

Regional-scale variability in the response of benthic macroinvertebrate assemblages to a marine heatwave

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Table S1. Details of surveys conducted at each location for each habitat. Sources of previous survey data were: (1) Vanderklift & Kendrick (2004), (2) Vanderklift, unpublished data, (3) Wernberg et al. (2008), (4) Wernberg, unpublished data, and (5) recent survey data collected for this study.

Location	Latitude	Habitat	Site name	Survey years	Source #	
Hamelin	34.2°S	Reef flats	Ham F1	1999, 2000, 2001, 2013, 2014	1,2,5	
			Ham F2	1999, 2000, 2001, 2013, 2014	1,2,5	
			Ham F3	2005, 2006, 2013, 2014	3,4,5	
			Ham F4	2005, 2006, 2013, 2014	3,4,5	
			Ham F5	2005, 2006, 2013, 2014	3,4,5	
		Reef slopes	Ham S1	1999, 2000, 2001, 2013	1,2,5	
			Ham S2	1999, 2000, 2001, 2013	1,2,5	
			Ham S3	1999, 2013, 2014	1,2,5	
			Marmion	31.8°S	Reef flats	Mar F1
Mar F2	1999, 2000, 2001, 2013, 2014, 2015	1,2,5				
Mar F3	1999, 2000, 2001, 2013, 2014, 2015	1,2,5				
Mar F4	2005, 2006, 2013, 2014, 2015	3,4,5				
Mar F5	2005, 2006, 2013, 2014, 2015	3,4,5				
Reef slopes	Mar S1	1999, 2000, 2001, 2013, 2014, 2015	1,2,5			
	Mar S2	1999, 2000, 2001, 2013, 2014, 2015	1,2,5			
	Mar S3	1999, 2000, 2001, 2013, 2014, 2015	1,2,5			
	Jurien	30.2S	Reef flats		Jur F1	2000, 2013, 2014, 2015
Jur F2				2000, 2004, 2013, 2014, 2015	1,2,5	
Jur F3				2005, 2013, 2014, 2015	3,4,5	
Jur F4				2005, 2013, 2014, 2015	3,4,5	
Jur F5				2005, 2013, 2014, 2015	3,4,5	
Reef slopes			Jur S1	1999, 2013, 2014, 2015	1,2,5	
			Jur S2	1999, 2013, 2014, 2015	1,2,5	
			Jur S3	1999, 2013, 2014, 2015	1,2,5	
			Kalbarri	27.4°S	Reef flats	Kal F1
Kal F2	2005, 2013, 2014, 2015	3,4,5				
Kal F3	2005, 2013, 2014, 2015	3,4,5				
Kal F4	2005, 2006, 2013, 2014, 2015	3,4,5				
Kal F5	2005, 2006, 2013, 2014, 2015	3,4,5				
Reef slopes	Not surveyed (lack of suitable habitat and historical data)					

Table S2. Results of PERMANOVA to test for differences in invertebrate assemblage structure before and after the heatwave event ('HW', fixed factor) and between locations ('Lo', fixed factor). Permutations were based on a Bray-Curtis similarity matrix constructed from square-root transformed abundance data (4999 permutations under a reduced model). Significant factors (at $P < 0.05$) are indicated with an asterisk (*). Separate analyses were conducted for the two reef habitats: (a) reef flats and (b) reef slopes.

(a) Reef flats

Source	df	SS	MS	F	P
HW	1	4765	4765	4.493	0.001*
Lo	3	41171	13744	12.940	0.001*
LoxHW	3	12790	4263.3	4.020	0.001*
Res	86	91206	1060.5		
Total	93	161810			

(a) Reef slopes

Source	df	SS	MS	F	P
HW	1	7645	7645	7.904	0.001*
Lo	2	7856	3928	4.061	0.001*
HWxLo	2	5760	2880	2.977	0.001*
Res	37	35789	967		
Total	42	61017			

Table S3. Invertebrate assemblages on reef flats. Results of PERMANOVA to test for overall differences in assemblage structure between years, and specifically between pre-HW and post-HW assemblage structure using *a priori* planned contrast. The planned contrast (C1) examined differences between pre-MHW surveys (i.e. all surveys before 2011) and post-MHW surveys (i.e. all surveys after 2011). Permutations were based on a Bray-Curtis similarity matrix constructed from square-root transformed abundance data (4999 unrestricted permutations). Significant factors (at $P < 0.05$) are indicated with an asterisk (*).

(a) Hamelin

Source	df	SS	MS	F	P
Year	6	21596	3599	1.925	0.053
(C1)	1	5053	5054	2.266	0.098
Res	15	28044	1869		
Total	21	49641			

(b) Marmion

Source	df	SS	MS	F	P
Year	7	8723	1246	0.919	0.588
(C1)	1	894	894	0.662	0.606
Res	20	27092	1354		
Total	27	35816			

(c) Jurien

Source	df	SS	MS	F	P
Year	5	8276	1655	1.175	0.295
(C1)	1	5141	5141	4.006	0.003*
Res	16	22533	1408		
Total	21	30810			

(d) Kalbarri

Source	df	SS	MS	F	P
Year	4	8557	2139	8.445	0.002*
(C1)	1	7757	7757	30.382	0.001*
Res	17	4306	253		
Total	21	12864			

Table S4. SIMPER analyses to determine which taxa contributed most to the observed differences in assemblage structure between pre-HW years and post-HW years, on reef flats. Top 3 contributors to dissimilarities are shown for each location/habitat where significant differences were detected (see Table S3).

Jurien: Average dissimilarity between pre-HW and post-HW samples = 66.24%

Species	Before HW	After HW	Av.Diss	Diss/SD	Contrib%	Cum.%
	Av.Abund	Av.Abund				
<i>Heliocidaris erythrogramma</i>	2.59	2.11	13.52	1.27	20.42	20.42
<i>Lunella torquata</i>	1.39	0.42	11.53	1.31	17.41	37.83
<i>Centrostephanus tenuispinus</i>	0.00	1.10	9.25	0.98	13.97	51.79

Kalbarri: Average dissimilarity between pre-HW and post-HW samples = 100.00%

Species	Before HW	After HW	Av.Diss	Diss/SD	Contrib%	Cum.%
	Av.Abund	Av.Abund				
<i>Lunella torquata</i>	0.98	0.00	48.80	1.62	48.80	48.80
<i>Dicathais orbita</i>	0.69	0.00	37.70	1.08	37.70	86.50
<i>Astraliium</i> spp.	0.34	0.00	13.50	0.68	25.86	100.00

Table S5. Invertebrate assemblages on reef slopes. Results of PERMANOVA to test for overall differences in assemblage structure between years, and specifically between pre-HW and post-HW assemblage structure using a *a priori* planned contrast. The planned contrast (C1) examined differences between pre-MHW surveys (i.e. all surveys before 2011) and post-MHW surveys (i.e. all surveys after 2011). Permutations were based on a Bray-Curtis similarity matrix constructed from square-root transformed abundance data (4999 permutations under a reduced model). Significant factors (at $P < 0.05$) are indicated with an asterisk (*).

(a) Hamelin

Source	df	SS	MS	F	P
Year	4	10203	2550	1.451	0.183
(C1)	1	4050	4050	2.204	0.088
Res	8	14062	1757		
Total	12	24265			

(b) Marmion

Source	df	SS	MS	F	P
Year	5	8505	1701	2.357	0.004*
(C1)	1	4555	4555	5.778	0.001*
Res	12	8662	721		
Total	17	17168			

(c) Jurien

Source	df	SS	MS	F	P
Year	3	8400	2800	2.879	0.008*
(C1)	1	5645	5645	5.359	0.009*
Res	8	7778	972		
Total	11	16179			

Table S6. SIMPER analyses to determine which taxa contributed most to the observed differences in assemblage structure between pre-HW years and post-HW years, on reef slopes. Top 3 contributors to dissimilarities are shown for each location/habitat where significant differences were detected (see Table S5).

Marmion: Average dissimilarity between pre-HW and post-HW samples = 53.53%

Species	Before HW	After HW	Av.Diss	Diss/SD	Contrib%	Cum.%
	Av.Abund	Av.Abund				
<i>Heliocidaris erythrogramma</i>	1.59	2.79	10.23	1.07	19.12	19.12
<i>Centrostephanus tenuispinus</i>	0.00	1.13	7.85	1.28	14.67	33.79
<i>Petricia vernicina</i>	0.98	0.00	5.94	1.06	11.10	44.89

Jurien: Average dissimilarity between pre-HW and post-HW samples = 70.25%

Species	Before HW	After HW	Av.Diss	Diss/SD	Contrib%	Cum.%
	Av.Abund	Av.Abund				
<i>Centrostephanus tenuispinus</i>	0.47	3.66	21.36	1.58	30.37	30.37
<i>Phyllacanthus irregularis</i>	2.04	0.86	11.07	1.54	15.74	46.11
<i>Tripneustes gratilla</i>	0.00	1.16	7.38	0.74	11.08	55.19

Table S7. Total abundance and taxon richness of invertebrate assemblages on reef flats. Results of PERMANOVA to test for overall differences in abundance and richness between years, and specifically between pre-HW and post-HW assemblage structure using *a priori* planned contrast. The planned contrast (C1) examined differences between pre-MHW surveys (i.e. all surveys before 2011) and post-MHW surveys (i.e. all surveys after 2011). Permutations were based on Euclidian distances between untransformed abundance/richness data (999 unrestricted permutations). Significant factors (at $P < 0.05$) are indicated with an asterisk (*).

(a) Hamelin

Total abundance

Source	df	SS	MS	F	P
Year	6	29.852	4.9753	1.1667	0.388
(C1)	1	18.002	18.002	4.7487	0.059
Res	15	63.967	4.2644		
Total	21	93.818			

Taxon richness

Source	df	SS	MS	F	P
Year	6	12.997	2.1662	1.6777	0.201
(C1)	1	4.097	4.097	2.8988	0.116
Res	15	19.367	1.2911		
Total	21	32.364			

(b) Marmion

Total abundance

Source	df	SS	MS	F	P
Year	7	242.09	34.66	0.7786	0.641
(C1)	1	39.09	39.09	0.9291	0.360
Res	20	890.37	44.51		
Total	27	1133			

Taxon richness

Source	df	SS	MS	F	P
Year	7	7.664	1.094	0.802	0.599
(C1)	1	1.795	1.795	1.407	0.228
Res	20	27.30	1.365		
Total	27	34.96			

(c) Jurien**Total abundance**

Source	df	SS	MS	F	P
Year	5	399.79	79.958	1.048	0.397
(C1)	1	82.293	82.293	1.071	0.307
Res	16	1219.7	76.229		
Total	21	1619.5			

Taxon richness

Source	df	SS	MS	F	P
Year	5	5.451	1.090	1.214	0.371
(C1)	1	3.989	3.989	5.041	0.061
Res	16	14.367	0.897		
Total	21	19.818			

(d) Kalbarri**Total abundance**

Source	df	SS	MS	F	P
Year	4	26.364	6.590	6.224	0.010*
(C1)	1	24.934	24.934	25.66	0.001*
Res	17	18.000	1.058		
Total	21	44.364			

Taxon richness

Source	df	SS	MS	F	P
Year	4	8.018	2.004	10.326	0.001*
(C1)	1	7.889	7.889	46.023	0.001*
Res	17	3.300	0.194		
Total	21	11.318			

Table S8. Total abundance and taxon richness of invertebrate assemblages on reef slopes. Results of PERMANOVA to test for overall differences in abundance and richness between years, and specifically between pre-HW and post-HW assemblage structure using *a priori* planned contrast. The planned contrast (C1) examined differences between pre-MHW surveys (i.e. all surveys before 2011) and post-MHW surveys (i.e. all surveys after 2011). Permutations were based on Euclidian distances between untransformed abundance/richness data (999 unrestricted permutations). Significant factors (at $P < 0.05$) are indicated with an asterisk (*).

(a) Hamelin

Total abundance

Source	df	SS	MS	F	P
Year	4	351.64	87.91	2.9969	0.089
(C1)	1	55.451	55.451	1.149	0.33
Res	8	234.67	29.333		
Total	12	586.31			

Taxon richness

Source	df	SS	MS	F	P
Year	4	23.974	5.9936	2.9356	0.088
(C1)	1	13.546	13.546	5.5678	0.055
Res	8	16.333	2.0417		
Total	12	40.308			

(b) Marmion

Total abundance

Source	df	SS	MS	F	P
Year	5	543.1	108.63	1.126	0.388
(C1)	1	0.005	0.005	0.005	1.00
Res	12	1157.3	96.44		
Total	17	1700.5			

Taxon richness

Source	df	SS	MS	F	P
Year	5	6.277	1.255	0.664	0.699
(C1)	1	1.388	1.388	0.806	0.472
Res	12	22.667	1.888		
Total	17	28.944			

(c) Jurien

Total abundance

Source	df	SS	MS	F	P
Year	3	678.00	226.00	0.720	0.555
(C1)	1	348.44	348.44	1.226	0.325
Res	8	2512.7	314.08		
Total	11	3190.7			

Taxon richness

Source	df	SS	MS	F	P
Year	3	10.25	3.41	4.100	0.073
(C1)	1	10.02	10.03	14.556	0.016*
Res	8	6.66	0.833		
Total	11	16.91			

Table S9. Dominant taxa on reef flats. Results of PERMANOVA to test for overall differences in the abundance of dominant taxa between years, and specifically between pre-HW and post-HW assemblage structure using *a priori* planned contrast. The planned contrast (C1) examined differences between pre-MHW surveys (i.e. all surveys before 2011) and post-MHW surveys (i.e. all surveys after 2011). Permutations were based on Euclidian distances between untransformed abundance/richness data (999 unrestricted permutations). Significant factors (at $P < 0.05$) are indicated with an asterisk (*).

(a) *Heliocidaris erythrogramma*

Hamelin

Source	df	SS	MS	F	P
Year	6	23.273	3.8788	1.402	0.254
(C1)	1	0.006	0.006	0.0187	1.000
Res	15	41.5	2.7667		
Total	21	64.773			

Marmion

Source	df	SS	MS	F	P
Year	7	121.10	17.300	0.9561	0.478
(C1)	1	15.939	15.939	0.8873	0.373
Res	20	361.87	18.093		
Total	27	482.96			

Jurien

Source	df	SS	MS	F	P
Year	5	182.52	36.504	1.002	0.452
(C1)	1	52.728	52.728	1.479	0.262
Res	16	582.80	36.425		
Total	21	765.32			

Kalbarri: not found

(b) *Lunella torquata*

Hamelin

Source	df	SS	MS	F	P
Year	6	11.991	1.9985	0.9639	0.479
(C1)	1	0.34091	0.34091	0.15949	0.763
Res	15	31.1	2.0733		
Total	21	43.091			

Marmion

Source	df	SS	MS	F	P
Year	7	124.28	17.754	0.966	0.452
(C1)	1	38.084	38.084	2.182	0.160
Res	20	367.43	18.372		
Total	27	491.71			

Jurien

Source	df	SS	MS	F	P
Year	5	50.906	10.181	0.707	0.674
(C1)	1	22.111	22.111	1.706	0.239
Res	16	230.37	14.398		
Total	21	281.27			

Kalbarri

Source	df	SS	MS	F	P
Year	4	9.754	2.438	4.273	0.018*
(C1)	1	9.740	9.740	20.053	0.004*
Res	17	9.700	0.570		
Total	21	19.455			

(c) *Astraliium* spp.

Hamelin

Source	df	SS	MS	F	P
Year	6	4.4545	0.74242	2.2273	0.087
(C1)	1	2.1879	2.1879	6.0217	0.056
Res	15	5.00	0.33333		
Total	21	9.4545			

Marmion

Source	df	SS	MS	F	P
Year	7	50.424	7.203	0.802	0.584
(C1)	1	0.123	0.123	0.014	0.950
Res	20	179.43	8.971		
Total	27	229.86			

Jurien

Source	df	SS	MS	F	P
Year	5	2.371	0.4745	1.186	0.289
(C1)	1	0.010	0.0108	0.024	1.000
Res	16	6.400	0.53333		
Total	21	8.772			

Kalbarri

Source	df	SS	MS	F	P
Year	4	1.790	0.447	2.718	0.096
(C1)	1	0.876	0.876	4.720	0.094
Res	17	2.800	0.164		
Total	21	4.590			

Table S10. Dominant taxa on reef slopes. Results of PERMANOVA to test for overall differences in the abundance of dominant taxa between years, and specifically between pre-HW and post-HW assemblage structure using *a priori* planned contrast. The planned contrast (C1) examined differences between pre-MHW surveys (i.e. all surveys before 2011) and post-MHW surveys (i.e. all surveys after 2011). Permutations were based on Euclidian distances between untransformed abundance/richness data (999 unrestricted permutations). Significant factors (at $P < 0.05$) are indicated with an asterisk (*).

(a) *Heliocidaris erythrogramma*

Hamelin

Source	df	SS	MS	F	P
Year	4	216.73	54.183	1.9481	0.16
(C1)	1	0.46886	0.46886	0.017	0.972
Res	8	222.5	27.813		
Total	12	439.23			

Marmion

Source	df	SS	MS	F	P
Year	5	202.5	40.50	3.983	0.028*
(C1)	1	68.05	68.05	4.246	0.054
Res	12	122.00	10.167		
Total	17	324.5			

Jurien

Source	df	SS	MS	F	P
Year	3	54.250	18.083	1.018	0.435
(C1)	1	0.0277	0.0277	0.001	1.000
Res	8	142.00	17.750		
Total	11	196.25			

(a) *Phyllacanthus irregularis*

Hamelin

Source	df	SS	MS	F	P
Year	4	13.141	3.2853	8.2996	0.005*
(C1)	1	4.0458	4.0458	3.6294	0.105
Res	8	3.1667	0.39583		
Total	12	16.308			

Marmion

Source	df	SS	MS	F	P
Year	5	118.00	23.600	1.475	0.260
(C1)	1	0.222	0.222	0.011	0.961
Res	12	192.00	16.00		
Total	17	310.00			

Jurien

Source	df	SS	MS	F	P
Year	3	61.583	20.528	1.895	0.169
(C1)	1	61.361	61.361	7.062	0.039*
Res	8	86.667	10.833		
Total	11	148.25			

(c) *Centrostephanus tenuispinus*

Hamelin

Source	df	SS	MS	F	P
Year	4	19.026	4.7564	1.3274	0.333
(C1)	1	10.859	10.859	3.243	0.072
Res	8	28.667	3.5833		
Total	12	47.692			

Marmion

Source	df	SS	MS	F	P
Year	5	37.611	7.522	5.887	0.001*
(C1)	1	16.056	16.056	6.963	0.003*
Res	12	15.333	1.277		
Total	17	52.944			

Jurien

Source	df	SS	MS	F	P
Year	3	2148.9	716.31	4.4909	0.032*
(C1)	1	910.03	910.03	3.6186	0.047*
Res	8	1276	159.5		
Total	11	3424.9			

(d) *Tripneustes gratilla*

Hamelin: not found

Marmion: not found

Jurien

Source	df	SS	MS	F	P
Year	3	262.25	87.417	1.1566	0.355
(C1)	1	34.028	34.028	0.40855	0.639
Res	8	604.67	75.583		
Total	11	866.92			

Figure S1. Mean abundance (\pm SE) of *Helicoidaris* on reef slopes at Marmion over 3 consecutive survey years, prior to the MHW event. Means are generated from 3 independent sites that were resurveyed each year during the Austral summer (Jan-March).

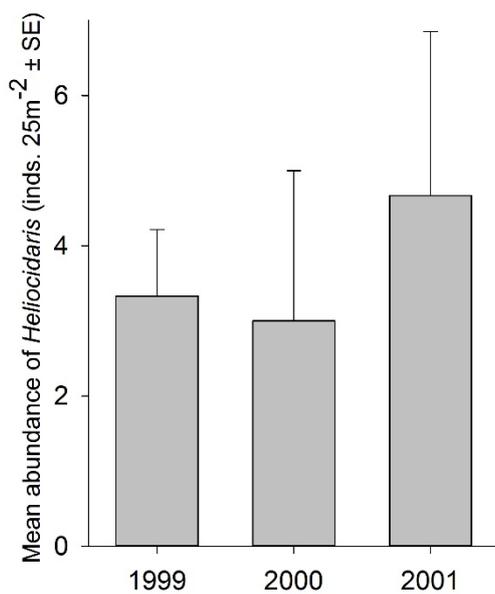
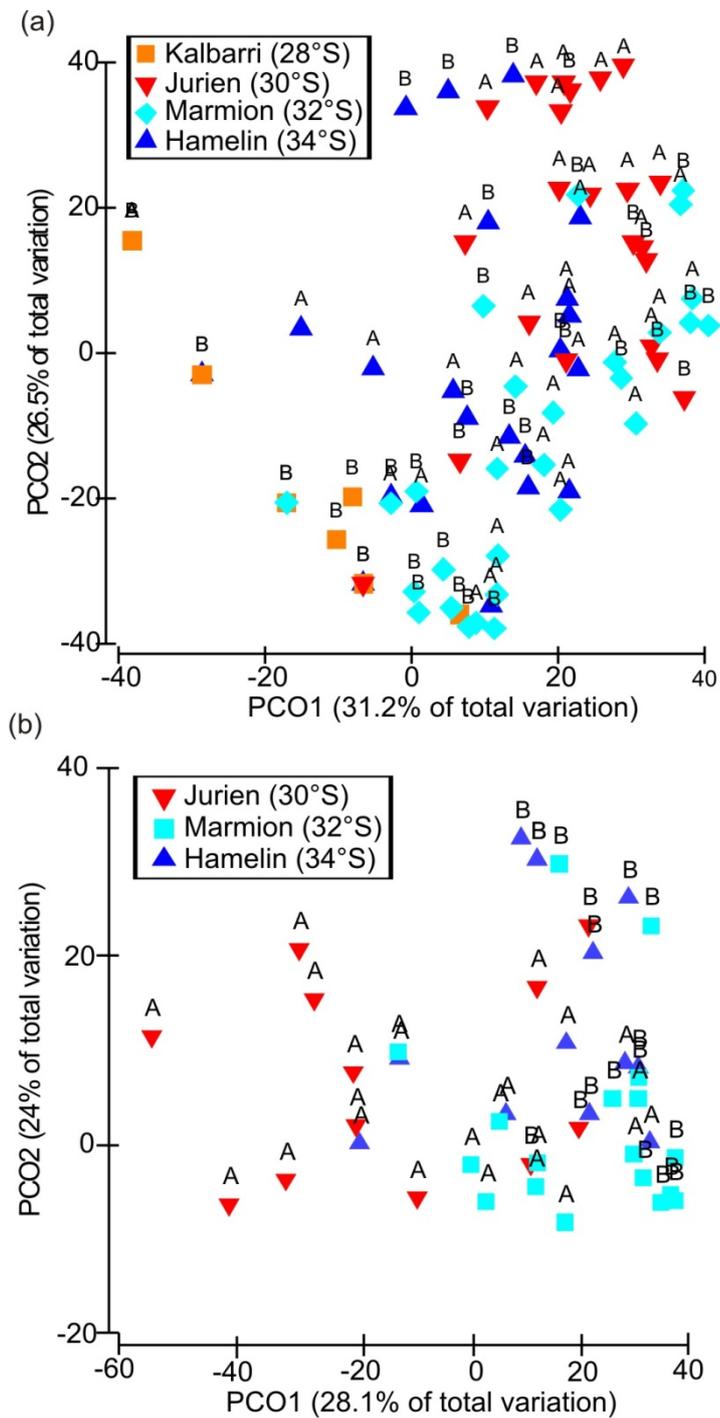


Figure S2. PCO plots depicting macro-invertebrate assemblage structure at each location before (B) and after (A) the heatwave, on both reef flats (a) and reef slopes (b). Ordinations are based on Bray-Curtis similarities of square-root transformed abundance data.



LITERATURE CITED

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