

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

Thomas Wernberg, Dan A. Smale, Fernando Tuya, Mads S. Thomsen, Timothy J. Langlois, Thibaut de Bettignies, Scott Bennett, Cecile S. Rousseaux

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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 $>2.5^{\circ}\text{C}$ 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.

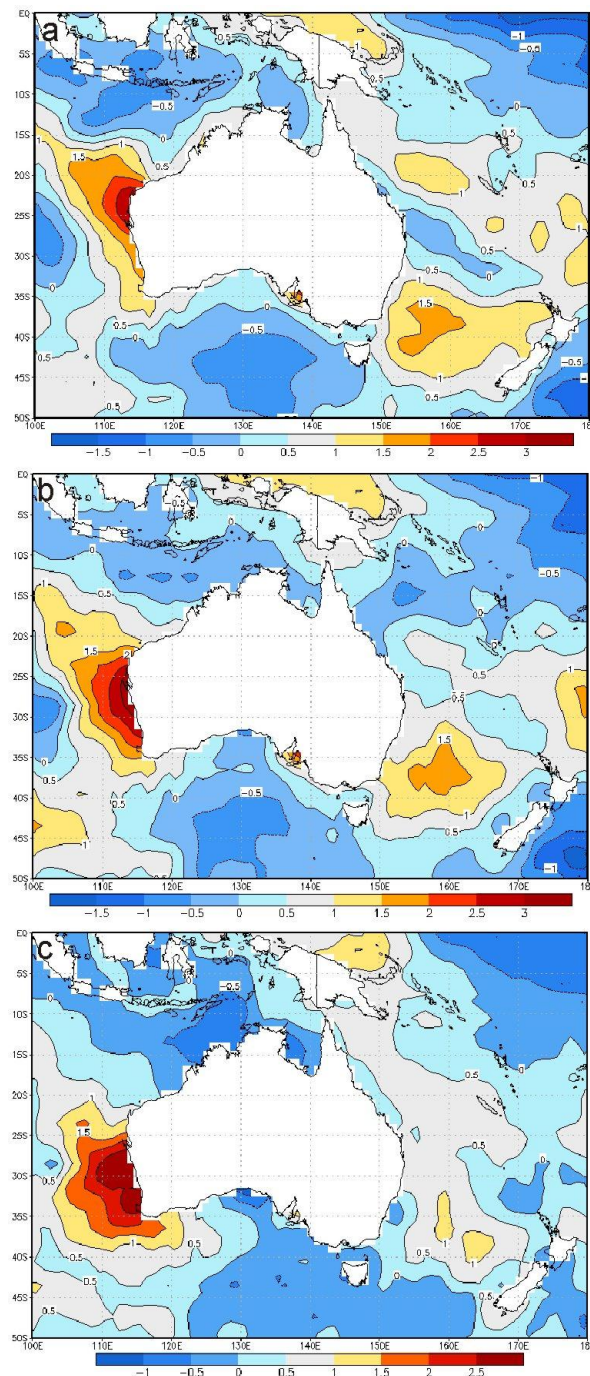


Figure S2. Sea surface temperatures (SST) and anomalies, obtained from the Met Office Hadley Centre's sea ice and sea surface temperature (HadISST1) data at <http://climexp.knmi.nl> (Rayner et al., *Geophys. Res.*, 2003, 108[D14]: 4407), calculated against a 1971-2000 baseline. Annual maximum SST (red 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 °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 °C), exceeding the previous maximum (TSA = 1.045 °C) by up to 0.45 °C (43%).

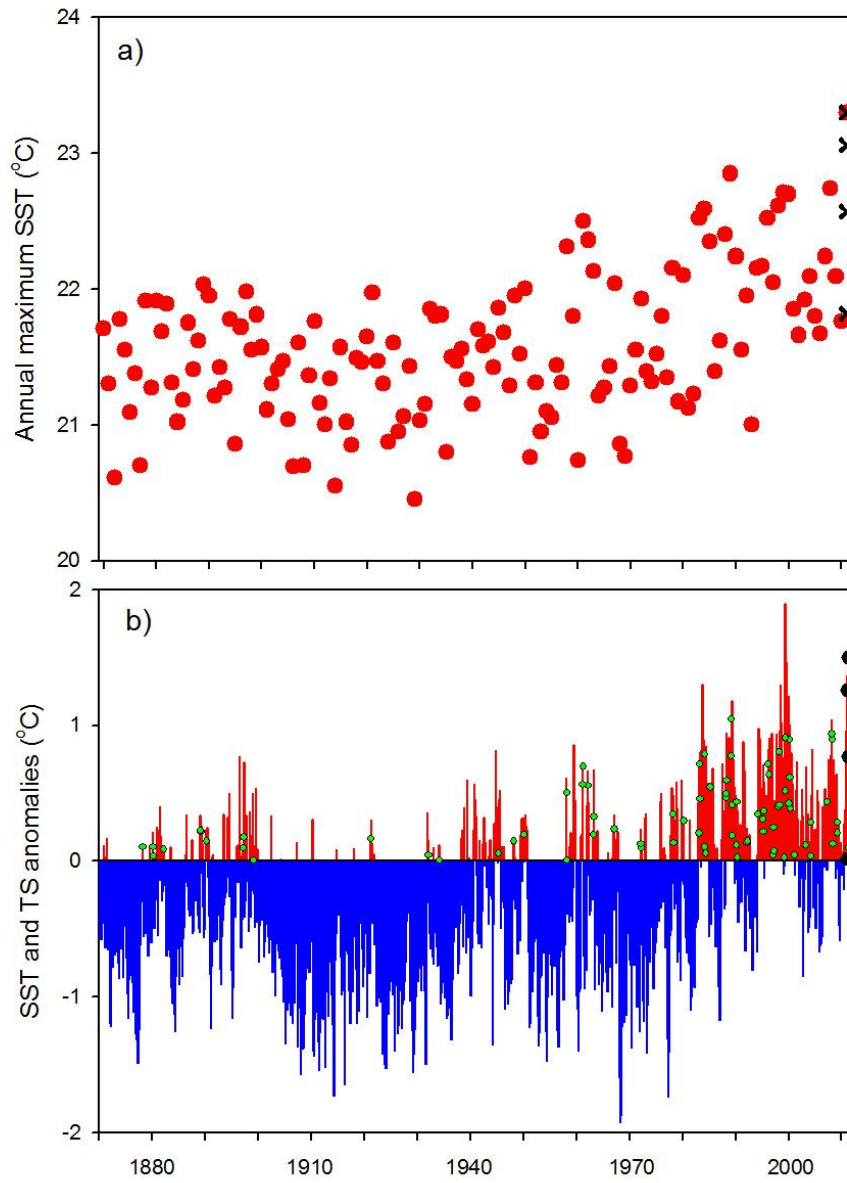


Figure S3. Temperature characteristics of Jurien Bay (JB: 33.5-34.5°S; 114.5-115.5°E) and Hamelin Bay (HB: 31.5-32.5°S; 114.5-115.5°E) from November 1981 until March 2012 (data source as in Fig. S1). Annual maximum SST (**a**) in JB (red line) and HB (blue line). Red and blue crosses represent monthly 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.

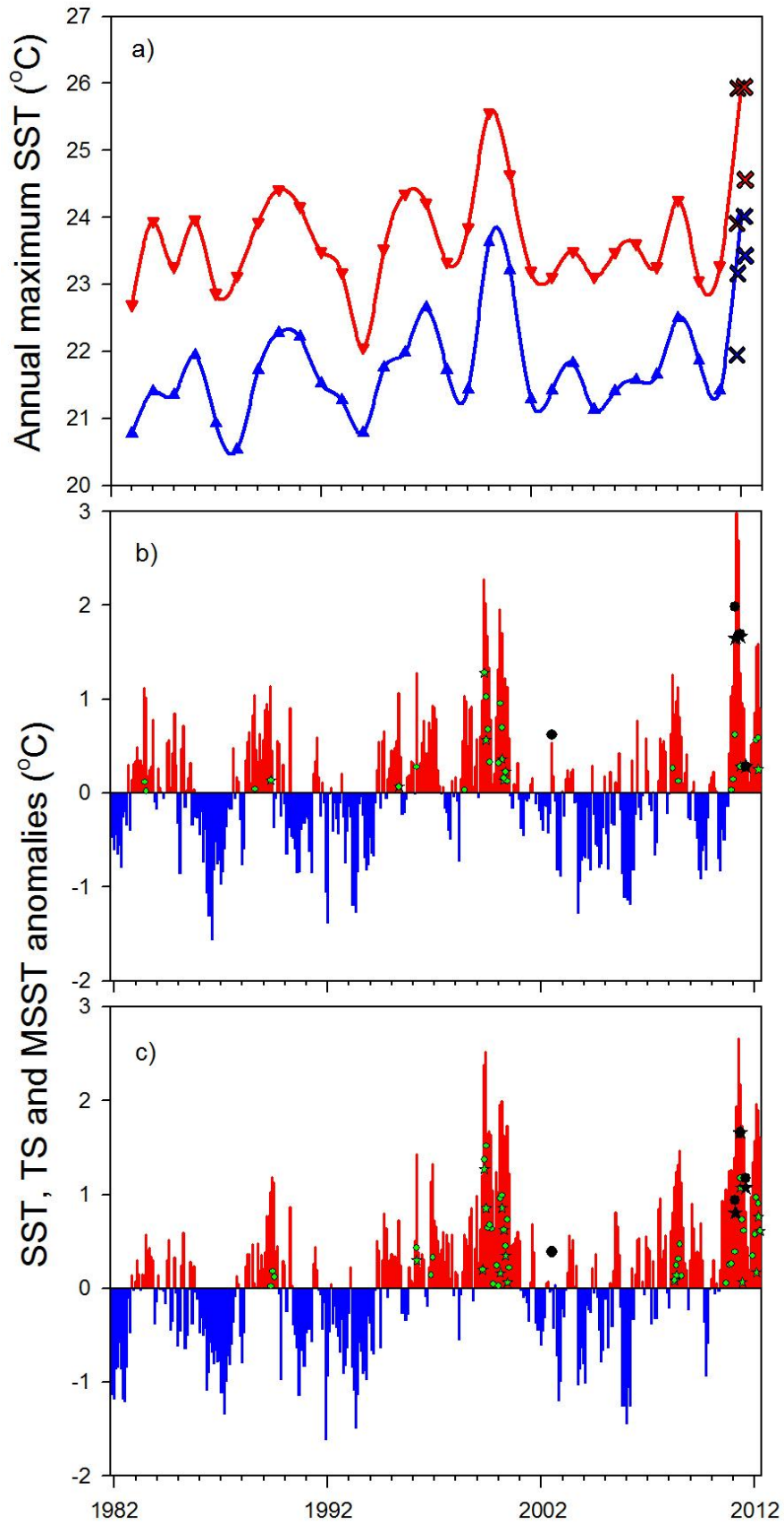


Table S1. PERMANOVA tests to examine differences between locations and years in community structure of benthic macroalgae and invertebrates, and demersal fishes. Permutations (999 under a reduced model) were based on a Bray-Curtis similarity matrix generated from either square-root transformed percent 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.

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