Supplementary Material

Materials and Methods

Temperature, length-at-day, development-time and evacuation data were extracted from data tables and/or by digitizing figures retrieved from the published literature (Table S1). The Atlantic cod data (Brander 1995) were an exception where the stock-specific weight-at-age estimates were converted to stock-specific length-at-age estimates by using literature-based stock-specific weight-at-length regressions (Kohler et al. 1970; Daan 1974; O'Brien and Monroe 2001; Lilly et al. 2003; Marshall et al. 2004). The latter regressions revealed one general (model) relation for the 19 cod stocks across their N Atlantic range (Fig. S4). The validity of this strong relation was tested by examining the mean annual length- and weight-at-age estimates for northern cod (North Atlantic Fisheries Organization, statistical Division 2J3KL) over the period 1977 to 1992 inclusive (n=551). This examination showed that the observed 2J3KL data fit within one standard deviation of the general model (Fig. S4).

Where average daily temperature estimates were not provided, they were estimated using linear interpolation of the weekly, monthly, annual etc. estimates. The *GDD* estimate at day *n* (°C•d) was calculated as:

$$GDD(n) = \sum_{i=1}^{n} \left(T_i - T_{Th}\right) \cdot \Delta d, \quad T_i \geq T_{Th} \tag{1}$$

where T_i is the mean daily temperature at day *i*, T_{Th} is the predetermined threshold temperature and Δd is a set time step (sampling frequency, i.e. 1 d). Initially, T_{Th} was set at 0°C (see below). All *GDD* and *LaD* time series were validated for normality using a Shapiro-Wilk test (α=0.05). Variation in size (*LaD*) and variation in physiological time, *GDD,* were compared and quantified through linear regression for each dataset, producing a relation of the form:

$$LaD = \beta \cdot GDD + \alpha \tag{2}$$

where β is the slope (mm $(°\mathrm{C}\bullet\mathrm{d})^{-1}$) and α is the intercept (mm) of the *LaD* at *GDD* relation (see Table S2). The above methods were applied in a similar manner to resolve *LaD* as a function of calendar time. For the evacuation trials (Fig. 6) variation in normalized stomach fullness index (*nSFI*) and variation in *GDD* were compared and quantified through linear regression for each dataset, producing a relation of the form:

$$nSFI = \theta \cdot GDH + \rho \tag{3}$$

where θ is the slope $(°\mathrm{C}\bullet\mathrm{h})^{-1}$ and ρ is the intercept (mm) of the *GDD-nSFI* relation (see Table S3). All statistical analyses were performed using Matlab (Version 6.5, MathWorks Inc.). Statistical significance was generally evaluated at α=0.05.

As the Celsius scale is an arbitrary one (McLaren 1995), any growth model including temperature must include an estimate of the threshold temperature (T_{Th}). When a growth model uses a mean temperature there is an implicit assumption that T_{Th} = 0ºC. This can be avoided by using an absolute temperature scale based on heat energy (i.e. Kelvin, the S.I. unit for thermodynamic temperature). However, integration of Kelvin temperature results in smoothing (due to the relatively large values each datum in the series will have; e.g. 10ºC=283.15ºK) of fluctuations in the *GDD* series (ºC) that parallel those of the *LaD* series. Thus, it is more physiologically-relevant to choose a temperature scale and threshold that correspond to the minimum limit of the organism and its environment; e.g. perhaps near -2ºC for marine fish. We tested the incorporation of various threshold temperatures (T_{Th}; °C) in the GDD metric (relative to the 0°C default) by examining the change in the coefficient of determination (r^2) in the *LaD* at *GDD* function when varying T_{Th} between -20 and 20°C in 1°C increments. This range more than captured all of the variation in T_{Th} that we discovered in the published literature. Only those data offering a variation in temperature and accompanied by time were included (20 datasets). While the location of the maximum r^2 varied greatly among datasets, each described a characteristic and rapid decay in the r^2 at some positive T_{Th} (Fig. S5). The location of this rapid decay was defined as the maximum useable threshold arbitrarily, but conservatively, determined at the point of a 10% decrease in explained variation relative to the maximum r^2 (i.e. maximum explained variation in *LaD* by *GDD*); here termed the "$10\%T_{Th}$". While there is considerable variation in the value of the $10\%T_{Th}$ among datasets, two interesting patterns were revealed (Fig. S6). First, warm-water snapper (*Pagrus auratus*) exhibited a higher (Wilcoxon Rank Sum, n=20, P=0.0076) geometric mean $10\%T_{Th}$= 19.3ºC than did cold-water fish (grayling *Thymallus thymallus*, Atlantic salmon *Salmo salar*, herring *Clupea harengus*) with geometric mean $10\%T_{Th}$=12.2ºC; possibly the result of life-history adaptation to their environments. Second, the $10\%T_{Th}$ does not fall below 4°C. Interestingly, and perhaps meaningfully, this is the average temperature below the thermocline in temperate marine waters (Dando and Burchett 1996) and is the temperature of maximum density in freshwater. Changing the 10% criterion to some lower value results in a similar pattern with a slightly lower elevation.

Supplementary Figures

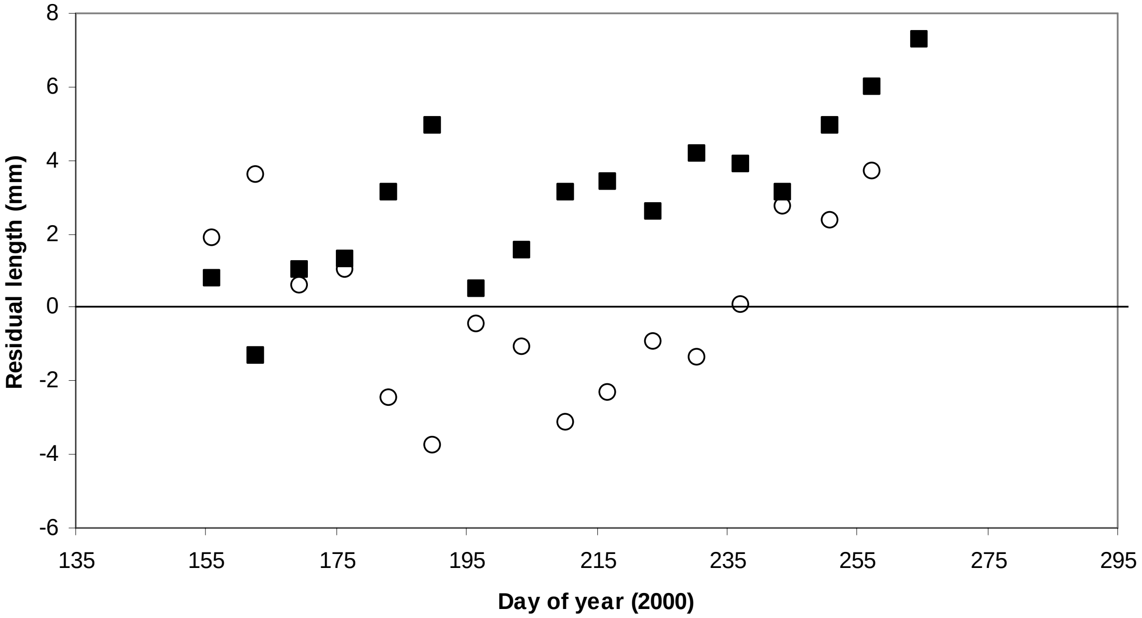

Fig. S1. Scattergram showing the residuals (mm) from the modified VBGF method (Dion and Hughes 2004, filled squares) with those from the GDD method (open circles) for the 2000-year-class of age-0+ Arctic grayling. Mean square errors for the modified VBGF method and GDD method are 15.1 and 6.0 mm^2 respectively. The residuals from the modified VBGF method (Dion and Hughes 2004) demonstrate a significant trend ($r^2=0.66$; $P<0.0001$) while the residuals from the GDD method do not ($P=0.66$).

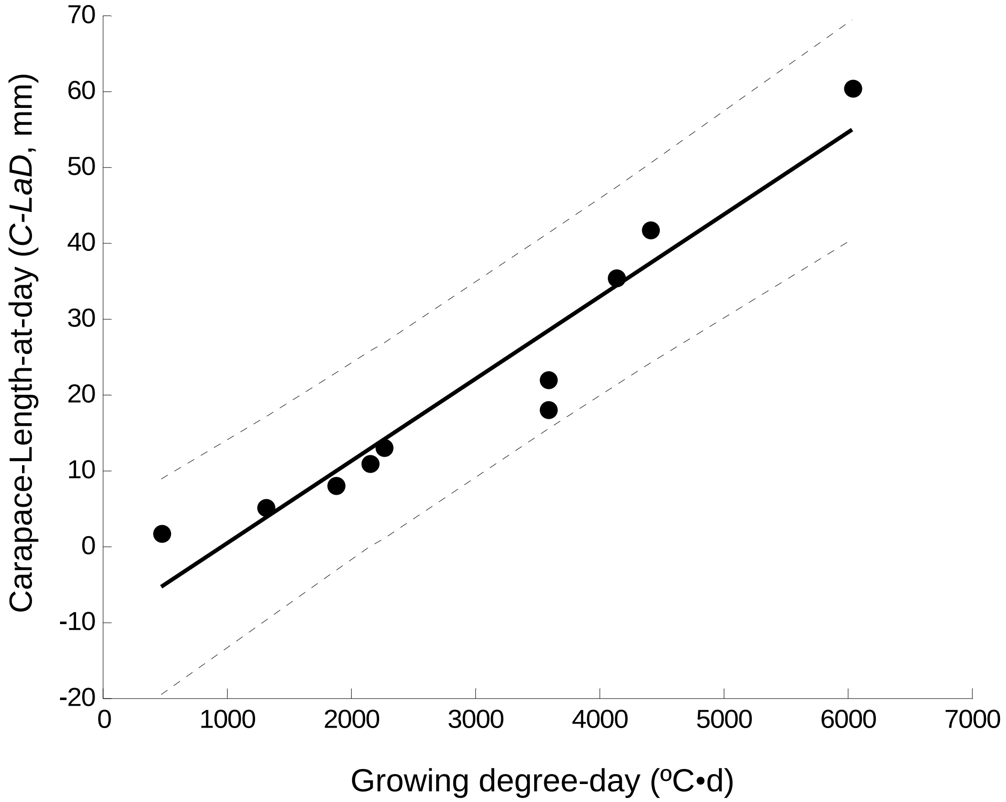

Fig. S2. Carapace length-at-day (*C-LaD*, mm; filled circles) and *GDD* (ºC•d) for juvenile red king crab (*Paralithodes camtschatica;* Stevens 1990). Linear regression (solid line; *C-LaD*=0.011•*GDD* – 10.6mm; r^2=0.92; P<0.0001) and 95% prediction intervals (dashed lines) are provided. Stevens (1990) used a $\log_e$-linear fit to these data, presumably to avoid the arguably meaningless negative y-intercept provided here. This pattern may reflect an unresolved thermal constant related to early development.

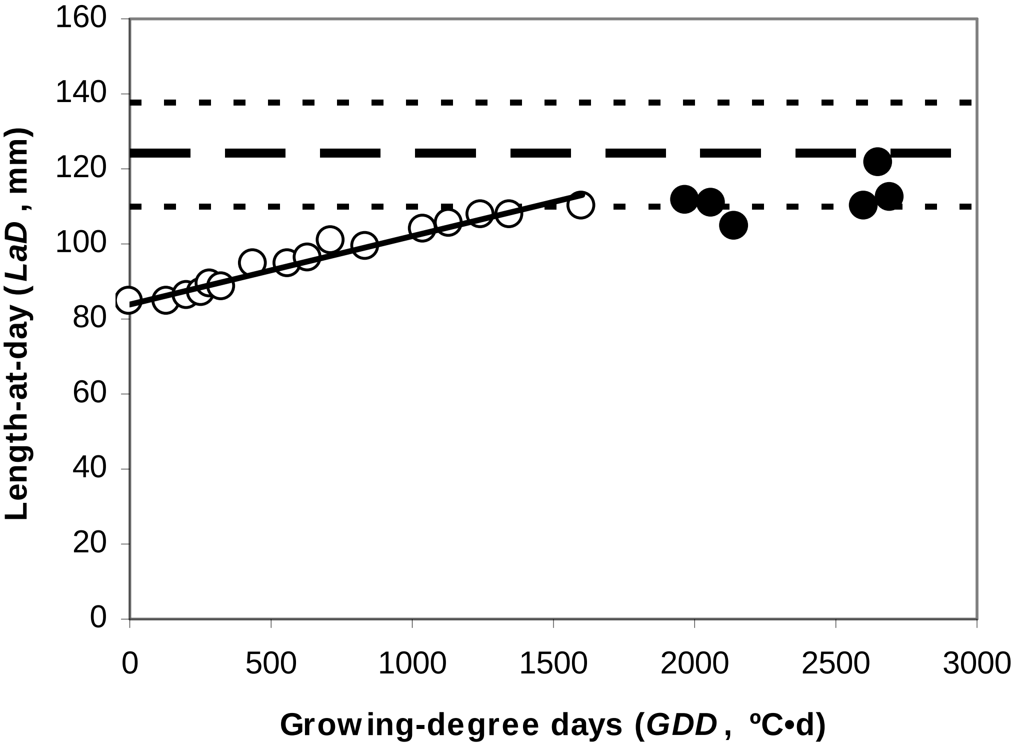

Fig. S3. Length-at-day (mm) as a function of *GDD* (ºC•d) for juvenile Atlantic salmon (Jones et al. 2002). Open circles and solid line denote data included in *GDD-LaD* relation (*LaD*=0.019•*GDD*+83.6mm; r^2=0.97; P<0.0001), and filled circles those excluded. Dashed and dotted lines at 124 ± 14mm (standard deviation) illustrates the approximate size-at-smoltification for fish in this area (Hutchings and Jones 1998).

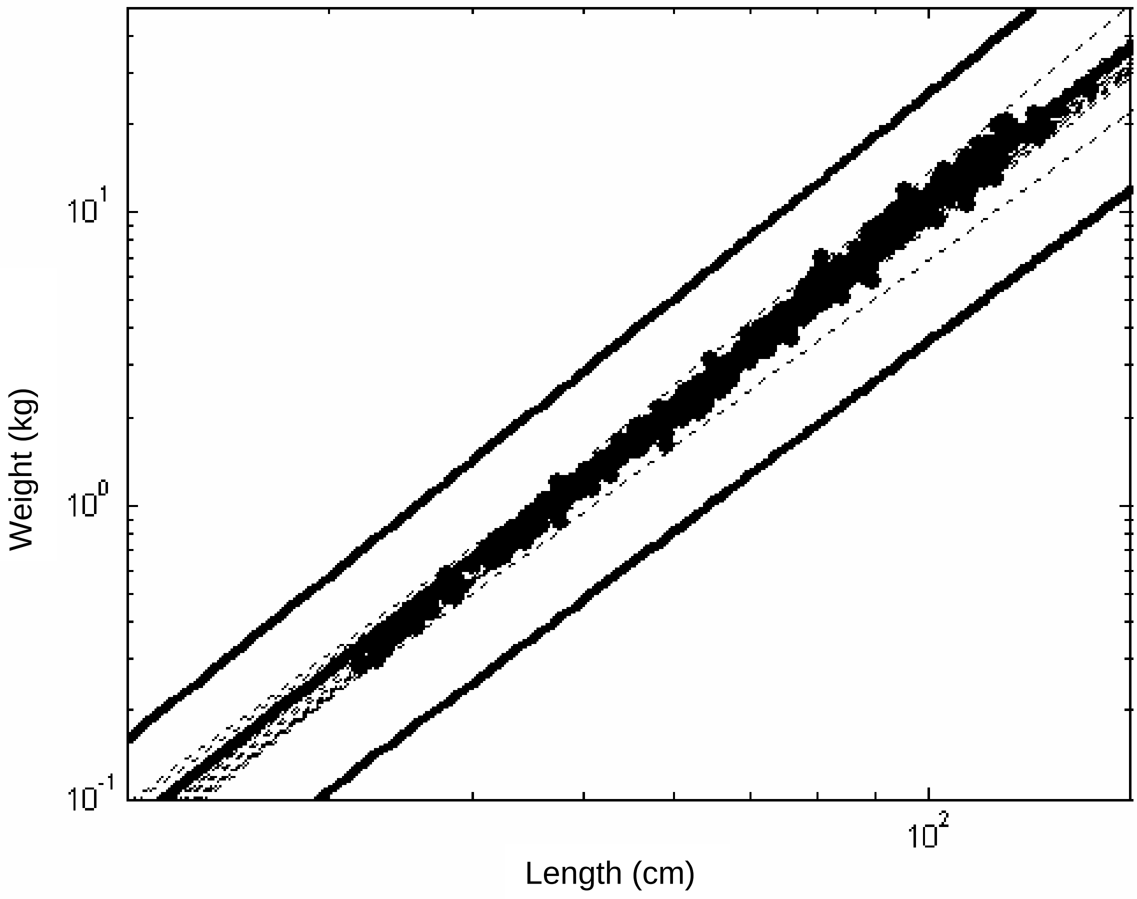

Fig. S4. Weight-at-length relation used to convert weight-at-age (kg) to length-at-age (cm) for Atlantic cod data. Thin dotted lines denote length-weight relations for 17 cod stocks across the North Atlantic (Kohler et al. 1970; Daan 1974; O'Brien and Monroe 2001; Lilly et al. 2003; Marshall et al. 2004). Thick solid lines denote mean length-at-weight parameters ± standard deviation ($W=8.9\text{x}10^{-6}\bullet L^{3.03}$). Filled circles are mean annual length- and weight-at-age estimates for northern cod (North Atlantic Fisheries Organization, statistical Division 2J3KL) over the period 1977 to 1992 inclusive (n=551).

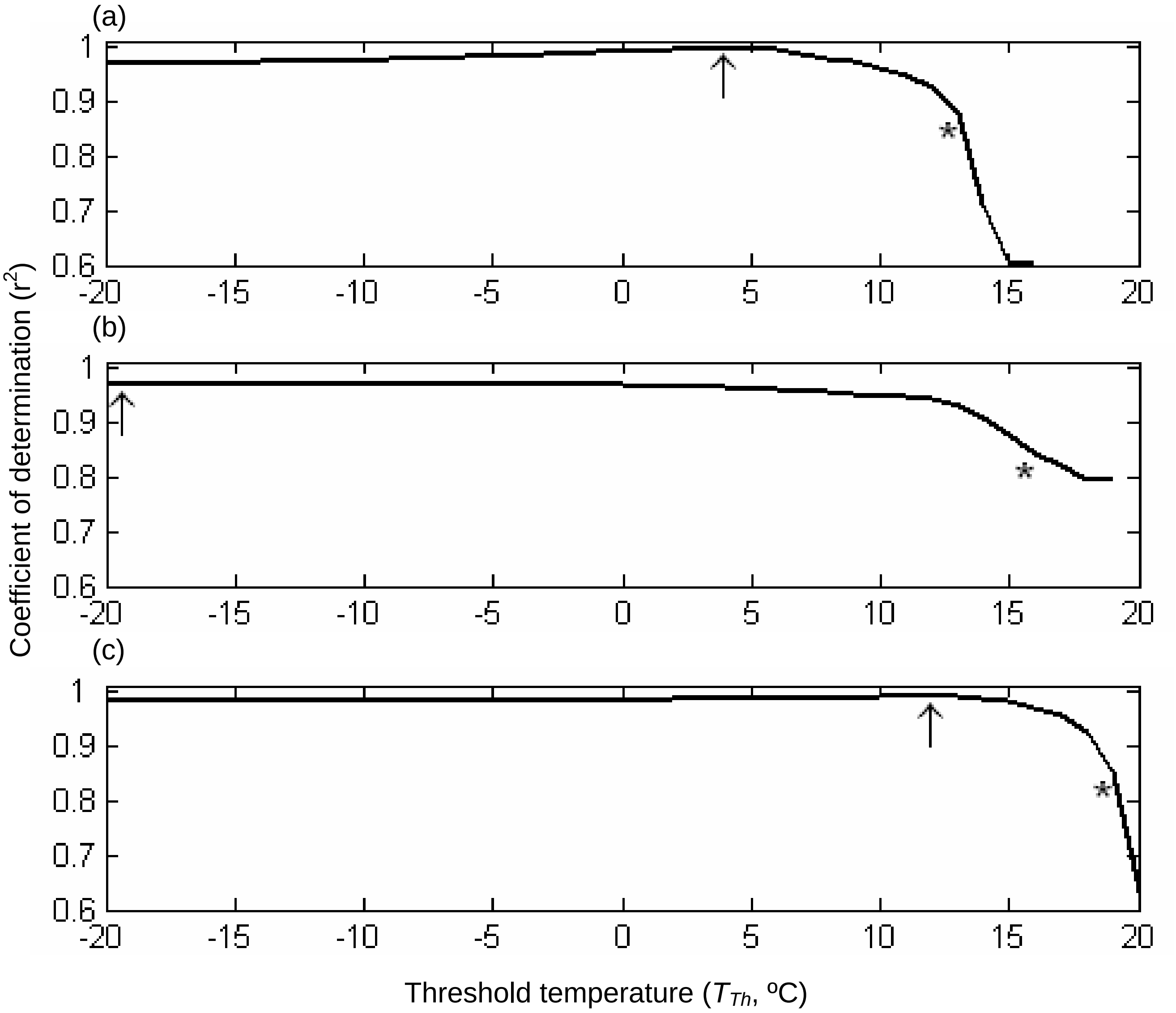

Fig. S5. Variation in the coefficients of determination (r^2) in the *LaD* at *GDD* relation due to changing the threshold temperature (T_{Th}) over the range between -20ºC and 20ºC for three example datasets covering the full range in the position of the maximum r^2 (arrow): a) Arctic Grayling (Alaska, Dion and Hughes 2004), b) European grayling (France, Mallet et al. 1999), c) snapper (New Zealand, Francis 1994). * indicates position of $10\%T_{Th}$; i.e. a 0.10 decrease in r^2 relative to the maximum.

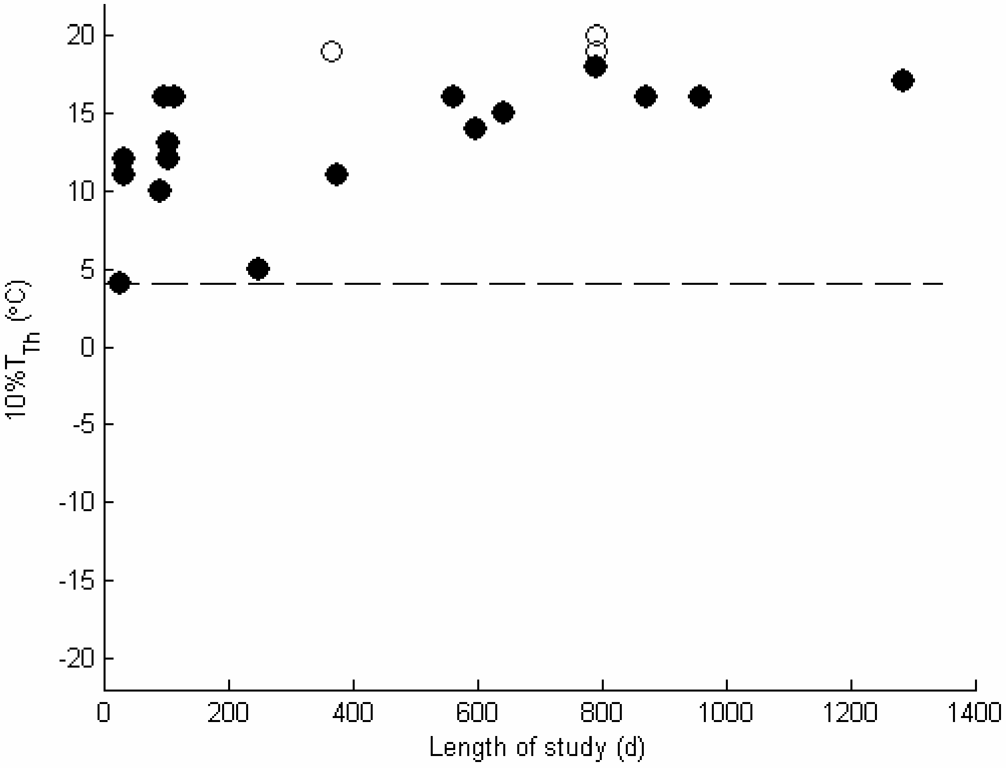

Fig. S6. Position of the *10%*T_{Th} for cold-water (filled circles; n=17) and warm-water (open circles; n=3) fish where cold-water fish are those inhabiting a mean temperature of 10±3°C and warm-water fish are New Zealand snapper inhabiting 17±2°C. Dashed line indicates *10%*T_{Th}=4°C.

Supplementary Tables

Table S1: Summary of published data used to examine the GDD method

Species Study	Location (field/lab; environment; location)	Source, length (mm), data secured	*GDD* provided? (Threshold temperature, T_{Th})	Calculation of *GDD*	
				Temperature (ºC) obtained in source from:	daily mean temperature
herring (*Clupea harengus*) Folkvord et al. 2004	lab; marine; Norway	Figure 2a (digitized)	no	Figure 1	digitized
houting (*Coregonus oxyrhynchus*) Malzahn et al. 2003	lab; marine; North Sea	Figure 3 (digitized)	Figure 3 (digitized) $^{+}$	n/a	
Arctic grayling (*Thymallus thymallus*) Dion and Hughes 2004	field; freshwater; Alaska	Figure 1e-h (digitized)	no	daily temperature provided by originating authors	
minnow (*Phoxinus phoxinus*) Mills 1988	field; freshwater; Finland	Table 2	Table 2 (T_{Th}=5ºC)	n/a	
spider crab (*Mithraculus forceps*) Penha-Lopes et al. 2006	lab ; marine; Florida	Table 1	no	Table 1	

Table S1 cont.

red king crab (*Paralithodes camtschatics*) Stevens 1990	field; marine; Alaska	Figure 3 (digitized)	Figure 3 (digitized)+	n/a	
European grayling (*Thymalluis thymallus*) Mallet et al. 1999	field; freshwater; France	Figure 4ab (digitized)	no	Figure 4ab	digitized and interpolated
snapper (*Pagrus auratus*) Francis 1994	field; marine: New Zealand	Figure 8 (digitized)	no	Figure 4	digitized and interpolated
Atlantic salmon (*Salmo salar*) Jones et al. 2002	field; anadromous; Scotland	Figure 1a (digitized)	no	Figure 1c	digitized and interpolated
threespine stickleback (*Gasterosteus aculeatus*) Wright et al. 2004	lab; freshwater; Scotland	Figure 2a (digitized)	no	text, constant	
Atlantic cod (*Gadus morhua*) Brander 1995	field, marine, North Atlantic	Table 1	No	Table 1	interpolated
burbot (*Lota lota*) Kjellman and Eloranta 2002	field; freshwater; Finland	Figure 1b (digitized)	Figure 1b (digitized)+	n/a	

Table S1 cont.

chinook salmon (*Onchorhynchus tshawytscha*) Alderdice and Velsen 1978	lab; anadromous; Pacific	Table 1*	no	Table 1: Incubation temperatures 1.7 to 18.1ºC
trout (*Salmo fario*) Gray 1928	lab; freshwater; unknown	Table 1*	no	Table 1: Incubation temperatures 2.8 to 12.2ºC
Atlantic cod (*Gadus morhua*) Pepin et al. 1997	lab; marine; Newfoundland	Figure 1*	no	Figure 1: Incubation temperatures 1 to 7ºC
yellowtail flounder (*Limanda ferruginea*) Benoit and Pepin 1999	lab; marine; Northwest Atlantic	Figure 4*	no	Figure 1: Incubation temperatures 5 to 13ºC
freshwater sculpin (*Cottus nozawae)* Miyasaka et al. 2005	lab; freshwater; Japan	Figure 1**	no	text, constant

*days to hatching

**stomach fullness index (*SFI*) where *SFI* = ln[{1000• (dry mass of stomach contents)/(dry mass of fish body)} +1].

$^{+}T_{Th}$ =0 assumed

Table S2: A comparison of the relation between calendar time (days) and physiological time (*GDD*, ºC•d) to size-at-age and egg development among the datasets we examined. Shaded values indicate statistical similarity among trials of a given study. Arrow indicates common linear relation among trials of a given study when possible.

			Calendar time (d)					Physiological time (*GDD*; ºC•d)				
			Linear regression: *LaD*= *β* •Time + *α*					Linear regression: *LaD*= *β* •*GDD* + *α*				
Species and relevant figures	Descriptors	Data (n)	Slope (*β*) mm•d^{-1}	Intercept (*α*) mm	r^2	P (α=0.05)	Comparison	Slope (*β*) x 10^{-2} mm•(ºC•d)$^{-1}$	Intercept (*α*) mm	r^2	P (α=0.05)	Comparison
herring (*Clupea harengus*) Folkvord et al. 2004 Fig.2abcdef	constant 4ºC	5	0.12	10.6	0.95	0.005	ANCOVA Different slopes P<0.0001	3.0	10.5	0.93	0.0074	ANCOVA Similar slopes P=0.91 Similar intercepts P=0.19
	constant 12ºC	6	0.38	10.7	0.98	0.0002		3.2	10.8	0.98	0.0012	
	variable 4ºC,8ºC,4ºC	6	0.18	10.0	0.94	0.0016		3.1	10.2	0.96	0.0004	
	variable 12ºC,8ºC,12ºC	6	0.33	11.0	0.97	0.0003		3.3	10.6	0.98	0.0001	
	Combined Trials	23	n/a					3.4	10.3	0.98	<0.0001	↵
houting (*Coregonus oxyrhynchus*) Malzahn et al. 2003 Fig. 2gh	17.5ºC, fed	5	0.41	9.82	0.97	0.0018	ANCOVA Different slopes P=0.0001	2.3	9.8	0.97	0.0017	ANCOVA Similar slopes P=0.10 Different intercepts P=0.0009
	17.5ºC, starved	5				0.13					0.13	
	8.4ºC, fed	9	0.22	10.2	0.99	<0.0001		2.7	10.2	0.99	<0.0001	
	8.4ºC, starved	9				0.11					0.11	
Arctic grayling (*Thymallus thymallus*) Dion and Hughes 2004 Fig. 2ij, 3, S1	Nordale 2000	16	0.71	-89.9	0.94	<0.0001	ANCOVA Marginal slopes P=0.032	6.5	15.6	0.99	<0.0001	ANCOVA Similar slopes P=0.44 Different intercepts P=0.0088
	Nordale 2001	14	0.84	-110.5	0.98	<0.0001		6.2	14.7	0.98	<0.0001	
	Bona 2000	13	0.57	-72.7	0.97	<0.0001	ANCOVA Different slopes P=0.0003	5.0	13.5	0.97	<0.0001	ANCOVA Marginal slopes P=0.026
	Bona 2001	14	0.80	-111.3	0.96	<0.0001		6.1	8.7	0.95	<0.0001	

Table S2 cont.

minnow (*Phoxinus phoxinus*) Mills 1988 Fig. 2kl	1978 year-class	7	0.017	14.3	0.99	<0.0001	ANCOVA Similar slopes P=0.85 Different intercepts P=0.0014	1.1	7.4	0.99	<0.0001	ANCOVA Similar slopes P=0.19 Marginal intercepts P=0.032
	1979 year-class	6	0.017	15.7	0.99	<0.0001		1.1	7.6	0.99	<0.0001	
	1980 year-class	5	0.017	14.1	0.99	0.0003		1.1	7.1	0.99	<0.0001	
	1981 year-class	4	0.018	11.9	0.99	0.0022		1.1	7.0	0.99	0.0003	
spider crab (*Mithraculus forceps*) Penha-Lopes et al. 2006 Fig.2mn	25ºC	4	0.079	0.58	0.98	0.0077	ANCOVA Similar slopes P=0.41 Different intercepts P=0.01	0.11	0.97	0.99	0.001	ANCOVA Similar slopes P=0.86 Marginal intercepts P=0.031
	28ºC	4	0.086	0.70	0.99	0.0015		0.11	1.0	0.99	0.001	
red king crab (*Paralithodes camtschatics*) Stevens 1990 Fig. S2		11	n/a					1.1	-10.6	0.92	<0.001	n/a
European grayling (*Thymallus thymallus*) Mallet et al. 1999	1977 year-class	10	0.28	107.5	0.95	<0.0001	ANCOVA Different slopes P<0.0001	2.7	98.4	0.96	<0.0001	ANCOVA Different slopes P<0.0001
	1978 year-class	9	0.30	-22.4	0.97	<0.0001		2.8	84.5	0.98	<0.0001	
	1979 year-class	10	0.27	-90.5	0.95	<0.0001		2.6	96.4	0.95	<0.0001	
	1980 year-class	7	0.33	-295.96	0.96	0.0001		3.2	56.6	0.98	<0.0001	
	1981 year-class	6	0.20	-185.6	0.94	0.0014		1.9	110.9	0.94	0.0014	
	1993 year-class	9	0.21	46.3	0.93	<0.0001		1.8	116.2	0.93	<0.0001	
	1994 year-class	10	0.31	-157.3	0.97	<0.0001		2.6	47.8	0.97	<0.0001	
	1995 year-class	6	0.38	-361.8	0.97	0.0003		3.4	18.3	0.98	0.001	
snapper (*Pagrus auratus*) Francis 1994	1987 year-class	14	0.18	50.2	0.98	<0.0001	ANCOVA Similar slopes P=0.38 Similar intercepts P=0.23 ↲	1.1	51.7	0.98	<0.0001	ANCOVA Similar slopes P=0.26 Similar intercepts P=0.78 ↲
	1988 year-class	17	0.18	53.6	0.97	<0.0001		1.1	55.5	0.97	<0.0001	
	1989 year-class	7	0.21	47.8	0.95	0.0002		1.2	70.8	0.97	0.0001	
	Combined Trials	38	0.18	52.6	0.97	<0.0001		1.1	50.6	0.98	<0.0001	

Table S2 cont.

Atlantic salmon (*Salmo salar*) Jones et al. 2002 Fig. S3	mean, front	15	0.10	84.9	0.84	<0.0001	n/a	1.9	83.6	0.97	<0.0001	n/a
threespine stickleback (*Gasterosteus aculeatus*) Wright et al. 2004	Frongoch, front	13	0.36	5.3	0.99	<0.0001	ANCOVA Different slopes P<0.0001	2.0	5.3	0.99	<0.0001	ANCOVA Different slopes P<0.0001
	Ayrs Burn, front	13	0.43	4.8	0.99	<0.0001		2.4	4.8	0.99	<0.0001	
	Endrick, front	14	0.34	5.2	0.99	<0.0001		1.9	5.2	0.99	<0.0001	
	Hogganfield, front	12	0.38	4.9	0.99	<0.0001		2.1	4.9	0.99	<0.0001	
	Kelvin, front	12	0.41	5.6	0.99	<0.0001		2.2	5.6	0.99	<0.0001	
Atlantic cod (*Gadus morhua*) Brander 1995 Fig. 5, S4	1	2				n/a	Linear Regression P=0.10				n/a	Linear Regression P<0.0001; r^2=0.93
	2	1				n/a					n/a	
	3	2				n/a					n/a	
	4	3				0.16					0.16	
	5	3	0.37	230.5	0.99	0.028		3.7	230.5	0.99	0.028	
	6	3	0.35	192.9	0.99	0.014		4.0	192.9	0.99	0.014	
	7	3	0.45	238.4	0.99	0.043		4.1	238.4	0.99	0.043	
	8	3	0.33	317.8	0.99	0.05		3.3	317.8	0.99	0.05	
	9	2				n/a					n/a	
	10	2				n/a					n/a	
	11	2				n/a					n/a	
	12	2				n/a					n/a	
	13	2				n/a					n/a	
	14	2				n/a					n/a	
	15	3				0.19					0.19	
	16	3	0.19	300.1	0.99	0.010		3.2	300.1	0.99	0.010	
	17	3				0.11					0.11	
	Combined Trials	n/a						3.4	280	0.93	<0.0001	

Table S2 cont.

burbot (*Lota lota*) Kjellman and Eloranta 2002	1978 year-class	14	n/a	3.7	10.5	0.98	<0.0001	ANCOVA Similar slopes P=0.06 Marginal intercepts P=0.04
	1979 year-class	6		4.8	2.9	0.99	<0.0001	
chinook salmon eggs *(Onchorhynchus tshawytscha)* Alderdice and Velsen 1978 Fig. 4ab	Mean time to hatching	57	64.7 ± 41.9 d (±65%)	516 ± 40ºC·d (±7.8%)				
trout eggs (*Salmo fario*) Gray 1928 Fig. 4ab	Mean time to hatching	14	86.4 ± 38.2 d (±44%)	493 ± 48ºC·d (±9.7%)				
Atlantic cod eggs (*Gadus morhua*) Pepin et al. 1997 Fig. 4cd	Mean time to hatching	11	20.0 ± 5.01 d (±25.1%)	65.6 ± 29.1ºC·d (±44.4%)				
yellowtail flounder eggs (*Limanda ferruginea*) Benoit and Pepin 1999 Fig. 4cd	Mean time to hatching	57	6.38 ± 2.05 d (±32%)	52.2 ± 3.33ºC·d (±6.4%)				

Table S3: A comparison of the relation between calendar time (days) and physiological time (*GDD*, ºC•d) to normalized stomach fullness index (*nSFI*). Shaded values indicate statistical similarity among trials. Arrow indicates common linear relation among trials.

			Calendar time (hours)					Physiological time (*GDH*; ºC•h)				
			Linear regression: $nSFI= \theta \cdot \text{Time} + \rho$					Linear regression: $nSFI= \theta \cdot GDH + \rho$				
Species and relevant figures	Descriptors	Data (n)	Slope (θ) x 10^{-2} d^{-1}	Intercept (ρ)	r^2	P (α=0.05)	Comparison	Slope (θ) x 10^{-3} $(ºC \cdot h)^{-1}$	Intercept (ρ)	r^2	P (α=0.05)	Comparison
freshwater sculpin (*Cottus nozawae*) Miyasaka 2005 Fig. 6	2ºC	7	-1.6	1.0	0.85	0.0033	ANCOVA Different slopes P=0.0081	-8.2	1	0.85	0.003	Similar slopes P=0.49 Similar intercepts P=0.92
	7ºC	7	-3.5	0.98	0.92	<0.0001		-4.9	0.98	0.92	0.0006	
	12ºC	6	-5.3	0.97	0.82	0.013		-4.4	0.97	0.82	0.013	
	Combined Trials		n/a					-4.6	0.97	0.88	<0.0001	↵

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