The following supplement accompanies the article

Functional responses of North Atlantic fish eggs to increasing temperature

Stavroula Tsoukali*, André W. Visser, Brian R. MacKenzie

*Corresponding author: stts@aqua.dtu.dk

Marine Ecology Progress Series 555: 151–165 (2016)

Table S1. Intercept and slope values of the regression lines fitted to the development time (ln-transformed) and temperature (°C), and to the development rate (d^{-1}) and temperature data. The development time (Dev) and average degree-days (*DD*) at the optimal temperature (T_{opt}) are also given. a_d and b_d represent the intercept and slope of the ln(days) vs. temperature linear regression, and a_r and b_r represent the intercept and slope of the development rate vs. temperature linear regression

Species name	Area	Species code	a_d	b_d	a_r	b_r	Dev	*DD*
Anchovy	Bay of Biscay	An	3.01	-0.113	-0.509	0.051	1.5	19.5
Sprat	Baltic Sea	Sp.b	2.87	-0.098	0.038	0.012	7.2	85.6
Blue whiting	NE Atlantic	BW	2.65	-0.106	-0.007	0.022	5.1	46.1
Capelin	NW Atlantic	c.nw	3.64	-0.036	0.026	0.001	30.1	314.9
Capelin	Barents Sea	c.Bs	4.21	-0.135	0.013	0.003	45.1	317.4
Capelin		All data[1]	4.20	-0.133	0.013	0.004	---	---
Chub mackerel	Pacific	cm	3.36	-0.130	-0.584	0.054	2.5	19.4
Cod	NW Atlantic	codgb	3.25	-0.109	0.020	0.010	14.2	117.5
Cod	Irish Sea	cod.Ir	3.46	-0.125	-0.004	0.012	11.8	119.1
Cod	NW Atlantic	cod.Nf	3.58	-0.123	0.028	0.005	17.4	196.4
Cod	Norway	cod.Norw	3.75	-0.158	-0.018	0.013	11.7	120.8
Cod	North Sea	cod.NS	3.36	-0.100	0.025	0.007	14.5	141.1
Cod	NW Atlantic	cod.NWF	3.63	-0.149	0.019	0.008	14.5	125.0
Cod	Baltic Sea	cod25	3.63	-0.157	0.016	0.009	16.1	116.4
Cod	Baltic Sea	cod27	3.21	-0.124	0.032	0.010	10.3	94.2
Gilthead sea bream	France	gsb	2.70	-0.105	-0.234	0.038	2.8	26.5
Herring	North Sea	H.a	3.57	-0.104	-0.004	0.009	9.9	101.4
Herring	Baltic Sea	H.b	3.82	-0.128	-0.034	0.012	10.0	91.2
Herring	Clyde	H.sC	3.88	-0.135	-0.027	0.012	18.4	86.9
Herring	Norway	H.sN	4.04	-0.149	-0.021	0.011	13.2	97.6
Haddock	NW Atlantic	hadd	3.15	-0.116	0.018	0.012	11.4	93.8
Hake	Norway	hake	2.92	-0.104	-0.041	0.020	5.5	53.6
Horse mackerel	Celtic Sea	hm	3.18	-0.131	-0.335	0.044	3.1	23.8
Mackerel	Celtic Sea	M.w	3.62	-0.145	-0.119	0.024	5.7	46.5
Mackerel	Biscay Bay	M.s	3.41	-0.131	-0.099	0.023	4.2	41.8
Mackerel	North Sea	M.ns	3.30	-0.114	-0.266	0.032	3.1	43.5
Mackerel	NW Atlantic	M.nw	3.27	-0.122	-0.210	0.030	4.0	33.7
Menhaden	NW Atlantic	menh	3.16	-0.128	-0.409	0.052	1.5	18.5
Plaice	Irish Sea	plaice	3.71	-0.136	-0.017	0.012	13.4	86.7
Sand lance	NW Atlantic	SL	4.69	-0.125	0.005	0.003	48.7	394.8
Sardine	Portugal coasts	Sd	2.90	-0.115	-0.301	0.042	2.7	25.0
Sprat	English channel	Sp	2.73	-0.117	-0.083	0.032	3.8	32.1
Turbot	France	turbot	2.58	-0.072	-0.090	0.021	3.4	47.8

[1] the regression line was fitted to the capelin pooled data for temperatures < 11°C

Table S2. Optimal temperature range (T_{range}) for egg development and survival given by the highest and lowest temperatures; T_{opt} is the mean value of the optimal range. The average spawning temperatures T_{spw}, collated from the literature, are also given. T_{th} is the estimated threshold temperature

Species name		Species code	Optimal temperature range			Spawning temperature range			
			T_{opt}	lower	upper	T_{spw}	lower	upper	T_{th}
Anchovy	Bay of Biscay	An	23.0	19.7	26.3	18.5	14.0	23.0	9.9
Sprat	Baltic Sea	Sp.b	8.6	5.9	11.4	5.5	3.0	8.0	-3.2
Blue whiting	NE Atlantic	BW	9.4	6.9	11.8	10.0	9.0	11.0	0.3
Capelin	NW Atlantic	c.nw	6.5	2.3	10.6	7.7	1.4	14.0	-4.0
Capelin	Barents Sea	c.Bs	3.0	0.0	7.0	4.0	1.5	6.5	-4.0
Chub mackerel	Pacific	cm	18.6	14.0	23.2	18.6	14.0	23.2	10.8
Cod	NW Atlantic	codgb	6.0	2.0	10.0	6.3	3.0	9.5	-2.3
Cod	Irish Sea	cod.Ir	9.0	6.0	12.0	6.5	6.0	7.0	-2.3
Cod	NW Atlantic	cod.Nf	5.8	2.0	9.6	6.3	3.0	9.5	-5.5
Cod	Norway	cod.Norw	8.0	6.0	10.0	3.8	3.0	4.5	-2.3
Cod	North Sea	cod.NS	6.0	5.0	7.0	6.0	5.0	7.0	-3.7
Cod	NW Atlantic	cod.NWF	6.3	3.0	9.5	6.3	3.0	9.5	-2.4
Cod	Baltic Sea	cod25	5.4	5.0	5.7	5.0	3.0	7.0	-1.9
Cod	Baltic Sea	cod27	6.1	0.2	12.0	5.0	3.0	7.0	-3.1
Gilthead sea bream	France	gsb	15.5	11.6	19.4	17.9	13.0	17.9	6.1
Herring	North Sea	H.a	12.4	7.0	17.7	11.0	9.0	13.0	2.1
Herring	Baltic Sea	H.b	11.9	8.2	15.7	11.5	6.0	17.0	2.8
Herring	Clyde	H.sC	6.8	2.8	10.8	8.5	5.5	11.5	2.1
Herring	Norway	H.sN	9.5	5.0	14.0	6.0	4.5	7.5	2.1
Haddock	NW Atlantic	hadd	6.9	0.8	12.9	7.8	5.5	10.0	-1.4
Hake	Norway	hake	11.9	9.2	14.5	11.5	10.0	13.0	2.1
Horse mackerel	Celtic Sea	hm	15.3	13.0	17.6	14.3	9.5	19.0	7.7
Mackerel	Celtic Sea	M.w	12.4	9.8	15.1	12.8	9.5	16.0	4.3
Mackerel	Biscay Bay	M.s	14.8	11.9	17.8	12.8	9.5	16.0	4.9
Mackerel	North Sea	M.ns	19.5	14.9	24.2	11.5	10.0	13.0	5.4
Mackerel	NW Atlantic	M.nw	15.4	13.3	17.5	14.8	11.5	18.0	6.9
Menhaden	NW Atlantic	menh	20.1	16.1	24.2	19.0	13.0	25.0	7.8
Plaice	Irish Sea	plaice	8.0	3.2	12.8	6.5	5.0	8.0	1.5
Sand lance	NW Atlantic	SL	6.0	2.0	10.0	5.2	4.0	6.3	-2.1
Sardine	Portugal coasts	Sd	16.5	13.0	20.0	15.3	13.5	17.0	7.2
Sprat	English channel	Sp	11.0	6.2	15.9	12.8	7.5	18.0	2.6
Turbot	France	turbot	18.2	13.2	23.1	14.0	13.0	15.0	4.3

Table S3. Statistical significance of the coefficients of the survival curves. Numbers in bold, italicized text indicate statistically significant results (i.e. p-value<0.05) for all three estimated coefficients. Coefficients refer to the parameters of the Gaussian equation:

$$S = a_s * e^{\frac{-(T-b_S)^2}{2*c_S^2}}$$

			Coefficient values			p-values		
Species name	Area	Species code	a_s	b_s	c_s	a_s	b_s	c_s
Anchovy	Bay of Biscay	An	0.63	23.00	3.30	0.416	0.035	0.207
Herring	North Sea	H.a	0.39	12.39	5.35	0.000	0.000	0.194
Herring	Baltic Sea	H.b	1.06	11.95	3.73	0.883	0.000	0.002
Sprat	Baltic Sea	Sp.b	1.32	8.63	2.73	0.372	0.000	0.002
Blue whiting	NE Atlantic	BW	1.03	9.36	2.43	0.951	0.000	0.043
Capelin	NW Atlantic	c.nw	0.62	6.46	4.13	0.119	0.001	0.265
Horse mackerel	Celtic Sea	hm	0.58	15.32	2.32	0.165	0.000	0.001
Mackerel	Celtic Sea	M.w	1.36	12.44	2.62	***0.042***	***0.000***	***0.000***
Mackerel	Bay of Biscay	M.s	0.45	14.84	2.94	0.057	0.002	0.063
Mackerel	North Sea	M.ns	0.24	19.55	4.65	0.006	0.002	0.222
Mackerel	NW Atlantic	M.nw	0.52	15.39	2.10	***0.008***	***0.000***	***0.000***
Sprat	English Channel	Sp	0.59	11.04	4.87	***0.002***	***0.000***	***0.000***
Herring	Clyde	H.sC	0.68	6.82	3.98	***0.002***	***0.000***	***0.003***
Cod	Irish Sea	cod.Ir	1.00	7.80	6.86	0.906	0.054	0.268
Cod	NW Atlantic	cod.Nf	0.40	5.78	3.80	0.003	0.024	0.176
Cod (Baltic)	Baltic Sea	cod27	0.56	6.08	5.88	***0.007***	***0.002***	***0.039***
Haddock (NWA)	NW Atlantic	hadd	0.41	6.85	6.05	***0.001***	***0.001***	***0.049***
Menhaden	NW Atlantic	menh	0.56	20.13	4.04	0.494	0.055	0.299
Plaice (Ireland)	Irish Sea	plaice	0.77	7.98	4.78	0.132	0.045	0.254
Gilthead sea bream	France	gsb	0.20	15.46	3.91	***0.000***	***0.000***	***0.003***
Turbot	France	turbot	0.54	18.16	4.97	***0.002***	***0.000***	***0.017***

Table S4. List of data type (development and survival data given as raw data, extracted from figures or estimated by equations), number of replicates per experimental temperature and number of experimental temperature for each study used here

Species common name	Species code	Region	Data type	Experimental setup		Source
				Replicates of experimental T (°C)	No. of experimental T (°C)	
Ammodytes americanus Sand lance	SL	NW Atlantic	Raw data	na	4	Smigielski et al. 1984
Clupea harengus Baltic herring	H.b	Kiel Baltic Sea	Extracted from figure; Extracted from figure;	na	16; 10	Blaxter & Hempel 1963, Peck et al. 2012c
Clupea harengus Herring Spring spawners	H.sC H.sN	Clyde Clyde, North Sea Norway	Raw data; Extracted from figure	na na	8; 16	Blaxter 1956; Blaxter & Hempel 1963
Clupea harengus Herring Autumn spawners	H.a	Buchan, Downs, Minch North Minch, North Sea	Extracted from figure; Raw data	na na	18; 8	Blaxter & Hempel 1963 Blaxter 1956
Engraulis encrasicolus Anchovy	An	Bay of Biscay Gulf of Cadiz	Extracted from figure; equation	2 replicates; 3 replicates	7; 5	Ibaibarriaga et al. 2007a; Bernal et al. 2012
Mallotus villosus Capelin Beach spawning	c.nw	Trinity bay and Notre Dame Bay, Newfoundland	Extracted from figure	12 replicates	3	Penton & Davoren 2013
Mallotus villosus Capelin offshore spawning	c.nw	Trinity bay, Newfoundland	Extracted from figure	12 replicates	3	Penton & Davoren 2013

Mallotus villosus Capelin offshore spawning	c.Bs	Barents Sea	Extracted from figure and raw data	na	4	Gjosaeter & Gjosaeter 1986
Micromesistius poutassou Blue whiting	BW	NE Atlantic	Extracted from figure	none	11	Coombs & Hiby 1979
Sardina pilchardus Sardine	Sd	Portugal coasts	Raw data; Raw data; Raw data	None; None; na	5; 5; 4	Miranda et al. 1990; Olmedo et al. 1990 Blaxter 1969 in Miranda et al. 1990
Scomber japonicus Chub mackerel	cm	Pacific	Extracted from figure	5 replicates	7	Hunter & Kimbrell 1980
Scomber scombrus Mackerel	M.s	Biscay Bay-southern stock	Raw data	30 replicates	12	Mendiola et al. 2006
	M.w	Biscay Bay/Celtic Sea-western stock	Raw data	3 replicates	12	Lockwood et al. 1977
	M.ns	North Sea	Extracted from figure	na	6	Danielssen & Iversen 1977
	M.nw	NW Atlantic-Massachusetts	Extracted from figure	2 replicates	8	Worley 1933
Sprattus sprattus Baltic sprat	Sp.b	Baltic sea	Raw data; Extracted from figure	2 replicates; 4 replicates	5; 10	Nissling 2004; Petereit et al. 2008
Sprattus sprattus Sprat	Sp	English channel German Bight, North Sea	Raw data; Extracted from figure	11 replicates; na	19; 7	Thompson et al. 1981; Alheit et al. 1987
Trachurus trachurus Horse mackerel	hm	Celtic Sea NE Atlantic-Iberian region	Raw data; Extracted from figure	2 replicates; 6 replicates	10;6	Pipe & Walker 1987; Cunha et al. 2008
Gadus morhua Atlantic cod	cod.Ir	Irish Sea	Raw data	8 replicates	4	Geffen et al. 2006
	cod.NS	North Sea	Extracted from figure	na	8	Thompson & Riley 1981
	cod.Norw	Norwegian Sea	Extracted from figure	na	7	Iversen & Danielssen 1984
	cod.BtW	Baltic Sea, western	Extracted from figure	na	3	Wieland et al. 1994 and references
	cod.SD25	Baltic Sea, SD25	Extracted from figure	na	7	Wieland et al. 1994
	cod.SD27	Baltic Sea, SD27	Raw data	2 replicates	5	Nissling 2004
	cod.GeB	Georges Bank	Equation	6 replicates	6	Laurence & Rogers 1
	cod.Nf	Newfoundland	Equation	6 replicates	5	Pepin et al. 1997
	cod.NWF	Bay of Fundy, NW Atlantic	Extracted from figure	na	18	Peterson et al. 2004
Melanogrammus aeglefinus haddock	hadd	Georges Bank	Equation	6 replicates	6	Laurence & Rogers 1976
Scophthalmus maximus turbot	turbot	France	Extracted from figure	na	7	Devauchelle et al. 1988
Pleuronectes platessa plaice	plaice	Irish Sea	Extracted from figure	1 replicates	4	Fox et al. 2003

Brevoortia tyrannus Atlantic menhaden	menh	Long Island, NW Atlantic	Extracted from figure	2 replicates	4	Ferraro 1980
Sparus aurata Gilthead seabream	gsb	France	Equation	4 replicates	12	Camus & Koutsikopoulos 1984
Merluccius merluccius European hake	hake	Norway	Raw data	na	3	Bjelland & Skiftesvik 2006

na: no information is provided by the reference about the number of replicates

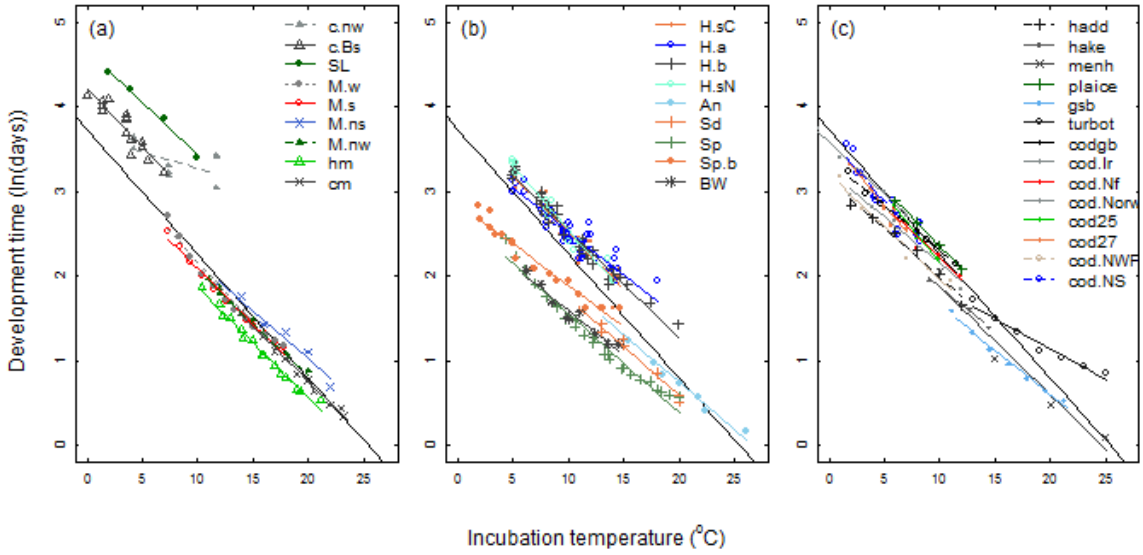

Fig. S1. Developmental period of eggs till 50% hatch, reared in laboratory conditions and at a wide range of temperature. Time given in days (transformed with the natural logarithm) and temperature in °C. Linear regression line fitted to the pooled data (POOLEDDATA) is shown with a black thick line in all panels. Species and populations are indicated with different symbols and colours

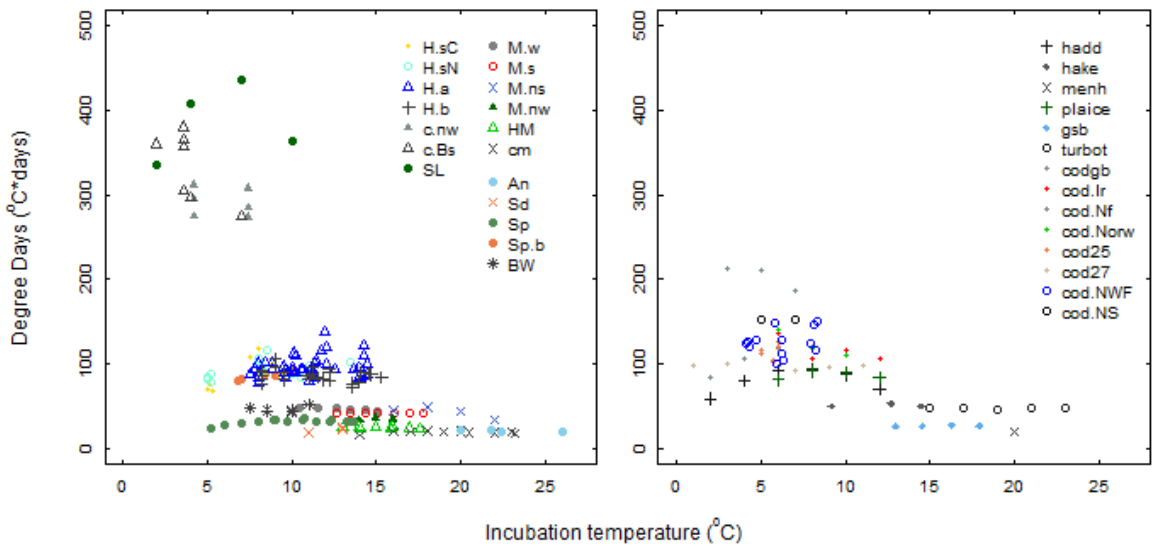

Fig. S2. Degree-days estimated for each experimental temperature for each species and population within the optimal temperature range for survival. The threshold temperature is species/stock-specific and is presented in Table S2

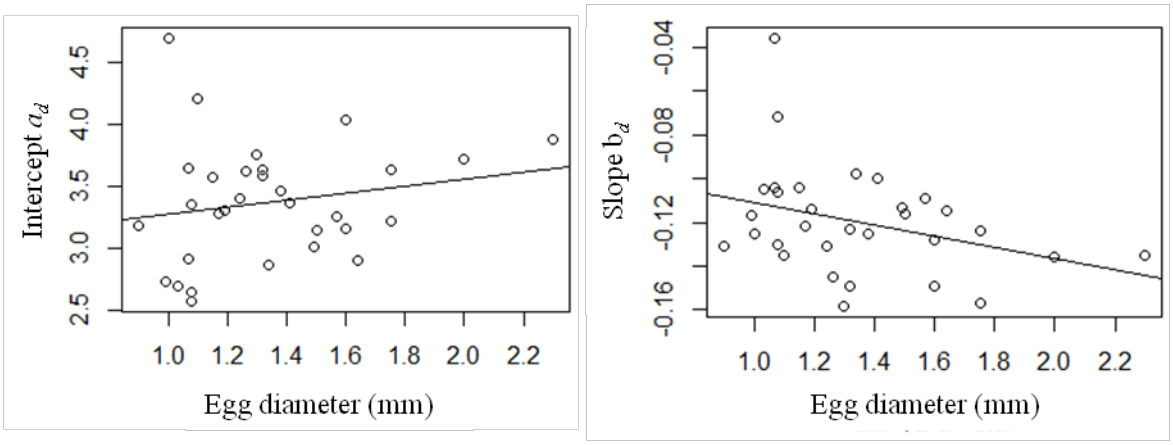

Fig. S3. Regression between the egg diameter (ED; mm) and the (left) intercept (a_d) and the (right) slope (b_d) of ln-development time and temperature regression. Output of regression lines: $a_d = 0.28 \times ED + 2.99$, p-value = 0.31; $b_d = -0.026 \times ED - 0.085$, p-value = 0.06

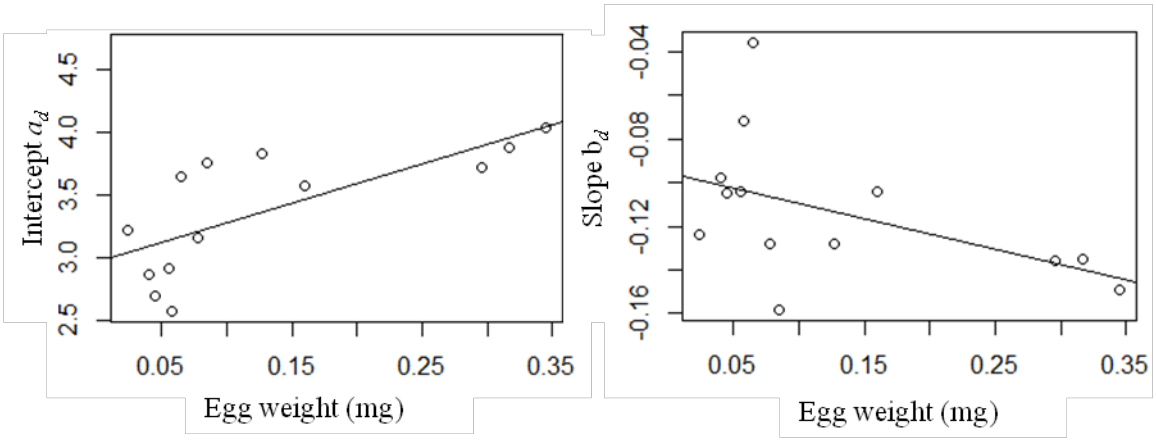

Fig. S4. Regression between the egg weight (EW; mg) and the (left) intercept (a_d) and the (right) slope (b_d) of ln-development time and temperature regression. Output of regression lines: $a_d = 3.12 \times EW + 2.96$, p-value = 0.005; $b_d = -0.142 \times EW - 0.095$, p-value = 0.09