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Supplementary material

Range extensions in anemonefishes and host sea anemones in eastern Australia: potential constraints to tropicalisation

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Sea-temperature patterns

There were distinct differences in minimum, maximum and average sea temperature across-shelf in the Solitaries Region for the 3 years before the present survey, with warmer sea temperature further offshore. South Solitary Island had the highest sea temperatures of the survey locations in the Solitaries (16.8°C minimum, 26.8°C maximum, 21.6°C average), whereas temperatures were lower at inshore sites (16.4°C minimum, 25.7°C maximum, 21.2°C average).

Although Fish Rock had average and maximum sea temperatures very similar to those of South Solitary, the minimum temperature recorded was much lower at Fish Rock (14.5 *v.* 16.8°C). Further inshore at Smoky Cape (Black Rock, Green Island), average, maximum and minimum temperatures were ~0.5–1°C lower than at Fish Rock.

The average temperature at Broughton Island over the study period was 2.8°C lower than that at Fish Rock. The proportion of time that sea-temperature was below 18°C was much higher at Broughton Island and the proportion of time it was above 24°C much lower.

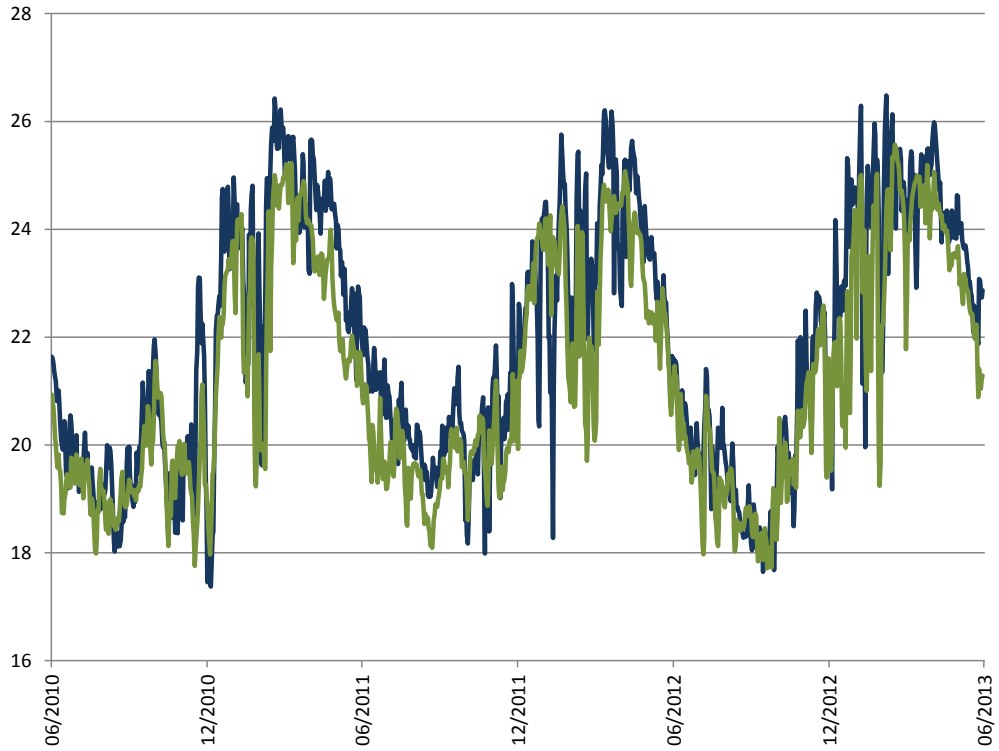

Fig. S1. Daily average sea temperatures (°C) from logging thermistor stations recording every 30 min at inshore Solitaries (green line) *v*. Fish Rock (blue line).

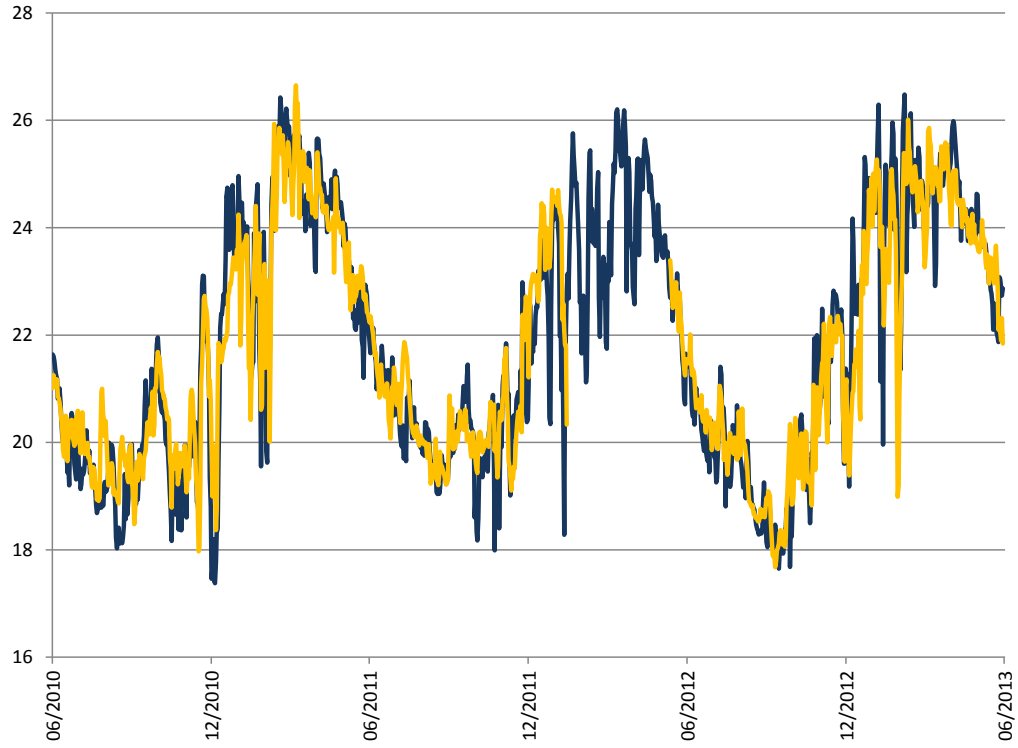

Fig. S2. Daily average sea temperatures (°C) from logging thermistor stations recording every 30 min at South Solitary Island (orange line) *v*. Fish Rock (blue line).

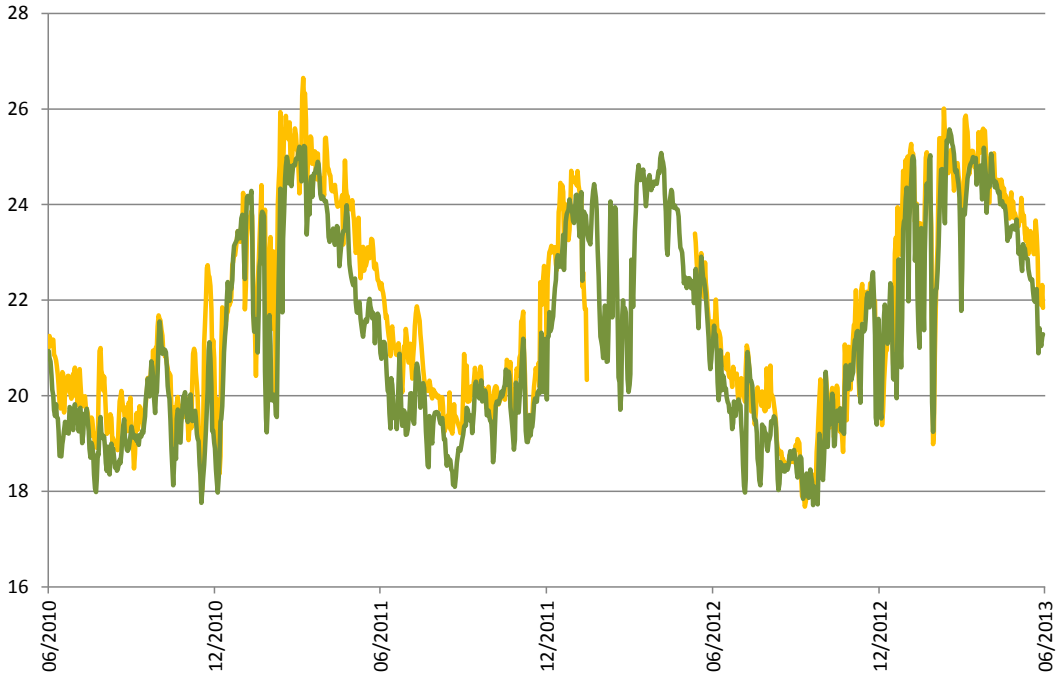

Fig. S3. Daily average sea temperatures (°C) from logging thermistor stations recording every 30 min at inshore Solitaries (green line) *v.* South Solitary Island (orange line).

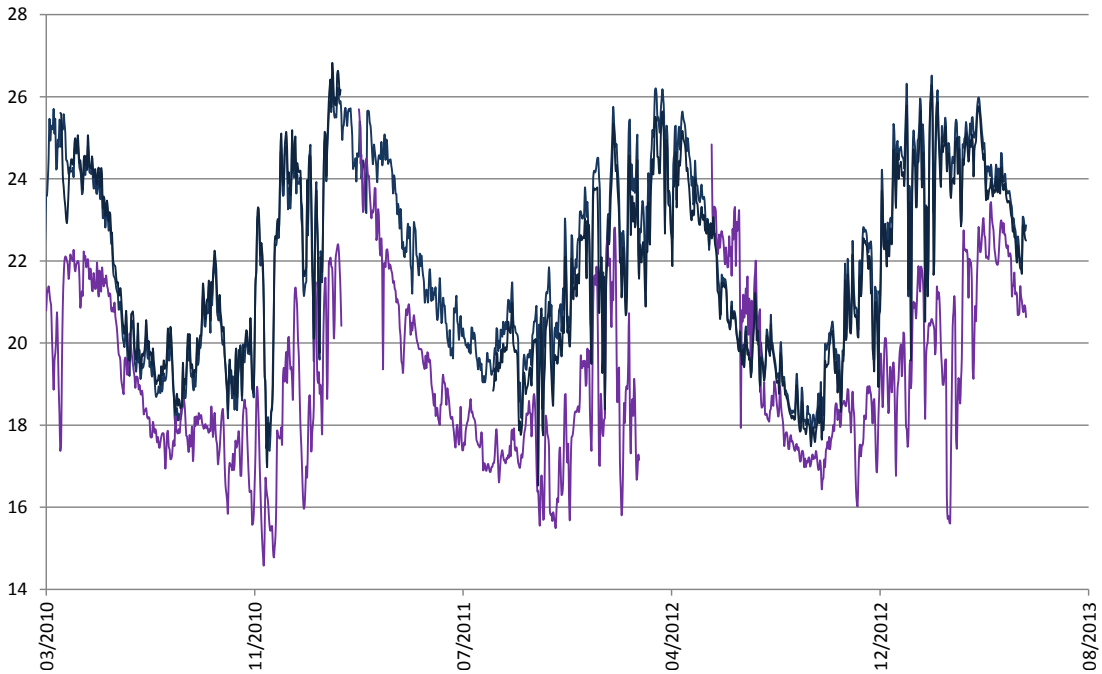

Fig. S4. Daily average sea temperatures (°C) from logging thermistor stations recording every 60 min at Fish Rock (blue line) *v.* Broughton Island (purple line).

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GLM results

Table S1. Collinearity

Collinear	(Pearson and Spearman correlations)
Pearson	Latitude and minimum temperature (0.9)
Pearson, Spearman	Maximum temperature and average temperature (0.76, 0.86)
Spearman	Distance from shore and average temp (0.70)

Summary

Entacmaea quadricolor

Where *E. quadricolor* was recorded, it was more abundant with a greater area of emergent rock and with higher average temperatures and a greater distance from shore. The final model for *E. quadricolor* was emergent rock + average temperature (AIC 45.8), with both variables being significant (Table 3 of the main paper), although a model with emergent rock + distance from shore (AIC 46.7) was similar. This supported observed patterns, with highest abundance offshore at islands where sea temperature is higher, on average, than it is closer to the mainland coast. Individually, emergent rock was the most important predictor (AIC 51.5) of the abundance of *E quadricolor*. Area of emergent rock + average temperature explained ~68% of the variation for the count model. Area of emergent rock individually explained ~31% of the variation.

Heteractis crispa

Where *H. crispa* was recorded, it was more abundant with a greater area of emergent rock and with higher average temperatures. The final model was emergent rock + average temperature (AIC 93.0), with both significantly contributing to abundance (Table 3 of the main paper). Models with emergent rock + maximum temperature (AIC 99.1), maximum temperature (AIC 103.1) and emergent rock (AIC 105) were less suitable. Area of emergent rock + average temperature explained ~31% of the variation for the count model. Area of emergent rock individually explained ~22% of the variation.

Amphiprion akindynos

Where *A. akindynos* was recorded, it was more abundant with a greater area of emergent rock and with a higher maximum temperature. The final model was emergent rock + maximum temperature (AIC 72.8), with both significantly contributing to abundance (Table 3 of the main paper). The model with emergent rock (AIC 73.0) was similar and maximum temperature (AIC 78.5) was less suitable. Area of emergent rock + maximum temperature explained ~24% of the variation for the count model. Area of emergent rock individually explained ~21% of the variation.

Amphiprion latezonatus

Where *A. latezonatus* was recorded, it was more abundant with a greater area of emergent rock and with higher average temperatures. The final model was emergent rock + average temperature (AIC 42.1), with emergent rock marginally (0.07) contributing to abundance (Table 3 of the main paper). Models with emergent rock + average temperature + distance from shore (AIC 49.0), emergent rock (AIC 49.6) or average temperature (AIC 51.8) were less

suitable. Area of emergent rock + average temperature explained ~68% of the variation for the count model and area of emergent rock individually explained ~31% of the variation. This was similar to that found for *E. quadricolor*.

Dascyllus trimaculatus

Where *D. trimaculatus* was recorded, it was more abundant with a greater area of emergent rock and less abundant with a decreasing minimum temperature. The final model was emergent rock + minimum temperature (AIC 112.3), with both significantly contributing to abundance (Table 3 of the main paper). Area of emergent rock + minimum temperature explained ~26% of the variation for the count model. Area of emergent rock individually explained ~21% of the variation.

Table S2. GLM output

Bold variables show final models based on lowest AIC for each species

Entacmaea quadricolor

Model: zero-inflated negative binomial

Call: zeroinfl(formula = Eq ~**emerge_rk + AvTemp**, data = anemone, dist = 'negbin')

Pearson residuals

Min.	1Q	Median	3Q	Max.
–0.9688169	–0.0824485	–0.0011823	–0.0001437	1.4700244

Count model coefficients (negbin with log link)

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	–234.0401	83.0570	–2.818	0.004835**
emerge_rk	0.6385	0.1689	3.781	0.000156***
AvTemp	10.6490	3.8052	2.799	0.005133**
Log(theta)	0.1311	0.7653	0.171	0.864014

Zero-inflation model coefficients (binomial with logit link)

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	549.089	1394.006	0.394	0.694
emerge_rk	–1.918	5.256	-0.365	0.715
AvTemp	–25.231	63.918	–0.395	0.693

Signif. codes 0'***' 0.001'**' 0.01'*' 0.05'.' 0.1' ' 1

Theta = 1.14

Number of iterations in Broyden–Fletcher–Goldfarb–Shanno (BFGS) optimisation: 4951

Log-likelihood: –15.91 on 7 d.f.

d.f.	AIC	
7	46.73931	emerg rk + dist shore
7	45.82391	emerg rk + av temp
5	51.50527	emerg rk

Diagnostic test on non-zero sites

Emergent rock

Call: glm(formula = I(Eq > 0) ~**emerge_rk**, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.4221	–0.4576	–0.3028	–0.2914	2.3955

Coefficients

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	–3.1376	1.2710	–2.469	0.0136 *
emerge_rk	0.3891	0.1749	2.225	0.0261 *

Signif. codes 0'***' 0.001'**' 0.01'*' 0.05'.' 0.1' ' 1

(Dispersion parameter for binomial family taken to be 1)
Null deviance: 23.053 on 20 d.f.
Residual deviance: 16.013 on 19 d.f.
Akaike information criterion: 20.013

Emergent rock + Av temp

glm(formula = I(Eq > 0) ~**emerge_rk + AvTemp**, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.22566	–0.12100	–0.01047	–0.00007	1.73737

Coefficients

	Estimate	s.e.	*z*-value	Pr(> |z|)
(Intercept)	–409.373	411.131	–0.996	0.319
emerge_rk	1.140	1.303	0.875	0.381
AvTemp	18.680	18.762	0.996	0.319

(Dispersion parameter for binomial family taken to be 1)
Null deviance: 23.0527 on 20 d.f.
Residual deviance: 7.4646 on 18 d.f.
Akaike informatio criterion: 13.465
Number of Fisher scoring iterations: 9

Heteractis crispa

Model: zero-inflated negative binomial

Call: zeroinfl(formula = Hc ~**emerge_rk + AvTemp**, data = anemone, dist = 'negbin', link = 'logit')

Pearson residuals

Min.	1Q	Median	3Q	Max.
–1.0067	–0.5106	–0.2718	0.3431	2.5022

Count model coefficients (negbin with log link)

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	–131.68645	21.09320	–6.243	4.29e-10***
emerge_rk	0.20212	0.04707	4.294	1.76e–05***
AvTemp	6.19892	0.97236	6.375	1.83e–10***
Log(theta)	1.94895	0.83850	2.324	0.0201*

Zero-inflation model coefficients (binomial with logit link)

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	92.0926	67.6519	1.361	0.173
emerge_rk	–0.3306	0.1657	–1.995	0.046*
AvTemp	–4.2059	3.1336	–1.342	0.180

Signif. codes 0'***' 0.001'**' 0.01'*' 0.05'.' 0.1' ' 1

Theta = 7.0213
Number of iterations in Broyden–Fletcher–Goldfarb–Shanno (BFGS) optimisation: 61
Log-likelihood: –39.54 on 7 d.f.

d.f.	Akaike information criterion	
7	93.08987	emerg rk + av temp
7	99.17366	emerg rk + maxTemp
5	103.15948	MaxTemp

Diagnostic test on non-zero sites

Emergent rock

Call: glm(formula = I(Hc > 0) ~**emerge_rk**, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.7068	–0.6475	–0.5759	0.6808	1.9383

Coefficients

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	–1.7127	0.7826	–2.188	0.0286*
emerge_rk	0.3057	0.1394	2.193	0.0283*

Signif. codes 0'***' 0.001'**' 0.01'*' 0.05'.' 0.1' ' 1

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 27.910 on 20 d.f.

Residual deviance: 21.983 on 19 d.f.

AIC: 25.983

Emergent rock + Av temp

glm(formula = I(Hc > 0) ~**emerge_rk + AvTemp**, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.4027	–0.7472	–0.4278	0.4364	2.1703

Coefficients

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	–98.2909	65.3569	–1.504	0.133
emerge_rk	0.3437	0.1639	2.097	0.036*
AvTemp	4.4897	3.0289	1.482	0.138

Signif. codes 0'***' 0.001'**' 0.01'*' 0.05'.' 0.1' ' 1

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 27.91 on 20 d.f.

Residual deviance: 19.38 on 18 d.f.

Akaike informatio criterion: 25.38

Number of Fisher scoring iterations: 5

Amphiprion akindynos

Model: zero-inflated negative binomial

Call: zeroinfl(formula = Aa ~**emerge_rk + MaxTemp**, data = anemone, dist = 'negbin')

Pearson residuals

Min.	1Q	Median	3Q	Max.
–1.1880	–0.5140	–0.3180	0.1905	2.8810

Count model coefficients (negbin with log link)

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	–19.21787	9.93833	–1.934	0.0531
emerge_rk	0.10066	0.05013	2.008	0.0447*
MaxTemp	0.76966	0.38042	2.023	0.0431*
Log(theta)	9.58731	107.92486	0.089	0.9292

Zero-inflation model coefficients (binomial with logit link)

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	24.3071	31.2929	0.777	0.4373
emerge_rk	–0.3131	0.1529	–2.048	0.0405*
MaxTemp	–0.8630	1.1864	–0.727	0.4670

Signif. codes 0'***' 0.001'**' 0.01'*' 0.05'.' 0.1' ' 1

Theta = 14578.6547

Number of iterations in BFGS optimisation: 138

Log-likelihood: –29.42 on 7 d.f.

d.f.	AIC	
7	72.83895	emerg rk + maxT
5	73.01584	emerg rk
5	78.52842	maxT

Diagnostic test on non-zero sites

Emergent rock

Call: glm(formula = I(Aa > 0) ~emerge_rk, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.7068	–0.6475	–0.5759	0.6808	1.9383

Coefficients

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	–1.7127	0.7826	–2.188	0.0286*
emerge_rk	0.3057	0.1394	2.193	0.0283*

Signif. codes 0'***' 0.001'**' 0.01'*' 0.05'.' 0.1' ' 1

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 27.910 on 20 d.f.

Residual deviance: 21.983 on 19 d.f.

Akaike information criterion: 25.983

Emergent rock + Max.Temp

glm(formula = I(Aa > 0) ~**emerge_rk + Max.Temp**, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.5456	–0.7510	–0.5110	0.4994	2.1076

Coefficients

	Estimate	s.e.	*z*-value	Pr(>|z|)		
(Intercept)	–26.6429	30.9108	–0.862	0.3887		
emerge_rk	0.3204	0.1508	2.124	0.0336*		
MaxTemp	0.9488	1.1724	0.809	0.4183		
Signif. codes	0'***'	0.001'**'	0.01'*'	0.05'.'	0.1' '	1

(Dispersion parameter for binomial family taken to be 1)
Null deviance: 27.910 on 20 d.f.
Residual deviance: 21.296 on 18 d.f.
Akaike information criterion: 27.296
Number of Fisher scoring iterations: 4

Amphiprion latezonatus

Model: zero-inflated negative binomial

Call: zeroinfl(formula = Al ~emerge_rk + AvTemp, data = anemone, dist = 'negbin')

Pearson residuals

Min.	1Q	Median	3Q	Max.
–1.501525	–0.065799	–0.006035	–0.002055	1.603183

Count model coefficients (negbin with log link)

	Estimate	s.e.	*z*-value	Pr(>|z|)	
(Intercept)	–92.90266		68.48319	–1.357	0.1749
emerge_rk	0.17044	0.09543	1.786	0.0741.	
AvTemp	4.30423	3.13232	1.374	0.1694	
Log(theta)	10.49798	n.a.	n.a.	n.a.	

Zero-inflation model coefficients (binomial with logit link)

	Estimate	s.e.	*z*-value	Pr(>|z|)		
(Intercept)	407.509	495.143	0.823	0.411		
emerge_rk	–1.180	1.583	–0.745	0.456		
AvTemp	–18.595	22.592	–0.823	0.410		
Signif. codes	0'***'	0.001'**'	0.01'*'	0.05'.'	0.1' '	1

Theta = 36242.3641
Number of iterations in Broyden–Fletcher–Goldfarb–Shanno (BFGS) optimisation: 117
Log-likelihood: –14.09 on 7 d.f.

d.f.	Akaike information criterion	
5	49.62044	emerg rk
5	51.85001	av temp
[1]	42.18975	emerg rock + av temp

Diagnostic test on non-zero sites

Emergent rock

glm(formula = I(Al > 0) ~**emerge_rk**, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.4221	–0.4576	–0.3028	–0.2914	2.3955

Coefficients

	Estimate	s.e.	*z*-value	Pr(>|z|)	
(Intercept)	–3.1376	1.2710	–2.469	0.0136*	
emerge_rk	0.3891	0.1749	2.225	0.0261*	
Signif. codes	0'***'	0.001'**'	0.01'*'	0.05'.'	0.1' ' 1

(Dispersion parameter for binomial family taken to be 1)
Null deviance: 23.053 on 20 d.f.
Residual deviance: 16.013 on 19 d.f.
Akaike information criterion: 20.013
Number of Fisher scoring iterations: 5

Emergent rock + Average Temp

Call: glm(formula = I(Al > 0) ~**emerge_rk + AvTemp**, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.22566	–0.12100	–0.01047	–0.00007	1.73737

Coefficients

	Estimate	s.e.	*z*-value	Pr(> |z|)
(Intercept)	–409.373	411.131	–0.996	0.319
emerge_rk	1.140	1.303	0.875	0.381
AvTemp	18.680	18.762	0.996	0.319

(Dispersion parameter for binomial family taken to be 1)
Null deviance: 23.0527 on 20 d.f.
Residual deviance: 7.4646 on 18 d.f.
Akaike informatin criterion: 13.465
Number of Fisher scoring iterations: 9

Dascyllus trimaculatus

Model: zero-inflated negative binomial

Call: zeroinfl(formula = Dt ~emerge_rk + MinTemp, data = anemone, dist = 'negbin')

Pearson residuals

Min.	1Q	Median	3Q	Max.
–0.71491	–0.42456	–0.19496	–0.06307	1.63963

Count model coefficients (negbin with log link)

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	51.0409	13.1541	3.880	0.000104***
emerge_rk	1.0776	0.2248	4.793	1.64e-06***
MinTemp	–3.3528	0.8850	–3.788	0.000152***
Log(theta)	–0.4188	0.6817	–0.614	0.538978

Zero-inflation model coefficients (binomial with logit link)

	Estimate	s.e.	*z*-value	Pr(>|z|)		
(Intercept)	65.801	66.294	0.993	0.321		
emerge_rk	1.174	1.297	0.905	0.365		
MinTemp	–4.664	4.710	–0.990	0.322		
Signif. codes	0'***'	0.001'**'	0.01'*'	0.05'.'	0.1' '	1

Theta = 0.6578
Number of iterations in Broyden–Fletcher–Goldfarb–Shanno (BFGS) optimisation: 151
Log-likelihood: –49.16 on 7 d.f.
Akaike information criterion: 112.32 emergent rock + minTemp

Diagnostic test on non-zero sites

Emergent rock

glm(formula = I(Dt > 0) ~**emerge_rk**, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.7068	–0.6475	–0.5759	0.6808	1.9383

Coefficients

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	–1.7127	0.7826	–2.188	0.0286*
emerge_rk	0.3057	0.1394	2.193	0.0283*

Signif. codes 0'***' 0.001 '**' 0.01'*' 0.05'.' 0.1' ' 1

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 27.910 on 20 d.f.

Residual deviance: 21.983 on 19 d.f.

Akaike information criterion: 25.983

Number of Fisher scoring iterations: 4

Emergent rock + minTemp

glm(formula = I(Dt > 0) ~**emerge_rk + MinTemp**, family = binomial(link = 'logit'), data = anemone)

Deviance residuals

Min.	1Q	Median	3Q	Max.
–1.8040	–0.7584	–0.3958	0.6886	1.6069

Coefficients

	Estimate	s.e.	*z*-value	Pr(>|z|)
(Intercept)	8.0768	8.8291	0.915	0.3603
emerge_rk	0.4142	0.1886	2.196	0.0281*
MinTemp	–0.6462	0.5921	–1.091	0.2751

Signif. codes 0'***' 0.001'**' 0.01'*' 0.05'.' 0.1' ' 1

(Dispersion parameter for binomial family taken to be 1)

Null deviance: 27.910 on 20 d.f.

Residual deviance: 20.703 on 18 d.f.

Akaike information criterion: 26.703

Number of Fisher scoring iterations: 4