping with climate change. *Conserv. Physiol.* **6**, cox076-cox076, (2018).

55 Teletchea, F., Gardeur, J. N., Kamler, E. & Fontaine, P. The relationship of oocyte diameter and incubation temperature to incubation time in temperate freshwater fish species. *J. Fish Biol.* **74**, 652-668, (2009).

56 McDowell, R. M. *The Reed field guide to New Zealand freshwater fishes*. (2000).

57 Hunter, J. R. & Kimbrell, C. A. Early life history of pacific mackerel, *Scomber japonicus*. *Fish. Bull.* **78**, 89-101, (1980).

58 Mendiola, D., Ibaibarriaga, L. & Alvarez, P. Thermal effects on growth and time to starvation during the yolk-sac larval period of Atlantic mackerel *Scomber scombrus* L. *J. Fish Biol.* **70**, 895-910, (2007).

59 Giguere, L. A., Cote, B. & Stpierre, J. F. Metabolic rates scale isometrically in larval fishes. *Mar. Ecol. Prog. Ser.* **50**, 13-19, (1988).

60 Laurence, G. C. Influence of temperature on energy utilization of embryonic and prolarval tautog, *Tautoga onitis*. *J. Fish. Res. Board. Can* **30**, 435-442, (1973).

61 Olla, B. L. & Samet, C. Effects of Elevated Temperature on Early Embryonic Development of the Tautog, *Tautoga onitis*. *Trans. Am. Fish. Soc.* **107**, 820-824, (1978).

62 Bozek, M. A., Paulson, L. J. & Wilde, G. R. Effects of ambient Lake Mohave temperatures on development, oxygen consumption, and hatching success of the razorback sucker. *Environ. Biol. Fishes* **27**, 255-263, (1990).

63 Volpe, E. P. Embryonic Temperature Adaptations and Relationships in Toads. *Physiol. Zool.* **26**, 344-354, (1953).

64 Noland, R. & Ultsch, G. R. The roles of temperature and dissolved oxygen in microhabitat selection by the tadpoles of a frog (*Rana pipiens*) and a toad (*Bufo terrestris*). *Copeia*, 645-652, (1981).

65 Mitchell, N. J. & Seymour, R. S. Effects of temperature on energy cost and timing of embryonic and larval development of the terrestrially breeding moss frog, *Bryobatrachus nimbus*. *Physiol. Biochem. Zool.* **73**, 829-840, (2000).

66 Mueller, C. A., Joss, J. M. P. & Seymour, R. S. The energy cost of embryonic development in fishes and amphibians, with emphasis on new data from the Australian lungfish, *Neoceratodus forsteri*. *J. Comp. Physiol. B Biochem. Syst. Environ. Physiol.* **181**, 43-52, (2011).

67 Seymour, R. S., Geiser, F. & Bradford, D. F. Metabolic cost of development in terrestrial frog eggs (*Pseudophryne bibronii*). *Physiol. Zool.* **64**, 688-696, (1991).

68 Geiser, F. & Seymour, R. S. Influence of Temperature and Water Potential on Survival of Hatched, Terrestrial Larvae of the Frog *Pseudophryne bibronii*. *Copeia* **1989**, 207-209, (1989).

69 McLaren, I. A. Temperature and Frog Eggs : A reconsideration of metabolic control. *J. Gen. Physiol.* **48**, 1071-1079, (1965).

70 Goldstein, J. A., Hoff, K. v. S. & Hillyard, S. D. The effect of temperature on development and behaviour of relict leopard frog tadpoles. *Conserv. Physiol.* **5**, 75, (2017).

71 Rodda, K. R. & Seymour, R. S. Functional morphology of embryonic development in the Port Jackson shark *Heterodontus portusjacksoni* (Meyer). *J. Fish Biol.* **72**, 961-984, (2008).

72 Rodda, K. R. *Development in the Port Jackson shark embryo.* Doctor of Philosophy thesis, The University of Adelaide, (2000).

73 Ligon, D. B. & Lovern, M. B. Interspecific variation in temperature effects on embryonic metabolism and development in turtles. *ISRN Zool.* **2012**, 13, (2012).

74 Janzen, F. J. The Influence of Incubation Temperature and Family on Eggs, Embryos, and Hatchlings of the Smooth Softshell Turtle (*Apalone mutica*). *Physiol. Zool.* **66**, 349-373, (1993).

75 Booth, D. T., Thompson, M. B. & Herring, S. How incubation temperature influences the physiology and growth of embryonic lizards. *J. Comp. Physiol. B Biochem. Syst. Environ. Physiol.* **170**, 269-276, (2000).

76 Flatt, T., Shine, R., Borges-Landaez, P. A. & Downes, S. J. Phenotypic variation in an oviparous montane lizard (*Bassiana duperreyi*): the effects of thermal and hydric incubation environments. *Biol. J. Linn. Soc.* **74**, 339-350, (2001).

77 Elphick, M. J. & Shine, R. Longterm effects of incubation temperatures on the morphology and locomotor performance of hatchling lizards (*Bassiana duperreyi*, Scincidae). *Biol. J. Linn. Soc.* **63**, 429-447, (1998).

78 Reid, K. A., Margaritoulis, D. & Speakman, J. R. Incubation temperature and energy expenditure during development in loggerhead sea turtle embryos. *J. Exp. Mar. Biol. Ecol.* **378**, 62-68, (2009).

79 Patel, S. H. *et al.* Climate impacts on sea turtle breeding phenology in Greece and associated foraging habitats in the wider Mediterranean region. *PLoS ONE* **11**, (2016).

80 Booth, D. T. & Astill, K. Incubation temperature, energy expenditure and hatchling size in the green turtle (*Chelonia mydas*), a species with temperature-sensitive sex determination. *Aust. J. Zool.* **49**, 389-396, (2001).

81 Spotila, J. R., Standora, E. A., Morreale, S. J. & Ruiz, G. J. Temperature-dependent sex determination in the green turtle (*Chelonia mydas*) - effects on the sex-ratio on a natural nesting beach. *Herpetologica* **43**, 74-81, (1987).

82 Whitehead, P. J. & Seymour, R. S. Patterns of metabolic rate in embryonic crocodilians *Crocodylus johnstoni* and *Crocodylus porosus*. *Physiol. Zool.* **63**, 334-352, (1990).

83 Shine, R. Reptilian viviparity in cold climates: testing the assumptions of an evolutionary hypothesis. *Oecologia* **57**, 397-405, (1983).

84 Ligon, D. B. & Lovern, M. B. Temperature Effects During Early Life Stages of the Alligator Snapping Turtle *Macrochelys temminckii*. *Chelonian Conserv. Biol.* **8**, 74-83, 10, (2009).

85 Booth, D. T. & Thompson, M. B. in *Egg Incubation: Its Effects on Embryonic Development in Birds and Reptiles* (eds D. C. Deeming & G. W. Ferguson) Ch. 20, 325-344 (Cambridge University Press, 1991).

86 Nelson, N. J., Thompson, M. B., Pledger, S., Keall, S. N. & Daugherty, C. H. Egg mass determines hatchling size, and incubation temperature influences post-hatching growth, of tuatara *Sphenodon punctatus*. *J. Zool.* **263**, 77-87, (2004).

87 Heather L. Les, Ryan T. Paitz & Rachel M. Bowden. Living at Extremes: Development at the Edges of Viable Temperature under Constant and Fluctuating Conditions. *Physiol. Biochem. Zool.* **82**, 105-112, (2009).

88 Leshem, A., Ar, A. & Ackerman, R. A. Growth, Water, and Energy Metabolism of the Soft-Shelled Turtle (*Trionyx triunguis*) Embryo: Effects of Temperature. *Physiol. Zool.* **64**, 568-594, (1991).

89 Lamb, K. P. Some effects of fluctuating temperatures on metabolism, development, and rate of population growth in the cabbage aphid, *Brevicoryne brassicae*. *Ecology* **42**, 740-745, (1961).

90 Stevens, M. Development and survival of *Chironomus tepperi* Skuse (Diptera: Chironomidae) at a range of constant temperatures. *Aquat. Insects* **20**, 181-188, (1998).

91 McFarlane, A. & McLusky, D. S. The oxygen consumption of chironomid larvae from Loch Leven in relation to temperature. *Comp. Biochem. Physiol. A* **43**, 991-1001, (1972).

92 Stevens, M. M. Development and Survival of *Chironomus tepperi* Skuse (Diptera: Chironomidae) at a Range of Constant Temperatures. *Aquat. Insects* **20**, 181-188, (1998).

93 Richards, A. G. The generality of temperature effects on developmental rate and on oxygen consumption in insect eggs. *Physiol. Zool.* **37**, 199-211, (1964).

94 Vinogradova, E. B. *Culex pipiens pipiens Mosquitoes: Taxonomy, Distribution, Ecology, Physiology, Genetics, Applied Importance and Control*. (Coronet Books Incorporated, 2000).

95 Powsner, L. The effects of temperature on the durations of the developmental stages of *Drosophila melanogaster*. *Physiol. Zool.* **8**, 474-520, (1935).

96 De Moed, G. H., De Jong, G. & Scharloo, W. The energetics of growth in *Drosophila melanogaster*: Effect of temperature and food conditions. *Neth. J. Zool.* **48**, 169-188, (1998).

97 Economos, A. C. & Lints, F. A. Developmental temperature and life span in *Drosophila melanogaster*. I. Constant developmental temperature: evidence for physiological adaptation in a wide temperature range. *Gerontology* **32**, 18-27, (1986).

98 Williams, C. M. *et al.* Thermal Variability Increases the Impact of Autumnal Warming and Drives Metabolic Depression in an Overwintering Butterfly. *PLoS ONE* **7**, e34470, (2012).

99 Williams, C. M., Hellmann, J. & Sinclair, B. J. Lepidopteran species differ in susceptibility to winter warming. *Clim. Res.* **53**, 119-130, (2012).

100 Bennett, V. A., Kukal, O. & Lee, R. E. Metabolic opportunists: feeding and temperature influence the rate and pattern of respiration in the high arctic woollybear caterpillar *Gynaephora groenlandica* (Lymantriidae). *J. Exp. Biol.* **202**, 47-53, (1999).

101 Morewood, W. *Temperature/Development Relationships and life history strategies of Arctiv Gynaephora species (Lepidoptera:Lymantriidae) and their insect parasitoids (Hymenoptera: Ichneumonidae and Diptera:Tachinidae), with refrence to predicted global warming* PHD thesis, University of Victoria, (1999).

102 Katsarou, I., Margaritopoulos, J. T., Tsitsipis, J. A., Perdikis, D. C. & Zarpas, K. D. Effect of temperature on development, growth and feeding of *Coccinella septempunctata* and *Hippodamia convergens* reared on the tobacco aphid, *Myzus persicae nicotianae*. *BioControl* **50**, 565-588, (2005).

103 Acar, E. B., Smith, B. N., Hansen, L. D. & Booth, G. M. Use of calorespirometry to determine effects of temperature on metabolic efficiency of an insect. *Environ. Entomol.* **30**, 811-816, (2001).

104 Swenk, M. H. & Bratt, C. H. The relation of temperature to the embryonic and nymphal development of the differential grasshopper *Melanoplus differentialis* Thomas. *Res. bull. - Univ. Nebr. (Linc. campus), Agric. Exp. Stn.* **122**, (1941).

105 Fielding, D. J. Developmental time of *Melanoplus sanguinipes* (Orthoptera : Acrididae) at high latitudes. *Environ. Entomol.* **33**, 1513-1522, (2004).

106 Chappell, M. A. Metabolism and thermoregulation in desert and montane grasshoppers. *Oecologia* **56**, 126-131, (1983).

107 Fisher, J. R. Temperature Effect on Postdiapause Development and Survival of Embryos of Three Species of *Melanoplus* (Orthoptera: Acrididae). *Ann. Entomol. Soc. Am.* **87**, 604-608, (1994).

108 Richards, A. G. & Suanraksa, S. Energy expenditure during embryonic development under constant versus variable temperatures (*Oncopeltus fasciatus* (Dallas)). *Entomol. Exp. Appl.* **5**, 167-178, (1962).

109 Baldwin, J. D. & Dingle, H. Geographic variation in the effects of temperature on life-history traits in the large milkweed bug *Oncopeltus fasciatus*. *Oecologia* **69**, 64-71, (1986).

110 Matteson, J. W. & Decker, G. C. Development of the European corn borer at controlled constant and variable temperatures. *J. Econ. Entomol.* **58**, 344-349, (1965).

111 Mackey, A. P. Growth and larval development of larval Chironomidae. *Oikos* **28**, 270-275, (1977).

112 Porter, S. D. Impact of temperature on colony growth and developmental rates of the ant, *Solenopsis invicta*. *Journal of Insect Physiology* **34**, 1127-1133, (1988).

113 Elzen, G. W. Oxygen consumption and water loss in the imported fire ant *Solenopsis invicta* Buren. *Comp. Biochem. Physiol. A* **84**, 13-17, (1986).

114 Howe, R. W. The effects of temperature and humidity on the rate of development and mortality of *Tribolium confusum* Duval (Coleoptera, Tenebrionidae). *Ann. Appl. Biol.* **48**, 363-376, (1960).

115 Ismael, D., Anger, K. & Moreira, G. S. Influence of temperature on larval survival, development, and respiration in *Chasmagnathus granulata* (Crustacea, Decapoda). *Helgol. Meeresunters* **51**, 463-475, (1997).

116 Ross, R. M., Quetin, L. B. & Kirsch, E. Effect of temperature on developmental times and survival of early larval stages of *Euphausia superba* Dana. *J. Exp. Mar. Biol. Ecol.* **121**, 55-71, (1988).

117 Quetin, L. B. & Ross, R. M. Effects of oxygen, temperature and age on the metabolic rate of the embryos and early larval stages of the Antarctic krill *Euphausia superba* Dana. *J. Exp. Mar. Biol. Ecol.* **125**, 43-62, (1989).

118 Yoshida, T., Toda, T., Hirano, Y., Matsuda, T. & Kawaguchi, S. Effect of temperature on embryo development time and hatching success of the Antarctic krill *Euphausia superba* Dana in the laboratory. *Mar. Freshwat. Behav. Physiol.* **37**, 137-145, (2004).

119 Anger, K. Temperature and the larval development of *Hyas araneus* L. (Decapoda : Majidae); extrapolation of laboratory data to field conditions. *J. Exp. Mar. Biol. Ecol.* **69**, 203-215, (1983).

120 Jacobi, C. C. & Anger, K. Effect of temperature on respiration of larval stages of *Hyas araneus* and *H. coarctatus* (Decapoda, Majidae). *Mar. Ecol. Prog. Ser.* **26**, 181-186, (1985).

121 McEdward, L. R. Effects of temperature on the body form, growth, electron transport system activity, and development rate of an echinopluteus. *J. Exp. Mar. Biol. Ecol.* **93**, 169-181, (1985).

122 Bingham, B. L., Bacigalupi, M. & Johnson, L. G. Temperature adaptations of embryos from intertidal and subtidal sand dollars (*Dendraster excentricus*, Eschscholtz). *Northwest Sci.* **71**, 108-114, (1997).

123 Fujisawa, H. Temperature sensitivity of a hybrid between two species of sea urchin differing in thermotolerance. *Dev. Growth Differ.* **35**, 395-401, (1993).

124 Padilla-Gamiño, J. L., Kelly, M. W., Evans, T. G. & Hofmann, G. E. Temperature and CO2 additively regulate physiology, morphology and genomic responses of larval sea urchins, *Strongylocentrotus purpuratus*. *Proc. R. Soc. Lond., Ser. B: Biol. Sci.* **280**, (2013).

125 Hammond, L. M. & Hofmann, G. E. Thermal tolerance of *Strongylocentrotus purpuratus* early life history stages: mortality, stress-induced gene expression and biogeographic patterns. *Mar. Biol.* **157**, 2677-2687, (2010).

126 Stanwell-Smith, D. & Peck, L. S. Temperature and Embryonic Development in Relation to Spawning and Field Occurrence of Larvae of Three Antarctic Echinoderms. *The Biological Bulletin* **194**, 44-52, (1998).

127 Cancino, J. M., Gallardo, J. A. & Brante, A. The relationship between temperature, oxygen condition and embryo encapsulation in the marine gastropod *Chorus giganteus*. *J. Mar. Biol. Assoc. U.K.* **91**, 727-733, (2010).

128 Zeidberg, L. D., Isaac, G., Widmer, C. L., Neumeister, H. & Gilly, W. F. Egg capsule hatch rate and incubation duration of the California market squid, *Doryteuthis* (= *Loligo*) *opalescens*: insights from laboratory manipulations. *Mar. Ecol.-Evol. Persp.* **32**, 468-479, (2011).

129 Vidal, E. A. G., DiMarco, F. P., Wormuth, J. H. & Lee, P. G. Influence of temperature and food availability on survival, growth and yolk utilization in hatchling squid. *Bull. Mar. Sci.* **71**, 915-931, (2002).

130 Zeidberg, L. D. *et al.* Estimation of spawning habitats of market squid (*Doryteuthis opalescens*) from field surveys of eggs off Central and Southern California. *Mar. Ecol.-Evol. Persp.* **33**, 326-336, (2012).

131 Oosthuizen, A., Roberts, M. J. & Sauer, W. H. H. Temperature effects on the embryonic development and hatching success of the squid *Loligo vulgaris reynaudii*. *Bull. Mar. Sci.* **71**, 619-632, (2002).

132 Martins, R. S., Roberts, M. J., Vidal, É. A. G. & Moloney, C. L. Effects of temperature on yolk utilization by chokka squid (*Loligo reynaudii* d'Orbigny, 1839) paralarvae. *J. Exp. Mar. Biol. Ecol.* **386**, 19-26, (2010).

133 Bayne, B. L. Growth and the delay of metamorphosis of the larvae of *Mytilus edulis* (L.). *Ophelia* **2**, 1-47, (1965).

134 Sprung, M. Physiological energetics of mussel larvae (*Mytilus edulis*). III. Respiration. *Mar. Ecol. Prog. Ser.* **18**, 171-178, (1984).

135 Caamal-Monsreal, C. *et al.* Effects of temperature on embryo development and metabolism of *O. maya*. *Aquaculture* **451**, 156-162, (2016).

136 Roller, R. A. & Stickle, W. B. Temperature and salinity effects on the intracapsular development, metabolic rates, and survival to hatching of *Thais haemastoma canaliculata* (Gray) (Prosobranchia: Muricidae) under laboratory conditions. *J. Exp. Mar. Biol. Ecol.* **125**, 235-251, (1989).