Fine-scale Movement of Northern Gulf of Mexico Red Snapper and Gray Triggerfish Estimated with Three-Dimensional Acoustic Telemetry

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Supplementary Materials

Supplementary Table 1. Acoustic tagged red snapper tracked during this study. Possible assigned fates are: emigrated from the array (em), mortality from predation (pred), unknown or ambiguous (unk), tag assumed to have fallen off of the fish (shed), and still alive and present within the array when the acoustic receivers were removed (at large).

Fish ID	TL (mm)	N days w/ position estimates	N reefs visited	N switch	Average days per reef = N days/(N switch + 1)	Daily home range (95% KDE)						Fate	Days between tagging and fate
						m³ (thousands)			m² (thousands)				
						med.	min.	max.	med.	min.	max.		
30-m array													
RS42	625	112	5	8	12.4	8.4	0.2	91.7	0.68	0.03	6.3	em	144.2
RS53	393	28	1	0	28	8.6	3.2	57.1	0.78	0.47	4.1	pred	28.4
RS16	466	38	1	0	38	8.9	3	31	0.7	0.4	2.1	em	38.4
RS19	508	39	1	0	39	10.6	5.1	156.6	0.67	0.43	11.8	unk	39.1
RS83	384	9	1	0	9	10.8	6	70.4	1.11	0.68	7.4	pred	8.8
RS9	461	51	2	1	25.5	11.5	4.9	27.9	0.76	0.51	2.1	em	164.5
RS62[1]	410	16	1	0	16	12	5.9	20.8	0.9	0.54	1.5	shed	16.1
RS78	387	11	5	9	1.1	12.2	4.8	65.9	1	0.61	7.2	shed	10.8
RS6[1]	376	48	1	0	48	14.9	8.1	60.1	1.1	0.68	4.4	shed	47.8
RS7	406	42	1	0	42	15.5	6.4	178.1	1	0.59	13.3	em	77.4
RS4	398	51	1	0	51	15.9	6.4	104.6	1.14	0.49	8.3	em	50.5
RS63	395	38	1	0	38	17.2	3.7	92.4	1.54	0.5	5.1	em	41.1
RS77	412	44	3	6	6.3	17.2	2.6	101	1.46	0.38	8.8	em	44.3
RS72	372	17	3	3	4.3	17.4	1.5	43.9	1.43	0.19	3.5	shed	16.6
RS82	394	23	2	1	11.5	18.7	5.6	43.6	1.45	0.48	2.9	shed	23.3
RS45	335	5	2	1	2.5	20	12.5	44.2	1.53	1.34	3	pred	4.6
RS52	366	4	1	0	4	20.5	8.6	135.6	1.42	0.75	11.9	em	4
RS76	408	58	3	15	3.6	22.1	4.5	124.5	1.99	0.58	10.7	em	58.4
RS57	331	190	2	2	63.3	25.2	2.4	302.4	2.19	0.41	27.4	at large	194.6
RS60	370	27	1	0	27	26.4	5.7	59.8	2.02	0.73	4.4	pred	27.4
RS46	366	36	1	0	36	28.6	7.1	132	2.15	0.6	8.2	em	35.5
RS74	440	39	7	42	0.9	28.9	5.8	302.8	3.78	0.54	24.9	em	38.5

| Fish ID	TL (mm)	N days w/ position estimates	N reefs visited	N switch	Average days per reef = N days/(N switch + 1)	Daily home range (95% KDE)						Fate	Days between tagging and fate
						m^3 (thousands)			m^2 (thousands)				
						med.	min.	max.	med.	min.	max.		
RS55	407	20	1	0	20	29	8.7	49	2.1	0.57	3.4	shed	19.5
RS69	519	55	5	72	0.8	29.7	5.4	185.5	2.91	0.43	10.2	shed	55.2
RS84	371	73	4	12	5.6	30.7	3.6	104.8	2.28	0.4	7.7	shed	73.7
RS58	360	59	1	0	59	30.8	6.6	87.4	2.26	0.55	6.4	shed	59.1
RS80	392	5	4	8	0.6	32	6.6	85.7	3.46	0.56	4.7	em	5.3
RS59	372	189	2	144	1.3	32.8	7.7	256.1	2.45	0.6	18.1	at large	188.9
RS75	427	5	4	3	1.3	33.6	7.2	93.7	2.52	0.68	6	em	4.5
RS50	356	147	2	130	1.1	34.5	6.8	180.5	2.5	0.54	12.2	pred	147.1
RS54	362	76	2	14	5.1	34.5	7.9	281.9	2.5	0.64	20.2	shed	76
RS49	390	123	2	2	41	37.5	1.2	402.8	2.63	0.18	27.9	shed	123.1
RS48	383	94	2	4	18.8	39.8	3.5	303.4	3.2	0.49	25.8	em	93.6
RS65	395	95	1	0	95	46.1	6.2	192.1	3.28	0.45	15.1	pred	133.8
RS64	395	92	5	19	4.6	50.8	12.5	482.9	3.31	0.82	35	shed	92.3
55-m array													
RS147	412	36	2	2	0.2	15	1.6	140.3	0.94	0.16	11	shed	36
RS119	493	32	1	0	32	17.9	6.6	77.1	0.88	0.48	2.9	shed	31.5
RS116	628	13	1	0	13	18.5	9.2	34.9	0.89	0.44	1.3	shed	13
RS105	529	16	1	0	16	21.9	16.5	54.5	1.09	0.79	2.3	shed	15.5
RS100[2]	554	26	1	0	26	23	5.7	62.7	1.15	0.53	2.7	shed	25.5
RS138	508	14	2	3	3.5	23.4	13.4	64	0.92	0.6	3.5	em	14.2
RS128	479	68	1	0	68	25.2	1.4	132.6	1.28	0.11	3.9	shed	68.8
RS129	439	88	1	0	88	26.2	9.6	71.5	1.41	0.56	3.3	shed	87.6
RS148	594	19	1	0	19	27.1	18.2	171.6	1.31	0.83	11.8	em	19
RS86	571	10	1	0	10	28.9	11	49.6	1.61	0.85	2.2	shed	9.7
RS100B[2]	595	29	1	0	29	30.4	16.6	139.1	1.47	0.94	8.5	em	28.5
RS124	414	111	2	1	55.5	31.8	11	135.5	1.93	0.79	7.2	at large	110.9
RS130	515	93	1	0	93	33.6	3.1	161	1.6	0.27	6.4	em	93.1
RS125	569	40	1	0	40	34.7	9.7	119.4	1.89	0.67	4.7	em	39.9

Fish ID	TL (mm)	N days w/ position estimates	N reefs visited	N switch	Average days per reef = N days/(N switch + 1)	Daily home range (95% KDE)						Fate	Days between tagging and fate
						m³ (thousands)			m² (thousands)				
						med.	min.	max.	med.	min.	max.		
RS120	615	70	2	1	35	35	13.8	79.8	1.61	0.67	3.8	shed	69.9
RS136	761	83	5	37	2.2	35.5	1.5	612.8	1.91	0.14	38.3	at large	110.1
RS163	443	79	1	0	79	36.1	12.6	221.9	1.89	0.82	14.2	shed	79.3
RS91	627	36	1	0	36	36.8	13.9	76.5	1.82	0.76	4	shed	37
RS155	623	64	2	1	32	37	7.9	135.8	1.6	0.43	5.8	shed	64.6
RS135	502	8	1	0	8	39.9	19.6	79.9	2.27	1.05	3.6	pred	8.1
RS158	464	98	2	1	49	40.3	5.8	86.8	1.77	0.38	3.9	at large	97.8
RS131	472	103	2	2	34.3	41	3.1	371.2	1.84	0.3	25.8	em	103.1
RS132	475	103	2	1	51.5	44.3	8	168.6	2.13	0.46	5.4	shed	104.7
RS92	610	40	1	0	40	63.1	17.4	286.7	2.62	0.86	19.7	shed	40.2
RS99	664	236	1	0	236	65.3	6	328.6	2.95	0.33	22	at large	323.6
RS142	696	4	1	0	4	145.5	47.6	318.8	5.49	1.64	17.2	em	4.4

[1] RS6 was recaptured after having shed the acoustic transmitter and retagged as RS62.

[2] RS100 was recaptured after having shed the acoustic transmitter and retagged as RS100B.

Supplementary Table 2. Acoustic tagged gray triggerfish tracked during this study. Possible assigned fates are: harvested by fishermen (harv), emigrated from the array (em), mortality from predation (pred), unknown or ambiguous (unk), tag assumed to have fallen off of the fish (shed), and still alive and present within the array when the acoustic receivers were removed (at large).

| Fish ID | FL (mm) | N days w/ position estimates | N reefs visited | N switch | Average days per reef = N days/(N switch + 1) | Daily home range (95% KDE) | | | | | | Fate | Days between tagging and fate |
						m^3 (thousands)			m^2 (thousands)				
						med.	min.	max.	med.	min.	max.		
GT37	431	16	1	0	16	4.7	2.6	8	0.4	0.29	0.5	harv	15.9
GT41	330	100	2	2	33.3	5.5	2	17.3	0.51	0.25	1.1	unk	100.1
GT23	348	141	3	67	2.1	7.2	2.2	42.3	0.55	0.21	3.6	em	141.2
GT26	419	94	5	68	1.4	7.9	3.2	223.9	0.52	0.29	24.8	em	94.2
GT21	485	4	1	0	4	11	6.8	83.1	0.64	0.55	5.2	em	4.3
GT20	378	16	1	0	16	11.9	4.5	21.8	0.79	0.4	1.5	harv	16
GT66	465	162	8	31	5.1	11.9	2.4	520.7	0.96	0.35	47.2	at large	194.9
GT32	429	45	3	50	0.9	12.6	3	152.5	0.84	0.31	12.1	pred	44.5
GT22	411	3	2	8	0.3	12.7	6.7	31.9	0.96	0.47	2.5	em	3.4
GT29	471	266	18	625	0.4	35.8	2.1	757.1	2.62	0.23	56.3	em	266.6
GT24	486	133	6	338	0.4	36.1	2.1	390.7	2.93	0.27	32.6	em	133.2
GT39	420	39	2	46	0.8	42.1	1.8	652.6	3.1	0.23	53.2	em	39.1
GT17	391	269	6	95	2.8	66.3	4.4	893.9	5.54	0.45	77.9	em	268.9
GT34	481	328	11	592	0.6	100.1	1.3	1087.3	8.67	0.19	74.1	shed	333.3
GT67	438	107	15	254	0.4	160.3	5.5	982.1	12.54	0.48	82.2	em	107.1
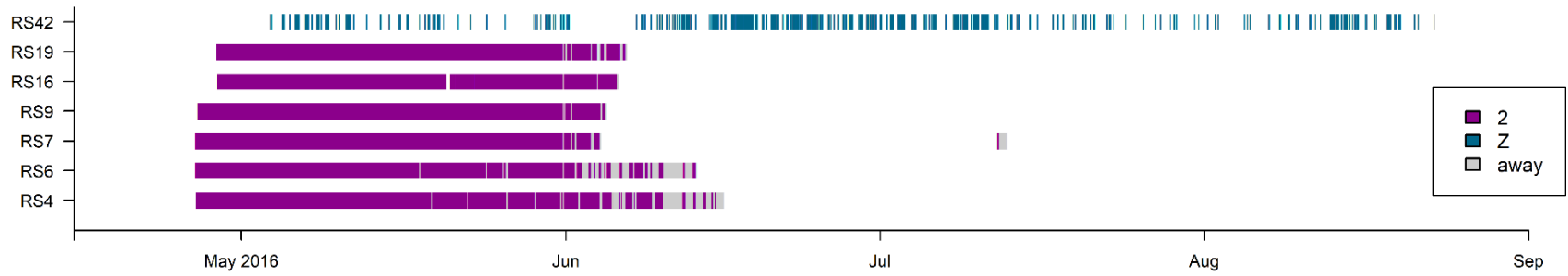
Supplementary Figure 1. Position history and daily closest reef for red snapper in the 30-m array from April 2016 through September 1, 2016. Days when the majority of fish positions were > 50 m from any reef are shown as "away".
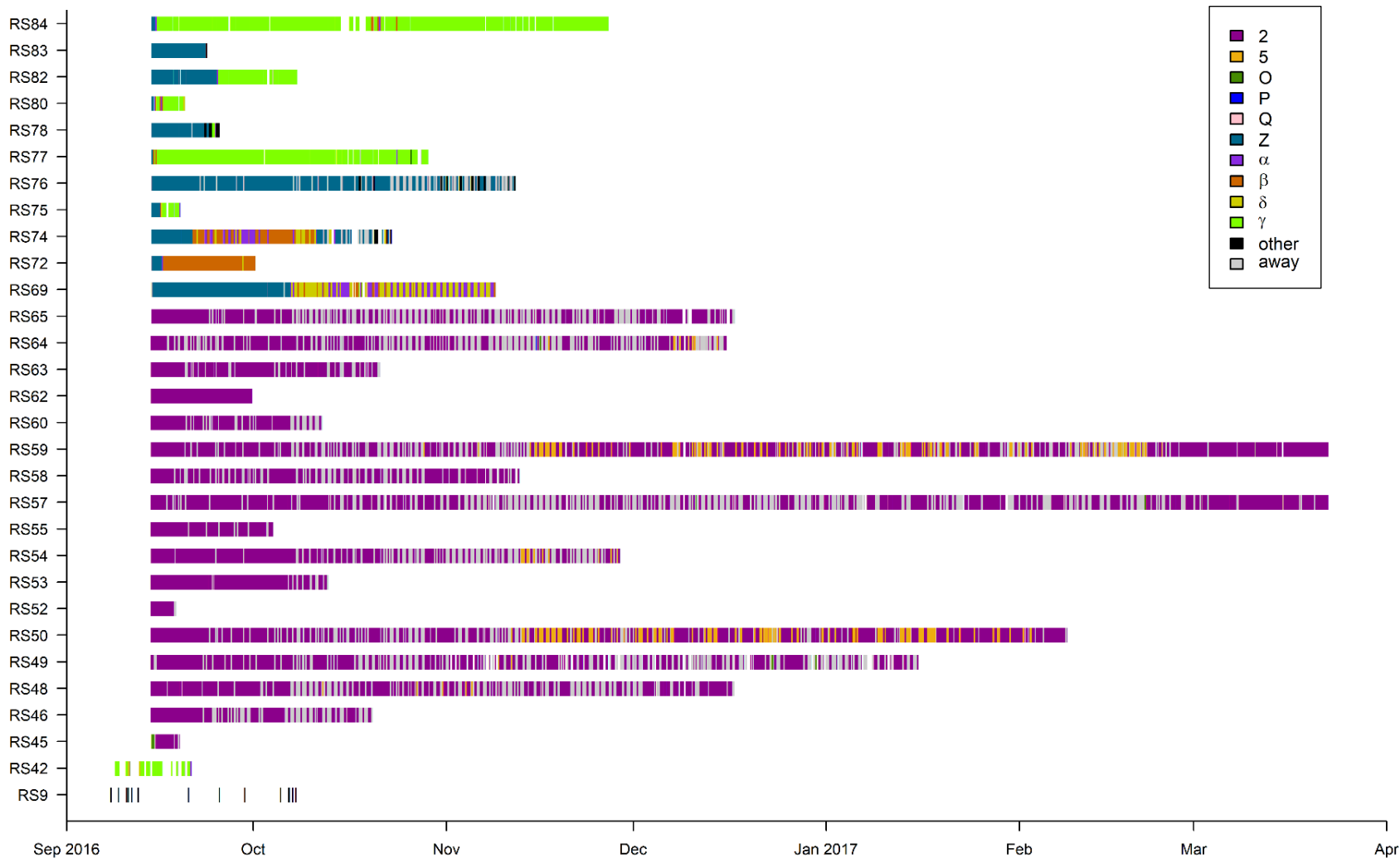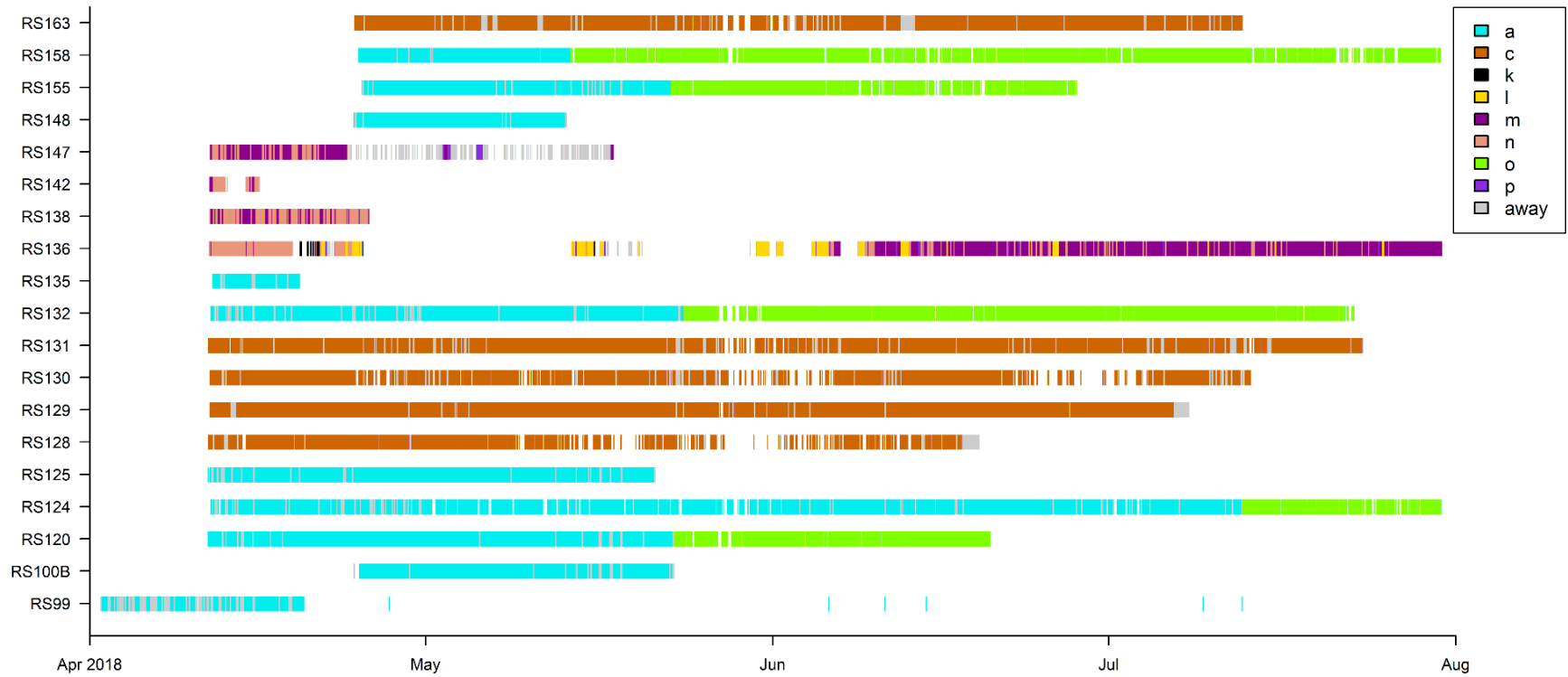
Supplementary Figure 2. Position history and resident reef for red snapper in the 30-m array from September 2016 through April 2017. Positions > 50 m from any reef are shown as "away". "Other" includes several reefs which combined accounted for << 1% of total positions (reefs 7, V, X, Y, and ε).
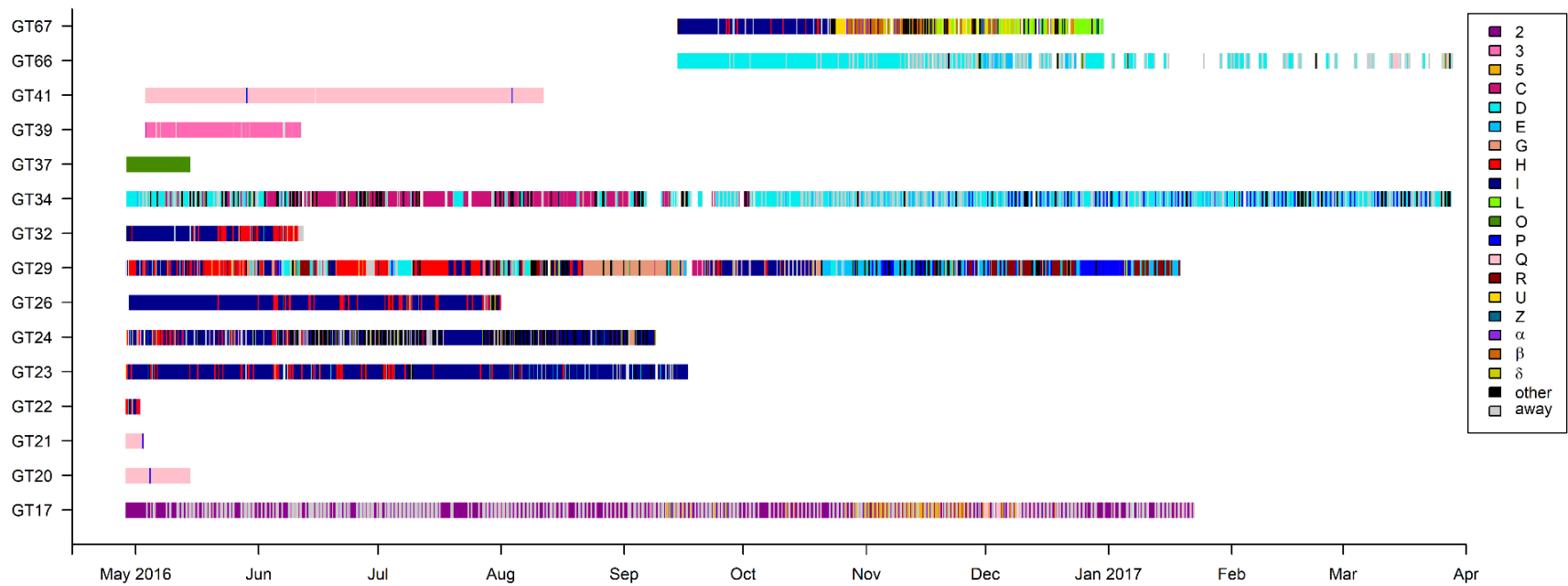
Supplementary Figure 3. Position history and resident reef for gray triggerfish in the 30-m array from April 2016 through April 2017. Positions > 50 m from any reef are shown as "away". "Other" includes several reefs which combined accounted for 1.5% of total positions (reefs 1, 6, A, B, F, J, K, M, S, X, Y, and γ).
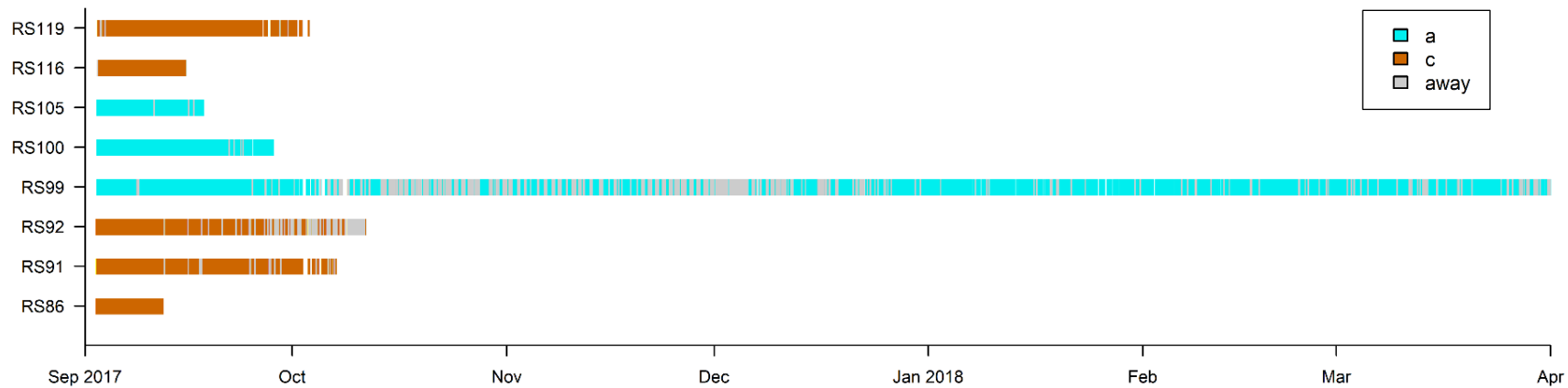
Supplementary Figure 4. Position history and resident reef for red snapper in the 55-m array from September 2017 through April 2018. Positions > 50 m from any reef are shown as "away".

Supplementary Figure 5. Position history and resident reef for red snapper in the 55-m array from April 2018 through August 2018. Positions > 50 m from any reef are shown as "away".
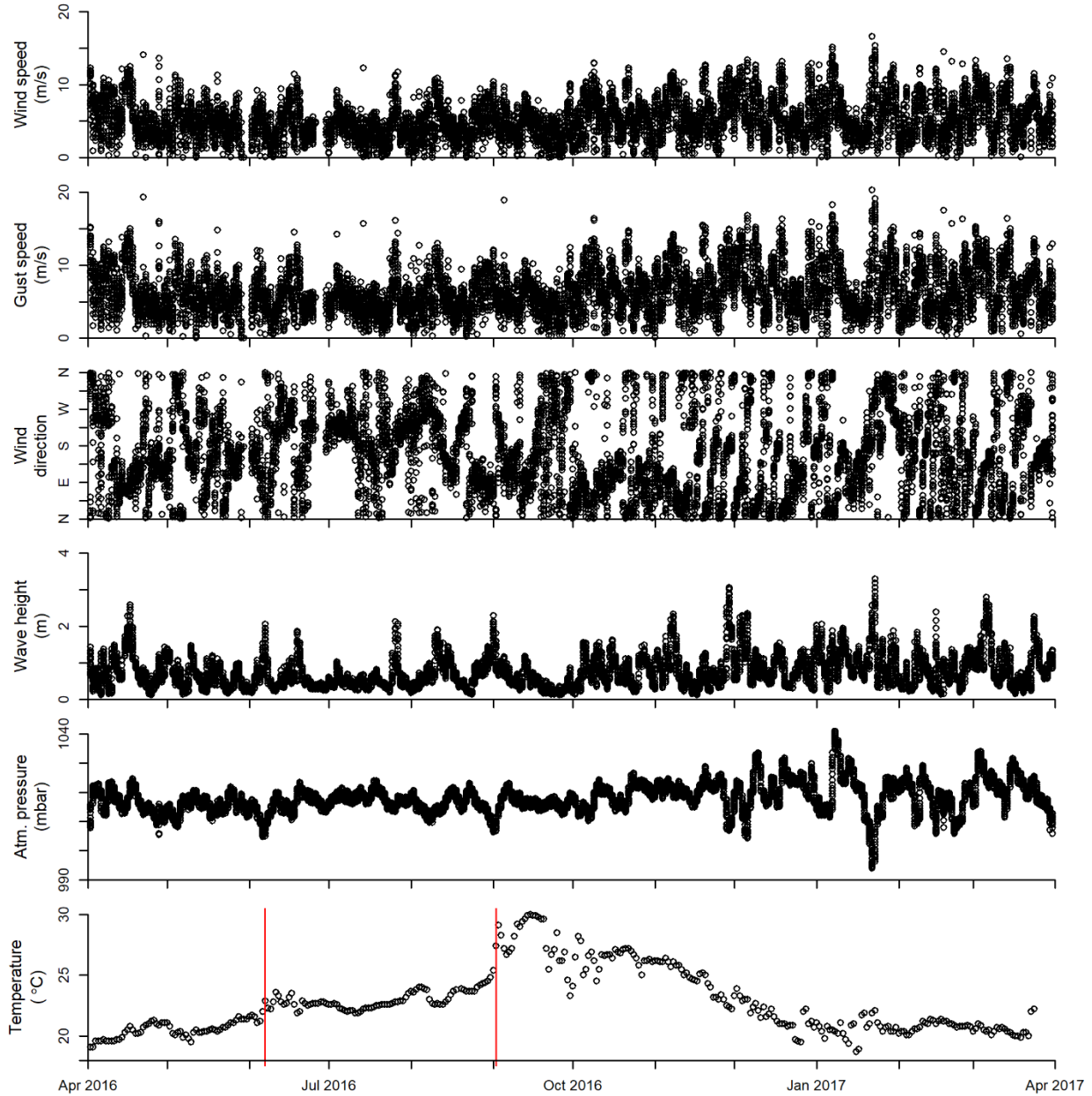
Supplementary Figure 6. Oceanographic conditions in the area of the 30-m array. Two named storms, Tropical Storm Colin and Hurricane Hermine, passed within 300 km of the array on 6 June 2016 and 2 September 2016 (vertical red lines on bottom pane). An unnamed storm system passed through the eastern GOM in late January 2017, causing high winds (>15 m/s), large waves (>3 m), and a drop in atmospheric pressure (below 994 mbar).
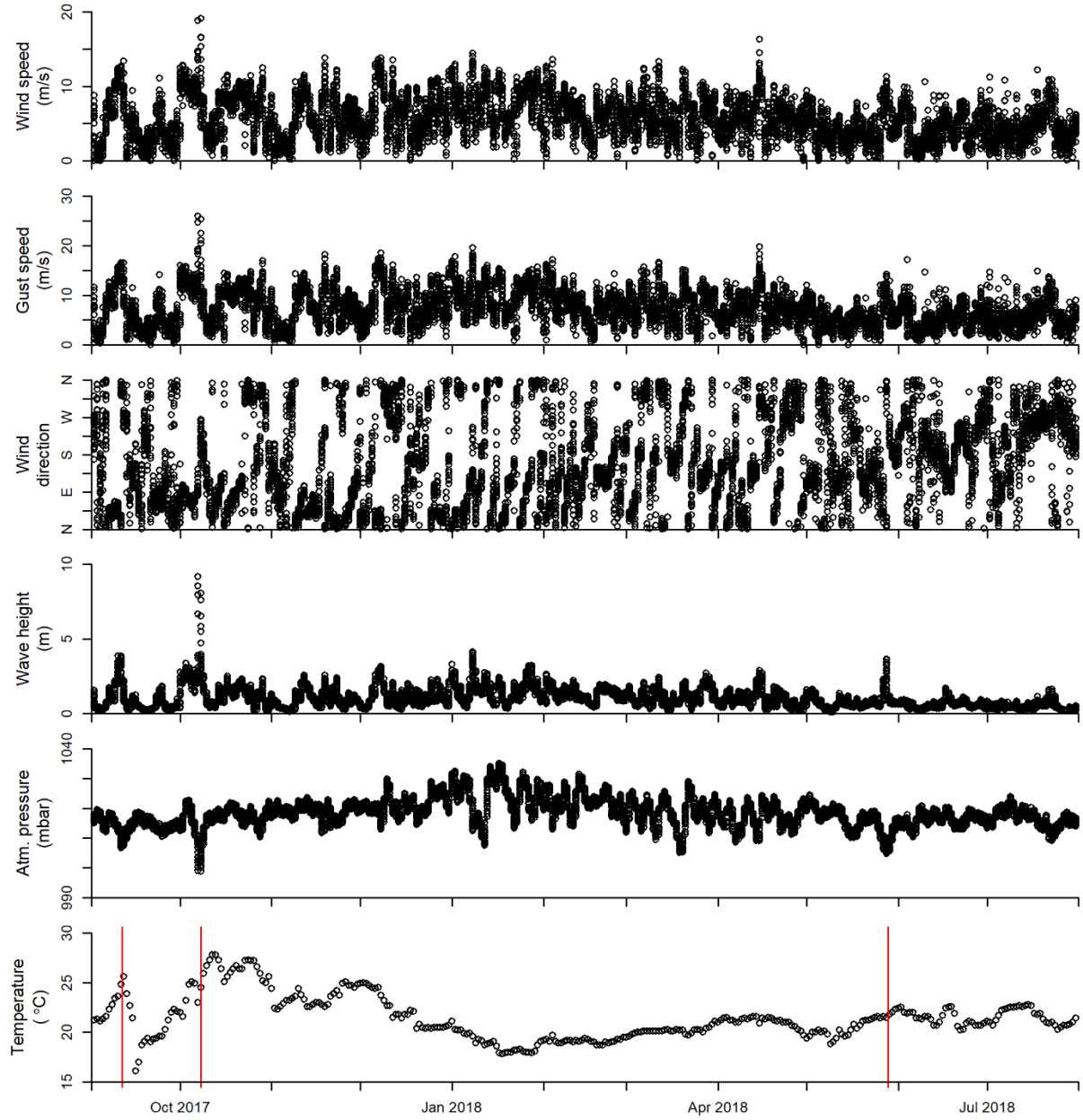
Supplementary Figure 7. Oceanographic conditions in the area of the 55-m array. Hurricane Irma, Hurricane Nate, and Tropical Storm Alberto affected conditions within the array on 11 September 2017, 8 October 2017, and 28 May 2018, respectively (vertical red lines on bottom pane).

Supplementary Table 3. Results of the GAMMs explaining variation of red snapper home range, height above bottom, and distance to reef.

Response variable	Model component	Value	SE	k	Estimated degrees of freedom	Estimated p-value
Home range (m²) variance explained = 0.12	*Fixed effects*					
	intercept	0.1611	< 0.001	1	1	< 0.001
	temperature	0.00853	0.002	1	1	< 0.001
	gust speed	0.00156	< 0.001	1	1	0.096
	atm. pressure	0.00095	< 0.001	1	1	0.501
	fish length	-0.00309	< 0.001	1	1	< 0.001
	wave height	-0.000073	< 0.001	1	1	0.921
	Random effects					
	individual + array (intercept)			61	61	
	Smooth terms					
	day × hour			15	11.75	< 0.001
	day			8	7.61	< 0.001
	hour			8	7.86	< 0.001
	temperature			9	8.56	< 0.001
	gust speed			9	4.50	< 0.001
	atm. pressure			9	6.76	< 0.001
	length			9	1	< 0.001
	wave height			9	4.21	< 0.001
	moon phase × hour			12	8.33	< 0.001
Home range (m³) variance explained = 0.14	*Fixed effects*					
	intercept	0.12	0.0005	1	1	< 0.001
	temperature	0.0037	0.001	1	1	< 0.001
	gust speed	0.00073	0.0005	1	1	0.112
	atm. pressure	0.00069	0.001	1	1	0.521
	fish length	-0.0044	0.0006	1	1	< 0.001
	Random effects					
	individual + array (intercept)			61	61	
	Smooth terms					
	day × hour			15	11.81	< 0.001
	day			8	7.7	< 0.001
	hour			8	7.86	< 0.001
	temperature			9	8.13	< 0.001
	gust speed			9	4.08	< 0.001
	atm. pressure			9	7.33	< 0.001
	length			9	1	< 0.001
	moon phase × hour			12	6.49	< 0.001
	moon phase			8	6.45	< 0.001
Height above bottom variance explained = 0.17	*Fixed effects*					
	intercept	3.55	0.42	1	1	< 0.001
	temperature	1.65	0.49	1	1	< 0.001
	wave height	-0.4	0.95	1	1	0.676
	atm. pressure	2.27	0.62	1	1	< 0.001
	wind speed	0.68	0.41	1	1	0.096
	Random effects					
	individual + array (intercept)			73	73	
	Smooth terms					
	day × hour			15	11.95	< 0.001
	day			8	7.99	< 0.001
	temperature			9	8.94	< 0.001
	moon phase			8	7.86	< 0.001
	wave height			9	8.11	< 0.001
	atm. pressure			9	8.49	< 0.001
	hour			8	7.56	< 0.001
	wind direction			8	7.44	< 0.001
	wind speed			9	6.63	< 0.001
	moon phase × hour			12	7.59	< 0.001

Supplementary Table 3. *continued*. Results of the GAMMs explaining variation of red snapper home range, height above bottom, and distance to reef.

Response variable	Model component	Value	SE	k	Estimated degrees of freedom	Estimated p-value
Distance to reef	*Fixed effects*					
variance explained	intercept	2.74	0.04	1	1	< 0.001
= 0.17	temperature	-0.23	0.13	1	1	0.070
	wave height	-0.09	0.06	1	1	0.122
	gust speed	-0.12	0.04	1	1	0.004
	atm. pressure	-0.19	0.09	1	1	0.034
	Random effects					
	individual + array (intercept)			61	61	
	Smooth terms					
	day × hour			15	12.19	< 0.001
	day			8	7.89	< 0.001
	hour			8	7.72	< 0.001
	temperature			9	8.08	< 0.001
	moon phase			8	7.45	< 0.001
	moon phase × hour			12	10.46	< 0.001
	wave height			9	7.1	< 0.001
	gust speed			9	5.49	< 0.001
	atm. pressure			9	8.1	< 0.001
	wind direction			8	5.6	< 0.001

Supplementary Table 4. Results of the GAMMs explaining variation of gray triggerfish home range, height above bottom, and distance to reef.

Response variable	Model component	Value	SE	k	Estimated degrees of freedom	Estimated p-value
Home range (m²)	*Fixed effects*					
variance explained	intercept	0.1650	0.002	1	1	< 0.001
= 0.26	wave height	-0.0197	0.004	1	1	< 0.001
	temperature	0.0050	0.003	1	1	0.103
	atm. pressure	0.0021	0.003	1	1	0.468
	fish length	-0.0045	0.002	1	1	0.013
	Random effects					
	individual (intercept)			15	15	
	Smooth terms					
	hour			8	7.87	< 0.001
	day			8	7.90	< 0.001
	day × hour			15	11.02	< 0.001
	wave height			9	7.73	< 0.001
	temperature			9	7.95	< 0.001
	moon phase × hour			12	6.73	< 0.001
	atm. pressure			9	7.10	< 0.001
	fish length			9	1.00	0.004
	wind direction			8	5.56	< 0.001
Home range (m³)	*Fixed effects*					
variance explained	intercept	0.12	0.001	1	1	< 0.001
= 0.28	wave height	-0.02	0.003	1	1	< 0.001
	temperature	0.0025	0.002	1	1	0.122
	atm. pressure	0.0009	0.002	1	1	0.622
	gust speed	-0.0003	0.001	1	1	0.807
	Random effects					
	individual (intercept)			15	15	
	Smooth terms					
	hour			8	7.83	< 0.001
	day			8	7.88	< 0.001
	day × hour			15	14.72	< 0.001
	wave height			9	8.27	< 0.001
	temperature			9	7.33	< 0.001
	moon phase × hour			12	6.95	< 0.001
	atm. pressure			9	7.1	< 0.001
	wind direction			8	5.51	< 0.001
	gust speed			9	5.37	< 0.001
Height above bottom	*Fixed effects*					
	intercept	2.60	0.46	1	1	< 0.001
variance explained	temperature	3.59	0.53	1	1	< 0.001
= 0.17	atm. pressure	-0.12	0.63	1	1	0.843
	wind speed	0.07	0.15	1	1	0.622
	wave height	0.18	0.17	1	1	0.269
	Random effects					
	individual (intercept)			15	15	
	Smooth terms					
	day × hour			15	12.38	< 0.001
	temperature			9	8.78	< 0.001
	hour			8	7.71	< 0.001
	moon phase			8	7.24	< 0.001
	atm. pressure			9	7.41	< 0.001
	moon phase × hour			12	7.00	< 0.001
	wind direction			8	5.71	< 0.001
	wind speed			9	3.65	< 0.001
	day			8	6.06	< 0.001
	wave height			9	3.84	< 0.001

Supplementary Table 4. *continued*. Results of the GAMMs explaining variation of gray triggerfish home range, height above bottom, and distance to reef.

Response variable	Model component	Value	SE	k	Estimated degrees of freedom	Estimated p-value
Distance to reef	*Fixed effects*					
variance explained	intercept	2.141	0.164	1	1	< 0.001
= 0.17	temperature	-0.033	0.14	1	1	0.811
	wave height	1.462	0.246	1	1	< 0.001
	atm. pressure	-0.239	0.218	1	1	0.272
	wind speed	0.084	0.106	1	1	0.429
	Random effects					
	individual (intercept)			15	15	
	Smooth terms					
	hour			8	7.82	< 0.001
	temperature			9	7.45	< 0.001
	day			8	7.8	< 0.001
	day × hour			15	14.65	< 0.001
	moon phase			8	6.38	< 0.001
	wave height			9	8.19	< 0.001
	atm. pressure			9	7.45	< 0.001
	moon phase × hour			12	8.54	< 0.001
	wind direction			8	6.02	< 0.001
	wind speed			9	6.29	< 0.001
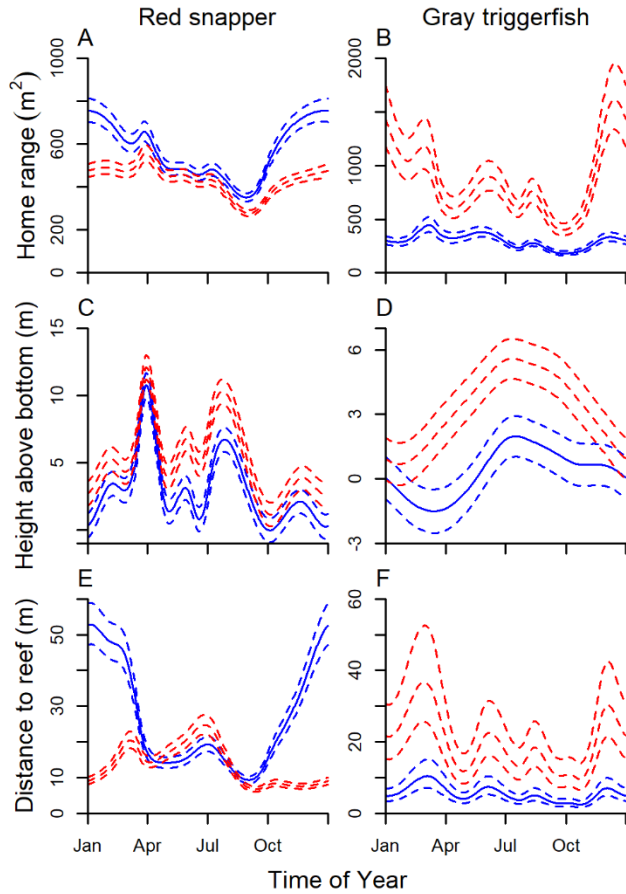
Supplementary Figure 8. GAMM predicted (solid line) and 95% CIs (broken line) of hourly home range (95% KDE; **A−B**), height above bottom (**C−D**), and distance to reef (**E−F**) of red snapper and gray triggerfish as a function of time of year. In each figure, time of day = 0000 is blue and 1200 is red.
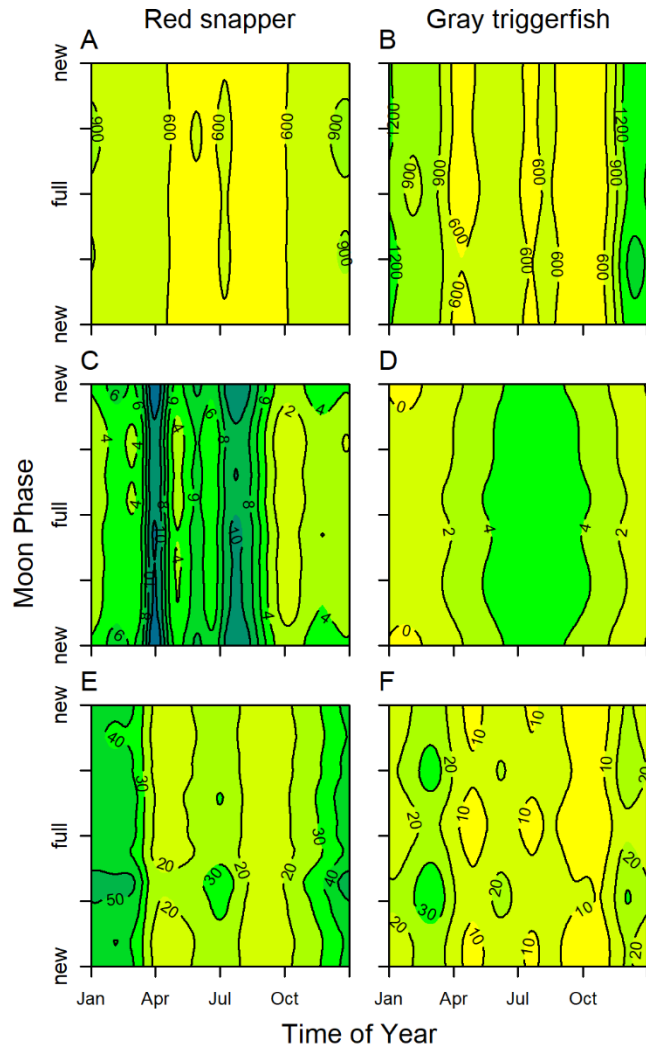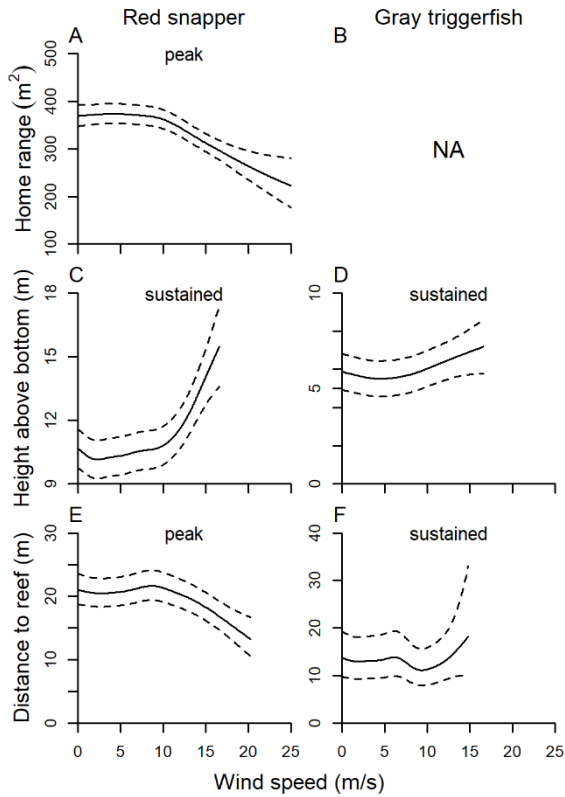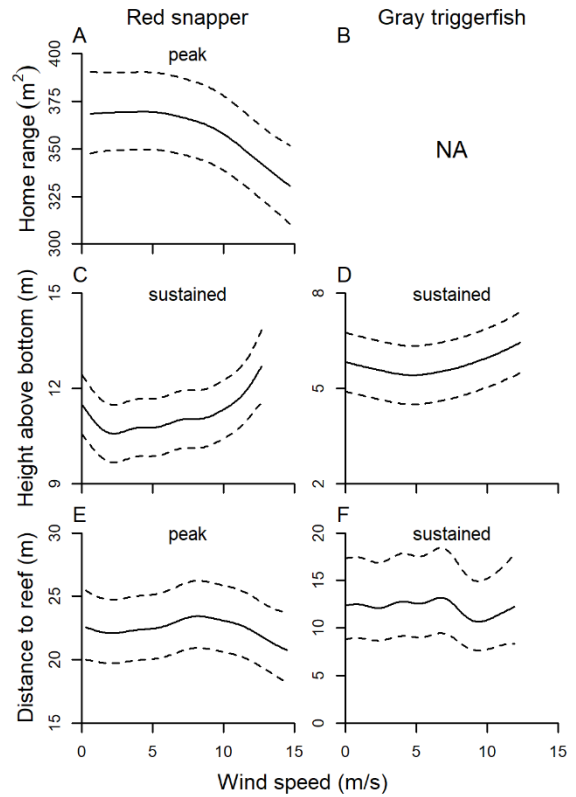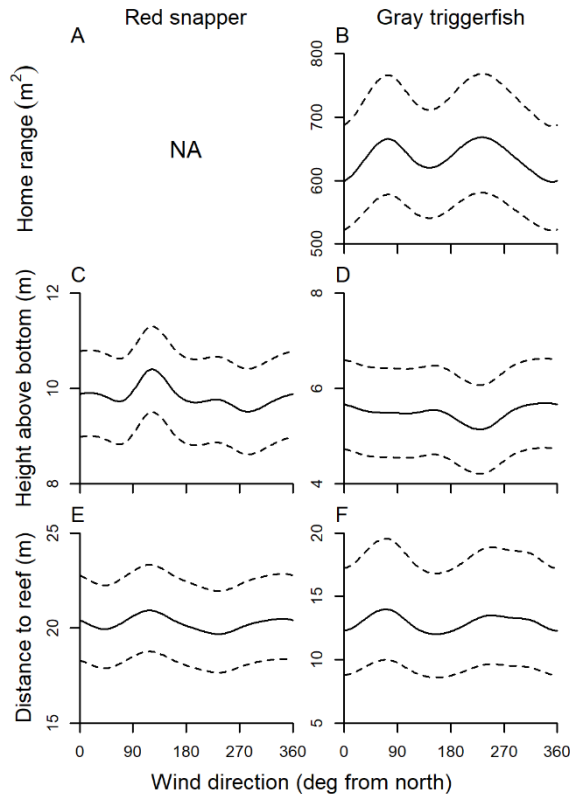
Supplementary Figure 9. GAMM predicted hourly home range (m^2; **A−B**), height above bottom (m, **C−D**), and distance to reef (m, **E−F**) of red snapper and gray triggerfish as a function of moon phase and time of year. Model predictions were calculated assuming 1800 and 1200 UTC-6 (dusk and noon) for red snapper and gray triggerfish, respectively.
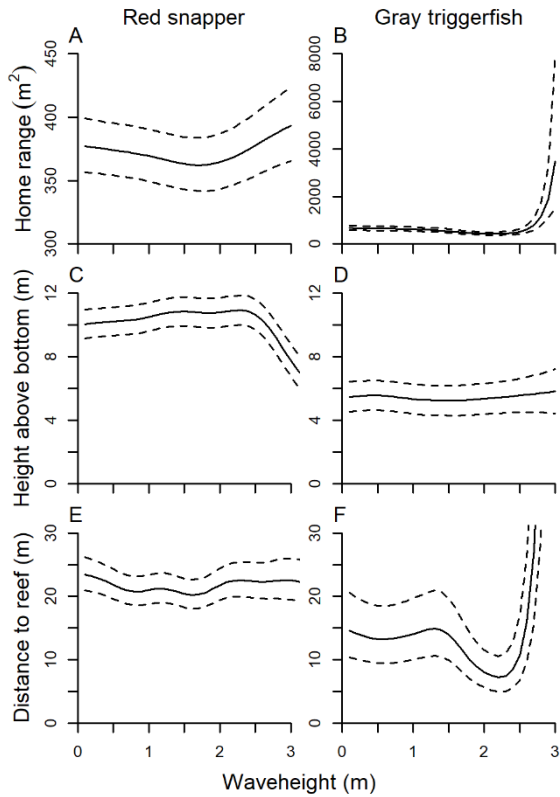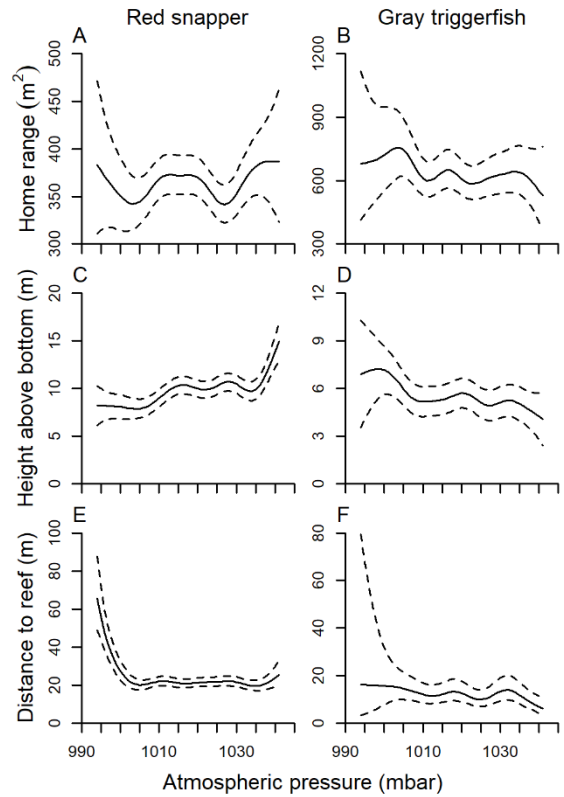
Supplementary Figure 10. GAMM predicted (solid line) and 95% CIs (broken line) of hourly home range (95% KDE; **A−B**), height above bottom (**C−D**), and distance to reef (**E−F**) of red snapper and gray triggerfish as a function of wave height.
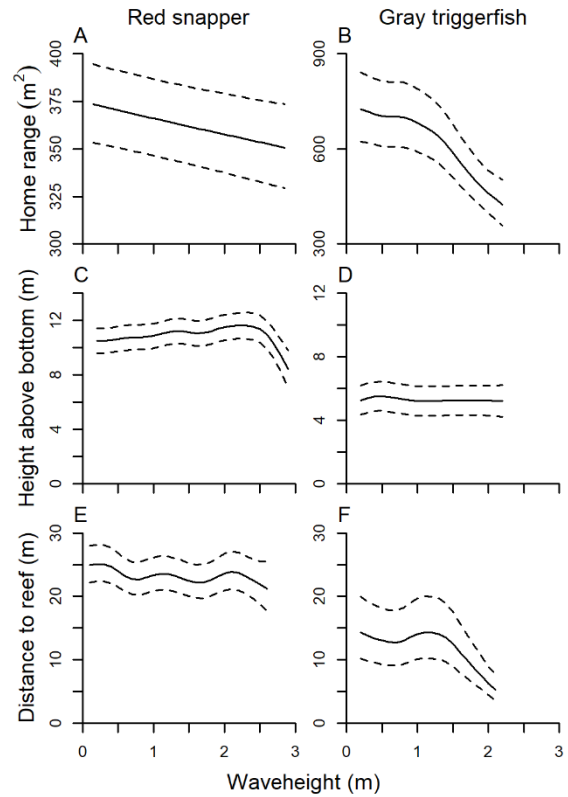
Supplementary Figure 11. GAMM predicted (solid line) and 95% CIs (broken line) of hourly home range (95% KDE; **A−B**), height above bottom (**C−D**), and distance to reef (**E−F**) of red snapper and gray triggerfish as a function of wave height. Position estimates outside the center 99% quantile for each variable were excluded from the model.

Supplementary Figure 12. GAMM predicted (solid line) and 95% CIs (broken line) of hourly home range (95% KDE; **A−B**), height above bottom (**C−D**), and distance to reef (**E−F**) of red snapper and gray triggerfish as a function of wind speed (either sustained or peak wind, as noted).

Supplementary Figure 13. GAMM predicted (solid line) and 95% CIs (broken line) of hourly home range (95% KDE; **A−B**), height above bottom (**C−D**), and distance to reef (**E−F**) of red snapper and gray triggerfish as a function of wind speed (either sustained or peak wind, as noted). Position estimates outside the center 99% quantile for each variable were excluded from the model.

Supplementary Figure 14. GAMM predicted (solid line) and 95% CIs (broken line) of hourly home range (95% KDE; **A−B**), height above bottom (**C−D**), and distance to reef (**E−F**) of red snapper and gray triggerfish as a function of wind direction.

Supplementary Figure 15. GAMM predicted (solid line) and 95% CIs (broken line) of hourly home range (95% KDE; **A−B**), height above bottom (**C−D**), and distance to reef (**E−F**) of red snapper and gray triggerfish as a function of atmospheric pressure.
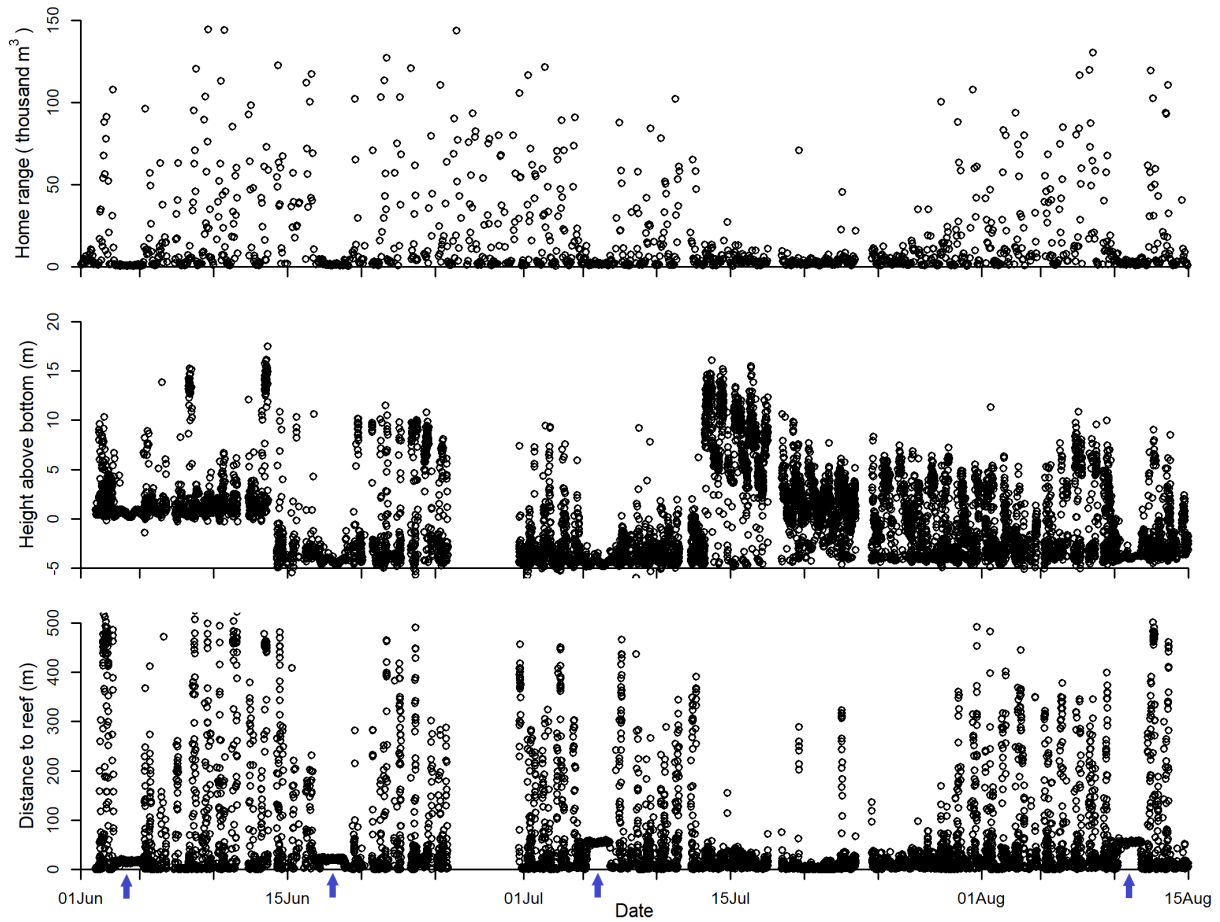
Supplementary Figure 16. Hourly home range (3-dimensional 95% KDE), height above bottom, and distance to reef of GT34 during the 2016 spawning season. Arrows note qualitative shifts in movement which persisted for approximately 2 days during each occurrence.

Array accuracy

Methods- We performed a "drift test" to validate positioning accuracy within the 55-m acoustic array by comparing VPS calculated coordinates to those recorded directly from the GPS positioning system on the boat. A Vemco V13T transmitter (identical to the transmitter used on tagged animals in this study, but with a shorter fixed delay between transmissions and a temperature rather than pressure sensor) was suspended approximately 3 m below the boat from the port side of the stern. The boat was allowed to drift for at least 10 minutes while the time, boat heading, and GPS coordinates from the ship's navigation system were recorded. The drift test was repeated at 5 different sites within the 55-m acoustic array: the center and each corner (NW, NE, SW, and SE; Fig. 17A). The GPS antenna is located on top of the wheelhouse in the center of the boat used for the drift test, which caused an offset between the recorded GPS location and the actual position of the transmitter. VPS transmitter positions were therefore corrected to the GPS antenna location based on the geometry of the boat (9.6 m and +18.4° relative to the bow) and the heading of the bow during each drift test (Fig. 17B).

Results-
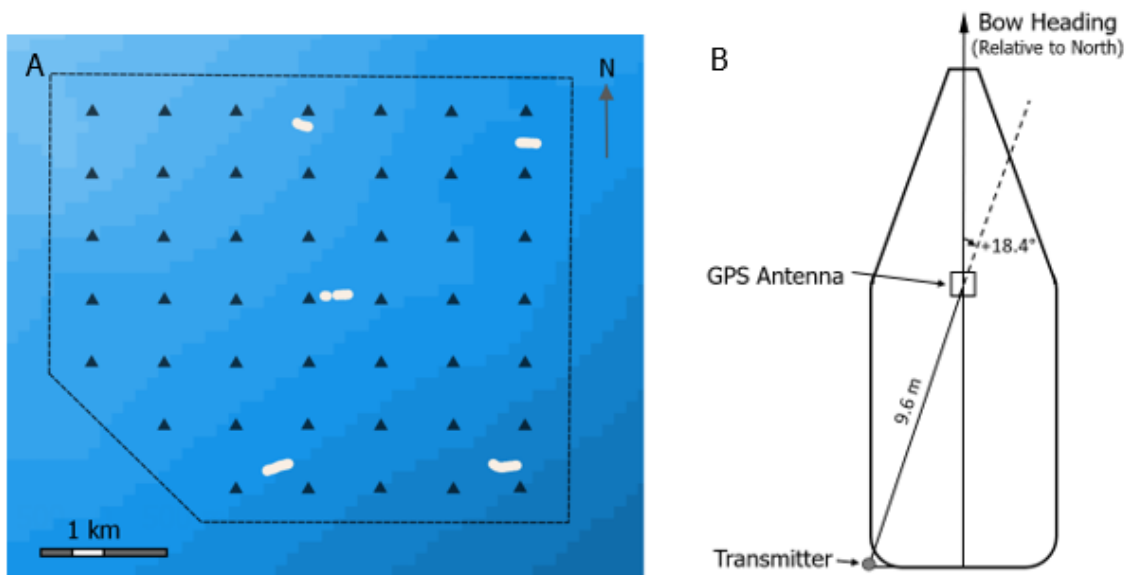
Supplementary Figure 17. Map and figure describing the drift test performed in the 55-m acoustic array to confirm the positioning accuracy of the array. A) Map showing the track of each drift test (white circles) within the array. The broken line indicates the approximate array extent and triangles indicate acoustic receiver positions. B) A diagram of the boat used for the

drift tests illustrating how transmitter locations were corrected to correspond to the GPS antenna according to the geometry of the boat and bow heading through the test.

Supplementary Table 5. Results of the drift test to evaluate positional accuracy of the 55-m array. Positioning efficiency is the percent of test tag transmissions that yielded VPS position estimates.

Site	Start (UTC)	End (UTC)	n Positions	Positioning efficiency	Accuracy (m)		HPE	
					mean	range	mean	range
NW	15:21	15:33	7	10%	7.9	4.1–10.4	3.9	3.8–4.0
NE	15:04	15:14	13	22%	5.1	3.1–7.6	4.6	3.3–6.9
Center	13:57	14:11	9	11%	1.0	0.0–3.7	3.9	3.0–5.4
SW	14:39	14:49	40	67%	4.3	0.5–8.2	3.2	2.4–6.2
SE	14:20	14:30	31	52%	3.7	0.0–6.4	3.3	2.6–4.4
Overall			100	30%	4.1	0.0–10.5	3.5	2.4–6.9