An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot

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Supplementary information

Figure S1. The 2011 heat wave in the southeast Indian Ocean. Blended SST anomaly map for January **(a)**, February **(b)** and March **(c)** 2011 (relative to a 1971-2000 baseline). The maps show a warming anomaly of >2.5°C developing and intensifying along the western coast of Australia. Data provided by the National Weather Service and the NOAA Operational Model Archive Distribution Systems (NOMADS) and were plotted using GrADS.

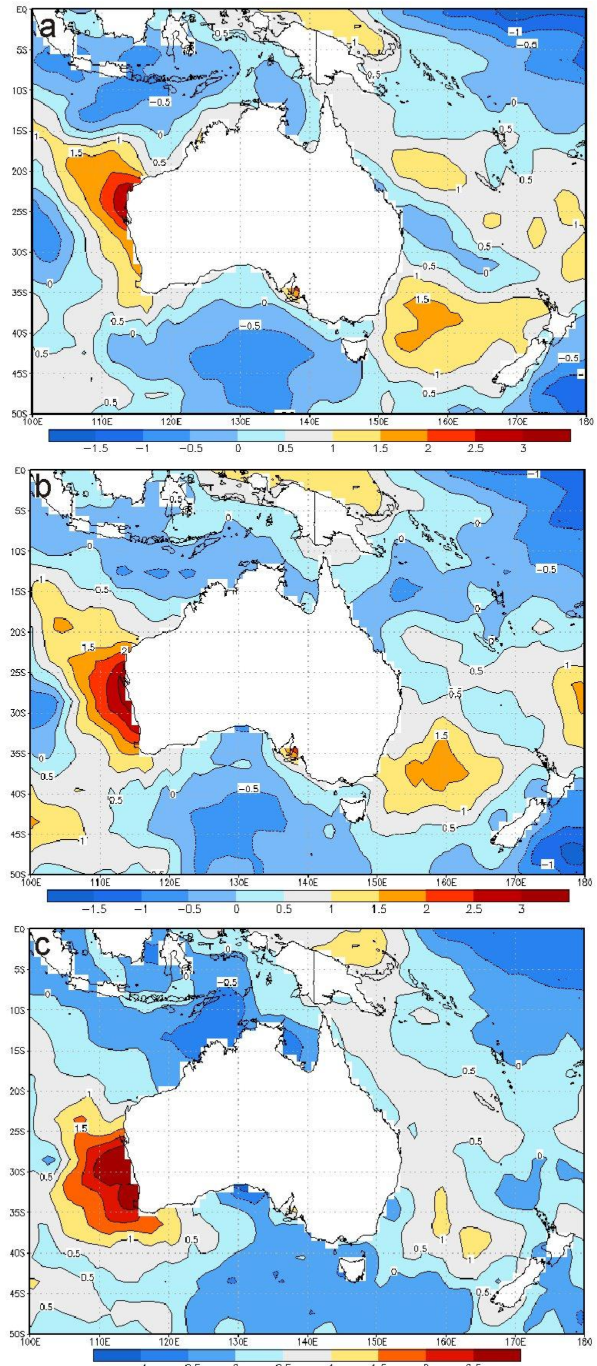
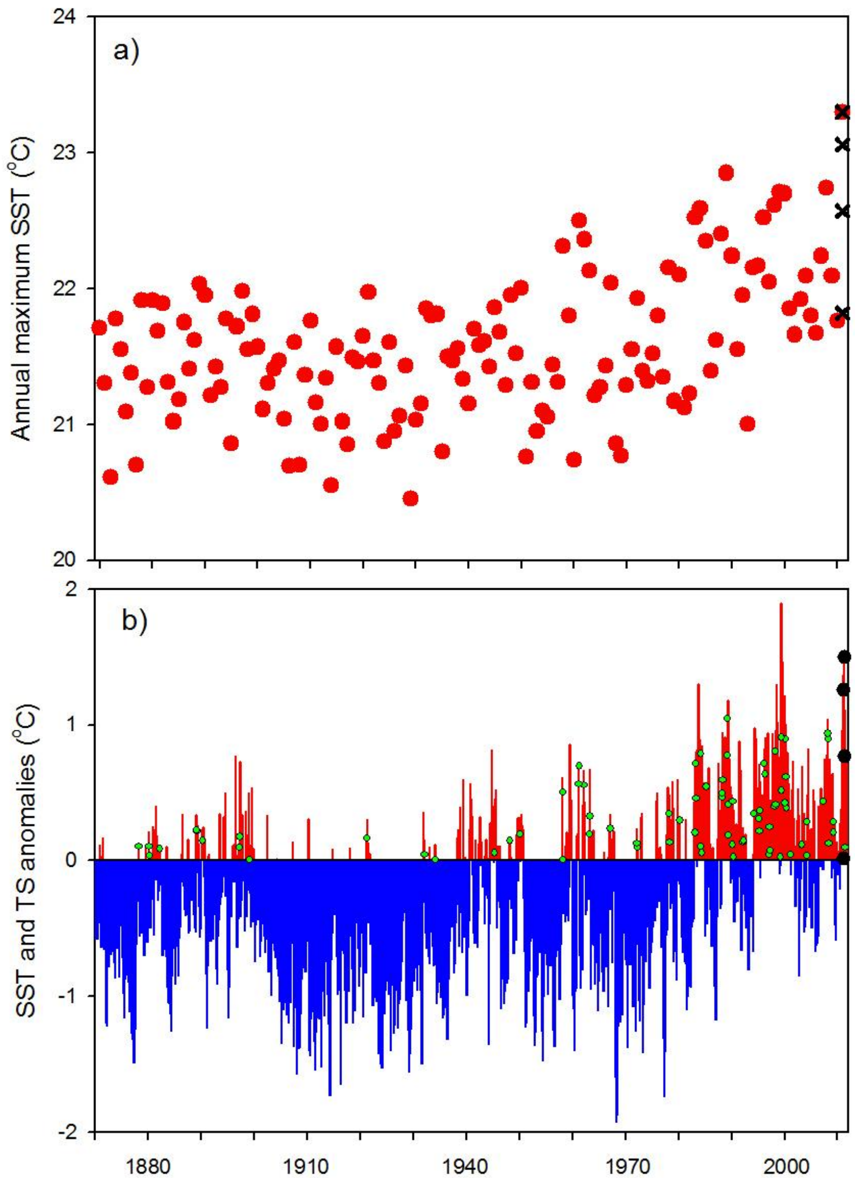


Figure S2. Sea surface temperatures (SST) and anomalies, obtained from the Met Office Hadley Centre's sea ice and sea surface temperature (HadISST1) data at http://climexp.knmi.nl (Rayner et al., Geophys. Res., 2003, 108[D14]: 4407), calculated against a 1971-2000 baseline. Annual maximum SST (red dots) and SST's during the four heat wave months (black crosses) (**a**). Monthly mean Sea Surface Temperature Anomalies (SSTA, blue and red bars) and Thermal Stress Anomalies (TSA, black and green dots, the latter representing the peak months of the heat wave; only positive values shown) (**b**). The thermal stress index TSA (only positive values shown) was defined as temperatures ≥1 °C in excess of the climatological maximum (1971-2001) (Selig et al. 2010, Global Ecol Biogeogr 19:397-411). The area for which data are presented is located approximately midway between Jurien Bay and Hamelin Bay (cf Fig. 1), and is representative for the study area (Smale & Wernberg, Mar Ecol Prog Ser, 2009, 387: 27-37.

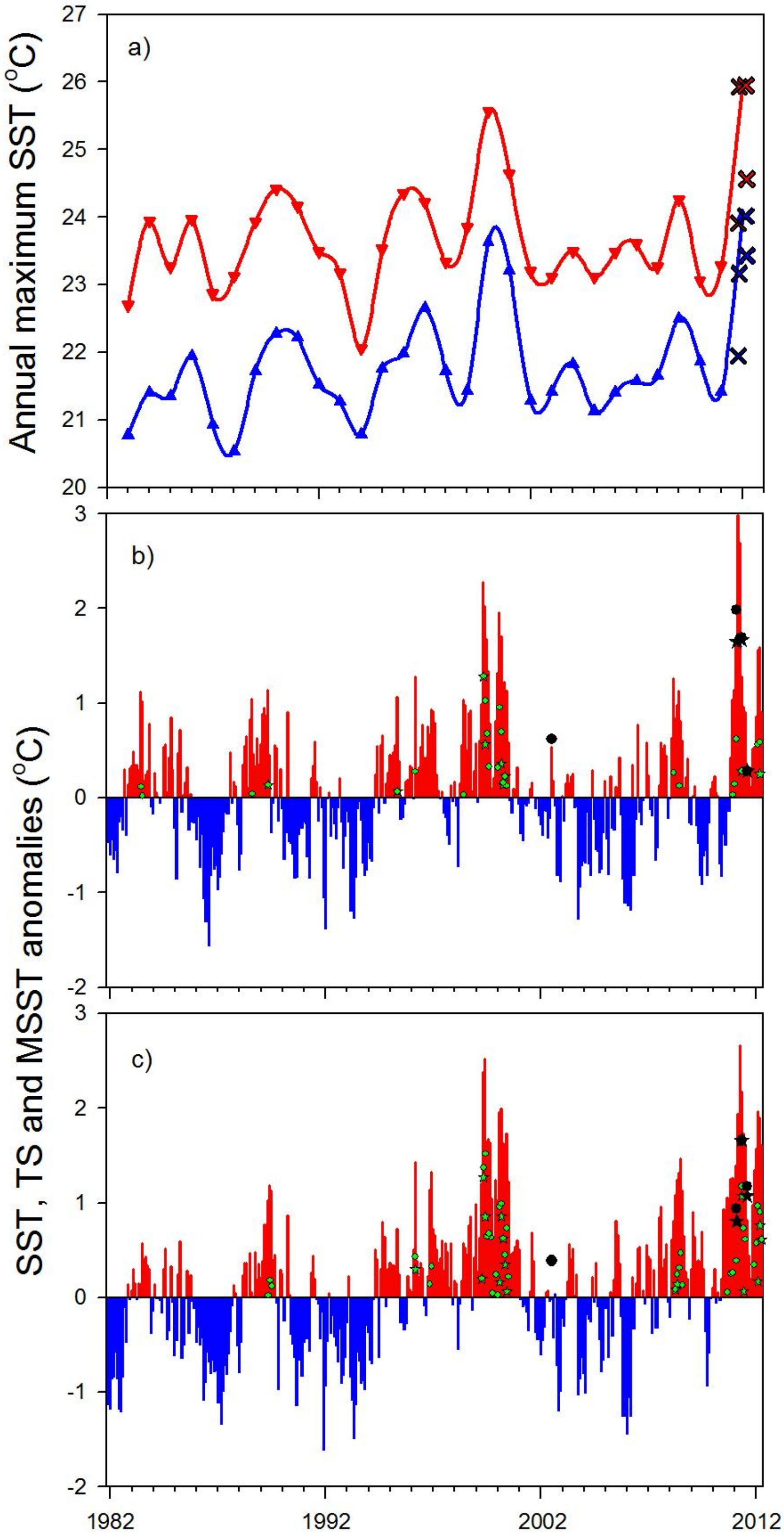
It can be seen that the past ~30 years has been substantially warmer than the preceding 110 years in the area. Superimposed onto this overall warming trend, the heat wave produced the two highest absolute temperatures (max 23.3 ^{o}C, Mar 2011) and the second-highest SST anomalies on record. This caused soaring thermal stress anomalies (cf. Fig. S3). Of the 10 highest monthly thermal stress anomalies on record, three were recorded during the four months of the heat wave, and at the peak (Feb-Mar 2011), the 2011-heat wave caused the highest thermal stress in >140 years for two consecutive months (TSA = 1.495 ^{o}C), exceeding the previous maximum (TSA = 1.045 ^{o}C) by up to 0.45 ^{o}C (43%).



a)
b)
Annual maximum SST (°C)
SST and TS anomalies (°C)
24
23
22
21
20
2
1
0
-1
-2
1880
1910
1940
1970
2000

Figure S3. Temperature characteristics of Jurien Bay (JB: 33.5-34.5°S; 114.5-115.5°E) and Hamelin Bay (HB: 31.5-32.5°S; 114.5-115.5°E) from November 1981 until March 2012 (data source as in Fig. S1). Annual maximum SST (**a**) in JB (red line) and HB (blue line). Red and blue crosses represent monthly mean SST's during the heat wave (Jan-Apr 2011) in JB and HB respectively. Monthly mean Sea Surface Temperature Anomalies (SSTA, red and blue bars), Thermal Stress Anomalies (TSA, stars) and Monthly Sea Surface Temperature Stress Anomalies (MSSTA, dots) for JB (**b**) and HB (**c**), relative to a 1971-2000 baseline. The thermal stress indices TSA and MSSTA (only positive values shown) were defined as temperatures ≥1 °C in excess of the climatological maximum or monthly mean (1971-2001) (Selig et al. 2010, Global Ecol Biogeogr 19:397-411). The black stars and dots represent the heat wave months.

The heat wave produced the highest SSTs (25.9 °C, 24.0 °C Feb-Mar 2011) and SST anomalies recorded since 1981 in both JB and HB. The derived thermal stress indices (TSA and MSSTA) were the highest recorded over ~30 years, exceeding the previous maximum by 31% and 50% in Jurien Bay and 9% and 55% in Hamelin Bay, respectively. A thermal event of almost similar magnitude occurred in early 2000. However, absolute temperatures were 0.4 °C cooler in both JB and HB, and this heat wave was likely less stressful to marine organisms than the 2011 heat wave because the high anomalies were recorded in cooler months (Apr-May 2000) where the recorded maximum temperatures did not exceed the climatological maximum as much. The 2000- and 2011 heat waves were 1.7 °C and 2.5 °C (44% more) warmer than the average maximum for the preceding 5 years respectively. Marine organisms therefore had better opportunity to acclimate to the 2000 heat wave compared to the recent 2011 event.



a)
b)
c)
Annual maximum SST (°C)
SST, TS and MSST anomalies (°C)
20
21
22
23
24
25
26
27
-2
-1
0
1
2
3
1982
1992
2002
2012

Table S1. PERMANOVA tests to examine differences between locations and years in community structure of benthic macroalgae and invertebrates, and demersal fishes. Permutations (999 under a reduced model) were based on a Bray-Curtis similarity matrix generated from either square-root transformed percent cover data (for benthos) or presence/absence data (for fish). Significant *P* values (<0.05) are highlighted in bold.

1. Benthos

Source	df	SS	MS	Pseudo-F	P
Year	4	1905	476.5	4.15	**0.001**
Location	1	1009	1009	8.79	**0.001**
Year x Location	4	813.2	203.4	1.77	**0.050**
Residual	20	2296	114.8		
Total	29	6026			

2. Fish

Source	df	SS	MS	Pseudo-F	P
Year	3	7792	2597	3.87	**0.001**
Location	1	4343	4343	6.48	**0.002**
Year x Location	3	5059	1686	2.51	**0.006**
Residual	16	10723	670		
Total	23	27919			

Table S2. One-way PERMANOVA tests with pre-planned, single degree of freedom contrasts to examine differences in community structure of benthic macroalgae and invertebrates between years. Permutations (999 under an unrestricted model) were based on a Bray-Curtis similarity matrix generated from square-root transformed percent cover data. Significant *P* values (<0.05) are highlighted in bold.

1. Jurien Bay

Source	df	SS	MS	Pseudo-F	P
Year	4	2151	537.8	4.47	**0.001**
06 vs 07	(1)	306.8	306.8	1.81	0.184
06,07 vs 09	(1)	357.2	357.2	2.06	0.120
06,07,09 vs 10	(1)	68.33	68.33	0.40	0.884
06,07,09,10 vs 11	(1)	1418	1418	9.53	**0.004**
Residual	10	1203	120.3		
Total	14	3354			

2. Hamelin Bay

Source	df	SS	MS	Pseudo-F	P
Year	4	568.1	142.1	1.29	0.239
06 vs 07	(1)	262.1	262.1	1.54	0.398
06,07 vs 09	(1)	121.4	121.4	0.76	0.579
06,07,09 vs 10	(1)	117.8	117.8	0.86	0.536
06,07,09,10 vs 11	(1)	67.01	67.01	0.54	0.796
Residual	10	1093	109.3		
Total	14	1662			

Table S3. One-way PERMANOVA tests with pre-planned, single degree of freedom contrasts to examine differences in demersal fish community composition between years. Permutations (999 under an unrestricted model) were based on a Bray-Curtis similarity matrix generated from presence/absence data. Significant *P* values (<0.05) are highlighted in bold.

1. Jurien Bay

Source	df	SS	MS	Pseudo-F	P
Year	3	6895	2298	5.55	**0.001**
06 vs 07	(1)	745.7	745.7	1.85	0.100
06,07 vs 10	(1)	3476	3476	7.00	**0.016**
06,07,10 vs 11	(1)	2673	2673	3.55	**0.010**
Residual	8	3312	414.1		
Total	11	10208			

2. Hamelin Bay

Source	df	SS	MS	Pseudo-F	P
Year	3	5956	1985	2.14	**0.010**
06 vs 07	(1)	2111	2111	2.11	0.097
06,07 vs 10	(1)	2968	2968	2.54	**0.030**
06,07,10 vs 11	(1)	876.3	876.3	0.70	0.677
Residual	8	7410	926.3		
Total	11	13367			

Table S4. One-way permutation-based ANOVA tests with pre-planned, single degree of freedom contrasts to examine between-year differences in the percent cover of key benthic taxa/functional groups at Jurien Bay. Permutations (999 under an unrestricted model) were based on a Euclidian distance similarity matrix generated from untransformed percent cover data. Significant *P* values (<0.05) are highlighted in bold.

1. Kelp (*Ecklonia radiata*)

Source	df	SS	MS	Pseudo-F	P
Year	4	2356	589.1	7.02	**0.005**
06 vs 07	(1)	223.1	223.1	1.39	0.408
06,07 vs 09	(1)	272.9	272.9	2.14	0.207
06,07,09 vs 10	(1)	92.11	92.11	0.75	0.395
06,07,09,10 vs 11	(1)	1768	1768	16.1	**0.007**
Residual	10	839.2	83.922		
Total	14	3195			

2. Encrusting coralline algae

Source	df	SS	MS	Pseudo-F	P
Year	4	1201	300.3	5.06	**0.015**
06 vs 07	(1)	118.5	118.5	2.48	0.318
06,07 vs 09	(1)	21.48	21.48	0.23	0.667
06,07,09 vs 10	(1)	49.78	49.78	0.68	0.439
06,07,09,10 vs 11	(1)	1011	1011	16.8	**0.006**
Residual	10	592.5	59.25		
Total	14	1793			

3. Turf-forming algae

Source	df	SS	MS	Pseudo-F	P
Year	4	180.3	45.09	24.2	**0.001**
06 vs 07	(1)	10.44	10.44	15.0	0.111
06,07 vs 09	(1)	1.531	1.531	0.69	0.463
06,07,09 vs 10	(1)	1.460	1.460	0.77	0.399
06,07,09,10 vs 11	(1)	166.9	166.9	67.7	**0.002**
Residual	10	18.59	1.859		
Total	14	198.9			

Table S5. One-way univariate PERMANOVA tests with pre-planned, single degree of freedom contrasts to examine between-year differences in key fish species at Jurien Bay. Permutations (999 under an unrestricted model) were based on a Euclidian distance similarity matrix generated from untransformed abundance data. Significant *P* values (<0.05) are highlighted in bold.

1. *Parma occidentalis*

Source	df	SS	MS	Pseudo-F	P
Year	3	484.6	484.6	2.87	**0.019**
06 vs 07	(1)	0.166	0.166	0.20	1.000
06,07 vs 10	(1)	0.500	0.500	0.73	0.737
06,07,10 vs 11	(1)	484.0	484.0	10.7	**0.004**
Residual	8	449.3	56.16		
Total	11	934			

2. *Chaetodon assarius*

Source	df	SS	MS	Pseudo-F	P
Year	3	240.2	80.08	3.07	**0.026**
06 vs 07	(1)	0	0	-	-
06,07 vs 10	(1)	0	0	-	-
06,07,10 vs 11	(1)	240.2	240.2	11.5	**0.009**
Residual	8	208.6	26.08		
Total	11	448.9			

2. *Labracinus lineatus*

Source	df	SS	MS	Pseudo-F	P
Year	3	6.250	2.083	25.0	**0.018**
06 vs 07	(1)	0	0	-	-
06,07 vs 10	(1)	0	0	-	-
06,07,10 vs 11	(1)	6.250	6.250	93.7	**0.006**
Residual	8	0.667	0.008		
Total	11	6.916			

Table S6. One-way univariate PERMANOVA tests with pre-planned, single degree of freedom contrasts to examine between-year differences in total macroalgal canopy cover and the relative contribution of tropical species to fish community composition at Jurien Bay. Permutations (999 under an unrestricted model) were based on a Euclidian distance similarity matrix generated from untransformed percent cover data of the canopy or the percentage composition of tropical species in fish communities. Significant *P* values (<0.05) are highlighted in bold.

1. Total macroalgal canopy cover

Source	df	SS	MS	Pseudo-F	P
Year	4	2657	664.3	35.1	**0.001**
06 vs 07	(1)	53.50	53.50	3.89	0.116
06,07 vs 09	(1)	9.031	9.031	0.53	0.485
06,07,09 vs 10	(1)	15.02	15.02	1.08	0.288
06,07,09,10 vs 11	(1)	2579	2579	125	**0.001**
Residual	10	188.8	18.88		
Total	14	2846			

2. Contribution of tropical species to overall fish community (%)

Source	df	SS	MS	Pseudo-F	P
Year	3	324.9	108.3	5.07	**0.019**
06 vs 07	(1)	19.63	19.63	0.80	0.490
06,07 vs 10	(1)	18.51	18.51	0.80	0.403
06,07,10 vs 11	(1)	286.8	286.8	13.7	**0.012**
Residual	8	170.7	21.34		
Total	11	495.7			

Table S7. Coarse taxonomic/functional groups used to quantify the structure of benthic communities during the study

Flora

Ecklonia radiata (kelp)
Scytothalia dorycarpa
Sargassum spp.
Brown macroalgae (other)
Encrusting coralline macroalgae
Encrusting macroalgae (non-coralline)
Articulated coralline macroalgae
Red macroalgae
Green macroalgae
Turf macroalgae

Fauna

Sponges
Ascidians
Bryozoans

Table S8. Demersal fish sampled during the study, including bioclimatic affinities (from various sources, including www.fishbase.org, Hutchins and Swainston's '*Sea Fishes of Southern Australia'* and various texts). Taxa with ambiguous distributions (n/a) were not included.

Aulohalaelurus labiosus	Subtropical
Austrolabrus maculatus	Temperate
Bodianus axillaris	Tropical
Bodianus frenchii	Subtropical
Centroberyx sp.	Temperate
Chaetodon assarius	Tropical
Cheilodactylus rubrolabiatus	Temperate
Chelmonops curiosus	Subtropical
Choerodon rubescens	Subtropical
Chromis klunzingeri	Subtropical
Coris auricularis	Subtropical
Dactylophora nigricans	Temperate
Dasyatis sp.	n/a
Diodon nicthemerus	Temperate
Epinephelides armatus	Temperate
Girella zebra	Subtropical
Glaucosoma hebraicum	Subtropical
Kyphosus cornelii	Subtropical
Kyphosus sydneyanus	Temperate
Labracinus spilurus	Tropical
Meuschemia sp.	n/a
Neatypus obliquus	Subtropical
Nemadactylus sp.	Temperate
Notolabrus parilus	Temperate
Odax acroptilus	Subtropical
Odax cyanomelas	Subtropical
Ophthalmolepis lineolatus	Temperate
Orectolobus maculatus	Temperate
Paraplesiops meleagris	Subtropical
Parma mccullochi	Temperate
Parma occidentalis	Subtropical
Pempheris klunzingeri	Subtropical
Pictilabrus laticlavius	Temperate
Plectorhinchus flavomaculatus	Tropical
Pseudocaranx sp.	n/a
Pseudolabrus biserialis	Subtropical
Scorpis sp.	n/a
Thalassoma sp.	Subtropical
Torquigener pleurogramma	Subtropical