

Movement Patterns and Habitat use of Adult Giant Trevally (*Caranx Ignobilis*) in the South China Sea

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Abstract

This paper presents the first application of pop-up satellite archival tags (PSATs) to giant trevally (*Caranx ignobilis*) in a "no-take" marine protected area (MPA) comprising in a major reef system in the South China Sea (Dongsha Atoll National Park). In order to determine appropriate management strategies in an around the MPA and to delimit stock boundaries to help restore populations, fundamental ecological information is required on movement patterns, habitat preferences and home range. In total 10 giant trevally were tagged from May 2016 to September 2018. Eight tags reported and remained affixed from 17 to 243 days and linear displacements ranged from 26 to 826 km from deployment to pop-up locations. Fish were mainly confined to the mixed-layer but occasionally made deeper descents (~50 -60 m) during nighttime and the distributions of time spent at depth (~0 - 67 m) and temperature (21.5 - 35.4°C) were significantly different between daytime and nighttime but the transitions were not pronounced. Most probable tracks calculated from a state-space Kalman filter suggested site-fidelity and/or cyclic N-S dispersal patterns possibly related to spawning or foraging as about half of the pop-up locations were within ~100 km of the tagging location. Given these findings and implications, it is possible that giant trevally may need to be managed at small spatial scales to preserve genetic diversity. Additional tagging studies, however, using genetic data and conventional tags to maximize cost-benefit and augmented with a sub-set of PSATs, will be required to test this hypothesis at a higher level of statistical power.

Introduction

Giant trevally (*Caranx ignobilis*) is a large (up to ~170 cm fork length, ~80 kg) top predator found broadly on coral reefs (Sudekum et al. 1991) but also enters estuaries and atolls as both juveniles and adults (Lédée et al. 2015; Meyer et al. 2007). It is sometimes referred to as a semi-pelagic species and is distributed in tropical and sub-tropical waters throughout Indo-Pacific (Glass et al. 2020). Due to their phenology, giant trevally have the ability to translocate nutrients over varying spatial scales (Papastamatiou et al. 2015; Sackett et al. 2017) and thus, this species provides an important ecological role.

Although captive specimens living more than 30 years may provide evidence of potential longevity (Sudekum et al. 1991), age and growth estimates using otoliths and bomb ^{14}C dating indicated giant trevally showed rapid growth and maximum ages of 25 years old in Hawaii (Andrews 2020). Giant trevally display high site fidelity with varying migratory habits which is thought to be predicated on foraging success (Daly et al. 2018; Lédée et al. 2015; Meyer et al. 2007; Sudekum et al. 1991). Giant trevally is primarily viewed as a piscivorous predator that has a wide range of dietary preferences, including benthic invertebrates, and can occupy several trophic positions (Farmer and Wilson 2010, Meyer et al. 2001, Sudekum et al. 1991). Spawning has been documented in Hawaii to occur in the summer months during full moons (Sudekum et al. 1991). Spawning aggregations of ~1000 individuals (~80-100 cm TL) have been reported in the daytime at 15-20 m (da Silva et al. 2014), but there is no information on how far giant trevally will travel to participate in aggregations in Hawaii (Johannes 1978).

The South China Sea is the largest marginal sea of the western Pacific Ocean, which extends across tropical and subtropical areas (Morton and Blockmore 2001). Dongsha Atoll (DA, also called the “Pratas Island”), is one of the biggest islands located in South China Sea and is approximately 340 km southeast of Hong Kong, 260 km south of Shantou on the Chinese mainland, and 445 km southwest of Kaohsiung, Taiwan (Neo et al. 2018). Dongsha Atoll is a major reef with over 646 species of fishes (Chen et al. 2011) and plays an important role as the main breeding and nursery grounds for numerous marine organisms (Chou 2016; Dai 2004). Moreover, due to a well-developed coral reef structure with high coral coverage, DA has been utilized as an important commercial fishing ground for several countries including China, Hongkong, Vietnam and Taiwan (Dai 2004). Because of its significance as an important conservation area, since 2007, DA has been designated a Taiwanese National Marine Park (McManus et al. 2010). The effectiveness of Marine Protection Areas (MPA) resorting populations of marine predators is complicated when their range extends across different countries, where they may be subject to different fisheries and management regulations (Daly et al. 2018). However, it is important to implement conservation efforts that target key areas and biological processes which are critical for species conservation (Meyer et al. 2007).

Multiple techniques have been employed to describe the geospatial movements of marine animals and these advances have provided ecological insights by connecting animal movements to measures of their physiology and responses to the environment (Block et al. 2011; Hussey et al. 2015). Short-term acoustic monitoring has revealed diel and seasonal shifts in habitat use of giant trevally (Lowe et al. 2006) and experiments conducted in Hawaii and the Great Barrier Reef showed environmental parameters played a key role in movement patterns (Lédée et al. 2015; Meyer et al. 2007).

Pop-up satellite archival tag (PSAT) technology is an established fisheries-independent tool to monitor ambient depth (pressure), temperature, and light levels on tags attached to animals to chronicle both horizontal and vertical movement patterns (Block et al. 1998; Lin et al. 2020; Schlenker et al. 2021). PSATs can offer many benefits to study vertical dive behaviors, as well as providing information on migration routes, possible spawning areas, thermal habitat, exchange rates between areas and post-release mortality (Chang et al. 2020; Griffiths 2020; Madigan et al. 2020; Musyl and Gilman 2019). Despite regional faunal surveys, there is little information on giant trevally movement patterns at and around DA. Without effective management, there is concern the coral reef ecosystem of the Dongsha Atoll National Park may not persist due to typhoons, flood plumes, and climate change (Cheng et al. 2020). The objective of this research was to use PSATs to gain fundamental ecological information on movement patterns, habitat preferences and home range to inform decision makers on protecting resources of Dongsha Atoll National Marine Park.

Methods And Materials

Field tagging techniques

PSATs were fitted with nylon umbrella tag heads and fluorocarbon tethers (123 kg breaking strength), attached by stainless steel crimps matching the diameter of the line. Stainless steel ball bearings (Sampo no. 6, Barneveld, NY, USA) were affixed ~ 15 cm from the tag head on the tether to reduce torque and precession (Musyl et al. 2011a, b).

Individuals were hauled directly aboard the tagging vessel using a sling and placed on a wet mattress. A moist chamois cloth was put over the fish's eyes and a saltwater hose placed in the mouth for ventilation. The tag heads and tethers were disinfected with alcohol and a bacitracin-neomycin ointment was applied before tagging to prevent wound ulceration and infection and the tag head was inserted approximately 6 cm in the dorsal musculature with a 35 cm tagging pole. Location of tag deployments were recorded using GPS. The tagging procedure was completed in approximately 60 s and PSATs were deployed on presumably healthy specimens over ~90 cm FL from recreational fishers using popping and jigging techniques (Fig. 1, Table 1).

Table 1
Details for pop-up satellite archival tags (PSATs) deployed on giant trevally.

PSAT ID	FL (cm)	Deployment Date	Reporting Date	Days-at liberty	Straight-line distance (km)	Data return rate (%)
#152338	138	2016/5/13	2016/6/25	44	97	69
#157382	112	2016/5/13	2016/12/26	227	796	4
#157381	120	2017/3/22	2017/8/5	136	173	40
#152337	102	2017/4/10	2017/8/15	127	287	20
#168983	113	2017/5/23	2017/11/4	165	70	11
#168984	118	2017/6/26	2017/8/21	56	827	38
#168980	122	2017/10/24	Non-reporting	–	–	–
#168982	115	2017/10/22	2017/11/8	17	26	69
#041792	90	2018/1/26	2018/9/26	243	42	7
#041816	126	2018/1/26	Non-reporting	–	–	–

Tags details and programming

X-tags (Microwave Telemetry, Columbia, MD) were programmed to release 240 days after deployment with a suite of fail-safe options to report in the case of mortality or premature release (Musyl et al. 2011b). PSAT and tether/tag head combinations were positively buoyant in water to discriminate a detached floating tag from a mortality (Musyl et al. 2011b). At the surface, PSATs transmit data to Argos and the X-Tag had variable memory capability and acquired temperature and pressure data every 15 min for the first 4 months, acquired data at 30 min intervals from 4 to 8 months, and at hourly intervals >8 months.

Specifications for temperature and pressure data points in the tags ranged from -4 to 40°C and from 0 to 1296 m (resolution 0.16 to 0.23°C, 0.34 to 5.4 m). Raw light-based geolocations were calculated and provided by the manufacturer (Musyl et al. 2011b) and the unscented Kalman filter (augmented with sea surface temperature (SST)) was used to calculate most probable tracks (MPTs) (Lam et al. 2008; Lam et

al. 2010). Linear displacements from tagging to pop-up locations were determined using the Great Circle Distance and pop-up locations were estimated by Doppler shift using Argos messages with location classes of 1 or higher.

Time at depth and temperature

Time-at-depth and time-at-temperature data were aggregated into 5 m and 1°C bins and were separated into daytime and nighttime periods by calculating times of local sunrise and sunset time (<https://www.usno.navy.mil/USNO>). Thermal habitat distributions were expressed as differences (Δ SST) from average daily SST estimates and individual temperature readings in the tags (Musyl et al. 2011a). The correlation of nighttime depth and lunar illumination (uncorrected for cloud cover; <https://www.usno.navy.mil/USNO>) was examined. Data return rates were calculated following Musyl et al. (2011b) where the amount of data downloaded was compared to the maximum possible expected amount if all data points (i.e., depth, temperature, geolocation) were received for the time at-liberty given the rate of data acquisition.

To explore differences in daytime and nighttime behavior, we used one-sample Kolmogorov–Smirnov tests to compare distributions of ambient temperature and depth data to that of a normal distribution and all were non-normally distributed (PAST version 4.0). As a result, we used non-parametric two-sample Kolmogorov–Smirnov and Mann–Whitney W-tests to compare differences in medians between daytime and nighttime data for depth and temperature distributions and Kruskal-Wallis non-parametric ANOVAs to compare medians across seasons (Zar 2010).

Change point modelling (Bayesian, “transdimensional” MCMC) was used to detect abrupt change points in the time series for depth and temperature (Gallagher et al. 2011) and was implemented in PAST version 4.0 (Hammer et al. 2001). The greatest vertical distances between cumulative distribution functions (D_N) among seasons for depth and temperature distributions were formatted into an input matrix for UPGMA (unweighted pair group method using arithmetic averages) clustering using Euclidean distances (Musyl et al. 2011a).

Results

Deployment information and data retrieval

Ten PSATs were deployed on giant trevally ranging from 90 to 138 cm FL around Dongsha Atoll National Park (Fig. 1) and two of the PSATs did not report. Retention periods for eight tags ranged from 17 to 243 days-at-liberty (Table 1) and we obtained a total of 1,015 days of depth and temperature data from the tags. Data return rates ranged from 7–69% and averaged 33% for depth, temperature and geolocation (Table 1).

Horizontal movement characteristic

Linear displacements ranged from 26 to 827 km (mean \pm SD, 289.8 \pm 332.7 km) (Table 1) and pronounced N-S movements were observed in the MPTs (Fig. 1). According to the MPTs, after being tagged in May

2016, #152338 traveled southwards ~500 km and changed direction to the north in the middle of June and then travelled back to the release area (Fig. S1-1A). Fish #157382 made similar movements during May and June but kept a more northerly course to China until November when it transited to Hainan Island in December after 227 days-at-liberty (Fig. S1-1B). Fish #157381 moved southerly about 1,000 km after being released in March but changed course in June to return to DA in August (Fig. S1-1C). Fish #152337 made similar movements as #157381 and moved close to Mainland China in September (Fig. S1-1D). Fish #168983 moved southerly after release in June and returned to DA in August (Fig. S1-2A) whereas #168984 moved southerly after release in June but stayed on that course for ~827 km (Fig. S1-2B). The PSAT attached to fish #168982 (17 days-at-liberty) popped-up near the release site (Fig. S1-2C). During 243 days-at-liberty, #041792 moved southerly about 1,200 km after release in January and then moved northerly to DA in August (Fig. S1-2D).

Vertical behavior and patterns

The diel vertical distribution of giant trevally were largely restricted to within ~67 m of the surface (Fig. S2) between 21.5-35.4°C (Table 2). The 95% confidence intervals for depth and thermal preferences was the surface to 20 m and 25 to 29°C (Fig. S3). Two-sample Kolmogorov-Smirnov and Mann-Whitney W-tests tests were significantly different between tags ($p < 0.001$) for 95% of all possible pairwise comparisons for day and night distributions of depth and temperature data indicating a high level of individual variability in movement patterns. Although daytime and nighttime depth distributions indicated significantly different diel patterns ($p < 0.001$, Fig. S4), the transitions were not pronounced. During daytime, giant trevally occupied the surface to 15 m (26°C to 29°C) and at nighttime from the surface to 20 m (23°C to 25°C) (Fig. 2). Individual variability in diving patterns have been reported in many tagging studies (e.g., Musyl et al. 2003; 2011a). We suggest variability in our study was due to individual variability and to limited data. To increase precision in the estimates, we pooled these data to compare what we found in the literature.

Table 2
Summary of the depth and temperatures obtained for pop-up satellite archival tags (PSATs) deployments on giant trevally.

PSAT ID	Day depth (m)	Night depth (m)	Day temp. (°C)	Night temp. (°C)
	Min. – max. (mean ±SD)			
#152338	0 – 43 (8.7±5.6)	0 – 67 (9.6±6.0)	21.5 – 32.1 (27.4±1.5)	21.5 – 30 (27.3±1.4)
#157382	0 – 12 (1.1±1.7)	0 – 33 (0.7±3.2)	24.8 – 31.5 (27.9±1.6)	23.2 – 32.3 (27.5±1.9)
#157381	0 – 40 (10±5.9)	0 – 40 (8.7±4.1)	23.1 – 30.1 (26.6±1.5)	23.1 – 30.3 (26.5±1.5)
#152337	0 – 36 (7.1±4.3)	0 – 46 (7.4±6.2)	22.9 – 30.5 (27.3±1.5)	23.4 – 30.5 (27.2±1.5)
#168983	0 – 32 (5.4±4.9)	0 – 36 (3.5±3.8)	24.3 – 30.7 (27.9±1.3)	22.9 – 30.3 (28.1±1.2)
#168984	0 – 35 (2.7±2.6)	0 – 17 (4.2±3.1)	26.2 – 35.4 (29.8±0.9)	27.1 – 33.9 (29.8±0.9)
#168982	0 – 21 (3.1±2.1)	0 – 18 (3.1±2)	25.5 – 28.2 (26.9±0.7)	24.3 – 28.2 (26.3±0.9)
#041792	0 – 41.7 (4.4±5.6)	0 – 53.8 (7.2±10.2)	23 – 31 (27.1±2.1)	23.2 – 30.3 (26.8±1.9)
Grand	0 – 43	0 – 67.2	21.5 – 35.4	21.5 – 33.9
Average	(7±5.7)	(6.9±5.3)	(27.5±1.7)	(27.4±1.7)

In DA, temperature-depth profiles were confined within the mixed-layer depth (MLD) with temperatures above 21°C, and the bottom of the MLD appears to be ~60 m (Fig. S5). The Δ SST analysis showed that ~98% of movements were within 4°C of the warmest water (Table 3). For tagged specimens that experienced several lunar cycles, tag #157381 exhibited a significant correlation between average nighttime depth and lunar illumination ($r^2 = 0.084$, $F_{1,134}=12.528$, $P<0.001$). The fish occupied deeper nighttime depths (Fig. 3) during the full moon and shallower depths during the new moon (Fig. 4).

Table 3

Cumulative percentage of temperature readings from PSATs attached to giant trevally expressed as differences of daily mean sea surface temperatures (Δ SST). SST calculated as per Nielsen et al. (2006) and is analogous to Brill et al.'s (1993) surface layer.

PTT ID	Time	Δ SST										
		0	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10
#152338	Day	7.7	42.1	70.8	87.1	94.8	96.8	98.7	99.4	99.7	99.9	100
	Night	4.4	39.4	65.2	83.1	94.9	98.4	99.5	99.8	99.9	100	
#157382	Day	24.5	73.6	83.5	99.3	100						
	Night	15.4	74.9	85.3	97.1	99.6	100					
#157381	Day	8.0	65.0	89.5	97.8	99.5	100					
	Night	8.0	63.3	86.7	96.0	98.9	100					
#152337	Day	7.9	57.8	85.7	95.7	98.8	99.8	100				
	Night	8.5	55.4	82.3	93.1	97.3	99.6	99.9	100			
#168983	Day	12.1	68.2	94.2	98.9	99.9	100					
	Night	11.7	79.9	96.3	99.6	99.9	100					
#168984	Day	8.4	59.7	91.0	96.6	98.6	99.9	100				
	Night	9.3	62.1	88.7	96.0	99.3	99.6	100				
#168982	Day	31.9	98.7	100								
	Night	6.7	60.7	94.0	100							
#041792	Day	12.9	72.3	91.3	98.1	99.0	99.4	99.7	99.7	100		
	Night	9.7	62.3	83.7	94.1	98.3	99.3	100				

Seasonal habitat and thermal differences

The cluster analysis on daytime and nighttime temperature and depth data indicates seasonal habitat and thermal differences were major grouping factors (Fig. 5). Giant trevally spent the majority of their time in the uniform surface-temperature layer during winter and spring (surface to 20 m; 22° to 28°C, Fig. S5; Table S1) but in summer and autumn, occupied significantly deeper depths (0 to 72 m) and experienced variable temperatures (21° to 34°C)(Fig. 6) that correlated with movements to lower latitudes which suggests evidence of tropical submergence (Kruskal-Wallis non-parametric ANOVA, $P < 0.005$).

Using the deployment with the longest days-at-liberty (243 days, #041792), changepoints were evident in the time series (Fig. 7) that corresponded to neap tides (Fig. 8). This analysis also suggested tropical submergence with deeper diving at lower latitudes.

Discussion

We documented possible site fidelity, temporal-spatial behavior and vertical habitat use of the first PSAT tagged adult giant trevally in the South China Sea. The diel activity patterns exhibited by giant trevally reported herein were similar to what other researchers have reported from different reef areas (Meyer et al. 2007; Daly et al. 2018, 2019). Dongsha Atoll is a major reef system in the South China Sea and plays an important role in the breeding and nursery grounds for numerous marine organisms (Chou 2016; Dai 2004). Dongsha Atoll is approximately 25 km in diameter and the reef table emerges above water during low tides and is approximately 46 km in length and 2 km in width (Chou 2016) and its well development ring-shaped reef supports a highly diverse fauna and flora (Dai 2004).

Habitat use

Our data suggested adult giant trevally may exhibit philopatry in DA which places additional significance in managing and maintaining this reef system. Several studies used acoustic tracking to monitor giant trevally residence patterns in coral reefs (Lédée et al. 2015; Meyer et al. 2007; Wetherbee et al. 2004) but limited acoustic receiver arrays may have underestimated distribution patterns. Given that giant trevally is capable of long distance (633 km) dispersal (Daly et al. 2019), acoustic monitoring arrays need to be placed over wide areas to cover their extensive home ranges which makes this technique cost-prohibitive. Understanding of the movement patterns and habitat preferences are essential for developing management plans (Zhang et al. 2020; Lin et al. 2021). Site fidelity studies can provide predictability of animal location during specific seasons and may thus optimize tag recovery planning (Sequeira et al. 2019). In this study, PSATs for two individuals popped-up away from the tagging site whereas five PSATs popped-up near the tagging location indicating their home range. Though our baseline data are limited, nevertheless, the information on possible site fidelity for adult fish will be important for optimizing the design of future tagging experiments to test this hypothesis (Gatti et al. 2020). To further maximize cost-benefit in site fidelity studies, incorporating the Argos goniometer to retrieve detached tags can provide the retrieval of high-resolution archived data which can lower overall costs (Lin et al. 2021).

Dongsha Atoll National Park is a “no-take” MPA (Emslie et al. 2015; Mellin et al. 2016). Meyer et al. (2007) indicated giant trevally undertake long-term seasonal migrations which may be linked to spawning activity. The occurrence of large numbers of giant trevally in deep-water channels around the full moon (da Silva et al. 2014) and putative courtship behaviors, including fish chasing and coloration changes, have been suggested to characterize spawning behavior (Daly et al. 2018; Meyer et al. 2007). Despite faunal surveys and the importance of Dongsha Atoll National Park as an important feeding ground (Chen et al. 2011), spawning of giant trevally has not been observed. Giant trevally is an important apex predator widely distributed across multiple habitat types with large home ranges (Glass et al. 2020). Giant trevally tagged in a South African MPA showed site fidelity patterns at specific and predictable times of the year (Daly et al. 2019). Lastly, there is evidence to support that MPAs increase resilience among coral reef communities and conserve ecosystems (Emslie et al. 2015; Mellin et al. 2016).

Vertical movement and thermal niche

Giant trevally showed more activity during nighttime than daytime and similar results were noted in the Great Barrier Reef (Lédée et al. 2015). Sudekum et al. (1991) found that giant trevally was feeding at nighttime but these findings are in contrast to Meyer et al. (2007). Wetherbee et al. (2004) found active crepuscular behavior and niche partitioning during nighttime. Glass et al. (2020) documented the spatial and trophic variability and variable niche widths of different life stages and suggested ontogenetic changes in diet and habitat utilization were driving factors to explain vertical movements.

Several studies on giant trevally used acoustic arrays and reported significant differences in vertical diving behavior that correlated with fish size (Lédée et al. 2015; Lin et al. 2021; Meyer et al. 2007). Meyer et al. (2007) reported giant trevally stayed within the detection radius of the arrays during daytime but traveled out of range at nighttime. Diel habitat shifts are common in reef fishes, especially for carangids where nocturnal and crepuscular behavior account for the maximum linear dimension of their daily home range (Holland et al. 1996; Meyer and Honebrink 2005). Daly et al. (2019) detected giant trevally at an aggregation site where fish exhibited clear diel patterns with maximum hourly detections recorded during midday. Given their dispersal and large home range, it is possible that some behaviors may have been influenced with different water masses and characteristics (e.g., tidal shifts, temperature) as our changepoint analysis indicated. Moreover, submerged or floating structures have been reported to influence the behavior of many pelagic species (Govinden et al. 2021; Hino et al. 2019; Musyl et al. 2003; Schaefer and Fuller 2010).

In this study, significant correlation between nighttime depth and lunar illumination was found and similar adjustments to dive patterns have been found in bigeye tuna (*Thunnus obesus*) (Musyl et al. 2003; Lin et al. 2021), Pacific bluefin tuna (*Thunnus orientalis*) (Furukawa et al. 2017) and pelagic sharks (Musyl et al. 2011a) to better follow and highlight prey to optimize prey encounters (Humphries et al. 2016). This optimal search strategy may also be utilized by giant trevally. The changepoint analysis indicated changes in vertical movement patterns (e.g., tropical submergence) related to entering different water masses but it is possible depth adjustments also provided enhanced foraging opportunities for giant trevally to mirror prey movements. Future research should consider complimentary biologging equipment including multi-sensor data loggers and video to record the possibility of aggregation, feeding and spawning behavior in Dongsha Atoll Marine Park.

Seasonal movement patterns

The marginal South China Sea comprise important fishing grounds because of the ample resources (e.g., high primary and secondary productivity; high nutrient concentrations) (Chen et al. 2008). Oceanographic characteristics including temperature, dissolved oxygen, thermal structure and feeding behaviors drive the movements and distribution of many pelagic fishes (Brill 1994; Musyl et al. 2003; Ohshimo et al. 2018). Daly et al. (2019) investigated photoperiod, seasonal sea temperatures and lunar phase in giant trevally and concluded these factors were important aggregation cues. Lédée et al. (2015) indicated movement in giant trevally was influenced by environmental parameters (light intensity, water temperature, tide height and wind speed) which suggest relevance for seasonal variability in movements. Dongsha Atoll Marine Park is the northernmost atoll in the South China Sea (Chou 2016), and the proximate environment is

affected seasonality by currents and oceanography (Morton and Blockmore 2001). The southwest monsoons in summer and the northeast monsoons propel the formation of gyres which may influence N-S seasonal migration patterns in giant trevally.

Conclusions

Giant trevally exhibited possible site fidelity and appeared to undertake N-S seasonal dispersal routes from Dongsha Atoll Marine Park. This study represents the first movement patterns recorded by biologging technology for giant trevally and suggests large home ranges for this species centered in Dongsha Atoll Marine Park. MPAs provide management tools and strategies to protect and conserve giant trevally resources. Future research should target different age and size classes with conventional and smaller implantable archival tags to better define the vertical and thermal niche and changes in habitat use to understand population connectivity and movement corridors.

Declarations

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References

1. Andrews AH (2020) Giant trevally (*Caranx ignobilis*) of Hawaiian Islands can live 25 years. *Mar Freshw Res* 71:1367–1372. <https://doi.org/10.1071/MF19385>
2. Block BA, Dewar H, Farwell C, Prince ED (1998) A new satellite technology for tracking the movements of Atlantic bluefin tuna. *Proc Natl Acad Sci* 95:9384–9389. <https://doi.org/10.1073/pnas.95.16.9384>
3. Block BA, Jonsen ID, Jorgensen SJ, Winship AJ, Shaffer SA, Bograd SJ, Hazen EL, Foley DG, Breed GA, Harrison AL, Ganong JE, Swithenbank A, Castleton M, Dewar H, Mate BR, Shillinger GL, Schaefer KM, Benson SR, Weise MJ, Henry RW, Costa DP (2011) Tracking apex marine predator movements in a dynamic ocean. *Nature* 475:86–90. <https://doi.org/10.1038/nature10082>
4. Brill RW (1994) A review of temperature and oxygen tolerance studies of tunas pertinent to fisheries oceanography, movement models and stock assessments. *Fish Ocean* 3:204–216. <https://doi.org/10.1111/j.1365-2419.1994.tb00098.x>
5. Chang CT, Lin SJ, Chiang WC, Musyl MK, Lam CH, Hsu HH, Chang YC, Ho YS, Tseng CT (2020) Horizontal and vertical movement patterns of sunfish off eastern Taiwan. *Deep Sea Res Part II: Top Stud Oceanogr* 175:104683. <https://doi.org/10.1016/j.dsr2.2019.104683>
6. Chen CTA (2008) Distributions of nutrients in the East China Sea and the South China Sea vonnection. *J Oceanogr* 64:737–751

7. Chen JP, Jan RQ, Huang CH, KuoJW, Shao KT (2011) Fishes of Dongsha Atoll in South China Sea. Marine National Park Headquarters, Kaohsiung (In Chinese)
8. Cheng YR, Chin CH, Lin DF, Wang CK (2020) The probability of an unrecoverable coral community in Dongsha Atoll Marine National Park due to recurrent disturbances. Sustainability 12:9052. <https://doi.org/10.3390/su12219052>
9. Chou Y (2016) Dongsha Atoll Research Station- A steady research platform in South China Sea. Kuroshio Science 10-1:23–27
10. da Silva IM, Hempson T, Hussey NE (2014) Giant trevally spawning aggregation highlights importance of community fisheries management no-take zone. Mar Biodivers 45:139–140. <https://doi.org/10.1007/s12526-014-0235-2>
11. Dai CF (2004) Dong-sha Atoll in the South China Sea: past, present and future, Okinawa, Japan
12. Daly R, Daly CAK, Bennett RH, Cowley PD, Pereira MAM, Filmalter JD (2018) Quantifying the largest aggregation of giant trevally *Caranx ignobilis* (Carangidae) on record: implications for management. Afr J Mar Sci 40:315–321. <https://doi.org/10.2989/1814232X.2018.1496950>
13. Daly R, Filmalter JD, Daly CAK, Bennett RHM, Pereira AM, Mann BQ, Dunlop SW, Cowley PD (2019) Acoustic telemetry reveals multi-seasonal spatiotemporal dynamics of a giant trevally *Caranx ignobilis* aggregation. Mar Ecol Prog Ser 621:185–197. <https://doi.org/10.3354/meps12975>
14. Emslie MJ, Logan M, Williamson DH, Ayling AM, MacNeil MA, Ceccarelli D, Cheal AJ, Evans RD, Johns KA, Jonker MJ, Miller IR, Osbrne K, Russ GR, Sweatman HPA (2015) Expectations and outcomes of reserve network performance following re-zoning of the Great Barrier Reef Marine Park. Curr Biol 25:983–992. <https://doi.org/10.1016/j.cub.2015.01.073>
15. Farmer BM, Wilson SK (2010) Diet of finfish targeted by fishers in North West Australia and the implications for trophic cascades. Environ Biol Fishes 91:71–85. <https://doi.org/10.1007/s10641-010-9761-3>
16. Furukawa S, Fujioka K, Fukuda H, Suzuki N, Tei Y, Ohshimo S (2017) Archival tagging reveals swimming depth and ambient and peritoneal cavity temperature in age-0 Pacific bluefin tuna, *Thunnus orientalis*, off the southern coast of Japan. Environ Biol Fishes 100:35–48. <https://doi.org/10.1007/s10641-016-0552-3>
17. Gallagher K, Bodin T, Sambridge M, Weiss D, Kylander M, Large D (2011) Inference of abrupt changes in noisy geochemical records using transdimensional changepoint models. Earth Planet Sci Lett 311:182–194. <https://doi.org/10.1016/j.epsl.2011.09.015>
18. Gatti P, Robert D, Fisher JAD, Marshall RC, Bris AL (2020) Stock-scale electronic tracking of Atlantic halibut reveals summer site fidelity and winter mixing on common spawning grounds. ICES J Mar Sci 77:2890–2904. <https://doi.org/10.1093/icesjms/fsaa162>
19. Glass JR, Daly R, Cowley PD, Post DM (2020) Spatial trophic variability of a coastal apex predator, the giant trevally *Caranx ignobilis*, in the western Indian Ocean. Mar Ecol Prog Ser 641:195–208. <https://doi.org/10.3354/meps13305>

20. Govinden R, Capello M, Forget F, Filmlalter JD, Dagorn L (2021) Behavior of skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), and bigeye (*T. obsesus*) tunas associated with drifting fish aggregating devices (dFADs) in the Indian Ocean, assessed through acoustic telemetry. *Fish Oceanogr*. <https://doi.org/10.1111/fog.12536>
21. Griffiths SP (2020) Restricted vertical and cross-shelf movements of longtail tuna (*Thunnus tonggol*) as determined by pop-up satellite archival tags. *Mar Biol* 167(8). <https://doi.org/10.1007/s00227-020-03733-7>
22. Hammer Ø, Harper DAT, Paul DR (2001) Past: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica* 4:1–9
23. Hino H, Kitagawa T, Matsumoto T, Aoki Y, Kimura S (2019) Changes to vertical thermoregulatory movements of juvenile bigeye tuna (*Thunnus obesus*) in the northwestern Pacific Ocean with time of day, seasonal ocean vertical thermal structure, and body size. *Fish Oceanogr* 28(4):359–371. <https://doi.org/10.1111/fog.12417>
24. Holland KN, Lowe CG, Wetherbee BM (1996) Movements and dispersal patterns of blue trevally (*Caranx melampygus*) in a fisheries conservation zone. *Fish Res* 25:279–292. [https://doi.org/10.1016/0165-7836\(95\)00442-4](https://doi.org/10.1016/0165-7836(95)00442-4)
25. Humphries NE, Schaefer KM, Fuller DW, Phillips GEM, Wilding C, Sims DW (2016) Scale-dependent to scale-free: daily behavioural switching and optimized searching in a marine predator. *Anim Behav* 113:189–201. <https://doi.org/10.1016/j.anbehav.2015.12.029>
26. Hussey NE, Kessel ST, Aarestrup K, Cooke SJ, Cowley PD, Fisk AT, Harcourt RG, Holland KN, Iverson SJ, Kocik JF, Flemming JEM, Whoriskey FG (2015) Aquatic animal telemetry: A panoramic window into the underwater world. *Science* 348: 1255642. <https://doi.org/10.1126/science.1255642>
27. Johannes RE (1978) Reproductive strategies of coastal marine fishes in the tropics. *Environ Biol Fish* 3:65–84
28. Lédée EJ, Heupel MR, Tobin AJ, Simpfendorfer CA (2015) Movements and space use of giant trevally in coral reef habitats and the importance of environmental drivers. *Anim Biotelem* 3:6
29. Lam CH, Nielsen A, Sibert JR (2008) Improving light and temperature based geolocation by unscented Kalman filtering. *Fish Res* 91:15–25. <https://doi.org/10.1016/j.fishres.2007.11.002>
30. Lam CH, Nielsen A, Sibert JR (2010) Incorporating sea-surface temperature to the light-based geolocation model TrackIt. *Mar Ecol Progr Ser* 419:71–84. <https://doi.org/10.3354/meps08862>
31. Lin SJ, Chiang WC, Musyl MK, Wang SP, Su NJ, Chang QX, Ho YS, Nakamura I, Tseng CT, Kawabe R (2020) Movements and habitat use of dolphinfish (*Coryphaena hippurus*) in the East China Sea. *Sustainability* 12:5793. <https://doi.org/10.3390/su12145793>
32. Lin SJ, Musyl MK, Chiang WC, Wang SP, Su NJ, Chang CT, Chang QX, Ho YS, Kawabe R, Yeh HM, Tseng CT (2021) Vertical and horizontal movements of bigeye tuna (*Thunnus obesus*) in southeastern Taiwan. *Mar Freshw Behav Physiol* 54:1–21. <https://doi.org/10.1080/10236244.2020.1852878>
33. Lowe CG, Wetherbee BM, Meyer CG (2006) Using acoustic telemetry monitoring techniques to quantify movement patterns and site fidelity of sharks and giant trevally around French Frigate Shoals and

Midway Atoll. Atoll Res Bull 543:281–303

34. Madigan DJ, Richardson AJ, Carlisle AB, Weber SB, Brown J, Hussey NE (2021) Water column structure defines vertical habitat of twelve pelagic predators in the South Atlantic. *ICES J Mar Sci* 78:867–883. <https://doi.org/10.1093/icesjms/fsaa222>
35. McManus JW, Shao KT, Lin SY (2010) Toward establishing a spratly islands international marine peace park: ecological importance and supportive collaborative activities with an emphasis on the role of Taiwan. *Ocean Dev Int Law* 41:270–280. <https://doi.org/10.1080/00908320.2010.499303>
36. Mellin C, Aaron MacNeil M, Cheal AJ, Emslie MJ, Julian Caley M (2016) Marine protected areas increase resilience among coral reef communities. *Ecol Lett* 19:629–637. <https://doi.org/10.1111/ele.12598>
37. Meyer CG, Holland KN, Papastamatiou YP (2007) Seasonal and diel movements of giant trevally *Caranx ignobilis* at remote Hawaiian atolls: implications for the design of marine protected areas. *Mar Ecol Prog Ser* 333:13–25. <https://doi.org/10.3354/meps333013>
38. Meyer CG, Holland KN, Wetherbee BM, Lowe CG (2001) Diet, resource partitioning and gear vulnerability of Hawaiian jacks captured in fishing tournaments. *Fish Res* 53:105–113. [https://doi.org/10.1016/S0165-7836\(00\)00285-X](https://doi.org/10.1016/S0165-7836(00)00285-X)
39. Meyer CG, Honebrink RR (2005) Transintestinal expulsion of surgically implanted dummy transmitters by bluefin trevally—implications for long-term movement studies. *Trans Am Fish Soc* 134:602–606. <https://doi.org/10.1577/T04-082.1>
40. Morton B, Blockmore G (2001) South China Sea. *Mar Pollut Bull* 42:1236–1263
41. Musyl MK, Brill RW, Boggs CH, Curran DS, Kazama TK, Seki MP (2003) Vertical movements of bigeye tuna (*Thunnus obesus*) associated with islands, buoys, and seamounts near the main Hawaiian Islands from archival tagging data. *Fish Oceanogr* 12:152–169. <https://doi.org/10.1046/j.1365-2419.2003.00229.x>
42. Musyl MK, Brill RW, Curran DS, Fragoso NM, McNaughton LM, Nielsen A, Kikkawa BS, Moyes CD (2011a) Postrelease survival, vertical and horizontal movements, and thermal habitats of five species of pelagic sharks in the central Pacific Ocean. *Fish Bull* 109:341–368
43. Musyl MK, Domeier ML, Nasby-Lucas N, Brill RW, McNaughton L, Swimmer Y, Lutcavage ME, Wilson SG, Galuardi B, Liddle JB (2011b) Performance of pop-up satellite archival tags. *Mar Ecol Prog Ser* 433:1–28. <https://doi.org/10.3354/meps09202>
44. Musyl MK, Gilman EL (2019) Meta-analysis of post-release fishing mortality in apex predatory pelagic sharks and white marlin. *Fish Fish* 20:466–500. <https://doi.org/10.1111/faf.12358>
45. Neo ML, Liu LL, Huang D, Soong K (2018) Thriving populations with low genetic diversity in giant clam species, *Tridacna maxima* and *Tridacna noae*, at Dongsha Atoll, South China Sea. *Reg Stud Mar Sci* 24:278–287. <https://doi.org/10.1016/j.rsma.2018.09.001>
46. Nielsen A, Bigelow KA, Musyl MK, Sibert JR (2006) Improving light-based geolocation by including sea surface temperature. *Fish Oceanogr* 15:314–325. <https://doi.org/10.1111/j.1365-2419.2005.00401.x>

47. Ohshimo S, Hiraoka Y, Sato T, Nakatsuka S (2018) Feeding habits of bigeye tuna (*Thunnus obesus*) in the North Pacific from 2011 to 2013. *Mar Freshw Res* 69:585–606. <https://doi.org/10.1071/MF17058>
48. Papastamatiou YP, Meyer CG, Kosaki RK, Wallsgrove NJ, Popp BN (2015) Movements and foraging of predators associated with mesophotic coral reefs and their potential for linking ecological habitats. *Mar Ecol Prog Ser* 521:155–170. <https://doi.org/10.3354/meps11110>
49. Sackett DK, Drazen JC, Popp BN, Choy CA, Blum JD, Johnson MW (2017) Carbon, nitrogen, and mercury isotope evidence for the biogeochemical history of mercury in Hawaiian marine bottomfish. *Environ Sci Technol* 51:13976–13984. <https://doi.org/10.1021/acs.est.7b04893>
50. Sequeira AMM, Heupel MR, Lea MA, Eguíluz VM, Duarte CM, Meekan MG, Thums M, Calich HJ, Carmichael RH, Costa DP, Ferreira LC, Fernández-Gracia J, Harcourt R, Harrison AL, Jonsen I, McMahon CR, Sims DW, Wilson RP, Hays GC (2019) The importance of sample size in marine megafauna tagging studies. *Ecol Appl* 29:e01947. <https://doi.org/10.1002/eap.1947>
51. Schaefer KM, Fuller DW (2010) Vertical movements, behavior, and habitat of bigeye tuna (*Thunnus obesus*) in the equatorial eastern Pacific Ocean, ascertained from archival tag data. *Mar Biol* 157(12):2625–2642. <https://doi.org/10.1007/s00227-010-1524-3>
52. Schlenker LS, Faillettaz R, Stieglitz JD, Lam CH, Hoenig RH, Cox GK, Heuer RM, Pasparakis C, Benetti DD, Paris CB, Grosell M (2021) Remote predictions of mahi-mahi (*Coryphaena hippurus*) spawning in the open ocean using summarized accelerometry data. *Front Mar Sci* 8:626082. <https://doi.org/10.3389/fmars.2021.626082>
53. Sfakiotakis M, Lane DM, Davies JB (1999) Review of fish swimming modes for aquatic locomotion. *IEEE J Ocean Eng* 24:237–252. <https://doi.org/10.1109/48.757275>
54. Sudekum AE, Parrish JD, Radtke RL, Ralston S (1991) Life history and ecology of large jacks in undisturbed, shallow, oceanic communities. *Fish Bull* 89:493–513
55. Wetherbee BM, Holland KN, Meyer CG, Lowe CG (2004) Use of a marine reserve in Kaneohe Bay, Hawaii by the giant trevally, *Caranx ignobilis*. *Fish Res* 67:253–263. <https://doi.org/10.1016/j.fishres.2003.11.004>
56. Zar JH (2010) *Biostatistical Analysis*. Prentice Hall, New Jersey
57. Zhang Y, Li Y, Zhang L, Wu Z, Zhu S, Li J, Li X (2020) Site fidelity, habitat use, and movement patterns of the common carp during its breeding season in the Pearl River as determined by acoustic telemetry. *Water* 12:2233. <https://doi.org/10.3390/w12082233>

Figures

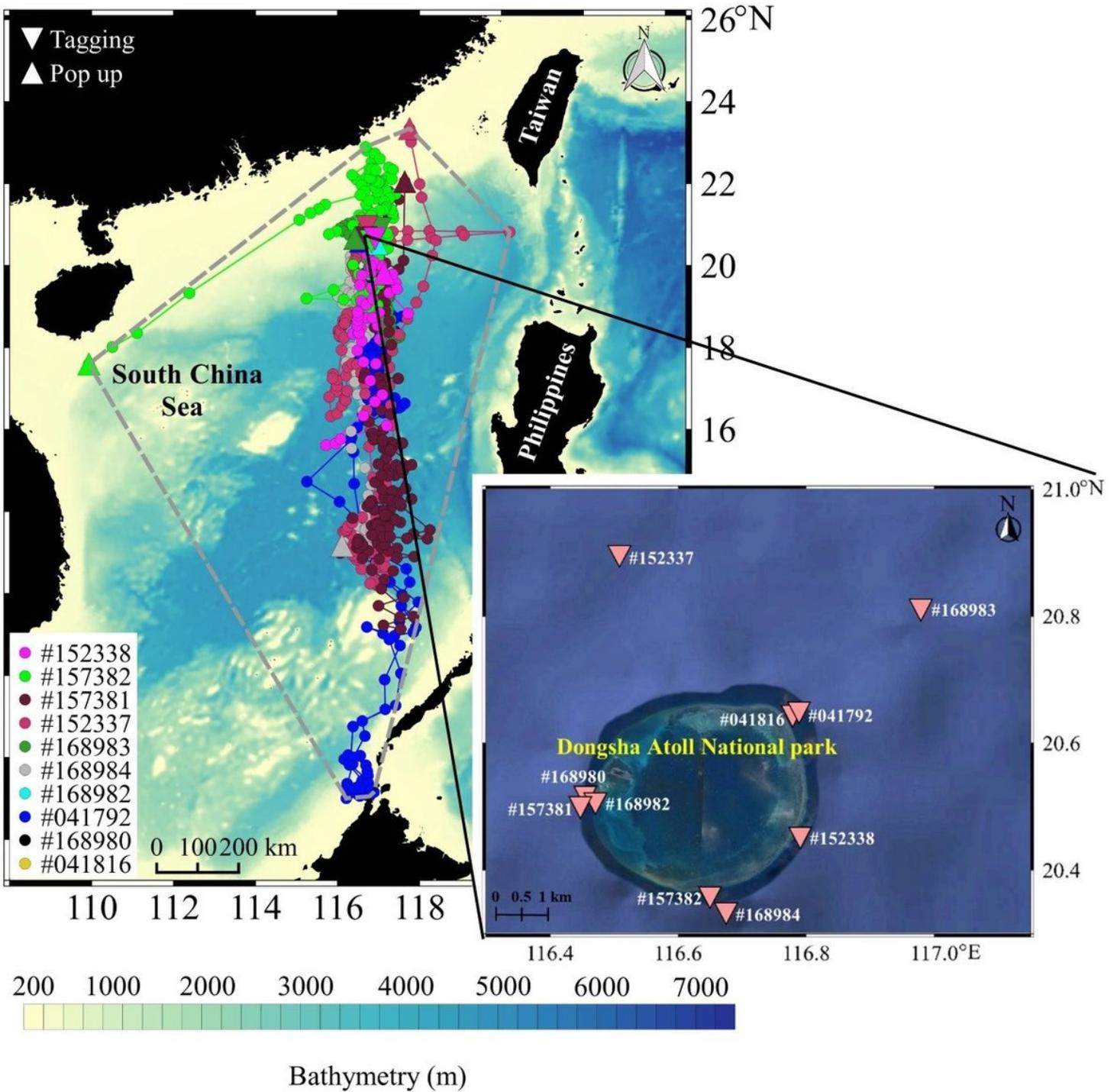


Figure 1

Map of PSAT deployments on giant trevally (inverted triangles) around Dongsha Atoll National Park. Most probable tracks (circles and line) where pop-up location are depicted by triangles and the grey polygon delimits the home range.

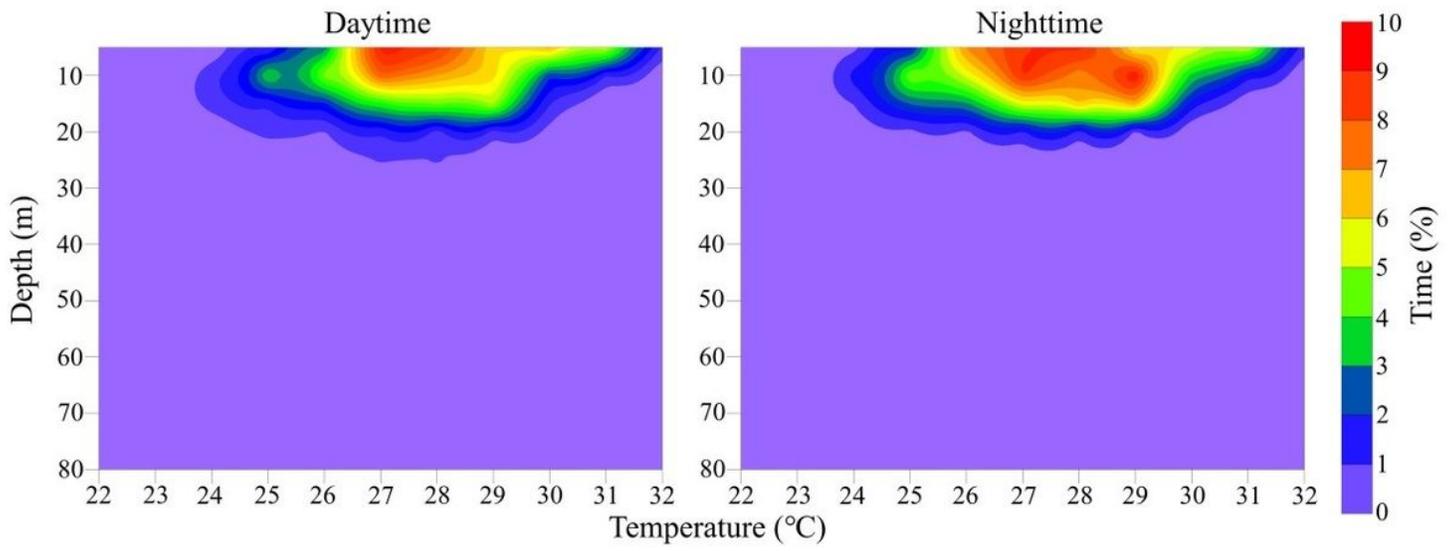


Figure 2

Aggregated temperature-depth profiles of giant trevally thermal preferences in (A) daytime and (B) nighttime.

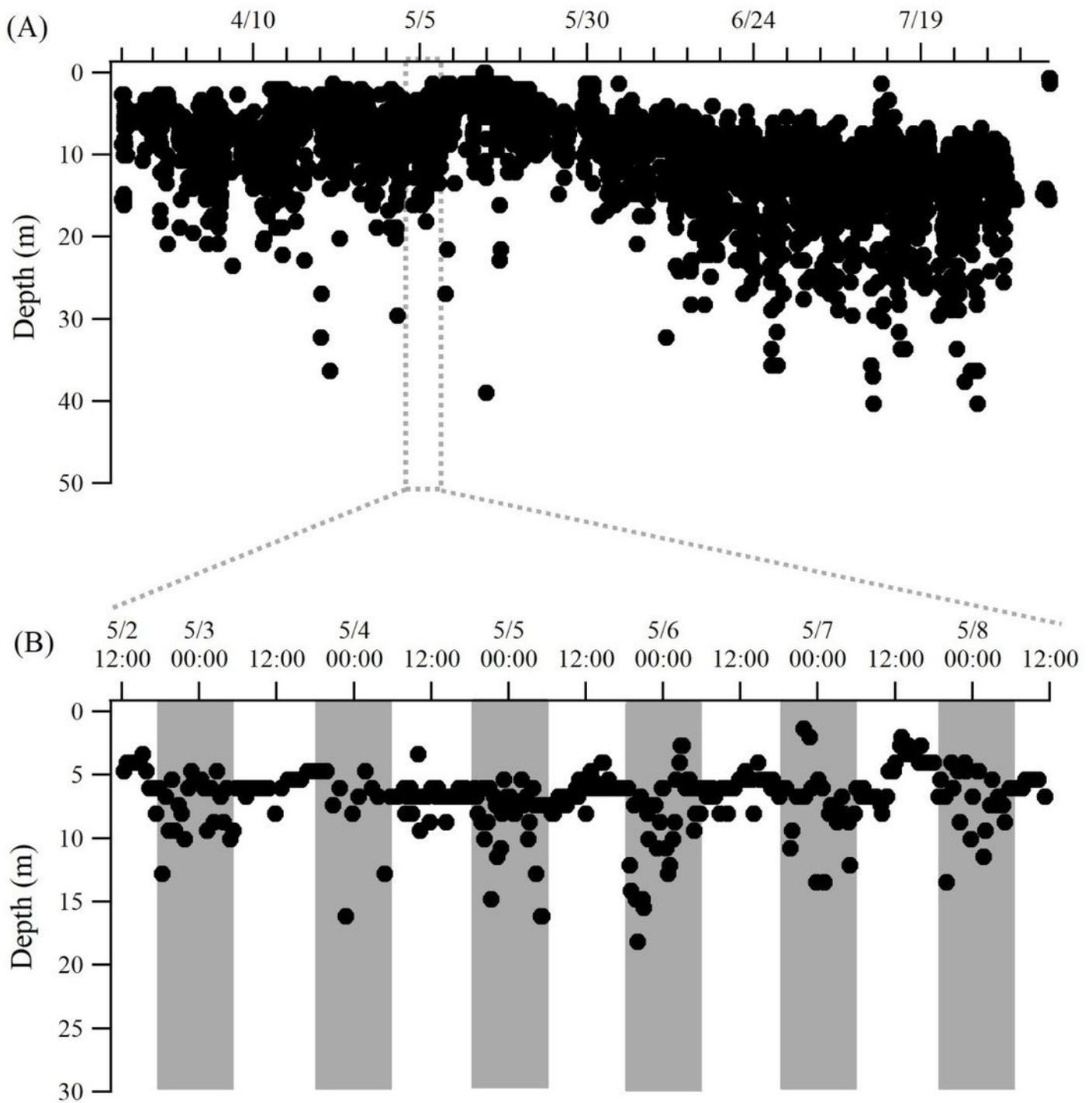


Figure 3

Depth records for Fish #157381. (A) Depth record covering 136 days at-liberty , while (B) shows expanded 6-day period during where the fish showed characteristic diel vertical movement patterns with crepuscular transitions. The grey horizontal bars indicate nighttime.

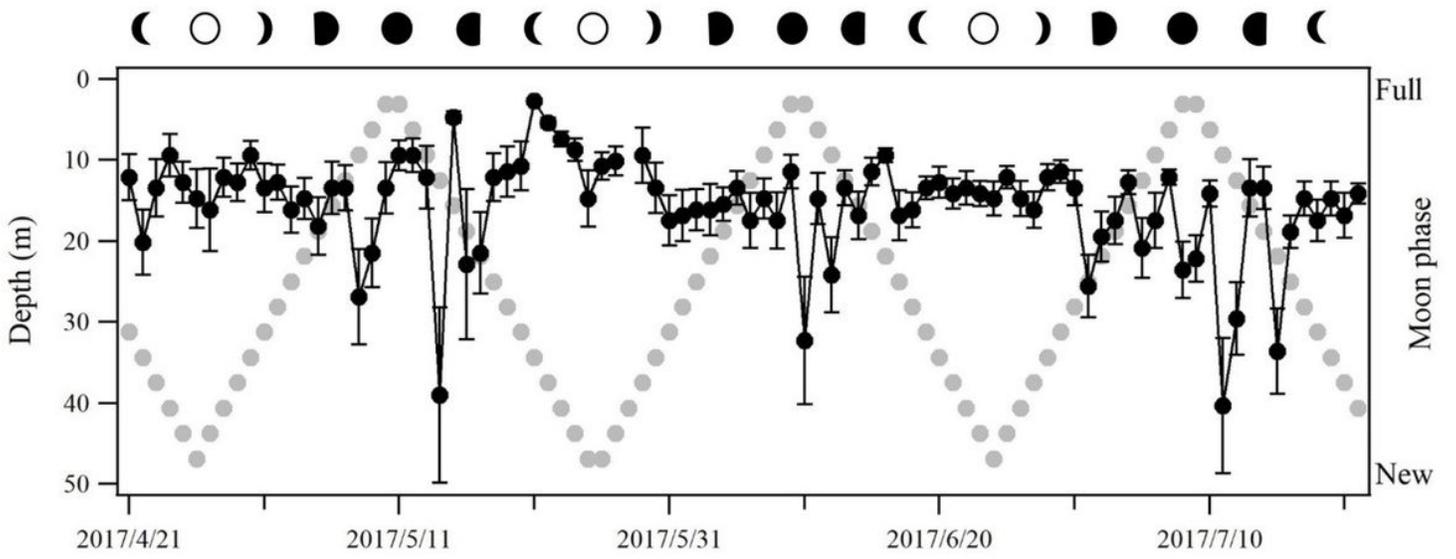


Figure 4

Lunar phase (grey dots) and average (\pm SD) nighttime depth of fish #157381.

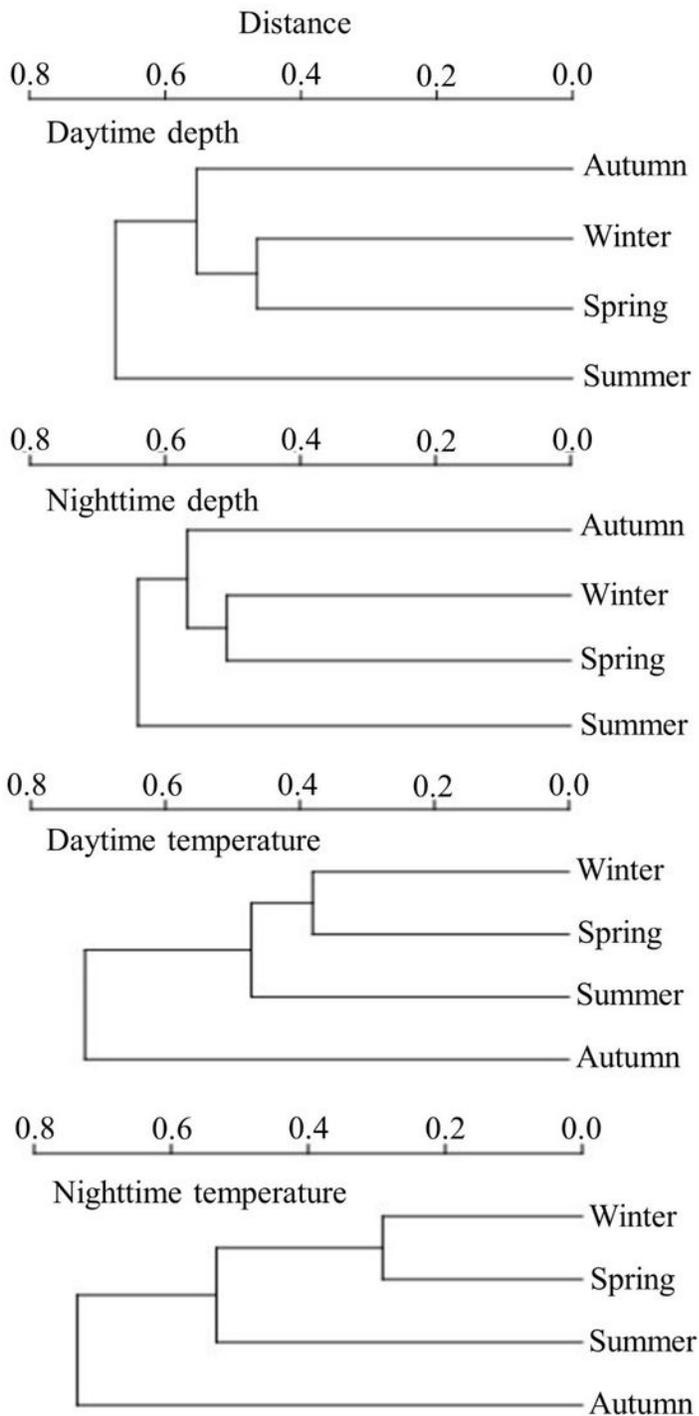


Figure 5

UPGMA (unweighted pair-group method using arithmetic averages) clustering using the Kolmogorov–Smirnov DN dissimilarity distance matrix on daytime and nighttime depth and temperature. Goodness-of-fit between the matrices and dendrograms were measured by the cophenetic correlation (0.95 daytime depth; 0.67 nighttime depth; 0.77 daytime temperature; 0.86 nighttime temperature) with correlations >0.9 considered very good (Musyl et al. 2011a).

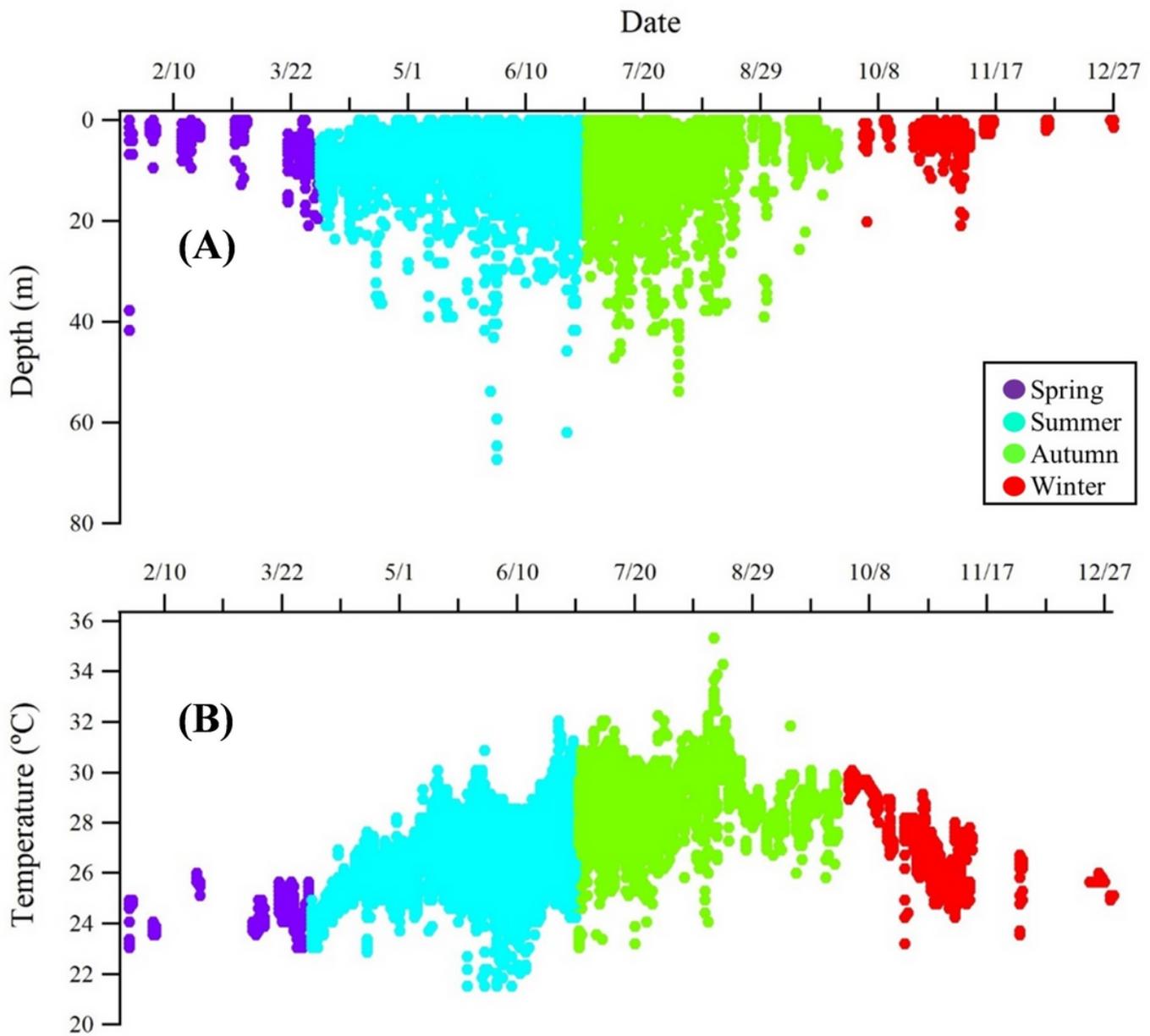


Figure 6

Combined time series data for giant trevally expressed by season (A) depth and (B) temperature obtained for PSATs.

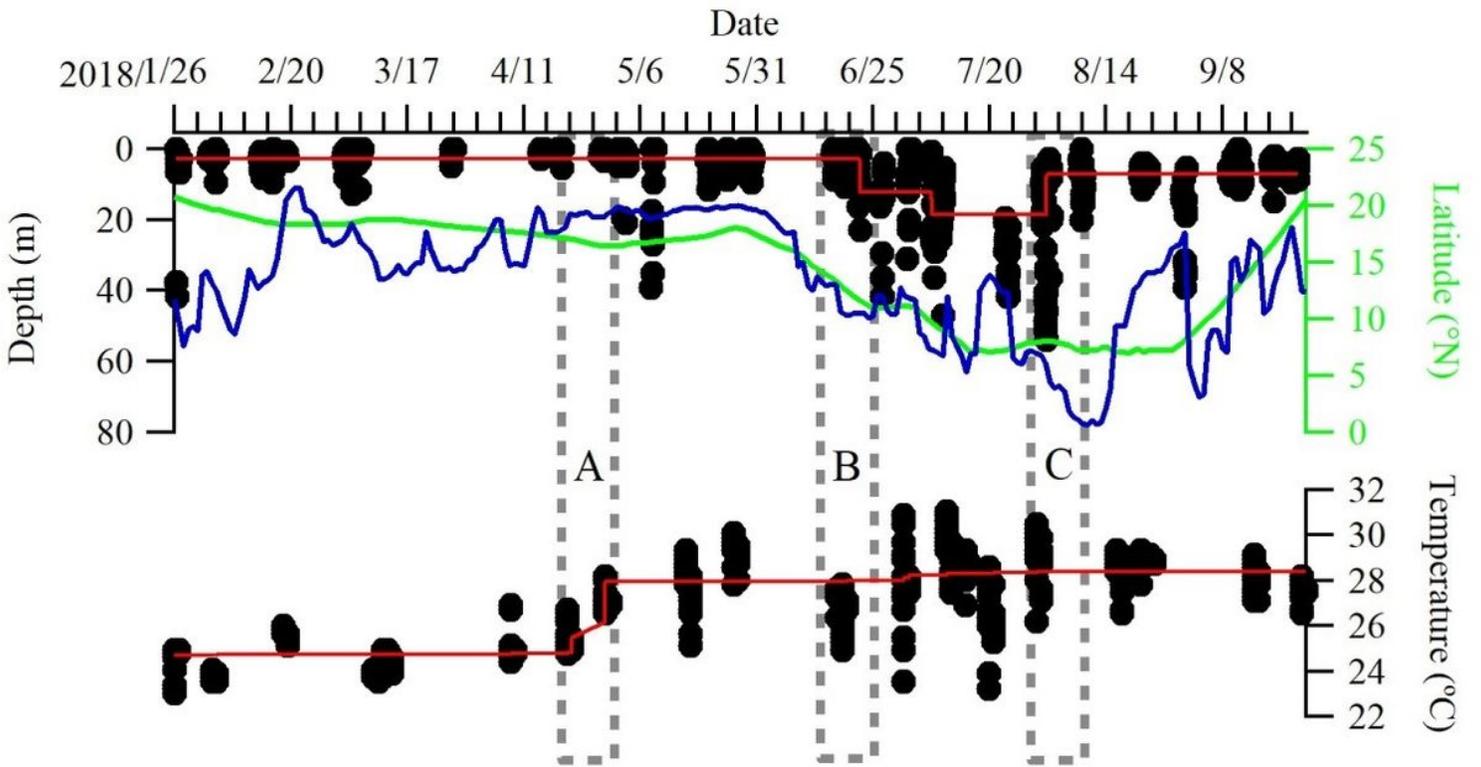


Figure 7

Changepoint model for #041792 in the time series for depth and temperature, mixed-layer depth (blue line) and latitude (green line). The black dots represent depth and temperature data downloaded from the PSAT. The “A”, “B” and “C” labelled changepoints correspond to low tide amplitudes in Fig. 10.

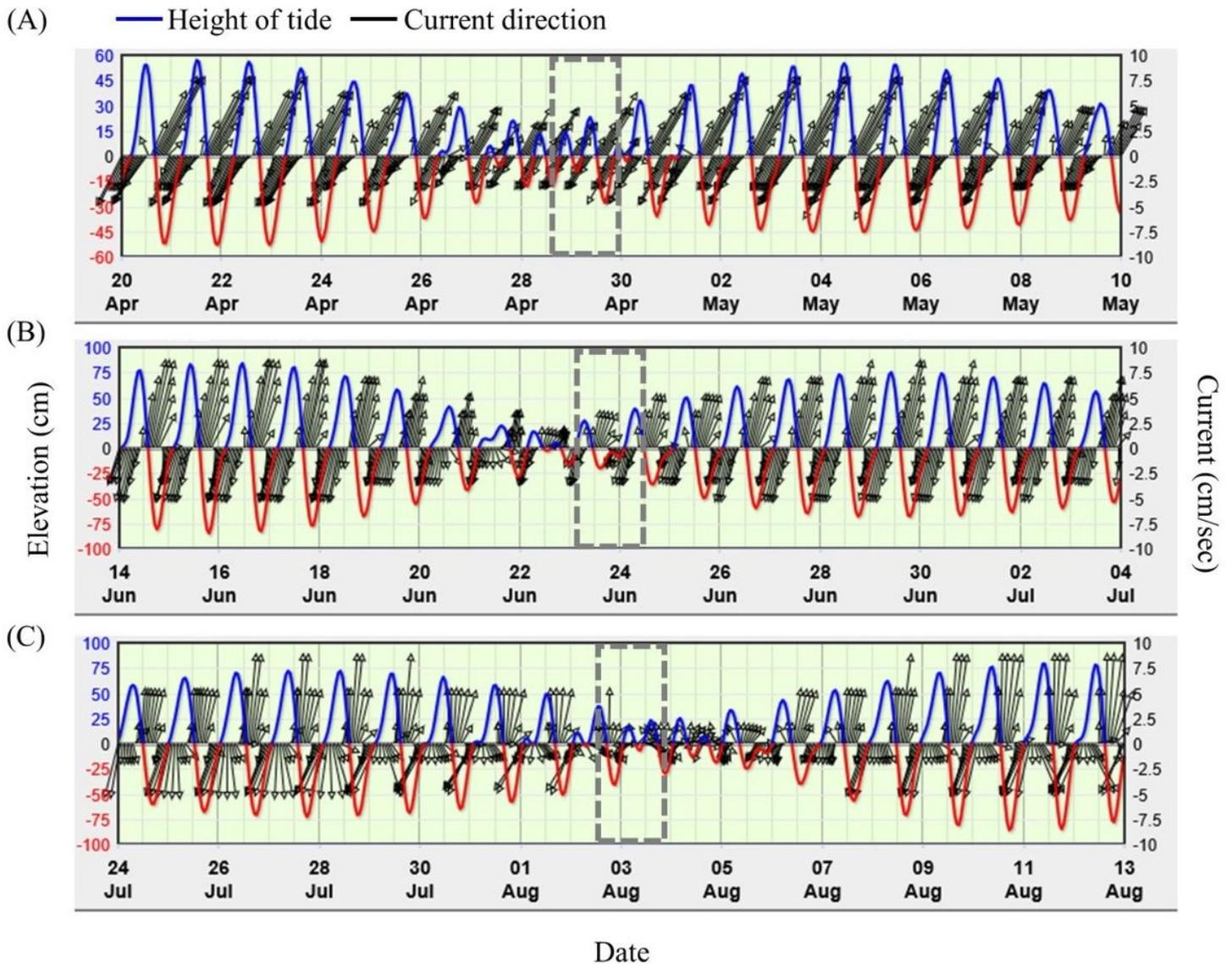


Figure 8

Changepoints for #041792 in the time series for tide elevation. Blue (high) and red (low) line indicates tidal height and black line indicates current vectors (Data source: TPXO, <https://www.tpxo.net/global>)

Supplementary Files

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