

SUPPLEMENTARAY INFORMATION

Deoxygenation following coral spawning and low-level thermal stress trigger mass coral mortality at Coral Bay, Ningaloo Reef

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Table S1. Timeline of disturbances at Bills Bay from 1973-2022. Only cyclones classified as Category 1 or above that passed within approximately 200km of Bills Bay are included. Thermal stress is defined as period with DHW is $\geq$ 8.

Day/Month	Year	Disturbance	Description	Impact on Hard Coral Cover	Source
4 th December	1973	Cyclone	Tropical Cyclone Beryl passed 10km north of Coral Bay	No data	bom.gov.au/cyclone
March	1975	Cyclone	Tropical cyclone Beverley passed through the North-west Cape with damage to a wooden jetty in Bills Bay reported	No quantifiable results however reports that Bill's Bay coral community was affected.	van Schoubroeck P and Long S, 2007
2 nd March	1977	Cyclone	Severe Tropical Cyclone Karen passed approximately 50km north-west of Coral Bay (Category 4)	No data	bom.gov.au/cyclone
no month recorded	1978	Anoxic Event	Coral spawning induced anoxia. Size and locality within Bills Bay unknown	Coral mortality occurred with 4 long-term monitoring sites	van Schoubroeck P and Long S, 2007
6 th March	1982	Cyclone	Severe Tropical Cyclone Ian passed approximately 10km west of Coral Bay	No data	bom.gov.au/cyclone
2 nd March	1984	Cyclone	Severe Tropical Cyclone Chloe passed north of Coral Bay	No data	bom.gov.au/cyclone
no month recorded	1987	Anoxic Event	Minor Fish kill reported washed up on Bills Bay, extent unknown	No data	Simpson, 1993; van Schoubroeck P and Long S, 2007
26 th March	1989	Anoxic Event	Coral spawning induced anoxia. Coral mortality decreased at sites further away from shore.	Decline before and after the event from a mean level of coral cover of 42.9% to 9.4%.	Simpson, 1993
no month recorded	1990	Cyclone	Cyclone Tina passed 70km east. Category 2	No data	bom.gov.au/cyclone
no month recorded	1990	<i>Drupella</i> outbreak	Mid 1980s to early 1990s unusually high densities of <i>Drupella cornus</i> along 100km of Ningaloo MP resulted in significant coral mortality	No data	Armstrong, 2007
12 th December	1995	Cyclone	Severe Tropical Cyclone Frank passed approximately 100km west of Coral Bay (Category 3)	No data	bom.gov.au/cyclone

21 st March	1999	Cyclone	Severe Tropical Cyclone Vance passed east of Coral Bay (Category 5)	No data	bom.gov.au/cyclone
April-June	1999	Thermal	DHW > 14 was recorded, falling below 8 during June	No data	(NOAA)
25 th February	2000	Cyclone	Tropical Cyclone Steve passed east of Coral Bay (Category 3)	No data	bom.gov.au/cyclone
April - May	2000	Thermal	DHW of 15 was recorded in April, falling below 8 during May	No data	(NOAA)
April	2001	Cyclone	Cyclone Alistair passed 150km south of Coral Bay. (Category 1)	No data	bom.gov.au/cyclone
3 rd April	2002	Anoxic Event	Coral Spawning induced anoxia. Major fish kill (estimated ~1 million).	80% mortality in nearshore reef, 30% mortality in mid reef; and 0% mortality in outer reef sites.	van Schoubroeck P and Long S, 2007
7 th March	2005	Anoxic Event	Fish and coral deaths are thought to have resulted from a combination of the high-water temperatures (29-31 degrees) and deoxygenation of the waters by decomposing coral larvae predicted to be from external source south of bills bay rather than the spawn created within the bay. Local reporting of spawn slicks before the spawning of Bills Bay corals has led to this prediction.	30% of hard corals were bleached, no mention of overall mortality.	van Schoubroeck P and Long S, 2007
March	2006	Cyclone	Cyclone Glenda passed 150 north-east as a Category 3.	No data	bom.gov.au/cyclone
no month recorded	2006	Cold Water Bleaching	No details	No data	Shedrawi, 2017
February	2008	Cyclone	Severe Tropical Cyclone Nicholas passed 20km west of Bill's Bay (Category 3)	No data	bom.gov.au/cyclone
28 th March	2008	Anoxic Event	The conditions, related to a tropical cyclone (TC Pancho) located offshore at the time, caused the accumulation of coral spawn in Bill's Bay for up nine days causing hypoxic conditions	40-20% decline in coral cover.	Armstrong, 2009
January - June	2011	Thermal	DHW > 24 recorded in April, with >8 DHW persisting through until June.	Combined with Cyclone Carlos to produce significant decline in coral cover. Declined from 42 to 31% (~26% mortality).	(NOAA) Coral Reef Watch Ningaloo 5 km Regional Virtual Station Shedrawi, 2017. Newnham, 2020
23 rd February	2011	Cyclone	Tropical Cyclone Carlos passed within 100km of Bill's Bay as Category 2. Correlated with thermal stress as well.	Severe impact due to increased SST. In combination with 2010/2011 heatwave.	bom.gov.au/cyclone

February - May	2013	Thermal	DHW > 8 recorded in Feb, reaching a maximum of 19 in April	No data	(NOAA) ABC 2022
13 th March	2015	Cyclone	Tropical Cyclone Olwyn passed just west of Coral Bay (~25km) as a Category 3.	No data	bom.gov.au/cyclone
April	2019	Anoxic Event	A minor anoxic event at Bill's Bay resulted in bleaching dominated by <i>Porites</i> spp following 2019 spawning event. Detected during regular aerial surveys of Ningaloo Reef. Most colonies survived. Images are available.	Minor - impacted colonies survived but rebleached in 2022.	Claire Ross DBCA, pers. comms.
April	2021	Thermal	Patches of bleaching occurred in Bill's Bay due to La Nina heatwave	Minor (<5% bleached in Bill's Bay).	Claire Ross DBCA, pers. comms.
24 th March	2022	Anoxic Event	Mass spawning event led to fish kills, and subsequent mass coral mortality. Other members of the community eg. Molluscs also impacted.	Catastrophic decline of coral cover in nearshore, inner-mid reef and mid-reef zones.	This study
April	2022	Thermal	La Nina heatwave resulted in some bleaching. Hard to disentangle from the anoxic event.	Based on outer reef (where anoxic event had less of an impact) 1-10% of coral was bleached. Relatively minor.	Claire Ross DBCA, pers. comms.

Sources:

- Simpson CJ, Cary JL, Masini RJ (1993) Destruction of corals and other reef animals by coral spawn slicks on Ningaloo Reef, Western Australia. *Coral Reefs* 12:185-191
- Armstrong SJ, Syme R (2009). Anoxic impacts at Bill's Bay, Ningaloo Marine Park associated with the 2008 coral spawning event. Marine Science Program Data Report Series: MSPDR2. January 2009. Marine Science Program, Department of Environment and Conservation, Perth, Western Australia. 19p.
- van Schoubroeck P and Long S (2007) Disturbance history of coral reef communities in Bill's Bay, Ningaloo Marine Park, 1989-2007. Data Report: MSP-2007_06. Marine Science Program, Department of Environment and Conservation, Perth, Western Australia (unpublished report).
- Shedrawi G, Falter JL, Friedman KJ, Lowe RJ, Pratchett MS, Simpson CJ, Speed CW, Wilson SK, Zhang Z (2017) Localised hydrodynamics influence vulnerability of coral communities to environmental disturbances. *Coral Reefs* 36:861-872
- Newnham TJ, Browne NK, Bumbak J, Loudon L, Wellington H, Shedrawi G, Hacker J, O'Leary M (2020) Long-term (70-year) monitoring of reef structure through high-resolution multidecadal aerial imagery. *Coral Reefs* 39:1859-1870
- Armstrong S (2007) Ningaloo Marine Park *Drupella* long-term monitoring program. *DiscoveringNingaloo*:26-30

Table S2. Coral community bleaching survey data obtained from the Department of Conservation and Attractions during rapid visual assessment surveys from 2019 – 2022.

Date	Location	Survey method	Comment	Source
26/02/2019	Bill's Bay	Rapid in-water checks	No bleaching observed	DBCA
26/04/2019	Bill's Bay	Aerial flight	Localised bleaching detected at Skeleton Beach only (-23.124267 S, 113.76425 E)	DBCA
12/07/2019	Bill's Bay	Aerial flight	Localised bleaching at Skeleton Beach only (-23.124267 S, 113.76425 E)	DBCA
17/08/2019	Bill's Bay	Photo-transects	80% coral bleaching of <i>Porites</i> spp. at Skeleton Beach only (-23.124267 S, 113.76425 E)	DBCA
24/11/2019	Bill's Bay	Photo-transects	No bleaching observed; long-term monitoring site	DBCA
18/02/2020	Bill's Bay	Rapid in-water checks	No bleaching observed	DBCA
17/04/2020	Bill's Bay	Aerial flight	No bleaching observed	DBCA
9/05/2020	Bill's Bay	Rapid in-water checks	No bleaching observed	DBCA
14/11/2020	Bill's Bay	Photo-transects	No bleaching observed; long-term monitoring site	DBCA
22/02/2021	Bill's Bay	Rapid in-water checks	No bleaching observed	DBCA
14/04/2021	Bill's Bay	Aerial flight	No bleaching observed	DBCA
15/04/2021	Bill's Bay	Rapid in-water checks	<1 % coral bleaching	DBCA
18/11/2021	Bill's Bay	Photo-transects	No bleaching observed; long-term monitoring site	DBCA
11/02/2022	Bill's Bay	Rapid in-water checks	No bleaching observed	DBCA
15/04/2022	Bill's Bay	Aerial flight	Severe coral mortality across inner and middle lagoon. Low to moderate bleaching on outer lagoon.	DBCA
5/04/2022	Bill's Bay	Photo-transects		DBCA
3/05/2022	Bill's Bay	and rapid in-water checks		DBCA

Table S3 Coordinates of the nine study sites surveyed in Bills Bay in 2016, 2017, 2018, 2022.

Site	Latitude (°S)	Longitude (°E)
1	-23.140575	113.769825
2	-23.139103	113.769811
3	-23.13725	113.769797
4	-23.140575	113.767217
5	-23.139047	113.767189
6	-23.137261	113.767178
7	-23.140569	113.763444
8	-23.1391	113.763056
9	-23.137289	113.764314

Table S4. Coordinates of the three sites surveyed in 2021.

Site	Latitude and Longitude coordinates (decimal degrees)
A	-23.13972°S, 113.76101°E (<i>near site 8 in the current study</i>)
B	-23.14105°S, 113.76712°E (<i>near site 4 in the current study</i>)
C	-23.132733°S, 113.760636°E (<i>approximately 400m north of site 9 in the current study</i>).

Table S5. Pairwise comparisons of level of benthic cover between years and across the three reef zones. Significant comparisons are bolded.

Groups (all sites)	t	P(perm)	Unique Perms
2016, 2017	0.31519	0.9097	9954
2016, 2018	0.8442	0.4891	9943
2016, 2022	10.552	0.0001	9954
2017, 2018	0.87274	0.4667	9939
2017, 2022	12.985	0.0001	9938
2018, 2022	11.606	0.0001	9948
Groups (near shore)	t	P(perm)	Unique Perms
2016, 2017	0.34679	0.885	8166

2016, 2018	1.1903	0.2325	8170
2016, 2022	5.0068	0.0001	8140
2017, 2018	1.4197	0.1456	8185
2017, 2022	6.792	0.0002	8157
2018, 2022	6.1034	0.0001	8163
Groups (inner-mid)	t	P(perm)	Unique Perms
2016, 2017	0.84011	0.4699	8111
2016, 2018	1.0459	0.3292	8187
2016, 2022	9.2649	0.0001	7429
2017, 2018	1.0571	0.3095	8183
2017, 2022	11.02	0.0001	7368
2018, 2022	10.005	0.0001	7366
Groups (mid-reef)	t	P(perm)	Unique Perms
2016, 2017	0.38499	0.9209	5613
2016, 2018	1.3216	0.1832	8105
2016, 2022	6.7652	0.0001	8155
2017, 2018	1.4612	0.1162	8158
2017, 2022	7.5935	0.0001	8209
2018, 2022	6.456	0.0002	8134

Table S6. Mean percent coral, turf, other algae and abiotic benthic cover from 2016-2022 at each site and overall.

	Year	Hard Coral (%) (cover)	Turf Algae (%) (% cover)	Other Algae (%) (% cover)	Abiotic (%) (% cover)
Site 1	2016	28.67 ± 8.41	40.33 ± 13.67	0.00	31.00 ± 21.08
	2017	49.67 ± 10.17	28.67 ± 4.33	0.00	21.67 ± 9.17
	2018	28.33 ± 3.18	20.67 ± 5.78	1.67 ± 1.20	49.33 ± 6.33
	2022	0.83 ± 0.83	62.08 ± 17.45	0.00	37.08 ± 17.56
Site 2	2016	29.33 ± 9.35	18.33 ± 2.91	0.00	52.33 ± 6.89
	2017	29.33 ± 7.97	25.00 ± 1.73	0.00	45.67 ± 9.35
	2018	38.67 ± 4.33	20.00 ± 6.56	4.00 ± 1.00	37.33 ± 10.48
	2022	0.00	80.42 ± 3.41	0.00	19.58 ± 3.41
Site 3	2016	58.00 ± 5.77	26.00 ± 8.08	0.00	16.00 ± 2.31
	2017	45.33 ± 5.93	21.67 ± 5.04	0.00	33.00 ± 5.57
	2018	53.67 ± 4.06	26.33 ± 7.80	3.33 ± 1.2	16.67 ± 11.35
	2022	0.83 ± 0.83	72.5 ± 9.01	0.00	26.67 ± 9.82
Site 4	2016	80.67 ± 4.33	17.00 ± 5.51	0.33 ± 0.33	2.00 ± 1.15
	2017	65.33 ± 8.95	20.33 ± 7.84	0.00	14.33 ± 6.98
	2018	66.67 ± 2.19	21.00 ± 2.65	0.67 ± 0.67	11.67 ± 2.19
	2022	4.17 ± 4.17	83.33 ± 5.07	0.00	12.5 ± 2.89
Site 5	2016	65.00 ± 8.62	5.67 ± 3.18	0.00	29.33 ± 5.84
	2017	63.67 ± 3.76	11.33 ± 0.88	0.00	25.00 ± 4.16
	2018	60.67 ± 11.22	14.67 ± 4.18	4.00 ± 2.00	20.67 ± 9.39
	2022	0.00	91.67 ± 2.92	0.00	8.33 ± 2.92
Site 6	2016	77.33 ± 3.18	19.00 ± 5.57	0.00	3.67 ± 2.73
	2017	79.67 ± 4.84	13.67 ± 4.10	0.00	6.67 ± 3.33
	2018	73.67 ± 3.48	24.00 ± 2.31	0.00	2.33 ± 1.2
	2022	0.00	92.50 ± 3.15	0.00	7.5 ± 3.15
Site 7	2016	52.33 ± 10.81	46.67 ± 11.46	1.00 ± 1.00	0.00
	2017	67.67 ± 2.73	25.67 ± 9.35	0.00	6.67 ± 6.67
	2018	44.33 ± 4.91	52.00 ± 6.03	1.33 ± 0.33	2.33 ± 1.45
	2022	0.00	80.42 ± 2.53	0.00	19.58 ± 2.53
Site 8	2016	47.00 ± 20.07	53.00 ± 20.07	0.00	0.00
	2017	47.00 ± 11.68	53.00 ± 11.68	0.00	0.00
	2018	30.33 ± 3.93	62.67 ± 3.48	2.33 ± 1.45	4.67 ± 4.18
	2022	3.75 ± 0.72	63.33 ± 12	1.67 ± 1.10	31.25 ± 11.81
Site 9	2016	83.00 ± 1.15	15.00 ± 2.08	1.00 ± 1.00	1.00 ± 1.00
	2017	62.33 ± 9.35	37.67 ± 9.35	0.00	0.00

	2018	74.00 ± 0.58	20.67 ± 0.33	1.67 ± 1.2	3.67 ± 1.45
	2022	0.83 ± 0.83	82.92 ± 5.42	0.83 ± 0.83	15.42 ± 6.14
Overall (all sites combined)	2016	57.93 ± 4.64	26.78 ± 4.04	0.26 ± 0.16	15.04 ± 4.07
	2017	56.67 ± 3.54	26.33 ± 3.04	0.00	17.00 ± 3.34
	2018	52.26 ± 3.56	29.11 ± 3.34	2.11 ± 0.41	16.52 ± 3.61
	2022	1.16 ± 0.51	78.80 ± 3.06	0.28 ± 0.17	19.77 ± 2.99

Table S7. Total colony abundance recorded on belt transects in 2018 and 2022.

Zone	Site	2018	2022
Nearshore	1	541	15
Nearshore	2	405	0
Nearshore	3	347	17
Inner-mid reef	4	373	20
Inner-mid reef	5	330	1
Inner-mid reef	6	448	4
Mid-reef	7	437	19
Mid-reef	8	296	55
Mid-reef	9	275	22
	Overall	3452	153

Table S8. Total colony abundance per genera in each reef zone in 2018 and 2022.

	2018				2022			
	Nearshore	Inner-mid	Mid	Total	Nearshore	Inner-mid	Mid	Total
<i>Acropora</i>	94	95	35	224	0	0	0	0
<i>Astrea</i>	13	8	0	21	0	1	0	1
<i>Astreopora</i>	5	0	18	23	0	0	0	0
<i>Coelastrea</i>	1	4	1	6	0	0	0	0
<i>Cyphastrea</i>	348	157	304	809	25	23	95	143
<i>Dipsastrea</i>	281	96	161	538	0	0	0	0
<i>Echinopora</i>	85	56	51	192	0	0	0	0
<i>Favites</i>	38	16	10	64	0	0	0	0
<i>Fungia</i>	12	54	23	89	0	0	0	0
<i>Galaxea</i>	54	171	90	315	0	0	0	0
<i>Goniastrea</i>	66	31	19	116	0	0	0	0
<i>Herpolitha</i>	5	2	0	7	0	0	0	0
<i>Hydnophora</i>	10	0	0	10	0	0	0	0
<i>Leptastrea</i>	14	4	1	19	0	0	0	0
<i>Leptoria</i>	1	0	0	1	0	0	0	0

<i>Leptoseris</i>	4	0	0	4	0	0	0	0
<i>Lobophylla</i>	6	7	11	24	0	0	0	0
<i>Montipora</i>	81	115	42	238	0	0	0	0
<i>Pachyseris</i>	39	33	58	130	0	0	0	0
<i>Paragoniastrea</i>	2	0	0	2	0	0	0	0
<i>Pavona</i>	6	1	0	7	0	0	0	0
<i>Platygyra</i>	6	11	8	25	0	0	0	0
<i>Pocillopora</i>	67	82	14	163	0	0	1	1
<i>Porites</i>	2	4	4	10	7	1	0	8
<i>Stylophora</i>	28	68	61	157	0	0	0	0
<i>Turbinaria</i>	25	136	97	258	0	0	0	0
Total	1293	1151	1008	3452	32	25	96	153



Figure S1. Imagery obtained during and after the 2022 anoxic event. (a) A dead stingray on the shoreline on 27th March 2022, photo by Lyle Shields/DBCA; (b) A dead moray eel (Family Muraenidae) on 28th March 2022, photo by Vince Brozek/DBCA; (c, d) Dead eel and fish and accumulating on the shoreline on 28th March 2022, photos by Vince Brozek/DBCA.

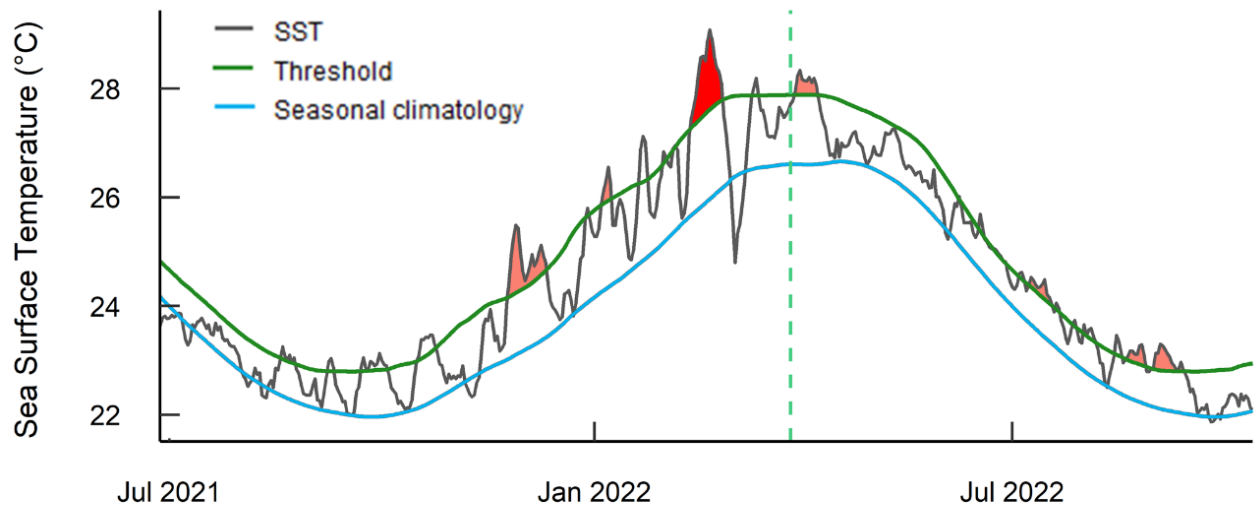


Figure S2. Heat stress during the 2021/22 summer for Coral Bay, Western Australia. Climatology was calculated using NOAA CRW 5km SST data with a baseline period of 25 years (1986–2011) and heat stress events are based on a seasonally varying threshold as per the specifications of Hobday et al. (2016) using NOAA CRW 5km satellite-based sea surface temperature. The vertical green dashed line indicates the timing of the deoxygenation event. The red filled area indicates the main heatwave event identified, while shaded orange areas indicate other heat stress during the year.

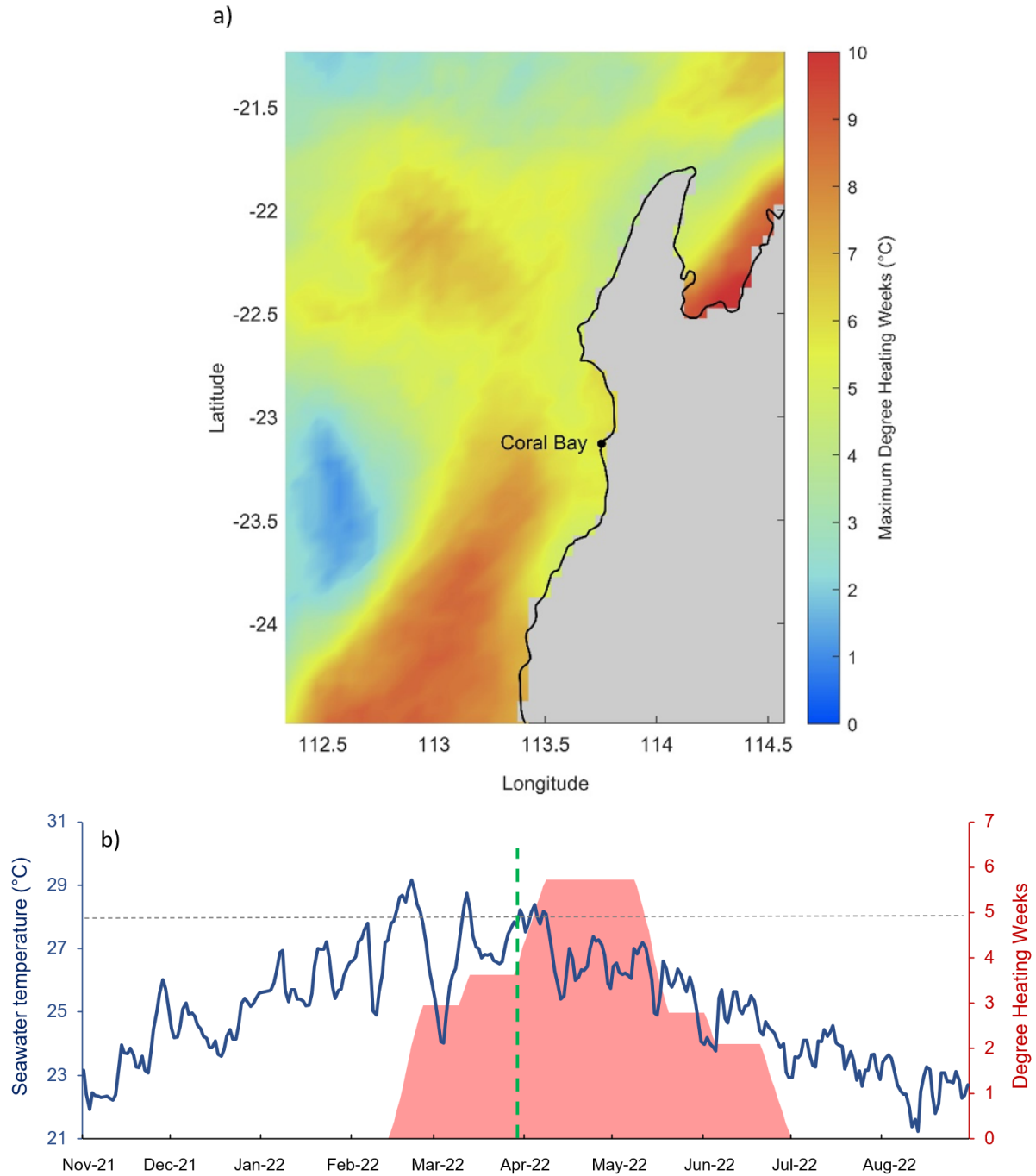


Figure S3. (a) Heat map of maximum degree heating weeks for Coral Bay based on NOAA CRW 5km Degree Heating Weeks and (b) timeseries of in-situ seawater temperature (Onset Hobo v2 temperature logger; accuracy ± 0.2 °C) and Degree Heating Weeks from Coral Bay, Ningaloo Reef, Western Australia. Grey dashed line represents the local coral bleaching threshold of 28°C. The vertical green dashed line indicates the timing of the deoxygenation event.

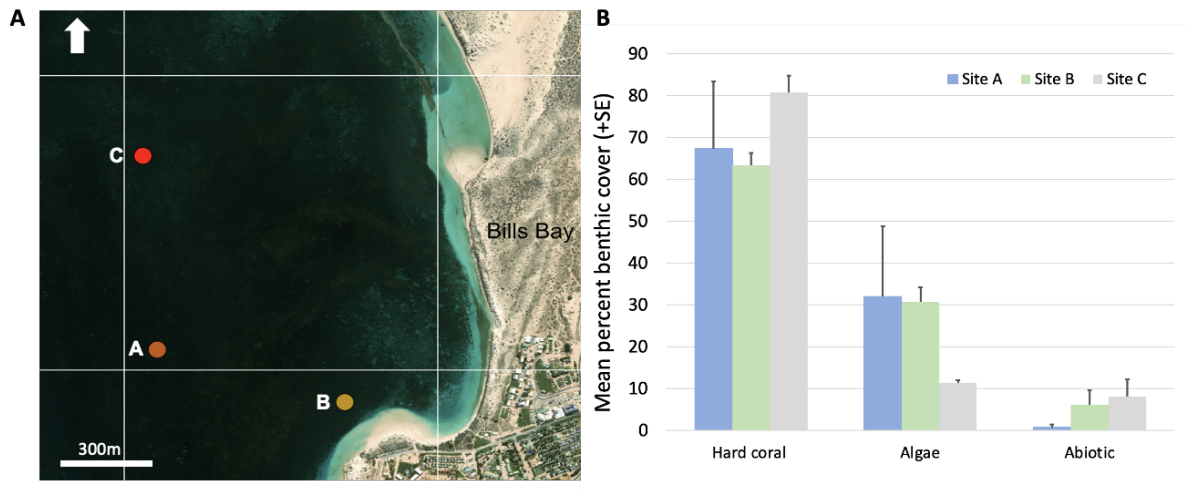


Figure S4. Location of sample sites from coral cover surveys in 2021. Percent coral cover was estimated on three replicate point intercept transects ($n = 50$ points per transect) at three sites in Bills Bay in 2021. See Table S2 for site coordinates.

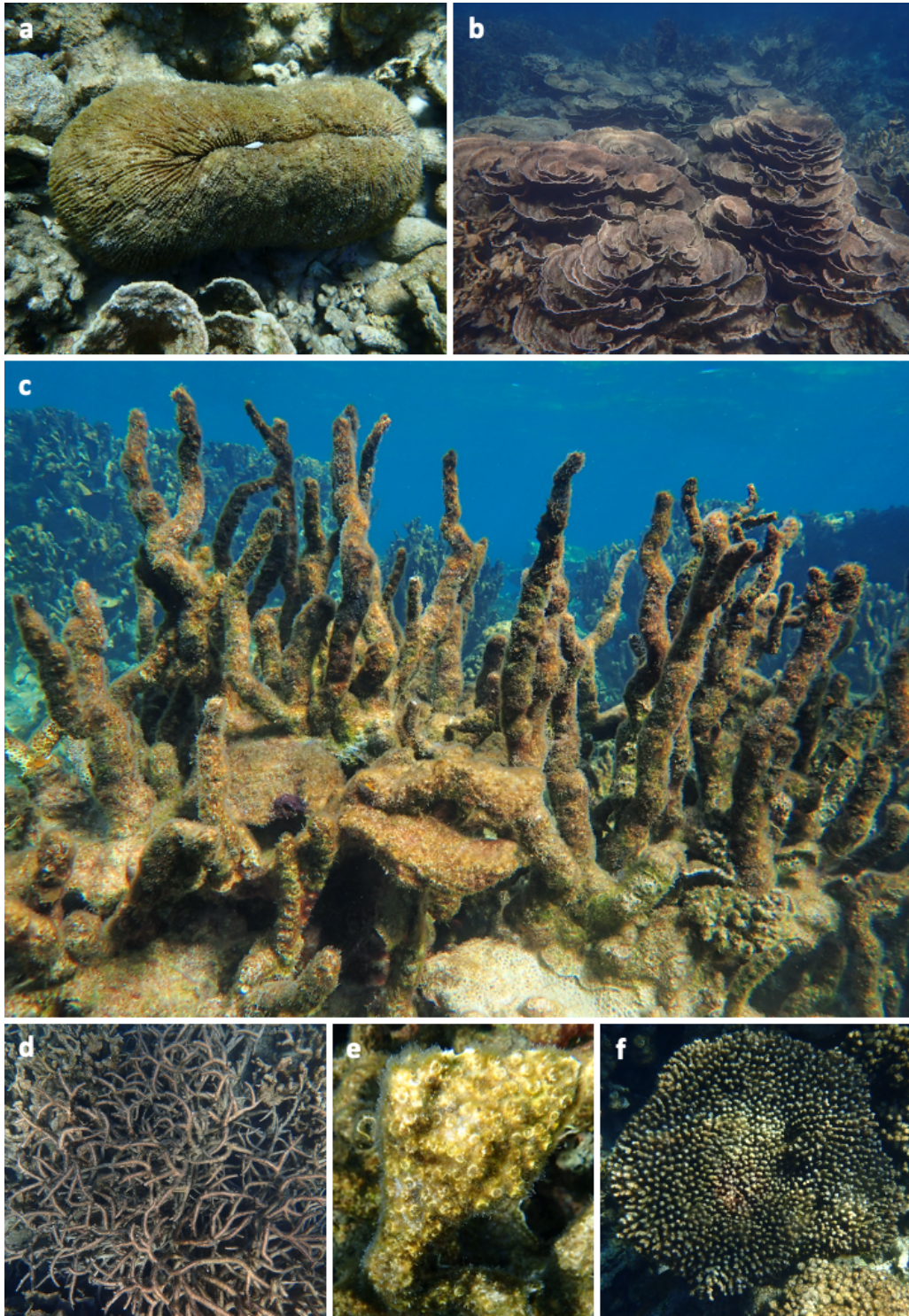


Figure S5. Bills Bay death assemblage in September 2022. A). *Ctenactis* colony, b). Plating *Montipora*, c). Branching *Echinopora*, d). Arborescent *Acropora*, e). Close up of *Echinopora* branch showing non-abrasion of corallites, f). Corymbose *Acropora* colony. Note all corals are covered in an even layer of turf algae indicating very light grazing by herbivores possibly due to the spike of resources available for herbivorous fishes and a reduction in the amount of predation as reef-associated fishes also experienced a mass die-off event (see Fig. S1).