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Oceanic migration behaviour of Pacific eels from Samoa

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The reproductive success and the early survival rates of catadromous eels are determined in their marine spawning areas, so finding them is crucial for understanding eel life history patterns. Three species of tropical Pacific freshwater eels occur throughout the western and central South Pacific Islands, (*Anguilla marmorata* Quoy and Gaimard, *Anguilla megastoma* Kaup, *Anguilla obscura* Günther: Jespersen, 1942). The spawning area of *A. obscura* remains unknown, while western populations of tropical *A. marmorata* and *A. megastoma* may spawn sympatrically in an area northwest of Fiji based on the collection of small leptocephali (Kuroki et al., 2008) and migration behaviour of satellite-tagged eels (Schabetsberger et al., 2015). Additional spawning populations are hypothesised to exist in the central South Pacific based on morphological (Watanabe, Miller, Aoyama & Tsukamoto, 2011; Watanabe et al., 2008) and genetic (Ishikawa, Tsukamoto & Nishida, 2004; Minegishi, Aoyama & Tsukamoto, 2008) evidence. However, genetic differences are subtle for *A. marmorata* and it may turn out that both species are panmictic throughout the South Pacific.

The islands of Samoa are situated in the centre of the South Pacific distribution of *A. marmorata* and *A. megastoma*, so the direction in which silver eels tagged with pop-up satellite archival transmitters (PSATs) are heading for their spawning area was tested. It has been hypothesised that the major current system of the westward flowing South Equatorial Current (SEC) transports eel leptocephali towards their freshwater growth habitats (Jellyman, 2003), so if this was the case Samoan silver eels should be heading east for spawning, if they return to where they originated. However, if they migrated in the opposite direction, their offspring could reach Samoan waters within the eastward flowing South Equatorial Counter Current (SECC; Domokos, 2009). In addition, eel diel vertical migration behaviour was compared with results from Vanuatu (Schabetsberger et al., 2013, 2015).

Silver eels were captured and tagged with PSATs in Samoa between February 20 and March 18, 2017 under permit 1041072 of the Ministry of Natural Resources and Environment. Various rivers on Upolu Island were intensively fished for 4 weeks with an ELT60 II electrofishing device (Grassl, 2.2 kW) from the mouth to ~2 km upstream. In addition, a group of local fishermen targeted silver eels with scoop nets in the island interior (Vaigafa River, outflow of Afolilo dam). Most of the hundreds of eels caught by electrofishing were released immediately after capture, but large eels (~ 80–112 cm total length) and those showing obvious signs of silvering (8 individuals, 52–80 cm, mean 59 cm) were transported in a cooler to the Ministry of Agriculture and Fisheries in Apia and kept in an aerated circular tank (1.5 m diameter) under a flow-through water supply for up to 10 days. Eels were anaesthetized in a freshwater bath containing 40 mg/L metomidate (Aquacalm, Syndel Canada) until motionless (described in detail in Schabetsberger et al., 2013, 2015) for examination, removal of fin clips and tagging. Three *A. marmorata* large enough for tagging (>0.5 kg) were caught by electrofishing in Leafe River near Lotofaga Village at the South Coast of Upolu. An additional large *A. megastoma* (115 cm) was caught by local fishermen in the highlands (Table 1). Silvering was confirmed through visual inspection of body colouration and the relative size of the eyes (Okamura et al., 2007). The morphological assignment to species through the dentition of the upper jaw was validated through genetic analyses of the mtDNA control region gene following Schabetsberger et al. (2015; accession numbers MG828825-MG828828). PSATs (MiniPAT, Wildlife Computers) were attached externally using a bridle and programmed to surface after 3 and 5 months. The eels were transported 6.3 km offshore from Apia and released at noon on March 9, 2017 at 13.775833°S, 171.749517°W. After pop-up, the tags drifted for 3 days at the ocean surface before starting transmission.

TABLE 1 Eels tagged on Samoa 2017 with pop-up satellite archival transmitters. "Release" refers to preprogrammed attachment lengths. Eye index is described in Okamura et al. (2007)

Species	Capture date	Tag number	Total length (cm)	Weight (kg)	Capture position freshwater	Eye index	Release (months)	Surface	Surface position	Deployment (days)	Distance travelled (km)	Speed (km/day)
A. marmorata	Feb 27, 2017	169391	64.3	0.58	13.967267°S 171.852175°W	14.70	3	March 21, 2017	13.082°S 173.6445°W	12	219	18
A. marmorata	Feb 27, 2017	169392	67.6	0.72	13.967267°S 171.852175°W	14.64	3	March 15, 2017	13.7864°S 172.1202°W	6	40	-
A. marmorata	Mar 07, 2017	169393	80.3	1.18	13.977426°S 171.854916°W	15.65	5	March 29, 2017	11.6422°S 172.8898°W	20	267	13
A. megastoma	Mar 08, 2017	169395	115.0	3.28	13.989933°S 171.588505°W	11.86	3	March 25, 2017	12.7917°S 171.8416°W	16	110	7

All tags surfaced prematurely after 6–20 days on the animals. The tags popped up 110–267 km WNW (291°–356°) from the point of release. The westward SEC flowed at approximately 0.2 m/s around the pop-up area (Globcurrent, 2017; Figure 1). Two *A. marmorata* (169391, 169393; Figure 2a,b) and the *A. megastoma* (169395; Figure 2c) exhibited regular and distinct diel vertical migrations between shallow night-time (20:00–05:00 hr) and deep daytime (08:00–17:00 hr) depths, whereas one *A. marmorata* (169392) irregularly moved between the surface and 160 m depth (not shown). It was either preyed upon early after release or was not ready for migration and was therefore omitted from further analysis. Ascents and descents were completed within 2–3 hr. Median night-time migration depths were 179 and 182 m for the two *A. marmorata*, and 194 m for the *A. megastoma*, corresponding to 23.0 and 22.3°C, respectively. The two *A. marmorata* increased their median daytime migration depths from 557 and 625 m after release to 787 and 793 m depth before pop-up of the tag, corresponding to a decrease of ambient daytime temperature of 7.6 to 5.4°C and from 6.6 to 5.6°C, respectively. The larger *A. megastoma* increased daytime depth from 634 to 809 m resulting in a temperature decrease from 6.8 to 5.6°C. Hence migration depths were similar for the two species and the wide range of body weights, although the lighter two *A. marmorata* moved approximately 10 m shallower than the *A. megastoma* during night and day (Table 1; Figure 2).

Both sexes of *A. marmorata* may migrate at almost identical depth in the ocean, although further evidence is needed to prove this hypothesis: Female *A. marmorata* grows larger than 2 m and may attain weights of more than 25 kg (Froese & Pauly, 2017; Machazek, 2017; Williamson & Boëtius, 1993). However, during

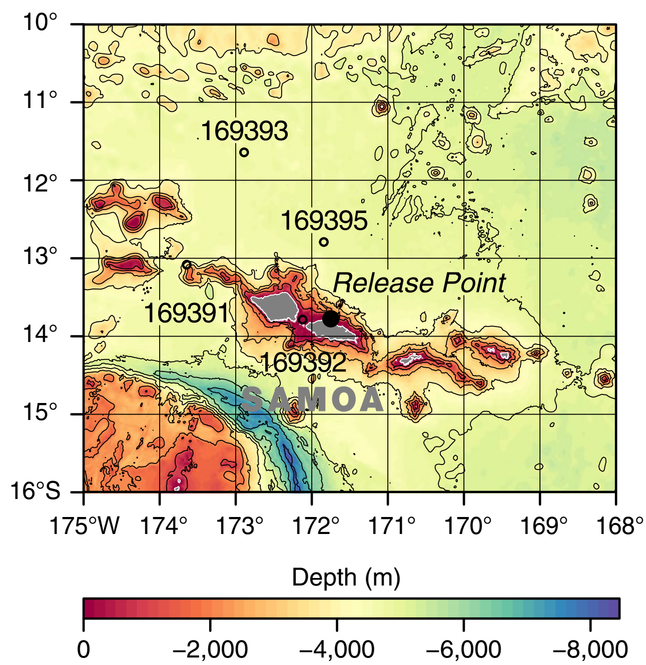

FIGURE 1 Pop-up locations of satellite tags put on three *A. marmorata* (169391–169393) and one *A. megastoma* (169395) from Upolu Island, Western Samoa

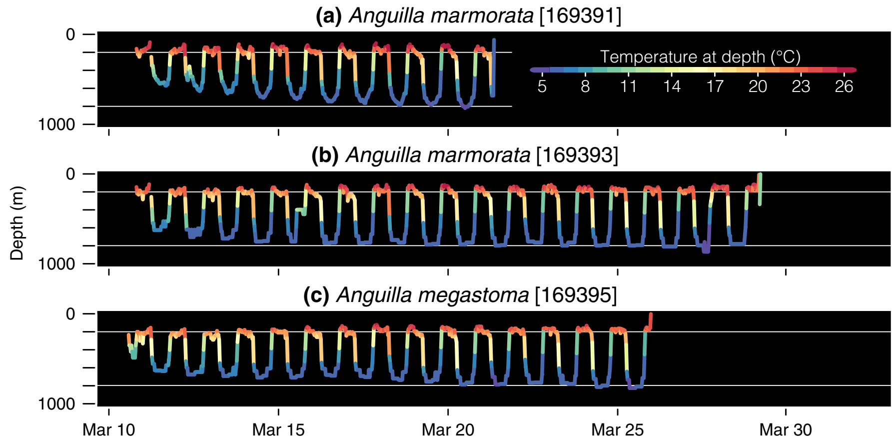

FIGURE 2 Diel vertical migrations of three eels tagged in Samoa in March 2017. Horizontal white lines indicate 200 and 800 m depths

the sampling in Samoan rivers, the majority of silver eels caught were only around 60 cm long and weighed less than 1 kg, although a number of large resident, probably female eels, exceeding 1 m total body length, were caught. Although it was not possible to sex these eels, they may have been males except for the 80 cm individual that could have also been a female. At dawn, small and large eels descended within 2–3 hr from around 180 m depth and 23°C to 800 m and 6°C. This would allow the eels to avoid visually oriented predators by migrating at low light levels during day and night (Schabetsberger et al., 2013). There is probably little difference for a 60 and a 120 cm eel in its susceptibility to oceanic predators, so they may both migrate at sufficiently low light levels where they remain undetected by most predators. In addition, little differences in diving behaviour between *A. marmorata* and *A. megastoma* were found, confirming earlier results from Vanuatu (Schabetsberger et al., 2013, 2015). All previously recorded and new trajectories showed similar migration depths during day and night with avoidance of the top 80 m as well as rapid ascents and descents during dusk and dawn, respectively.

It remains unknown whether predation or tag loss were responsible for premature release of the PSATs. Potential predators like sharks, swordfish, marlin and large tuna are caught in the area where the tags popped up (Western and Central Pacific Fisheries Commission, 2017). On the other hand, the tag attachment technique applied (Westerberg method) trades off a higher loss rate of tags (Økland, Thorstad, Westerberg, Aarestrup & Metcalfe, 2013) against a minimal invasion of the eel's body. For the three diel trajectories shown in Figure 2, all tags ascended during day or dusk, which could indicate predation by a visually hunting predator. Swimming performance of the two eels of < 1 kg body weight may have been impaired by the tags (Burgerhout et al., 2011; Methling, Tudorache, Skov & Steffensen, 2011), although the smallest eel (64 cm) exhibited a similar diel vertical migration trajectory as the largest (115 cm).

Subtracting the westward drift of the tags after pop-up, the eels still headed into a northern to northwestern direction. Assuming that they return to the place where they hatched, they could not have been transported to Samoa within the westward SEC. They also did not circle the island to reach waters on the south coast of the island. By bad luck, the northwest pointing tracks were too short to conclude that they had once reached the island within the eastward SECC. Around Samoa, the flow patterns and strengths of the two currents vary with season and ENSO events (Domokos, 2009). During a 2016 cruise of the University of Tokyo, a small *A. marmorata* leptocephalus (7.8 mm) was caught just north of American Samoa (Kuroki et al., unpublished data). Hence eels from the archipelago may not engage in long distance migrations, which would be similar to some Indonesian species (Aoyama, Wouthuyzen, Miller, Inagaki & Tsukamoto, 2003) and may spawn within local eddies developing from horizontal sheer between the two major current systems that could take the larvae back to the Samoan islands (Domokos, Seki, Polovina & Hawn, 2007). More tagging experiments are needed to confirm or exclude whether Samoan eels are heading northwest for spawning.

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