

Northern Benguela *Merluccius paradoxus* annual growth from otolith chronologies used for age verification and as indicators of fisheries-induced and environmental changes

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SUPPLEMENTARY MATERIAL

Table S1. Mean length (cm) at age determined (using the whole otolith method) from about 500-1000 survey otoliths for each year from 2000 to 2016.

Year	Age group (years)						
	1	2	3	4	5	6	7
2000	22.8	27.3	33.9	41.0	49.5	55.7	58.7
2001	22.5	27.4	33.4	41.4	47.8	53.3	58.4
2002	23.3	31.5	36.3	40.7	47.4	51.9	57.7
2003	22.1	31.0	37.1	43.0	48.6	53.8	53.1
2004	24.0	27.3	34.6	43.5	51.2	58.3	66.3
2005	19.7	24.0	33.2	42.6	50.4	57.6	59.8
2006	19.4	25.7	31.8	40.1	49.1	56.1	64.4
2007	22.2	27.7	35.3	40.4	46.1	50.1	54.3
2008	23.7	30.9	35.7	42.4	49.3	54.8	58.5
2009	24.3	28.8	34.8	42.4	49.6	54.8	57.1
2010	22.6	28.8	35.2	43.8	49.7	53.7	55.7
2011	22.8	25.9	35.9	42.6	49.8	54.1	56.3
2012	22.9	30.8	36.0	43.6	50.7	59.0	62.4
2013	23.9	29.8	35.7	42.2	49.3	55.5	60.2
2014	23.6	29.8	37.8	43.6	48.3	54.2	57.6
2015	22.2	29.0	38.5	43.3	49.4	51.9	57.9
2016	22.5	28.1	34.1	41.8	47.2	52.2	59.2

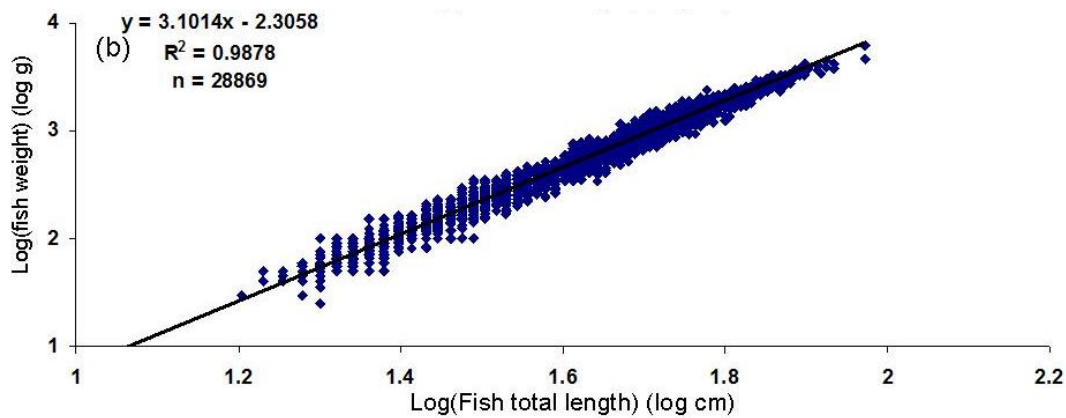


FIGURE S1. Weight – length relationship for *M. paradoxus* collected from Namibian biomass surveys 1999–2013.

Table S2. Results of the GLMM model optimization based on the survey length-weight data of *M. paradoxus* (Table 2). A series of models were fitted with using GLMM, with the full effects model structure in Equation 4. The models were sorted by AICc, and the best model, based on the minimum AICc, is highlighted in bold. DF = degrees of freedom; ΔAIC_c = difference between the AICc and the AICc of the model with the lowest AICc; LL = log likelihood.

Fixed effects	Random effects	DF	AIC_c	ΔAIC_c	LL
Log(Lt)*Sex + Quarter + Lat	1 Year	20	-78582.9	78.28	39311.47
Log(Lt) + Quarter + Lat	1 Year	18	-78577.9	83.32	39306.94
Log(Lt) + Sex + Quarter + Lat	1 Year	19	-78577.1	84.14	39307.54
Log(Lt)* Sex	1 Year + 1 Quarter + 1 Lat	8	-78535.1	126.13	39275.53
Log(Lt)	1 Year + 1 Quarter + 1 Lat	6	-78530.1	131.07	39271.06
Log(Lt) + Sex	1 Year	8	-77907.9	753.29	38961.95
Log(Lt)	1 Year + Quarter	6	-77907.8	753.35	38959.92
Log(Lt)	1 Year + 1 Quarter	5	-77897.9	763.31	38953.94
Log(Lt)	1 Year	5	-77888.7	772.49	38949.35
Log(Lt)		3	-75856.9	2804.26	37931.46

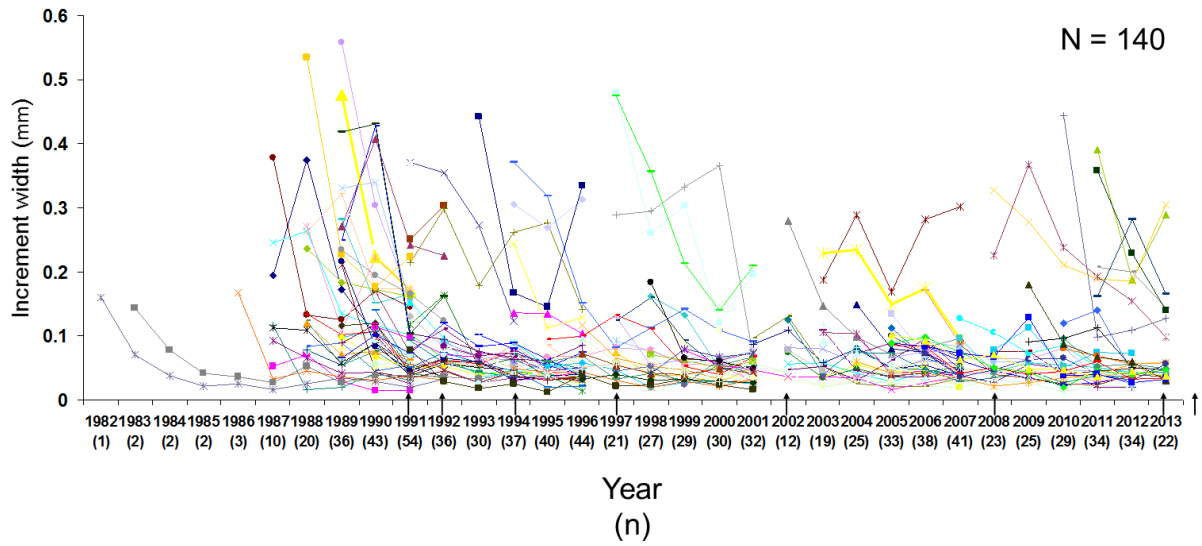


FIGURE S2. Absolute increment width against year of formation for all otoliths of 140 *M. paradoxus* caught off Namibia from surveys in 2014, 2013, 2008, 2002, 1997, 1994, 1992 and 1991 (indicated by arrows). N indicates the total number of increments representing that year.

Table S3. Results of the intrinsic effects (mixed effects) model optimization based on the full dataset of 1982 to 2013 otolith chronologies (Table 1). A series of models were fitted with ML, with the full intrinsic effects model structure in Equation 1. The models were sorted by AICc, and the best model, based on the minimum AICc, is highlighted in bold. AAC = Age-at-capture; Random age slopes for FishID and Cohort denoted by “Age|”; “1|” denotes only a random intercept was calculated; DF = degrees of freedom; ΔAIC_c = difference between the AICc and the AICc of the model with the lowest AICc; LL = restricted log likelihood; Cond. R² is the conditional R² variance explained by fixed and random factors, only calculated for the first nine models ($\Delta AIC_c < 3$).

Fixed effects	Random effects	DF	AIC_c	ΔAIC_c	LL	Cond. R²
Age + Axis	Age FishID	7	604.75	0	-295.31	0.815
Age + Axis + AAC	Age FishID	8	605.69	0.94	-294.76	0.817
Age + Axis + Sex	Age FishID	8	606.26	1.51	-295.04	0.816
Age * Sex + Axis	Age FishID	9	606.45	1.70	-294.12	0.815
Age * Axis	Age FishID	8	606.71	1.96	-295.27	0.816
Age + Axis	Age FishID + 1 Cohort	8	606.78	2.03	-295.30	0.815
Age + Axis + Sex + AAC	Age FishID	9	607.48	2.73	-294.63	0.817
Age * Axis + AAC	Age FishID	9	607.65	2.90	-294.71	0.817
Age + Axis + AAC	Age FishID + 1 Cohort	9	607.70	2.95	-294.74	0.817
Age + Sex + Axis	Age FishID + 1 Cohort	9	608.14	3.39	-294.96	
Age * Axis + Sex	Age FishID	9	608.23	3.48	-295.01	
Age * Sex + Axis	Age FishID + 1 Cohort	10	608.35	3.60	-294.04	
Age + Axis	1 FishID	5	608.56	3.81	-299.24	
Age * Axis	Age FishID + 1 Cohort	9	608.74	3.99	-295.26	
Age * Axis + Sex + AAC	Age FishID	10	609.45	4.70	-294.59	
Age * Sex + Axis + AAC	Age FishID + 1 Cohort	11	609.62	4.87	-293.65	
Age * Axis + AAC	Age FishID + 1 Cohort	10	609.66	4.91	-294.69	
Age * Axis + Sex	Age FishID + 1 Cohort	10	610.12	5.37	-294.92	
Age * Axis	Age FishID + 1 Cohort	9	608.74	3.99	-295.26	
Age + Axis	Age FishID + Age Cohort	10	610.23	5.48	-294.98	
Age * Sex + Axis	Age FishID + Age Cohort	12	610.84	6.09	-293.23	
Age + Axis + AAC	Age FishID + Age Cohort	11	611.22	6.47	-294.45	
Age + Sex + Axis	Age FishID + Age Cohort	11	611.33	6.58	-294.50	
Age * Sex + Axis + AAC	Age FishID + Age Cohort	13	612.32	7.57	-292.94	
Age + AAC	Age FishID + 1 Cohort	8	1046.48	441.73	-515.15	
Age + Sex + AAC	Age FishID + 1 Cohort	9	1047.22	442.47	-514.50	
Age + AAC	Age FishID + Age Cohort	10	1048.48	443.73	-514.10	
Age * Sex + AAC	Age FishID + 1 Cohort	10	1048.80	444.05	-514.27	
Age + Sex + AAC	Age FishID + Age Cohort	11	1049.70	444.95	-513.69	
Age	Age FishID + 1 Cohort	7	1064.63	459.88	-525.25	
Age	Age FishID + Age Cohort	9	1065.58	460.83	-523.68	
Age + Sex	Age FishID + 1 Cohort	8	1066.65	461.90	-525.24	
Age + Sex	Age FishID + Age Cohort	10	1067.55	462.80	-523.64	

Table S4. Results of the intrinsic effects plus extrinsic effects model optimization based on the full dataset of 1982 to 2013 otolith chronologies of *M. paradoxus* (Table 1). The three top models from the intrinsic effects selection were used, adding random effects year as intercept only (1|Year) or random effects age slope and intercept (Age|FishID). The models were fitted with ML and were sorted by AICc. The best model, based on the minimum AICc, is highlighted in bold. AAC = Age-at-capture; DF = degrees of freedom; ΔAIC_c = difference between the AICc and the AICc of the model with the lowest AICc; LL = restricted log likelihood; Cond. R^2 is the conditional R^2 variance explained by fixed and random factors.

Fixed effects	Random effects	DF	AIC_c	ΔAIC_c	LL	Cond. R^2
Age + Axis	Age FishID + 1 Year	8	603.14	0	-293.48	0.820
Age + Axis + AAC	Age FishID + 1 Year	9	603.70	0.56	-292.74	0.823
Age + Axis + Sex	Age FishID + 1 Year	10	605.49	2.34	-292.61	0.823
Age + Axis	Age FishID + Age Year	10	607.07	3.93	-293.40	0.821
Age + Axis + AAC	Age FishID + Age Year	11	607.63	4.49	-292.66	0.823
Age + Axis + Sex	Age FishID + Age Year	12	609.44	6.30	-292.53	0.823

Table S5. Optimal model parameter estimates and test statistics describing Fixed and Random sources of weight-at-length variation in *M. paradoxus* from research surveys along the Namibian coast 1994 to 2013.

Fixed effects				Random effects		
Covariate	Estimate	SE	t-value	Covariate	Variance component	Standard deviation
Intercept	6.189	0.0062	979.90	Year	0.0005	0.02186
Length	3.107	0.0021	1511.50	Residual	0.0071	0.08416
Sex M	-0.002	0.0011	-1.84	N = 37267		
Quarter 2	0.019	0.0047	3.98	Groups = 20		
Quarter 4	-0.023	0.0032	-6.95			
fLat18	-0.021	0.0046	-4.58			
fLat19	-0.007	0.0042	-1.62			
fLat20	-0.015	0.0042	-3.48			
fLat21	-0.013	0.0042	-3.10			
fLat22	-0.018	0.0042	-4.22			
fLat23	-0.008	0.0042	-1.90			
fLat24	-0.011	0.0042	-2.64			
fLat25	0.008	0.0043	1.95			
fLat26	0.010	0.0042	2.51			
fLat27	0.017	0.0042	4.07			
fLat28	0.012	0.0044	2.82			
fLat29	-0.001	0.0044	-0.28			
Length*Sex	-0.012	0.0041	-2.80			
Conditional R²	0.989					

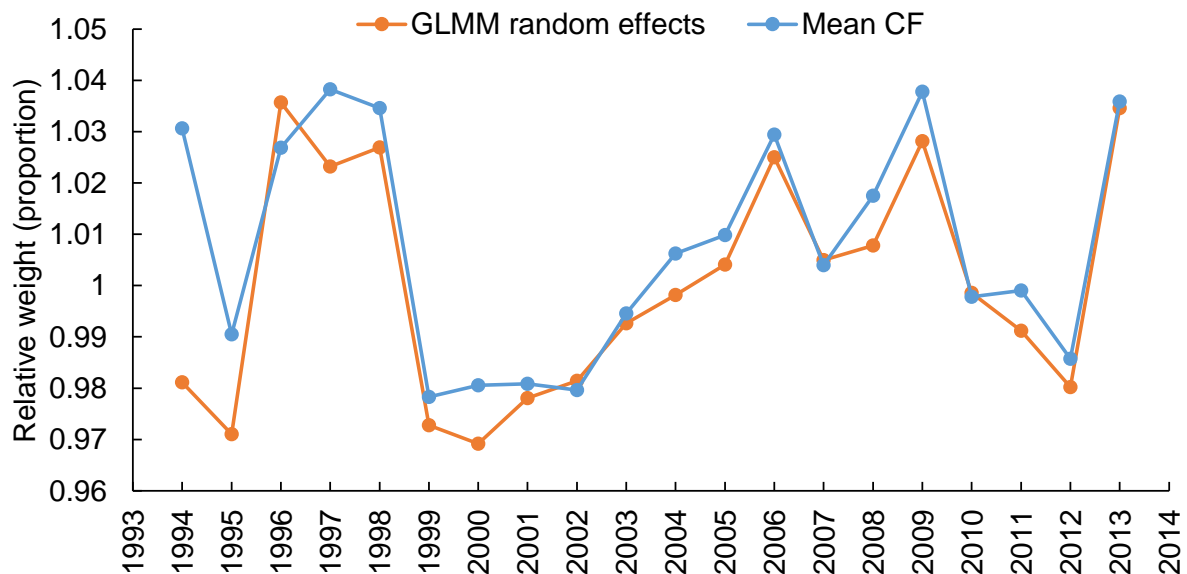


FIGURE S3. Relative weight (fish condition, CF) calculated as a mean for each summer survey* (blue) and predicted from a GLMM model (Equation 4) for each year (orange) for *M. paradoxus* caught along the Namibian coast during research surveys 1994 to 2013. *The mean relative weight of Quarter 2 was used for 1995.

FIGURE S3 shows that GLMM-estimated intercept and mean were similar, but in order to account for all factors (Equation 4), the GLMM-estimated condition factors (year-intercept) were used for all comparisons and correlations with *M. paradoxus* growth.

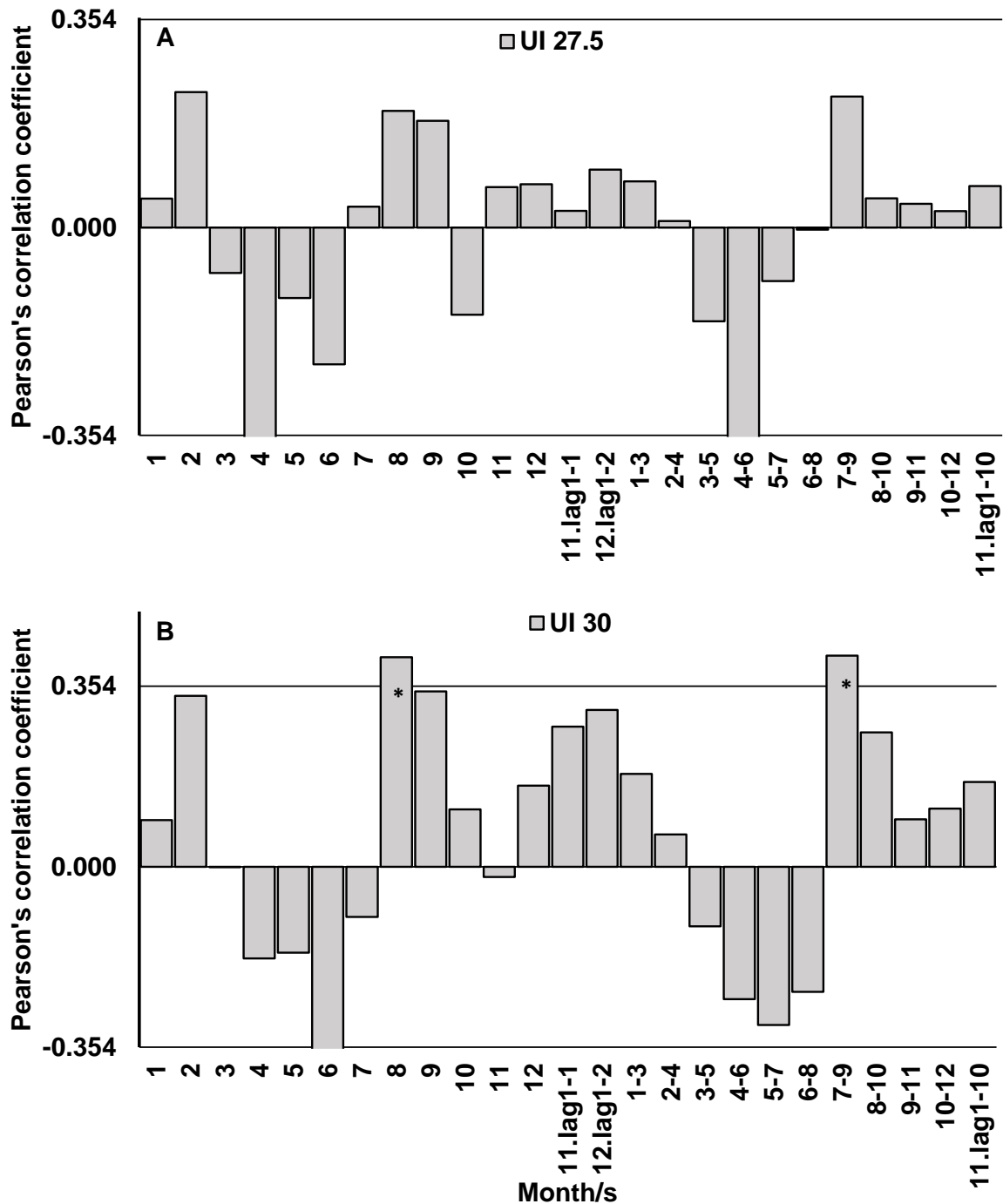


FIGURE S4. Pearson's correlation coefficients for *M. paradoxus* BLUP of annual otolith growth against mean monthly (lag 0) (1 to 12), mean 3-monthly (including lag 1 of 11 and 12), and mean annual (11.lag1-10) upwelling index calculated along the coast for (A) only the Lüderitz upwelling cell (27.5): the area 27°30'S; and for (B) the Namaqua upwelling cell (30): the area at 30°S. The vertical lines demarcate the 95% critical values (n=32, two-tailed). Correlation coefficients above the 95% critical value are demarcated with '*'.

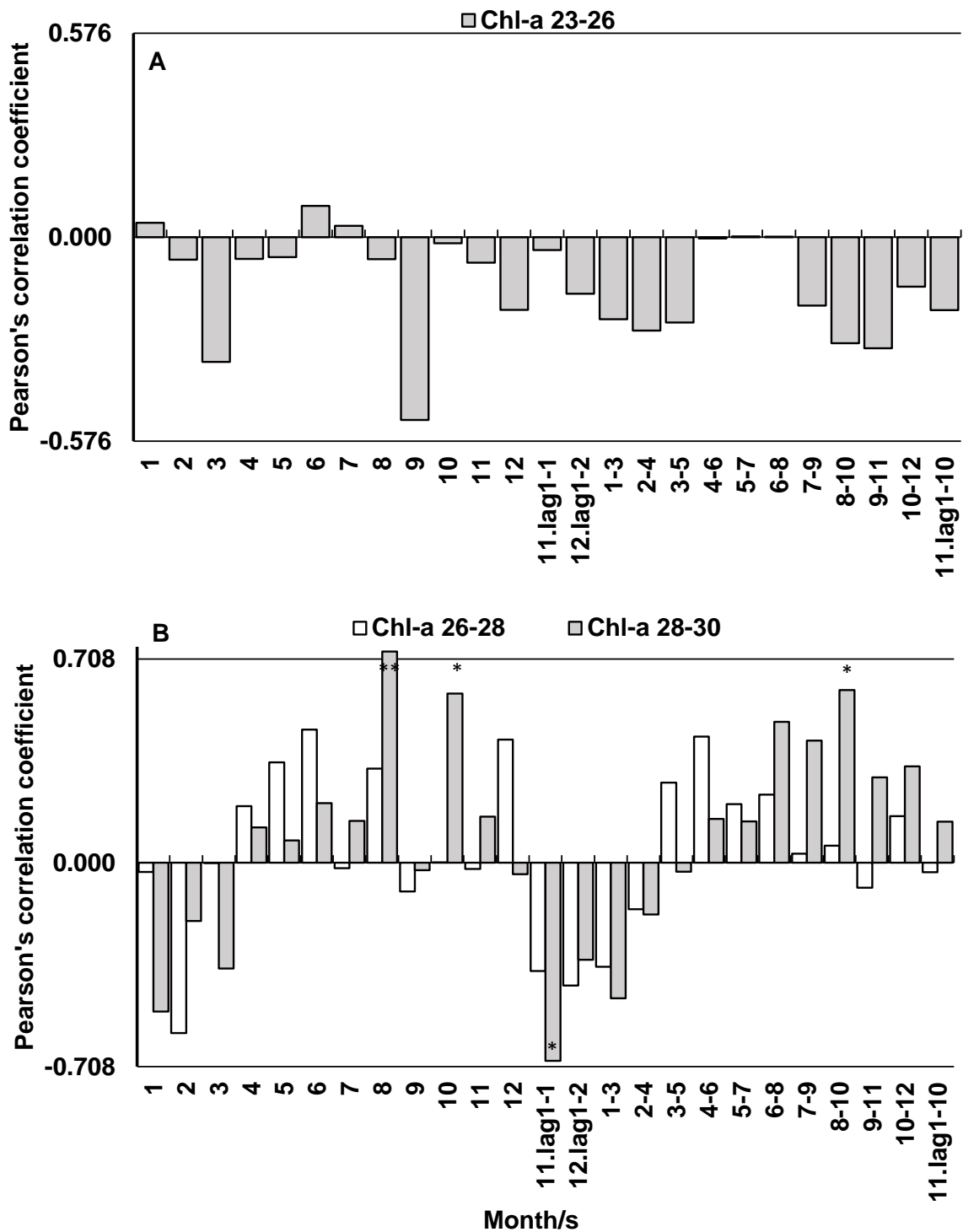


FIGURE S5. Pearson's correlation coefficients for *M. paradoxus* BLUP of annual otolith growth against mean monthly (lag 0) (1 to 12), mean 3-monthly (including lag 1 of 11 and 12), and mean annual (11.lag1-10) chlorophyll-a concentration in mg m^{-3} calculated for (A) Zone 4: the area -23.0 to -26.0 latitude, 10.0–15.0 longitude (Chl-a 23-26, grey bars); and for (B) LUC and Namaqua: the area -26.0 to -28.0 latitude, 10.0–15.0 longitude (Chl-a 26-28, white bars) and the area -28.0 to -30.0 latitude, 11.0–17.0 longitude (Chl-a 28-30, grey bars). The vertical lines demarcate the 99% critical values ($n=12$, two-tailed). Correlation coefficients above the 95% critical value are demarcated with '*' and those above the 99% value are demarcated with '**'.

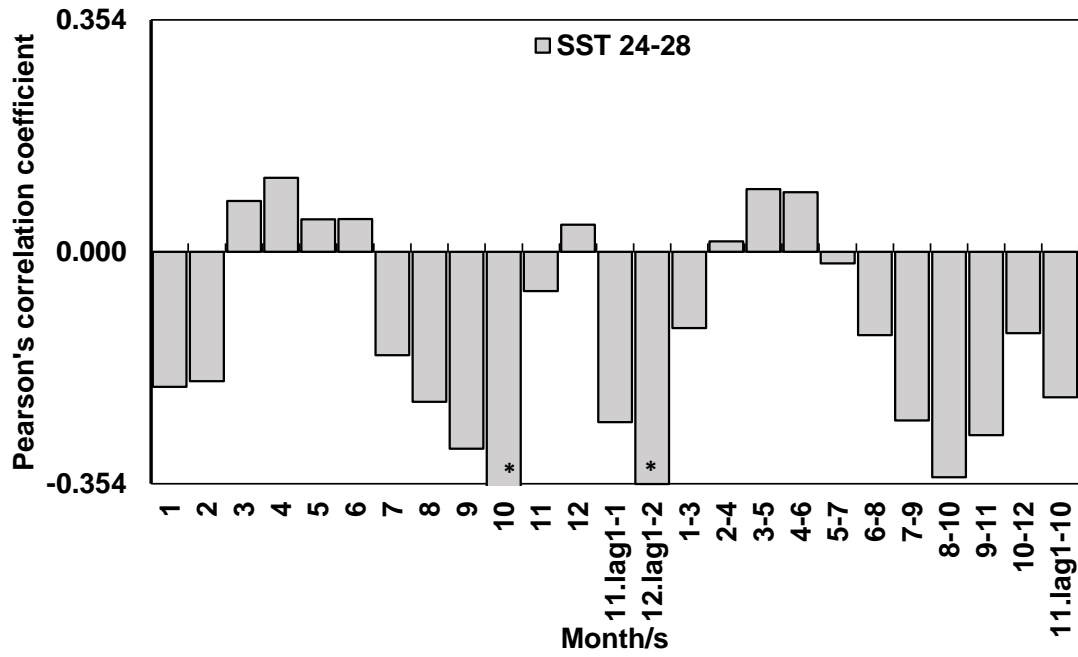


FIGURE S6. Pearson's correlation coefficients for *M. paradoxus* BLUP of annual otolith growth against mean monthly (lag 0) (1 to 12), mean 3-monthly (including lag 1 of 11 and 12), and mean annual (11.lag1-10) Sea Surface Temperature (SST) calculated for southern Namibia: the area -24.0 to -28.0 latitude, 13.0-15.0 longitude. The vertical lines demarcate the 95% critical values (n=32, two-tailed). Correlation coefficients above the 95% critical value are demarcated with '*'.

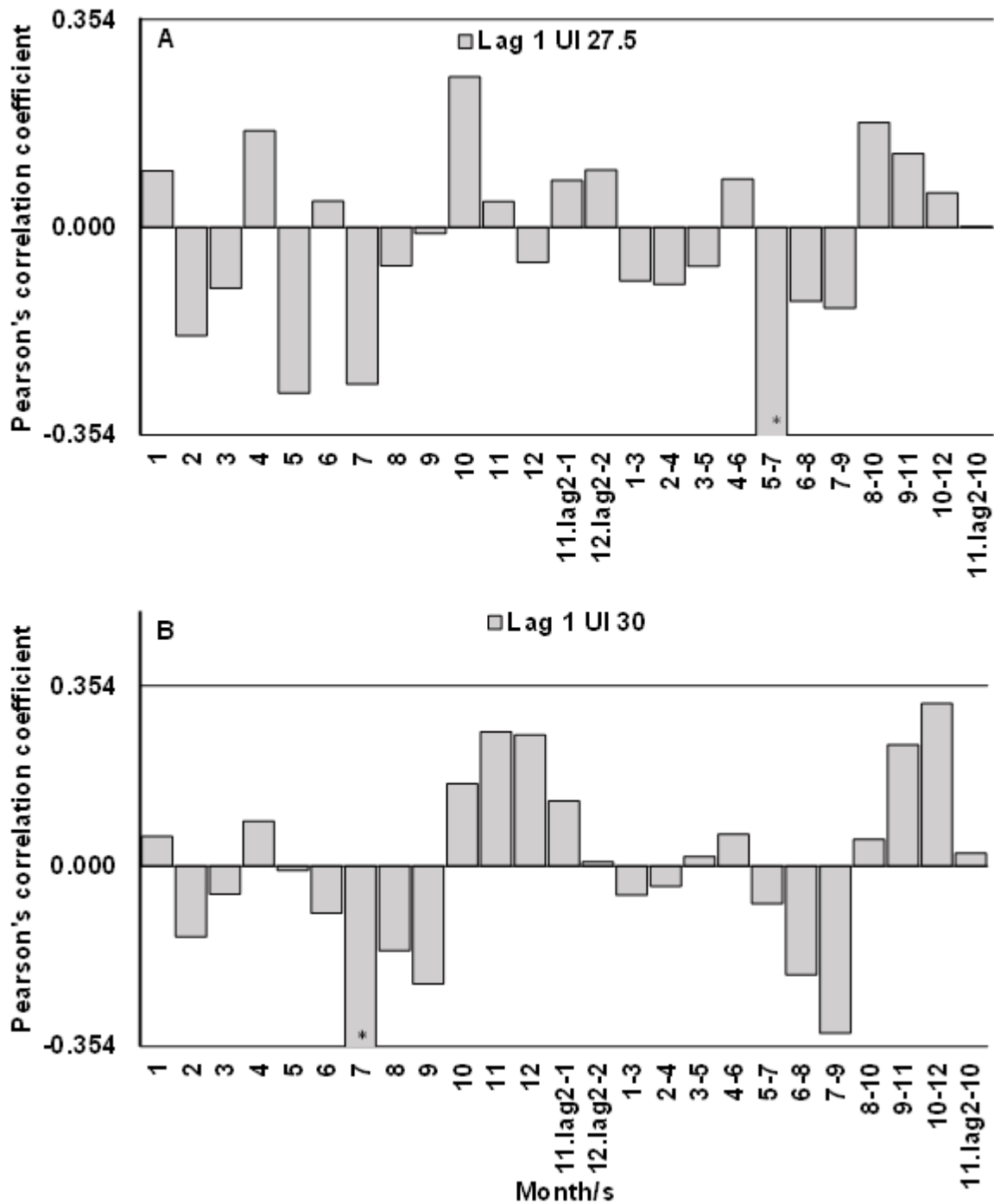


FIGURE S7. Pearson's correlation coefficients for *M. paradoxus* BLUP of annual otolith growth against previous year's (lag 1) mean monthly (1 to 12), mean 3-monthly (including lag 2 of 11 and 12), and mean annual (11.lag2-10) upwelling index calculated along the coast for (A) only the Lüderitz upwelling cell (27.5): the area 27°30'S; and for (B) the Namaqua upwelling cell (30): the area at 30°S. The vertical lines demarcate the 95% critical values (n=32, two-tailed). Correlation coefficients above the 95% critical value are demarcated with '*'. .

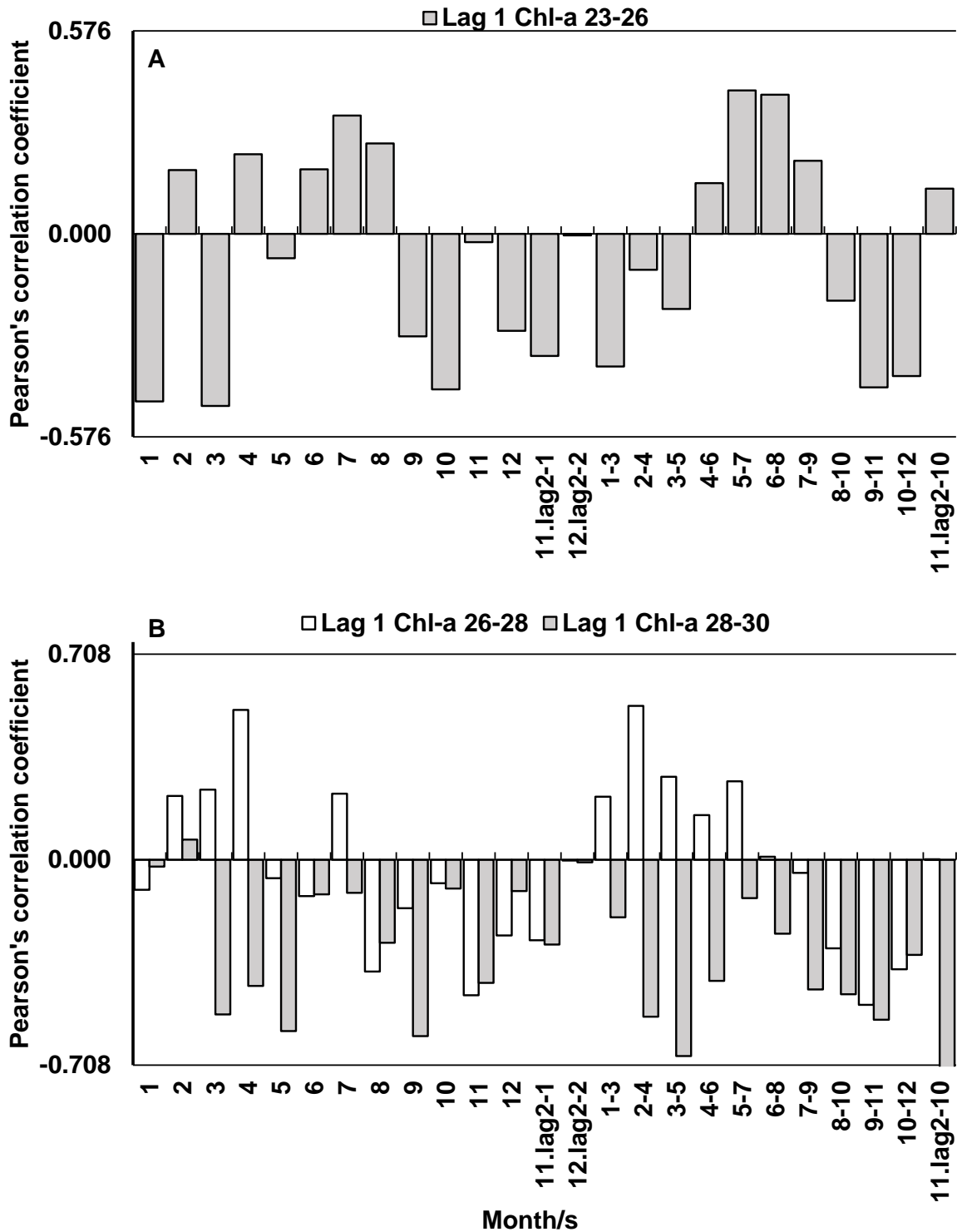


FIGURE S8. Pearson's correlation coefficients for *M. paradoxus* BLUP of annual otolith growth against previous year's (lag 1) mean monthly (1 to 12), mean 3-monthly (including lag 2 of 11 and 12), and mean annual (11.lag2-10) chlorophyll-a concentration in mg m^{-3} calculated for (A) Zone 4: the area -23.0 to -26.0 latitude, 10.0–15.0 longitude (Chl-a 23-26, grey bars); and for (B) LUC and Namaqua: the area -26.0 to -28.0 latitude, 10.0–15.0 longitude (Chl-a 26-28, white bars) and the area -28.0 to -30.0 latitude, 11.0–17.0 longitude (Chl-a 28-30, grey bars). The vertical lines demarcate the 99% critical values ($n=12$, two-tailed). Correlation coefficients above the 95% critical value are demarcated with '*' and those above the 99% value are demarcated with '**'.

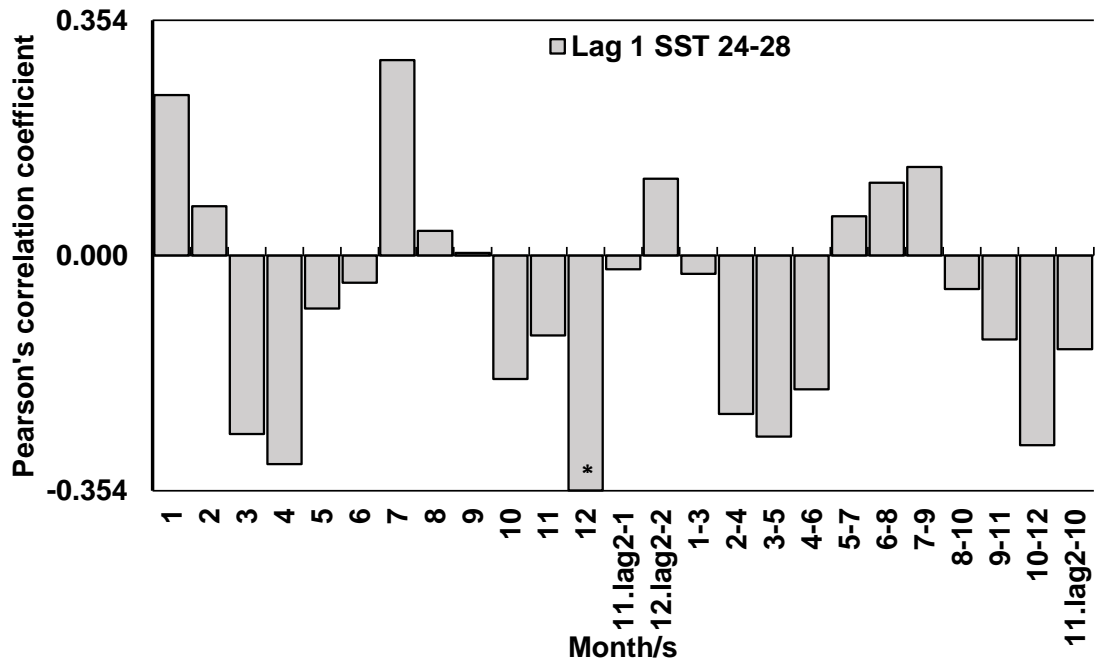


FIGURE S9. Pearson's correlation coefficients for *M. paradoxus* BLUP of annual otolith growth against lag 1 mean monthly (1 to 12), mean 3-monthly (including lag 2 of 11 and 12), and mean annual (11.lag2-10) Sea Surface Temperature (SST) calculated for southern Namibia: the area -24.0 to -28.0 latitude, 13.0–15.0 longitude. The vertical lines demarcate the 95% critical values (n=32, two-tailed). Correlation coefficients above the 95% critical value are demarcated with '*'.

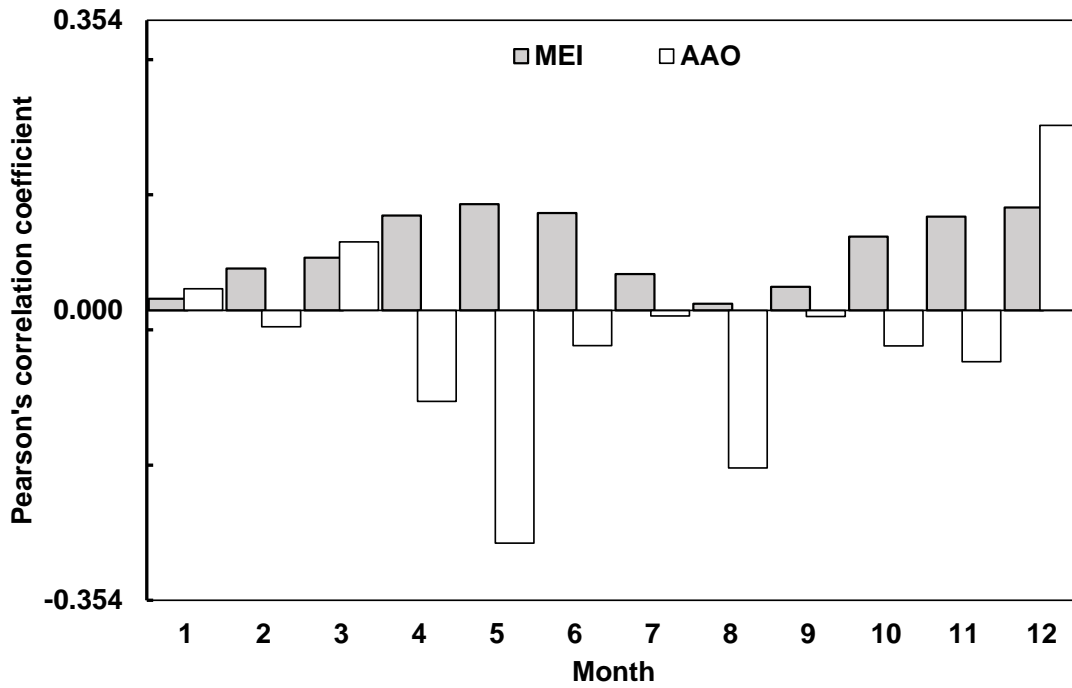


FIGURE S10. Pearson's correlation coefficients for *M. paradoxus* BLUP of annual otolith growth against the mean monthly (lag 0) (1 to 12) Multivariate El Niño Southern Oscillation Index (MEI grey bars) and Antarctic Annular Oscillation Index (AAO, white bars). The vertical lines demarcate the 95% critical values (n=32, two-tailed).

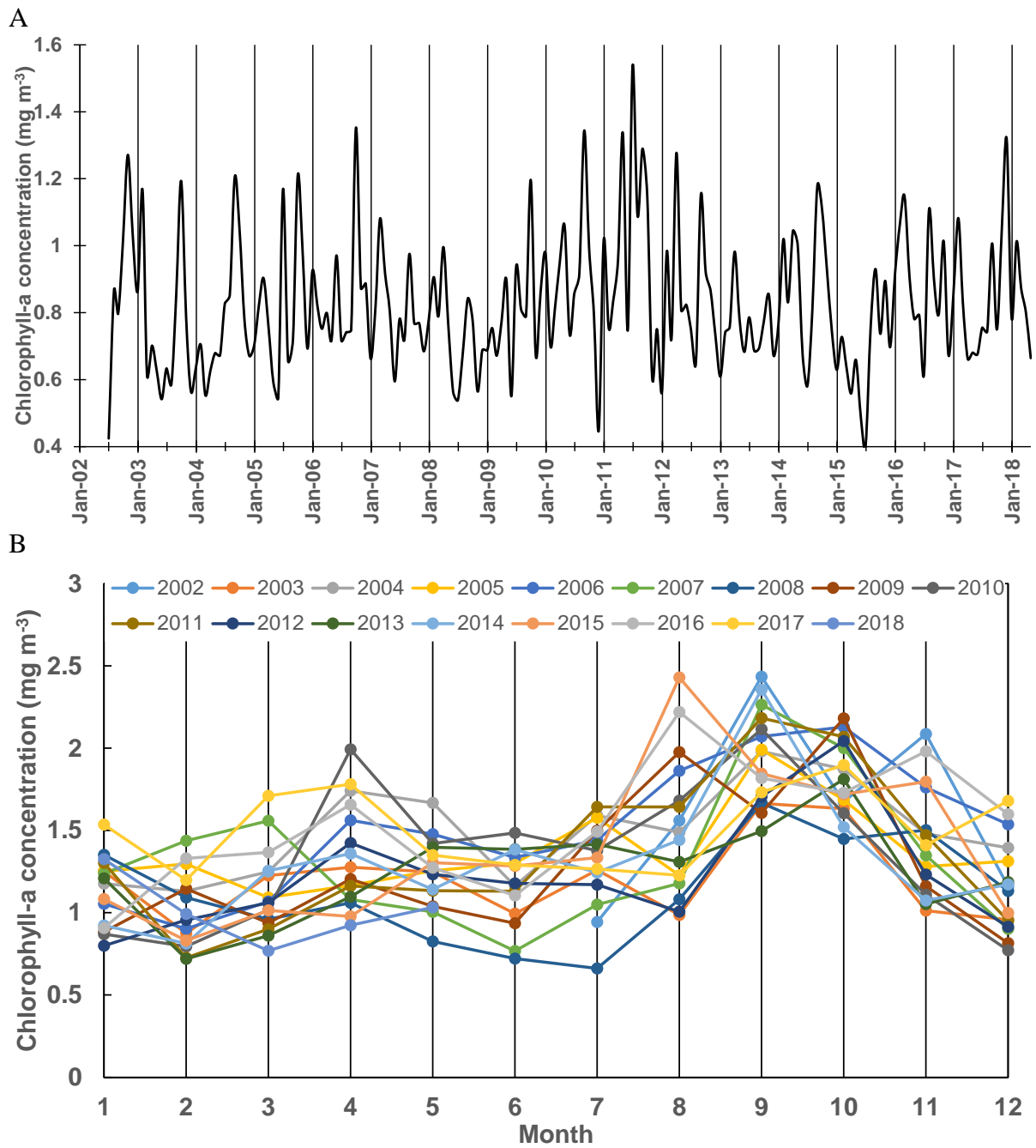


FIGURE S11. Mean monthly chlorophyll-a concentration (mg m⁻³) from satellite data for the area 28–30°S (Namaqua upwelling cell) shown A. from July 2002 to May 2018 and B. by month for each year.